Syracuse Scholar (1979-1991)

Volume 11
Issue 1 *Syracuse Scholar Spring 1991*

Article 7

3-21-1991

Life: what and how

Joseph D. Robinson

LIFE: WHAT AND HOW

JOSEPH D. ROBINSON

And the Lord God formed man of the dust of the ground, and breathed into his nostrils the breath of life; and man became a living soul.

—GENESIS

I collected the instruments of life around me, that I might infuse a spark of being into that lifeless thing that lay at my feet. . . . By the glimmer of the half-extinguished light, I saw the dull yellow eye of the creature open; it breathed hard, and a convulsive motion agitated its limbs.

—MARY SHELLY, ***Frankenstein***

THESE TWO IMAGES, of divine spirit and physical force bestowing life on inanimate matter, reflect both the range of popular conceptions that yet endure and the long history of those issues. The readily apparent differences between animate and inanimate objects, between the living and the dead, have suggested obvious explanations for those differences: life results from the addition to, the imposition on inanimate matter of some divine spirit or vitalizing force. For millennia efforts to understand life, to explain the living process, involved defining the criteria of life and identifying the spirits or forces giving rise to or underlying those criteria. What is life? An explicit answer to that question is not incorporated into our common fund of knowledge, is not an element of cultural literacy: it might thus seem the answer to that question remains a mystery. Yet in contemporary science, in biology, which is often defined as the science of living things, the question has apparently disappeared. Why that question no longer attracts scientific attention and what questions are pursued in its stead are the subjects of this essay. Before turning to the reasons for this, however, I will sketch the background of that question in terms of the two conceptions of spirit and force.

LIFE BESTOWED BY A VITAL SPIRIT

The account in Genesis is vividly evoked by Michelangelo's portrayal of the creation of Adam. There the two components meet, the inanimate material shape, crafted from the dust of the ground, and the vitalizing immaterial spirit, transmitted through the touch of God: the union of body and spirit form the living man. The immediate reasonableness of this account matches that striking image when the reverse of this transformation is considered, the transformation from life to death. Then the body of clay remains, inanimate when the spirit of life departs. The dead body differs in no grossly detectable physical qualities from the living organism; it differs only in the absence of the living spirit, imponderable, immaterial, yet conferring the ability to act, to move, to think. The criteria of life, then, are just those qualities that distinguish the living Adam from his dead body. And the spirit of life is that which is lost when those qualities disappear with death. Conversely, this spirit is what must be added to simple matter to bring forth the living man.

In the classical world this conception was elaborated on through the flowering of philosophical thought, with a range of distinctions and clarifications.[1] The spirit of life, as the psyche, was for Plato an immaterial substance that when joined to ordinary matter endowed it with those properties and actions characteristic of living bodies, such as movement and growth and reproduction. For Aristotle, the psyche conferred a dynamic state on matter, a rearrangement; the psyche enabled the faculties of life to be manifest, faculties arising from the essential organization that converts the potential to the actual.

Satisfaction with explanations depends in part on their congruence with general worldviews and in part on their ability to encompass the variety of phenomena considered to lie within their purview. As biological thought developed over the succeeding centuries both the recognized details and the perceived scope changed. The catalog of general properties ascribable to living organisms was not appreciably amended (although there were differing emphases placed on their relative importance), but a significant alteration in the context of the question prompted refinements and reformulations. In the classical era life was an attribute of macroscopic organisms, of people and dogs, trees and flowers, insects and worms. Moreover, life considered in terms of these animals and plants was an attribute expressed holistically: the organism as a whole was alive or dead. Although the functioning of particular parts and organs was recognized and described, life itself was a property of the total being.

By the middle of the nineteenth century, however, the formulation of the cell theory by Schleiden, Schwann, and others reordered this viewpoint, focusing attention on particular components of the organisms as living entities in their own right.[2] This new context for the question of what is life arose from an anatomical tradition that proceeded toward finer and finer detail, concentrating on organs constituting the living body, on tissues constituting the organs, on cells constituting the tissues. This progression was achieved through the development of the microscope, an instrument that also revealed a world of organisms previously invisible to science. The cell theory ultimately proclaimed that the fundamental unit of life is the cell: living beings exist as single-celled organisms or multicellular complexes. Indeed, it became apparent that even after the death of a complex organism—even after that irreversible event—parts of that body, the organs or tissues or cells, could still display various vital attributes. And in all cases the simplest survivable fragment manifesting the standard qualities of life was the cell.[3]

In the context of the cell theory the question of what is life can still be answered in the sense of Genesis, of Plato, of Aristotle, in terms of the spirit or psyche that animates the cell. A further biological problem is emphasized, however; a further role for spirit or psyche becomes prominent: the proper organization of the cells within the multicellular organisms. Indeed, these considerations dominated certain schools of

1. For an informative survey of changing conceptions of life-matter: T. S. Hall, *History of General Physiology*, 2 vols. (Chicago: University of Chicago Press, 1969).

2. Theodor Schwann, *Mikroskopische Untersuchungen über die Übereinstimmung in der Struktur und dem Wachstum der Tiere und Pflanzen* (Berlin, 1839); Matthias J. Schleiden, *Grundzüge der Wissenschaftlichen Botanik* (Leipzig, 1842).

3. The contrast between the life of the whole organism and the death of its component parts has attracted contemporary attention in the context of "brain death." When crucial brain cells have irreversibly lost their function while other cells (and organs) can be maintained by artificial means, the justification of various therapeutic choices may involve defining "death." Such a definition, however, is a matter of ethical choice and legal distinction, rather than a scientific issue.

embryologists and culminated in the characterization of particular principles endowed with the ability to guide the developmental process, such as the entelechy of Hans Driesch.[4] But despite the specific terminologies, the essential mechanism underlying the animate world remained for this tradition an intangible aspect of an immaterial world: the realm of vital principles, of vitalism.

4. H. Driesch, *The Science and Philosophy of the Organism* (London: A. C. Black, 1908).

The possibility that life represents or is a manifestation of a particular kind of matter (as a distinct category or through the action of a vital force on ordinary matter) was equally conceivable, equally arguable, in two particular contexts. One was the realm of organic chemistry. Analyses of living (or recently living) organisms by chemists of the eighteenth and early nineteenth centuries revealed a world of different and complex molecules that seemed to be formed only in living beings, that did not otherwise occur in the inanimate world, that could not then be synthesized by human artifice. A second and related possibility of life as a special sort of matter was argued from a close observation of cellular structure. When viewed through the microscopes of that time all cells seemed to be filled with a homogeneous gelatinous stuff, which came to be known as protoplasm, considered by some to be the ultimate embodiment of life, by others to represent the living composite of organic molecules. For either of these accounts of life—as a manifestation of organic molecules or of a particular, ordered, vital material, the protoplasm—a fundamental argument centered around the categorical distinction that living organisms were different from nonliving material and that this difference resulted from their particular composition.

Various schools of vitalism attached different emphases on life resulting from a vital spirit that transforms, organizes, and animates ordinary matter, or on life representing the specific consequences of a unique type of matter, organic or protoplasmic. The latter conceptions largely disappeared with demonstrations that the protoplasm is an inhomogeneous substance composed of identifiable molecules, organic chemicals that can nevertheless be synthesized in the laboratory. But arguments still persisted about the former conceptions characterizing life as the consequence of processes distinct from those in the physical world of inanimate objects. In the first half of this century the noted physicist Niels Bohr declared:

> *The existence of life must be considered as an elementary fact that cannot be explained, but must be taken as a starting point in Biology. . . . The asserted impossibility of a physical or chemical explanation of the function peculiar to life would be . . . analogous to the insufficiency of the mechanical analysis for the understanding of the stability of atoms.*[5]

5. N. Bohr, "Light and Life," *Nature* 131 (1933): 458–60.

The identification of a special and distinct vital force or principle, even when assigned to the realm of the natural world, is little different from conceptions of earlier vitalists whose animating spirits could not be further identified, explained, defined, or related to the inanimate world. Such an approach must confront the ability of competing explanations to account adequately for those same phenomena within the context of the scientific worldview, and without the invocation, ad hoc, of additional, particular vital forces.

LIFE INDUCED BY A NATURAL FORCE

In contrast to those views of life resulting from vital spirits or materials, an alternative view depicts life resulting from the imposition on ordinary matter of ordinary forces of some designated kind. This conception is reflected in the quotation from *Frankenstein*. An earlier passage in that novel asserts that the specific means by which Dr. Frankenstein endowed matter with the qualities of life would not be specified, and the term "spark" in the lines quoted should be viewed metaphorically. In a succession of vivid motion pictures, however, the graphic image is unequivocally fixed in our consciousness: the flash of the electrical discharge jolting that inanimate body into the stirrings of life. These depictions follow a tradition of explanation.

In the physical worldview of two centuries ago, heat, light, electricity, and magnetism occupied a particular niche, representing entities viewed sometimes as fundamental chemical substances, sometimes as subtle imponderable fluids distinct from ordinary matter, sometimes as composites of a more basic stuff such as the ether. Of these, heat, and more often electricity, were considered candidates for that animating force capable of vitalizing matter. Thus William Stukeley wrote: "all motion, voluntary and involuntary, generation, even life itself, all the operations of the vegetable kingdom . . . are owing to the activity of this electric fire. . . ."[6]

6. W. Stukeley, "The Philosophy of Earthquakes," *Philosophical Transaction of the Royal Society*, no. 497 (1750): 731–50.

Subsequent developments in biology, chemistry, and physics, however, made it unlikely that the principle of life could be identified with, or attributed to, some general force acting on inanimate matter. Although the relevance of chemical and physical processes to explaining the specific phenomena of the biological world became evident, it also became clear that the traditional catalog of attributes distinguishing the animate world could not be assigned to the actions of a single force, such as an electric spark or current, any more than it could be to the presence of some specifically organic interaction between molecules.

WHAT SHOULD BE EXPLAINED

The adequacy of explanations, of providing answers to particular questions, must be evaluated within the framework of what those explanations are required to accomplish. If answering the query of what is life requires merely a coherent formulation encompassing the particular phenomena selected, an explanation in terms of a vital spirit that animates inanimate matter can be sufficient. Indeed, if consistency with a scheme of spiritual beliefs is paramount, such explanations are preeminently satisfactory within that worldview. But if the acceptable answer must represent a coherent formulation within the scheme of scientific knowledge—consistent with the web of laws and hypotheses and principles and generalizations linked to experiment and observation, expressly avoiding the intrusion of interventions outside the natural realm—the class of vitalistic, supernatural explanations is categorically unsatisfactory.

In the context of scientific explanations the second alternative, that life results from some natural, physical force acting on inanimate matter, also fails. No known force in the natural world seems adequate to that task, no scientific formulation implies the necessary properties, no experimental evidence suggests a mechanism by which simple addition to matter produces the living organism.

A quite different line of argument, one with roots in certain strains of vitalism, describes the stirrings of life from inanimate matter as an "emergent" process, reflecting the highly complex organization of even the simplest microbe. However, just what that term means, just what explanatory burden it is intended to carry, is not clear. In the most straightforward interpretation, emergence can refer to the ability to perform new functions, to the availability of new capacities, that results when simple parts are assembled into certain complex structures. Thus, iron bars may be joined to form a bridge longer and stronger than any single unit, or shaped into gears and bearings and weights and a pendulum to form a clock whose structure and mechanism and principles remained unknown for millennia after the crude properties of iron bars were recognized. From the inanimate world such complex artifacts as automobiles and computers and pianos may be fashioned, artifacts whose characteristics may seem far removed from those of their components, displaying properties not easily inferred in full from understanding ordinary principles of chemistry and physics. Yet none of these artifacts is inherently mysterious. Their essential properties are explicable at successive levels of organization: the clock, for example, in terms of the law of the pendulum, the mechanics of gears, plus the logic of the organization; the components in terms of the structural properties of the metal; and those in terms of the chemical and physical properties of matter. Attributing the specific capabilities and functioning of a clock to the emergent properties inherent in its complexity may be a convenient mode of expression, but as a form of general explanation it seems trivial, adding nothing beyond the commonplace recognition that assembled parts may do more than those parts unassembled. Arguments about whether a whole is more than the sum of its parts ultimately devolve into quibbles about what is more, and how much or little potential is granted to those parts.

So in the biological world the significance of emergence seems to lie in the intent of those using the term: on whether their interest is in considering the particular properties inherent in the organism (or some holistic entity like the ecosystem or the world) or in considering how the component parts interact to give rise to those complex entities with their unique attributes. The latter course, under the label of "reductionism," is frequently praised as a mode of deeper understanding and castigated for its inattention to the integrated properties of the whole. It seems that such debates will not be settled soon. More to the point here is the question of whether holistic concerns, such as emergence, cast light on the question of what is life. A neat and tidy formulation, such as life is what emerges at certain levels of organization, fails to satisfy unless that organization can be specified, and specified, moreover, in the reductionistic sense—in terms of the essential form of that organization and the particular properties of the subunits. Consequently, while emergence may be a convenient notion in discussing complex systems, using the term can be a way to sidestep a fundamental concern, for that term fails to transmit any illuminating hint of the particular sorts of processes, qualities, and mechanisms that characterize life, that might answer the question of what is life.

WHAT ATTRIBUTES OF LIFE ARE SIGNIFICANT

Rather than seeking an ultimate definition in terms of vital spirits or animating forces, a more modest alternative is identifying the salient characteristics of life in the hope that this collection will provide the necessary insight into the greater question. This tactic, initially, is akin to the lexicographer's task, the simple drudgery of defining an unfamiliar or complex word with its more familiar synonyms, singly or as a composite. This tactic has, of course, a familiar history reaching into antiquity and begins with the simple enumeration of all the characteristics that distinguish in principle or practice between animate and inanimate. There is the expectation that refining and distilling such a list into its particular essences will some fine day result in the requisite definition in fundamental, comprehensive, informative terms.

Lists of qualities cataloged by the ancient Greeks and their successors include such plausible attributes as reproduction, nutrition, sensation, locomotion, volition, and reason, although the applicability of all those qualities to all forms of life requires further pruning. When, in later centuries, attention was focused on individual cells as the locus of life, these attributes were lumped into two main categories: reproduction (which can include embryonic development) and, for want of a better term, metabolism (which encompasses the nutritive and functional properties of the cell and their control). A further distinguishing characteristic that has been advanced, one of a different category, is complexity. As a first step toward answering the question of what is life, then, a composite characterization might be a complex system that is capable of reproducing itself, of constructing and sustaining itself from material and energy sources in its environment. Let us look at these attributes in turn, and then consider whether a more precise formulation is forthcoming and if so whether it is the sort of answer desired.

COMPLEXITY The notion of complexity may seem to be the most trivial attribute of living organisms; it is also one of the more difficult to characterize. Certainly, biological systems are complex in any of the several senses of that term. The simplest free-living organisms (those able to live on their own without depending on the presence of others, as must viruses) are bacteria, which contain thousands of kinds of components arranged in a definite and highly ordered structure. Even the simplest bacterium contains a central information store, the deoxyribonucleic acid (DNA) molecule that specifies the composition of particular ribonucleic acid (RNA) molecules that in turn specify the composition of some thousand different types of protein enzymes. These enzymes, then, are involved in the synthesis of that RNA, of themselves, and, in the course of cell multiplication, of the DNA as well. In addition, the enzymes participate in the metabolic network that extracts energy from the bacterium's nutrients and couples the energy flow from that source to those syntheses that maintain and nurture the bacterium and its functioning. And beyond this world of DNA, RNA, and proteins is still another population of molecules, lipids, carbohydrates, vitamins, and complex chemicals.

Nevertheless, although bacteria are the simplest organisms now alive on this planet, they may not be the smallest that could function adequately. For example, Morowitz proposed a "minimal" organism containing only forty-five enzymes with a corresponding DNA molecule an order of magnitude shorter than that of the smallest bacterium.[7] Still more minimal organisms are conceivable at the cost of efficiency and greater reliance on the abiotic production of nutrients in the environment: for example, organisms with simpler, less effective enzymes composed of only a half dozen varieties of amino acids and informational polymers chemically less complex than DNA and RNA.

7. H. J. Morowitz, "Biological Self-Replicating Systems," *Progress in Theoretical Biology* 1 (1967): 35–58.

Simple enumeration, however, is only one index of complexity; an essential characteristic of biological systems is their particular organization: the constituent parts are not random mixtures of molecules but are separated and joined in definite groupings created and maintained by the cell. Thus, the plasma membrane enclosing the bacterial contents and participating in the metabolic processes of the cell is constructed of specific proteins, carbohydrates, and lipids in an order that is necessary for those functions.

There are still further aspects of complexity, including information content and the length of the algorithm required to specify the system, aspects that may well be applicable to certain considerations of living organisms.[8] But the issues here are (1) whether complexity in any of these senses is a useful concept in distinguishing between animate and inanimate, and (2) whether the idea of complexity helps to understand the nature of life.

8. H. R. Pagels, *The Dreams of Reason* (New York: Bantam Books, 1989), 54–70.

For the first of these concerns, the answer seems to be no. The simplest counterexample arises from comparing a living cell with one killed, for example, by quick-freezing or a metabolic poison: with such lethal intervention certain essential functions are halted, but (at least initially) no detectable change in overall complexity results. A suitably killed amoeba is more complex than a live bacterium. Of course, the dead amoeba was once a living organism, and complexity can then be attributed to living or once-living entities. Hedging yet further, the definition could be broadened to include any product of a living or once-living organism, to include then honeycombs and birds' nests and printed circuit boards. Richard Dawkins recently suggested that biology should be considered as the science of complex systems, including the automobile with the amoeba.[9] The usefulness of such a definition to this inquiry of what is life, however, seems lacking.

9. R. Dawkins, *The Blind Watchmaker* (New York: W. W. Norton, 1987), 1.

Second, the mere presence and recognition of complexity does not seem to imply that it is an enlightening concept. Complexity may be more usefully regarded as the consequence of other requirements for life rather than as a primary qualification. Thus, there does seem to occur in the course of evolution an increasing complexity, which is probably interpretable as the result of natural selection for greater adaptability, selection for organisms able to meet more successfully environmental challenges.

REPRODUCTION The ability of living organisms to reproduce themselves, even if periodically or rarely in their lifetimes, is an obvious characteristic that has been recognized for millennia. The notion has been sharpened by the replacement of that common designation with the term replication, denoting the ability to reproduce exactly (or very nearly so) and further describing the duplication of an organism's genetic information, the internal plan of the construction and assembly of itself and its progeny. But if reproduction or replication is a characteristic of life, is it unique to the animate world? As with the criterion of complexity, this characteristic also applies to the inanimate world (although in this case dead organisms fail the test—they cannot reproduce).

The standard example of a replicating inanimate substance is an inorganic crystal, such as a mineral salt. Crystals may be highly organized with intricate structures, yet in the presence of a supersaturated solution of its components the crystal will grow by repeating on its surfaces that characteristic structural pattern. And if exposed to sufficient stresses the crystal will shatter, with each fragment then growing again. The act of division into daughter crystals need not be so fortuitous as an intermittent fracture; in the case of needlelike crystals the periodic division could result from inherent thresholds to natural turbulences.

Closer to conventional concepts of biological replication is the duplication of DNA, the molecule containing the cell's genetic information. DNA will replicate in a test tube containing a simple system of a catalyst (the enzyme DNA polymerase), the subunits of which DNA is composed, and the template DNA that is to be copied (actually a complementary copy is made, a sort of mirror image). In this example replication in the form of a complementary copy is achieved with the necessary help of a complex protein, the DNA polymerase, which is a product of living organisms (and how this example might be viewed if the enzyme were itself synthesized independently is subject to one's explanatory goals). To date, attempts to demonstrate self-replication by nucleic acid polymers alone (i.e., in the absence of enzymes) have been unsuccessful, although the abilities of RNA to act as a catalyst suggest that some form of RNA chain might be self-replicating when supplied merely with the subunits as precursors.

Whether viruses are classed as living organisms is a matter of definition: although they carry all the required information for replication, they do not contain in themselves the apparatus necessary for it and thus can reproduce only in living cells. What viruses can do on their own is to infect—to get themselves taken up by—living cells, where they then direct their own multiplication using the host's machinery. In this sense viruses are not "free-living"; but the extent to which any organism relies on other sources is, again, a matter of degree. Higher animals rely on plants or other animals for nutrients and particular chemicals such as vitamins, and even the simplest free-living organisms require external sources of energy, be it light or fermentable molecules, as well as sources of oxygen, hydrogen, carbon, nitrogen, and other elements.

A finer distinction between the animate and the inanimate worlds, as commonly divided, is the presence in living organisms (including viruses) of an information store, the genetic plan, a part that specifies the whole. In all these cases that genetic information is encoded in a nucleic acid polymer. Thus, unlike inanimate crystals whose replication is achieved by duplication in toto, and unlike DNA replication by the polymerase enzyme that produces a complementary copy of a template, conventional living organisms use two stages of reproduction: the replication of the information molecules, as crystals do (albeit with the help of protein catalysts), and the re-creation of the total organism designated by those information molecules. Animate from inanimate may be distinguished by using this criterion of an internal information store that is a small part of the overall organism. But although this may be an accurate description of current terrestrial life-forms, it is arguable whether this aspect satisfies a real sense of the difference between animate and inanimate. Moreover, this criterion may be too drastic for considerations of the actual origin of life, where the first "living" systems might have been simple replicators of certain organic polymers or even minerals. The potential creation of synthetic self-replicating machines raises further problems for distinguishing animate from inanimate with such criteria. Although the qualifying term "synthetic" might be considered the critical distinction, problems arise here as well: it is likely that in the future free-living organisms similar to present-day species will be synthesized through the assembly of nonliving components, and to separate these purely on their historical origin seems trivial in this context. Furthermore, to a great extent the particular organisms living today reflect their interactions with other organisms (including human beings), and the degree of such modification has been extensive in both the living world and the nonliving. If living systems are part of nature, then all consequences are natural, including the construction of synthetic organisms and self-replicating machines.

METABOLISM The third aspect of living systems, a composite of attributes assigned by the Greeks, can be lumped under the heading metabolism, which is used here to include the processes of transforming sources of energy in the environment into forms driving the organic activities of the cell—the functions of anabolism and catabolism, motion and translocation, response and homeostasis. Reproduction may be considered as a process of information flow, from generation to generation; correspondingly, metabolism may be considered as a process of energy flow, from the environmental source through the cellular machinery to the environmental sink, a flow of energy that is associated with creating and preserving the complex order within the organism while the disorder of the total thermodynamic system increases. And, as with complexity and reproduction, metabolism is applicable to the inanimate world as well. Indeed, even the examples given for the other two attributes are pertinent here as well. A crystal grows and replicates using the energy flows through its environment to create its ordered structure, dependent on the formation of supersaturated solutions through the action of sun and wind and rain and rock formation and crustal dynamics.

Between crystal growth in a hot spring or DNA replication in the test tube and the functioning of the simplest bacterium, however, is a readily distinguishable gulf. In the bacterium are multitudes of classes of processes achieved with highly refined catalytic efficiency and feedback control, whereas crystal growth does not involve an active transformation of its nutrients. Nevertheless, each characteristic singly has its counterpart in the inanimate world, most notably in the world of machines. Although the range of phenomena is not so developed and concentrated except as it is in the animate world, analyses into individual processes make it clear that no absolute criterion separates the living from the nonliving realms; these realms share general aspects of complexity, information transfer, and energy utilization.

WHAT IS THE NATURE OF LIFE

What is Life? is the title of a well-known book, written nearly fifty years ago by the theoretical physicist Erwin Schroedinger, that identified life with the conjunction of the latter two attributes, self-replication and ordering through a local decrease in entropy content.[10] It is probably the last prominent expression of that question and, as a simple characterization, captures what is probably the essential aspect. Max Perutz recently criticized that book, however, noting that its details of replication do not go beyond the experiments of Timoféeff-Ressovsky, Zimmer, and Delbrueck[11] and that his characterization of life as feeding off negative entropy is more accurately characterized as life driven by the flow of energy.[12] But the most pointed criticism is directed toward Schroedinger's conclusion that overlay this characterization, that the "mechanism [of life is] entirely different from the probabilistic one of physics, one that cannot be reduced to the ordinary laws of physics . . . because the construction is different from any yet tested in the physical laboratory" and that "living matter . . . is likely to involve other laws of physics hitherto unknown. . . ."[13] Perutz concluded that "the apparent contradictions between life and the statistical laws of physics can be resolved by invoking a science largely ignored by Schroedinger. That science is chemistry."[14] Indeed, the subsequent recognition of DNA and the elucidation of the replication process (which involves specific error detection mechanisms and error correction systems, proofreading and editing) demonstrated that Schroedinger's doubts were unfounded.

Although Schroedinger's qualms proved groundless, the positive aspects of his analysis are firm: life can be represented as a self-replicating system energized according to established principles of thermodynamics. Proper credit for a formal demonstration, however, belongs to the mathematician John von Neumann, who developed an abstract analysis applicable to all self-replicating automata, of which living organisms may be considered a subset.[15] The essential constituents in von Neumann's analysis are (1) a mechanism that when provided with the instructions will construct the entity described; (2) a mechanism that will copy any instruction provided to it; (3) a control unit that will cause mechanism 1 to construct the automaton described by the instructions, that will cause mechanism 2 to copy those instructions and insert them into the automaton just constructed, and that will cause the new automaton to be released as an independent structure; and (4) the instructions. All this is to be achieved through assembly from subunits available in the environment and driven by local energy flows. What is a living organism? It is merely a system that meets these basic requirements. If the simplest replicators are to be excluded, then this can be done by specifying some arbitrary level of complexity. If synthetic artifacts are to be excluded, then these too can be eliminated by fiat. But the crucial concept remains: the primary qualities of living cells, the attributes of life, are defined within von Neumann's formulation such that a self-replicating device can in principle be constructed. In a very real sense von Neumann answered the question of what is life.

10. E. Schroedinger, *What Is Life?* (Cambridge: Cambridge University Press, 1951).

11. N. W. Timoféeff-Ressovsky, K. G. Zimmer, and M. Delbrueck, in *Nachrichten der Biologie der Gesellschaft der Wissenschaften Goettingen* 1 (1935): 189–245.

12. M. F. Perutz, "Physics and the Riddle of Life," *Nature* 326 (1987): 555–58.

13. Schroedinger, *What is Life?* 76, 69.

14. Perutz, "Physics and the Riddle of Life," 558.

15. J. von Neumann, "The General and Logical Theory of Automata," in *Cerebral Mechanisms in Behavior*, ed. L. A. Jeffress (New York: John Wiley, 1951), 1–41.

Why, then, does such an explicit definition of life fail to satisfy? Why are Schroedinger and von Neumann not the heroes of biology for answering the age-old question? The dissatisfaction with the solution results, of course, from its generality. What is of pressing interest to contemporary biological research is *how* those general considerations are achieved in the biosphere. To understand how life is achieved it is necessary to identify the particular mechanisms by which reproduction occurs, by which energy flows are coupled to the synthesis of enzymes, the contraction of muscles, the transmission of nerve impulses. Although life on other planets may be fundamentally different and might be attainable through other processes, life on earth manifests common solutions to the problems of being a self-replicating automaton. In this interpretation life is not the result of a vital spirit imposed on matter, it is not the consequence of some particular forces that may or may not be peculiar to the animate realm; instead, life refers to a traditionally defined subset of systems that have the ability to self-replicate within their environment, systems with common properties representing their common ancestry. It is toward the discovery of these mechanisms, the understanding of these processes, that biological research is directed.

HOW IS THE LIVING STATE ACHIEVED

If merely accepting a definition of life in terms of von Neumann's self-replicating automaton is insufficient, and if the concerns inspiring research are instead the appreciation of how those criteria are achieved, we need to look briefly at four important questions.

1. How is the information for constructing the organism stored, replicated, and translated into a new organism? In the years since Schroedinger and von Neumann the general scheme has been elucidated and many of the aspects described in detail.[16] The information for constructing the organism is encoded as a sequence of bases in the polymer DNA (for certain viruses in the polymer RNA); the units of heredity, the genes, are identified with sequences in this polymer. The mechanism for replication, including proofreading and editing to ensure an error-free copy, is also well established. The process of translating the DNA code into the structure of specific proteins, through the intervention of the coding polymer RNA carrying that information to the site of protein synthesis, has been described in detail.[17] Equally important, but currently less well understood, are the mechanisms for controlling these processes, for regulating gene expression so that the translation of specific segments of DNA into proteins is turned on and off, for exerting the control necessary to achieve proper differentiation and organization of the cell and of the multicellular complexes. Although many details of these processes are missing at present, the general scheme is clear, with no lurking mysteries apparently unanswerable within contemporary research programs.

2. How are the energy sources and raw materials in the environment tapped to achieve the controlled functioning of the organism? This question, incorporating much of the traditional fields of physiology and biochemistry, has been answered with mechanistic descriptions: of radiant energy capture and transformation into chemical potential; of metabolic

16. B. Alberts et al., *The Molecular Biology of the Cell* (New York: Garland, 1989), 481–612.

17. Ibid.

cycles that make energy available for chemical synthesis and mechanical work; of macromolecular assembly into cellular structures; of enzyme mechanisms and regulatory control; of hierarchies of homeostatic processes responding to internal and external contingencies. Consequently, such ancient qualities as nutrition, growth, locomotion, and irritability have been reinterpreted in molecular detail. Although the general outline of a mechanistic formulation has been attained in these areas, there does remain a particularly murky set of problems, those subsumed by the quality of reason. Much is known about neural functioning in terms of cellular processes and about the scope of interactions between the cellular units. The particular organization that is thought to underlie brain function is being delineated. But fundamental problems of cognition remain unanswered, such as the process of speech production and comprehension. And one of the most obvious characteristics of the human mind, consciousness, resists attempts at physical explanation. That topic is the last refuge of vitalism, of the ineffable mystery of life; no unequivocal rebuttal to alternative modes of explanation is now available in this sphere.

Mechanistic explications of these two classes of processes, of reproduction and metabolism so construed, thus make concrete for the biological world von Neumann's formulation. The solutions represent what Ernst Mayr terms "proximate causes" and result from the reductionistic practices labeled variously as physiology, cell biology, molecular biology, biochemistry, and biophysics.[18] Two further classes of biological problems, representing "ultimate causes," incorporate these data but are historical: the questions of origins and ancestral development.

3. How did life on earth begin? Within the context of mechanistic explanations, this query seeks answers in terms of the prebiotic environment, including the forces acting on the available raw materials, answers that would describe with some consistency and plausibility the origins of the two preceding characteristics. At the moment there is much speculation, little evidence, and not very much plausibility. A central problem is how to account for the simultaneous appearance of both the machinery for replication and the embodiment of the information store; a common resolution is to make less stringent the requirement for one. Thus, self-replicating informational polymers are proposed, accepting the relative inefficiency of RNA (or some simpler precursor) as a catalyst—although even inefficient self-replication has yet to be demonstrated.[19] Alternatively, reproducing catalysts are proposed, accepting the inaccuracy of polypeptide enzymes (or some simpler precursor) as self-replicators—although even inaccurate reproduction has yet to be observed.[20] Either of these proposals could, in principle, be correct, and there is no conceptual mystery about how life could have arisen, merely the question of precisely how in real history it did occur.

4. How did the various forms of life come to be? This is the question addressed by Charles Darwin, the problem of the origin of species. His answer, natural selection and competition for survival,[21] provides a fundamental outlook on the problems of biology, not only answering this particular question but also illuminating two other issues as well. One of these is the source of apparent purpose in biological systems, since selection for a competitive advantage will endow organisms, cells, enzymes, and

18. E. Mayr, *The Growth of Biological Thought* (Cambridge: Harvard University Press, 1982), 67.

19. G. F. Joyce, A. W. Schwartz, S. L. Miller, and L. E. Orgel, "The Case for an Ancestral Genetic System Involving Simple Analogues of the Nucleotides," *Proceedings of the National Academy of Sciences, USA* 84 (1987): 4398–402; G. F. Joyce, "RNA Evolution and the Origins of Life," *Nature* 338 (1989): 217–24.

20. S. A. Kauffman, "Autocatalytic Sets of Proteins," *Journal of Theoretical Biology* 119 (1986): 1–24; F. Dyson, *Origins of Life* (Cambridge: Cambridge University Press, 1985), 40–59.

21. C. Darwin, *On the Origins of Species by Means of Natural Selection or the Preservation of Favored Races in the Struggle for Life* (London: Murray, 1859).

identifiable parts of enzymes with functional roles, with physiological justification. The other issue illuminated is the source of commonality in the solutions to biological problems, to the particular challenges of being a self-replicating automaton; again, the process of selection in the face of competition can be understood as the source of these similarities, both through common descent and through common functional need.

CONCLUSIONS

Life may be explicitly characterized, following von Neumann, as the particular ability to be a self-replicating automaton, a definition with a discrete, formal significance. Beyond this definition, however, lie the central quests of biological research, quests for an understanding of how life began, how organisms evolved into their present-day diversity, and how the mechanisms for carrying out those living functions do in fact operate. Over the past centuries research has progressed on all these fronts. Within the context of scientific explanation there appear no impenetrable mysteries although much detail is lacking—detail of general scientific interest and of potential utility in medicine, in agriculture, and in industry. And with this definition and these understandings comes the likely capability for synthesizing living organisms from nonliving components: no vital spirit, no physical spark is necessary, merely the proper organization of the particular components to achieve self-replication from available subunits, driven by ordinary energy flows.

Beyond these considerations of what and how lies another family of concerns, representing the possibility of some deep lesson to be drawn from these reflections. The shading of distinctions—from clay to crystal to virus to bacterium to human to robot—does not, however, represent a great chain of being fulfilling some principle of plenitude. The gradation of attributes, the sharing of qualities, reflects instead the spontaneous origin of life on earth, following universal physical laws. The common manifestations are due to the common requirements for being a self-replicator with mechanisms embodying physical processes. With this sense of commonality comes a recognition of links to all the beasts of the field and the fowl of the air. But we are all linked as well to the crystal and the clay, which we can also revere as life, or not, as we choose to define, as we choose to revere. The thread of life stretches throughout a demystified world. And this world of the lamb is also the world of the lion, of the pathogenic bacterium, of the lethal virus. The natural landscape reveals life feeding on life, and we are cousins to the bun as well as to the hamburger. The world of life exemplifies consumption and exploitation and competition as well as the beauty and the majesty we see there. Biology can no more than any other science reveal a universe of values, distinguish exemplars of virtue or vice. It cannot absolve the human race of its necessary task of making moral choices. Biology like any other science can only help to clarify the application and assist the implementation of those choices. ♦