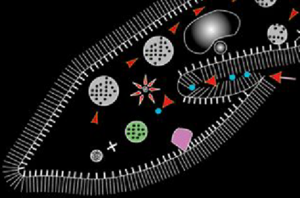
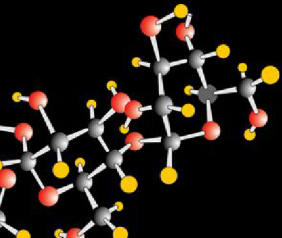


What is Life?

How Chemistry Becomes Biology



ADDY PROSS

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CONTENTS

PROLOGUE

> 'I spent the afternoon musing on Life. If you come to think of it, what a queer thing Life is! So unlike anything else, don't you know, if you see what I mean.'
>
> PG Wodehouse

The subject of this book addresses basic questions that have transfixed and tormented humankind for millennia, ever since we sought to better understand our place in the universe—the nature of living things and their relationship to the non-living. The importance of finding a definitive answer to these questions cannot be overstated—it would reveal to us not just who and what we are, but would impact on our understanding of the universe as a whole. Has the universe been fine-tuned to support life, as implied by proponents of the so-called anthropic principle? Or, to take a more Copernican view of man's place in the universe, 'is the human race just a chemical scum on a moderate-sized planet', as argued by Stephen Hawking, the noted physicist? A wider conceptual gulf would be hard to conceive.

Some 65 years ago another renowned physicist, Erwin Schrödinger, wrote a book whose catchy title *What is Life?* directly addressed the issue. In the opening lines of that book Schrödinger wrote:

> How can the events in space and time which take place within the spatial boundary of a living organism be accounted for by physics and chemistry? The preliminary answer . . . can be summarized as follows: The obvious inability of present-day physics and chemistry

> to account for such events is no reason at all for doubting that they can be accounted for by those sciences.

Sixty-five years have passed but despite the enormous advances in molecular biology in those years, illuminated by a long list of Nobel prizes, we continue to struggle with Schrödinger's simple and direct question. And a struggle it is. Carl Woese, one of the leading biologists of the twentieth century, has recently gone as far as to claim that the state of present-day biology is reminiscent of that of physics at the turn of the twentieth century, before Albert Einstein, Niels Bohr, Erwin Schrödinger, and the other great twentieth-century physicists totally revolutionized the subject; that the time for biology's revolution has finally come. Strong sentiments indeed! What is no less remarkable is that modern biology appears to be happily meandering along its current mechanistic path with most of its practitioners indifferent, if not oblivious, to the shrill cry for reassessment.

Yes, it is true that in this modern era we know unequivocally that there is no *élan vital*, that living things are made up of the same 'dead' molecules as non-living ones, but somehow the manner in which those molecules interact in a holistic ensemble results in something very special—us, and every other living thing on this planet. So, paradoxically, despite the profound advances in molecular biology over the past half-century, we still do not understand what life is, how it relates to the inanimate world, and how it emerged. True, over the past half-century considerable effort has been directed into attempts to resolve these fundamental issues, but the gates to the Promised Land seem as distant as ever. Like a mirage in the desert, just as the palm trees signalling the oasis seemingly materialize, shimmering on the horizon, they fade away yet again, leaving our thirst to understand unquenched, our drive to comprehend unsatisfied.

So what is the basis of this deeply troubling and persistent dilemma? To clarify in simplest terms where the problem lies, consider the following hypothetical tale: you are walking through a field and you suddenly come across a refrigerator—a fully functional refrigerator in a field with some bottles of beer inside, all nicely chilled. But how could a refrigerator be working in the middle of a field, apparently unconnected to any external energy source, yet maintaining a cold interior? And just what is it doing there, and how did it get there? You take a closer look and you see a solar panel on its top, which is connected to a battery, which in turn operates the compressor that all fridges have in order to function. So the mystery of *how* the refrigerator works is resolved. The refrigerator captures solar energy through the photovoltaic panel, so it is the sun that is the source of energy that operates the refrigerator and enables it to pump heat from cold to hot—in the opposite direction to the one that normally governs heat flow. Thus, despite Nature's drive to equalize the temperature inside and outside the cabinet, in this physical entity that we call a 'refrigerator', there exists a functional design that enables us to keep our food and drinks at a suitably low temperature.

But the mystery of how it got there in the middle of the field remains. Who put it there? And why? Now if I told you that no one put the refrigerator there—that it came about spontaneously through natural forces, you would react in total disbelief. How absurd! Impossible! Nature just doesn't operate like that! Nature doesn't spontaneously make highly organized far-from-equilibrium, purposeful entities—fridges, cars, computers, etc. Such objects are the products of human design—purposeful and deliberate. Nature, if anything, pushes systems *toward* equilibrium, toward disorder and chaos, *not* toward order and function. Or does it?

The simple truth is that the most basic living system, a bacterial cell, is a highly organized far-from-equilibrium functional system, which in a thermodynamic sense mimics the operation of a refrigerator, but is orders of magnitude more complex! The refrigerator involves the cooperative interaction of, at most, several dozen components, whereas a bacterial cell involves the interaction of thousands of different molecules and molecular aggregates, some of enormous complexity in themselves, all within a network of thousands of synchronized chemical reactions. In the case of the fridge, the function is obvious—to keep the beer or whatever else is in the cabinet cold by pumping heat from the cold interior to the hotter exterior. But what is the function of the bacterial cell with its organized complexity? Its function can be readily recognized simply by observing its action. Just as the function and workings of the refrigerator can be uncovered by inspecting its operation, so the cell's function—its purpose if you like—can be revealed by seeing what it does. And what do we see? Every living cell is effectively a highly organized factory, which, like any man-made factory, is connected to an energy source and power generator that facilitates its operation. If the energy source is cut off the factory ceases to operate. This miniature factory takes in raw material, and through the utilization of power from the factory's power generator, converts those raw materials into the many functional components, which will then be assembled to produce the factory's output. And what is that output? What does this highly elaborate nano-factory produce? More cells! Every cell is ultimately a highly organized and efficient factory for making more cells! The Nobel biologist Francois Jacob expressed it rather poetically: ‘the dream of every cell, to become two cells’.

And here precisely lies the life problem. Just as the likelihood of a functional fridge—cabinet, energy collector, battery, compressor, gas—spontaneously coming together naturally seems inconceivable, even if its parts were all readily available, the likelihood for the spontaneous formation of a highly organized far-from-equilibrium miniature chemical factory—a nano-factory—also seems inconceivable. It is not just common sense that tells us that highly organized entities don’t just spontaneously come about. Certain basic laws of physics preach the same sermon—systems tend toward chaos and disorder, not toward order and function. No wonder several of the great physicists of the twentieth century, amongst them Eugene Wigner, Niels Bohr, and Erwin Schrödinger, found the issue highly troublesome. Biology and physics seem contradictory, quite incompatible. No wonder the proponents of Intelligent Design manage to peddle their wares with such success!

The paradox inherent in the very existence of a living cell has profound consequences. It means that the issue of life’s emergence is not just some esoteric activity of historical interest, analogous to an individual seeking to uncover his family tree. Until the paradox associated with life’s emergence is resolved, we will not understand what life is. And, as final confirmation that understanding has been achieved, we will be able to translate that understanding into a coherent proposal for the synthesis of a chemical system that we would categorize as ‘living’.

The purpose of this book is to reassess this enthralling subject and demonstrate that a general law that underlies the emergence, existence, and nature of all living things can now be outlined. I will argue that thanks to a newly defined area of chemistry, termed by Günter von Kiedrowski 'Systems Chemistry', the existing chasm separating chemistry and biology can now be bridged, and that *the central biological paradigm, Darwinism, is just the biological manifestation of a broader physicochemical description of natural forces.* This admittedly ambitious attempt to merge biology into chemistry rests on the idea that there is a kind of stability in nature that has been previously overlooked, one I have termed *dynamic kinetic stability*. Amalgamating that form of stability into a Darwinian view of evolution leads to a *general (or extended) theory of evolution,* encompassing both biological *and* pre-biological systems. Interestingly, Darwin himself already understood that a general principle of life is likely to exist. In a letter to George Wallich in 1882 he wrote:

> I believe that I have somewhere said (but cannot find the passage) that the principle of continuity renders it probable that the principle of life will hereafter be shown to be part, or consequence, of some general law…

This book is an attempt to demonstrate that Charles Darwin in his genius and far-sightedness was right, and that such a theory can now be formulated. I will attempt to show that chemistry, the science that bridges physics and biology, can provide answers, still in part incomplete, to these fascinating questions. Achieving a better understanding of what life is may not only tell us who and what we are, but will hopefully provide greater insight into the very nature of the cosmos and its most basic laws.

In writing this book, I have benefited from interaction with and input from many people. In particular I wish to thank Jan Engberts, Joel Harp, Sijbren Otto, and Leo Radom for detailed comments and criticisms of an early draft, to Mitchell Guss, Gerald Joyce, Elio Mattia, Elinor and David O'Neill, and Peter Strazewski for general comments, and to Gonen Ashkenasy, Stuart Kauffman, Günter von Kiedrowski, Ken Kraaijeveld, Puri Lopez-Garcia, Meir Lahav, Michael Meijler, Kepa Ruiz-Mirazo, Robert Pascal, Eörs Szathmáry, Emmanuel Tannenbaum, and Nathaniel Wagner for valuable discussions that have contributed to my understanding, and to Nella, my wife, for many discussions and for her critical eye and insights which have greatly impacted on the text. Finally I owe a very special debt to my Editor at OUP, Latha Menon. Her profound scientific understanding and remarkable editorial skills ensured the text did not stray unnecessarily into stormy biological waters and contributed greatly to its final form. Of course any errors that remain are purely my own.

1

Living Things are so Very Strange

Living and non-living entities are strikingly different, yet somehow the precise manner in which these two material forms relate to one another has remained provocatively out of reach. Life's evident design, in particular, stands out, a source of endless speculation. The creativity and precision so evident in that design is nothing less than spectacular. The structural intricacy of the eye with its iris diaphragm, the lens with its variable focal length capability, the light-sensitive retina connected to the optic nerve for information transmission, is the classic example of nature's design capability. But that's just the very tip of the design iceberg. Due to the remarkable advances in molecular biology over the past six decades we have discovered that nature's design capabilities can be immeasurably greater. Take the ribosome, for example. The ribosome is a tiny organelle present in all living cells in thousands of copies that manufactures the protein molecules on which all life is based. It effectively operates as a highly organized and intricate miniature factory, churning out those proteins—long chain-like molecules—by stitching together a hundred or more amino acid molecules in just the right order, and all within a few seconds. And this exquisitely efficient entity is contained within a complex chemical structure that is just some 20–30 nanometres in diameter—that's just 2–3 millionths of a centimetre! Think about that—an entire factory, with all the elements you'd expect to find in any regular factory, but within a structure so tiny it is completely invisible to the naked eye. Indeed, for elucidating the structure and function of this remarkable organelle, Ada Yonath from the Weizmann Institute, Israel, Venkatraman Ramakrishnan from the Laboratory of Molecular Biology at Cambridge, and Thomas Steitz from Yale University were awarded the 2009 Nobel Prize in Chemistry.

No less impressive than life's extraordinary design capabilities is its breathtaking diversity, a perpetual source of inspiration. Red roses, giraffes, butterflies, snakes, towering redwoods, whales, fungi, crocodiles, cockroaches, mosquitoes, coral reefs—the mind boggles at nature's spectacular and unmitigated creativity. Literally millions of species, and that's before we have even touched upon the hidden kingdom, the bacterial one. That invisible kingdom is itself a source of overwhelming, almost incomprehensible diversity, one that is just beginning to come to light. But life's design and diversity are just two characteristics out of a wider set that serve to compound the mystery and uniqueness of the life phenomenon. Some of life's characteristics are so striking you don't have to be too observant to notice them. Take life's independent and purposeful character, for example. You can't miss it. My granddaughter certainly didn't, even when she was just 2 years old. She clearly appreciated the distinction between a real dog and a realistically looking toy one. She happily played with toy ones, but was afraid of real ones, not being quite sure what surprise a real one might have in store for her. She learnt very quickly that a toy dog's behaviour was predictable, while a real one had a mind of its own.

But there are other characteristics of life that are less obvious at first sight, though very obvious to the scientist in the lab, which also continue to tantalize and are in need of explanation. So if we want to understand what life is, where better to begin our journey of discovery than by considering the characteristics that distinguish living things from non-living ones. Ultimately, understanding life will require us to understand those special properties, both in themselves and how they came about. Some, as we will see, may be understood in Darwinian terms, though the debate about those explanations continues. Others, however, cannot be understood that way, and their very essence continues to trouble us. They certainly troubled the great physicists of the twentieth century, amongst them Bohr, Schrödinger, and Wigner, since several of life's characteristics appear to undermine the most basic tenets of modern science. Yet other characteristics have led some modern biologists to throw up their arms in despair. How else to interpret the recent description of life by Carl Woese: 'Organisms are resilient patterns in a turbulent flow—patterns in an energy flow.'[1] That obscure remark, verging on the mystical, comes from one of the leading molecular biologists of the twentieth century—the discoverer of the Archaea, the third kingdom of life. Woese's statement reaffirms how problematic the life issue continues to be.

So we have here an intriguing phenomenon—biologists, the scientists who devote themselves to the study of living systems, and who possess a deep appreciation of life's complexity, having successfully probed many of its key components, remain mystified by what life is, and physicists, with their deep understanding of nature's most fundamental laws, are no less confused. Both continue to struggle with the nature of life question and we can only conclude that the 3,000-year 'what is life' riddle remains that—a riddle. Let us then begin our journey of discovery by briefly considering each of the characteristics that makes life special, so different to inanimate matter, and discuss what makes those characteristics so strange, so very strange.

Life's organized complexity

Living things are highly complex. In fact the very first line in Richard Dawkins classic text *The Blind Watchmake*r begins with the remark that we animals are the most complicated things in the universe.[2] That attention-grabbing line on its own is enough to drive home the realization that we animals must be something very special. But what is it about us living things that makes us so complicated, or, to use the more scientific word, so complex? And what does the term 'complex' actually mean? At the risk of sounding circular, one could say the term 'complexity' is itself complex, not readily defined, and attempts over the years to quantify the concept have not proven too successful, at least not within a biological context. Let us then focus on the crucial aspect of complexity as it pertains to biology—the highly organized nature of living things.

In the non-living world it is easy to find examples of complexity. The shape of a boulder is certainly complex and in that case the complexity derives from its irregular shape. To describe its shape with precision would require information—the more irregular the shape, the more information would be required. The physical location of each point on the boulder's surface would need to be specified in some manner. The important point, however, is that we understand that the boulder's irregularity, the source of its complexity, is *arbitrary*. It could have been any one of a zillion other irregular shapes and the boulder would still be a boulder. It is not the particular irregularity of that boulder that makes it a boulder. By contrast, in the living world complexity is not arbitrary, but highly specific. Even the slightest structural change to that organized complexity may have dramatic consequences. For example, even a single change in a human's DNA sequence, one out of 3 billion units, may potentially lead to thousands of genetic diseases, such as sickle cell anaemia, cystic fibrosis, and Huntington's disease. Small changes to life's complex structure may well undermine the viability of that living system, and in extreme cases the living system may be living no longer.

What is quite extraordinary and hard to comprehend is that such organized complexity extends to entities as small as a bacterial cell, just one thousandth of a millimetre across. In many respects the bacterial cell operates like a highly sophisticated nano-scale factory, nano-scale meaning the factory components are of molecular size, that is, of the order of one millionth of a millimetre in length. That nano-factory involves a highly complex but integrated network of chemical reactions, which extract energy from the environment, storing it in a number of different chemical forms for use in the biosynthesis of essential cellular building blocks; the control and regulation of the cellular machinery to ensure proper function; the list goes on and on. The cell is not just a master chemist, but a master physicist as well. That microscopic entity uses every mechanical trick in the tradesman's book—pumps, rotors, motors, propellers, even scissors to snip here and there, all at nano-scale, to ensure cellular functions are carried out expeditiously, as required by the cell's 'purpose'.

But that undisputed complexity, so different to inanimate complexity, is puzzling and raises two immediate questions. How is the organized complexity of the cell maintained, and how did it come into being? Organized complexity and one of the most fundamental laws of the universe—the Second Law of Thermodynamics—are inherently adversarial. We won't go into the Second Law in any detail at this stage, but a very simple (and limited) expression of the Second Law is the statement that organized systems spontaneously tend toward disorganization, toward disorder. Nature prefers chaos to order, so disorganization is the natural order. Take a pack of cards in some highly ordered sequence—say four aces, followed by four kings, then by four queens, and so on, down to four twos—shuffle the deck and the sequence invariably becomes disordered. You'll almost certainly end up with some random sequence. The likelihood of some other highly ordered sequence being formed is very slight. That's the Second Law in action. The state of my desk at any point in time is further proof, if it were needed. No matter how often I tidy my desk, it always seems to quickly revert to its preferred disorganized state. Within living systems, however, the highly organized state that is absolutely essential for viable biological function is somehow maintained with remarkable precision. There is even a biological term for the phenomenon whereby that organized state is maintained—*homeostasis,* from the Greek meaning 'standing still'.

So how is the cell's organized complexity maintained, if a central law of physics and chemistry is constantly operating to undermine it? The answer to this first question is relatively easy, at least within the context of the Second Law: the living cell is able to maintain its structural integrity and its organization through the continual utilization of energy, which is in fact part of the cell's *modus operandi*. That's why we have to eat regularly to survive—to furnish the body with the necessary energy to enable the body's regulatory mechanisms to maintain life's organized homeostatic state. That also explains how my desk gets to be tidy occasionally—I expend energy now and then to restore a semblance of order whenever my desk has become too disordered to be functional. So there is no thermodynamic contradiction in life's organized high-energy state, just as there is no contradiction in a car being able to drive uphill in opposition to the Earth's gravitational pull, or a refrigerator in maintaining a cool interior despite the constant flow of heat into that interior from the warmer exterior. Both the car driving uphill and the refrigerator with its cold interior can maintain their energetically unstable state through the continual utilization of energy. In the car's case the burning of gasoline in the car's engine is the energy source, while in the case of the refrigerator, the energy source is the electricity supply that operates the refrigerator's compressor. In an analogous manner, energetically speaking, the body can maintain its highly organized state through the continual utilization of energy from some external source—the chemical energy inherent within the foods we eat, or, in the case of plants, the solar energy that is captured by the chlorophyll pigment found in all plants. No fundamental problem there.

But how the initial organization associated with the simplest living system came about originally is a much tougher question. Despite the widespread view that Darwinian evolution has been able to explain the emergence of biological complexity, that is not the case. Darwinian evolution *is* able to broadly explain how a simple single-cell living organism—what one might call the microbial Adam—eventually became an elephant, a whale, or a human. But Darwinian theory does not deal with the question how that primordial living thing was able to come into being. The troublesome question still in search of an answer is: *how did a system capable of evolving come about in the first place?* Darwinian theory is a *biological* theory and therefore deals with *biological* systems, whereas the origin of life problem is a *chemical* problem, and chemical problems are best solved with chemical (and physical) theories. Attempting to explain chemical phenomena with biological concepts is methodologically problematic for reasons we will discuss subsequently, and in some sense that approach may have been partly responsible for the conceptual dead-end the subject seems to have found itself in.

Significantly, Darwin himself explicitly avoided the origin of life question, recognizing that within the existing state of knowledge the question was premature, that its resolution at that time was out of reach. So the question of how the first microscopic complexity came into being remains problematic and highly contentious. Did a cellular precursor to that exquisitely complex miniature factory that is the living cell come together purely by chance, by the various bits and pieces randomly linking up in precisely the right manner? Not very likely. To draw on an analogy popularized by Fred Hoyle, the well-known astronomer (though famously misapplied), the likelihood of such an event would be similar to that of a whirlwind blowing through a junkyard and assembling a Boeing 747. Life's organized complexity *is* strange, very strange. And how it came about is even stranger.

Life's purposeful character

There is another facet to the organized complexity of living systems that has been strikingly evident to humankind for thousands of years—life's purposeful character. That purposeful character is so well defined and unambiguous that biologists have come up with a special name for it—teleonomy. The 'teleonomy' word was introduced about half a century ago to distinguish it from the 'teleology' word with its cosmic implications, and we will have more to say about how these terms relate to one another in chapters 2 and 8. At this point let us simply note that teleonomy, as a biological phenomenon, is empirically irrefutable. The term simply gives a name to a pattern of behaviour that is unambiguous—all living things behave as if they have an agenda. Every living thing goes about its business of living—building nests, collecting food, protecting the young, and, of course, reproducing. In fact, within the biological world that's how we broadly understand and predict what goes on. We understand a mother nurturing her offspring. We know better (or should know better) than to step between a mother bear and her cub. We understand two males competing for a female; we understand a stray cat rummaging through a trash bin. We intuitively understand the operation of the biological world, including, of course, all human activity, through life's teleonomic character.

In the non-living world, by comparison, understanding and prediction are achieved on the basis of quite different principles. No teleonomy there, just the established laws of physics and chemistry. You throw a ball into the air and you want to know where it will land? The precise landing point is not calculated by considering the ball's purpose. The ball has no purpose. Only Newton's laws of motion will provide the answer. You mix some chemical compounds together and you want to know whether they will react and what materials are likely to form? You consider and apply the appropriate chemical rules, depending on the nature of the problem, and you come up with a prediction. No purpose, no agenda—just inviolate laws of nature. The notion of purpose within the inanimate world was laid to rest with the modern scientific revolution of the seventeenth century.

The very existence of teleonomy however, leads us to a strange, even weird, reality: in some fundamental sense we are simultaneously living in *two* worlds each governed by its own set of rules—the laws of physics and chemistry within the inanimate world and the teleonomic principle that dominates the biological world. Indeed, given the existence of two distinct worlds we find ourselves interacting quite differently with each of those worlds. Consider our interactions within the inanimate world. We move from one place to another as required, we try to keep warm when it is cold, to keep dry when it rains, we build a physical enclosure to live in to protect ourselves and to facilitate life's activities. We learn to climb up slopes despite the gravitational force, to generate fire for cooking, to manufacture tools for improved function, to plug a hole in a leaking roof, to avoid physical injury, and so on. All of our interactions with the inanimate world are based on the recognition that there are certain laws of nature, described primarily by the physical sciences, which govern the manner in which the universe functions.

Understanding those laws helps us to keep out of trouble, and, even better, enables us to take advantage of nature's *modus operandi,* thereby allowing us to further life's goals more effectively. In fact that is the essence of technology—creating systems that exploit nature's laws in a beneficial manner.

Our interactions with the living world, however, are of a quite different kind and are much more complex. As we have already noted, the living world is teleonomic—all living creatures are busy furthering their agenda, and in doing so they must take into account the particular agenda of other living beings. Accordingly, living things create a web of interaction with other living things, making many of our actions mutually dependent. Consider us humans. We communicate and deal with members of our immediate family, with our work colleagues, with other members of our society in an endless series of interactions—by spoken and written word, more subtly without words, by gestures. Some of these interactions are cooperative in nature, some competitive. Ordering a cappuccino at the local café or going to the hairdresser exemplify cooperative interactions, while bargaining in the market over the price of some article or fending off an intruder are competitive interactions. Our lives involve endless interactions of both types as we individually pursue our 'purpose' and get on with life's goals. We also continually interact with a wide range of non-human life forms. Our need for sustenance is satisfied by feeding on other living creatures, both animal and vegetable, and we protect ourselves against the life forms that threaten us, whether multicellular creatures—bears, sharks, snakes, mosquitoes, or spiders—or from single-celled creatures—bacteria of endless variety. Many non-human interactions are cooperative—the pet dog that we feed which provides companionship and warns us of intruders, the billions of bacteria in our gut to which we happily provide room and board, and who return the favour by assisting us with our digestion and more.

We are so used to this dual state of affairs—matter that exists in both living and non-living forms—that much of what has been said here is glaringly obvious and very much taken for granted. Familiarity breeds acceptance, if not contempt. But if I were to tell you that on Mars all material forms obeyed one set of principles, yet on Venus they followed another different set, we would all be startled. How could that be? Two material forms broadly following two distinct sets of principles? The fact that here on Earth there exist two material forms that are distinct in character, are governed by different organizational principles, which comfortably coexist, and in fact continually undergo material interchange—non-living matter is continually transformed into living matter, and vice versa—demands some explanation. How can this stark duality in the nature of matter exist and what does it signify?

Before going any further let me be unequivocal and make one point perfectly clear: it goes without saying that within the teleonomic world the same underlying rules of physics and chemistry that govern the inanimate world are still operative. No doubt about that. When a person falls off a ladder the law of gravity is operative in exactly the same way as when a bag of sugar falls off a shelf. But in many respects those natural laws are of little or no use when applied to living systems. The law of gravity and the Second Law of Thermodynamics aren't particularly helpful when you are arguing with a neighbour over some property issue, or when seeking to renew an expired licence, or when fending off an aggressive dog. Within the living world those same laws have little predictive value—they are certainly operative but appear to be of only secondary importance. The underlying rules of physics and chemistry have somehow been taken hostage and overwhelmed by another more dominant set of principles. If you want to predict the actions of a crouching lion preparing to pounce on an unsuspecting zebra, a mother tending to her young, a lawyer planning to sue you on behalf of an aggrieved client, or indeed any other teleonomic action, the laws of physics and chemistry are of little use. Neither a physicist nor a chemist will be able to offer a useful prediction. If you want to make a prediction about some impending event in the living world, go ask a biologist, psychologist, economist, lawyer, or other teleonomic specialist, depending on the nature of the question.

Not surprisingly then, much of human knowledge and understanding involves the teleonomic, rather than the physicochemical world. Consider for a moment any large university with its many faculties, each dedicated to a particular field of enquiry. The faculties of humanities, commerce, and law (and to a lesser extent, the faculty of medicine), are dedicated to the teleonomic world with its many manifestations. There is just one faculty—the faculty of natural sciences—that dedicates itself specifically to the study of the natural world, and even within this faculty we find the department of biological sciences grappling awkwardly with the teleonomic reality, uncertain as to how the paradox of a dichotomic world can and should be resolved. That, then, is the undeniable, yet so far inexplicable reality—the laws of nature, as primarily articulated in the subjects of physics and chemistry, offer few insights into the predominantly teleonomic world of which we find ourselves very much a part.

Intriguingly, despite the irrefutable teleonomic character of living systems, some biologists still have difficulty in coming to terms with that extraordinary character. The troublesome 'purpose' word, now sanitized and repackaged into the scientifically acceptable 'teleonomy' word, still leaves many modern biologists squirming uncomfortably. The scientific revolution's overthrow of 2,000 years of teleological thinking has left biologists anxious and unwilling to accept even the slightest vestige of that earlier, misplaced way of thinking. But there is no denying the teleonomic principle. The evidence supporting it is simply overwhelming, all around, literally endless, and cannot simply be dismissed out of hand.

In fact, it is intriguing to point out that those biologists who have argued against the concept of teleonomy, have, without realizing it, demonstrated their total faith in the principle by their everyday actions. Those scientists, like us all, actually stake their lives on its validity. Every time we get into a motor car, for example, we are betting our lives on teleonomy! Our purpose in getting into our car is to get to some destination, and to do so safely. On the roads we have to manoeuvre through an endless stream of vehicular metal—the other cars—careering about hither and yon, a real threat to life and limb. The consequences of a collision between any two metal hunks can be personally disastrous, yet we happily accept that risk day by day. Why? Because of teleonomy. We know that within every other metal hunk careering about, there is a driver whose purpose is identical to our own—to get to his destination in one piece! Though one occasionally comes across an erratic driver who seems to prove the exception to the teleonomic rule, for most of us, on most days, that teleonomic principle operates reliably and, as anticipated, we arrive at our destination safely. So those so-called disbelievers in teleonomy are actually silent and committed believers. The world we have to navigate our way through on a daily basis is composed of both biological and non-biological systems. When dealing with the non-biological world we intuitively apply the laws of physics and chemistry. But, consciously or unconsciously, no person would be able to get through a single day without continuous application of the teleonomic principle. No doubt whatever, in the living world, teleonomy, as a predictive and explanatory principle, is the way to go.

The fact that multicellular animals, like us, behave in a purposeful manner may not appear that surprising. After all, as already noted, we animals are highly complex—we possess a brain and nervous system so it might be argued that in us animals the teleonomic character is just a reflection of significant neural complexity. But here's the surprise. It is not just multicellular cognitive beings—humans, monkeys, camels, and the like, with a brain and central nervous system that manifest this teleonomic character. That character is also clearly manifest at the level of the single cell! Put a bacterium in a glucose solution in which the glucose concentration is variable and the bacterium 'swims' toward the high concentration region. That phenomenon is called chemotaxis. The bacterium, which utilizes the glucose's chemical energy to power its metabolic processes, is effectively going out for dinner, much like the crouching lion about to pounce on a zebra.

Of course a bacterial cell cannot swim in the conventional sense of the word. A simple bacterium such as *E. Coli* is powered by several flagella, which, depending on the direction of flagella rotation, enable the bacterium to direct its motion within the solution. If the solution contains nutrition, then the bacterium rotates the