Radu Popa

Between Necessity and Probability: Searching for the Definition and Origin of Life

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With 58 Figures

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Everything we hear is an opinion not the fact.
Everything we see is a perspective not the truth.

Marcus Aurelius

Preface

The most complicated machines are made from words.
Jacques Lacan

Where does life come from? This is a question that has fascinated mankind since the beginning of time. As soon as somebody or 'something' (either life form or machine) becomes aware of itself, it also asks questions about its world and about its own origins. It is no mystery that the oldest myths and legends of human culture are so often centered on genesis motifs. Yet despite tremendous progress in science during the last century, we are still far from understanding the origin of life. Because we do not know exactly what life is (or maybe because we cannot agree upon this issue), a wide variety of theories and pseudo-theories have been proposed about the origin of life. The palette of visions concerning the origin of life has reached out in many directions: life being generated by incomprehensible-to-us mystical forces, spontaneous generation (Buchner 1855), creationism (Bernard 1878b), random genesis, panspermia (Arrhenius cited in Servos 1996), qualitative upgrades of quantitative accumulations (Oparin 1924), gradualist (smooth) 'upgrades' from lifeless matter into life, life as an inevitable natural consequence (Klabunovsky 2002), life as an emergent property of matter (Turian 1999), life as an extraterrestrial manipulation or a phenomenon from another physical dimension. Because human knowledge is a shared type of knowledge, our understanding of the world is collective. Therefore, most theories about early life are not fully independent of each other and show significant overlap.

The scientific field studying the physical meaning of life on Earth and in the Universe, its origin and its fundamental properties has been given various names such as prebiology (Rossler 1983), exobiology (Ponnamperuma 1972) or originology (Kompanichenko 1996). Another possible name that might better suggest the physical ambiguity of its study subject is 'parabiology'. Because this book is a quest and a challenge for the understanding of life anywhere and, whatever its physical substance, I prefer to use the term exobiology. Astrobiology, bioastronomy and artificial life are connected disciplines which, although interested in the same major issues, have more pragmatic purposes such as searching for life elsewhere, the quest for non-terrestrial types of life and the creation of artificial types of life.

Among all sciences, exobiology holds an unmatched record. It has the highest ratio between the number of hypotheses and the number of relevant findings. The reasons are quite simple. Earth is an old planet, almost 4.6 Gyr (giga years). Therefore the Earth we observe today is very different from the Earth in its beginnings. Without a time machine that would allow one to probe the early Earth, we will never be sure whether our models are an accurate representation of the environment in which life originated. Moreover, modern life is not simple but appears as an intricate web of large and complex molecules that seem very unlikely to have appeared spontaneously and that cannot exist independently of each other. For a biochemist or molecular biologist, this 'Gordian' knot has no apparent beginning but only endless loops and interdependencies. Therefore, modern life appears as a large collection of interlocked chicken-and-egg paradoxes. Consequently, life cannot be understood through either purely deductive logic or through purely experimental approaches. Facing such an enormous challenge, a society predisposed to philosophical, contemplative and intuition-based approaches is as helpless as a super-technological, pragmatic and deductive society. An integrated and realistic attitude seems the only sound approach toward scientific satisfaction.

Being aware that the vision presented here might contradict certain postulates that other theories about the origin of life consider as fundamental, I support the postulate that life emerged very early in the universe, that life is probably present in other forms in other parts of the universe as well, that life was 'pushed' into existence by understandable and foreseeable forces and that an intelligent mind is capable of understanding life as a general concept. Certainly, nothing is forever settled in science and no theory must be taken for granted, irrespective of how much experimental evidence we humans may have for it, and how precise that evidence may be. This is just a reminder of the relativity of our 'scientific truths', a warning that "in science one can proclaim a theory about reality as being the latest but never as the last theory." Consequently, although as an author I might be tempted to envision my opinion as legitimate, the interpretation of the origin, properties, meaning and definition of life presented here can offer no more than what current scientific knowledge would allow. Aware of this unavoidable caveat, I have tried throughout this study to be as open as possible to alternative interpretations. If not deliberate, it might sound ironical that quotes given at the beginning of some chapters are actually contradictory to what the chapters have to say.

Probably every scientific generation before us believed that the end of their quest was in sight. Yet to this day they have all failed to resolve their questions. Over and over, research has demonstrated that the intrinsic complexity of the living state is too overwhelming to resolve. Because later generations will scrutinize life and its origin with more experience and better insight than us, and with an appropriate respect for the magnificence of this subject, the purpose of any sound theory about life cannot be to clarify the problem, but to point questions in the right direction, to identify a plausible and not an ultimate answer and to navigate on a likeliest path through the fog of often conflicting experimental observations and alternative hypotheses. In exobiology one can never expect ultimate answers, only illumination.

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1 Introduction

> One can separate the logical form of an organism from its material basis of construction, ... its capacity to live and reproduce is a property of the form, not the matter.
>
> Emmeche 1992

According to Ernst Haeckel, "any detailed hypothesis whatever concerning the origin of life must, as yet, be considered worthless, because up till now we have no satisfactory information concerning the extremely peculiar conditions which prevailed on the surface of the earth at the time when the first organisms developed" (Haeckel 1866). Erwin Schrödinger (1943) also expressed pessimism regarding the chances of understanding life. In the same vein: "Life is like consciousness. If you think you can explain what it is, you got it all wrong" (Shaw 2002). Niels Bohr interpreted life as a fundamental property of matter analogous to certain quantum properties, to be taken as given, and thus allowing little if any logical scrutiny (Bohr 1933):

> '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, in a similar way as the quantum of action, which appears as an irrational element from the point of view of classical mechanical physics, taken together with the existence of elementary particles, forms the foundation of atomic physics.'

The modern day belief is that the origin of life may be unclear but that it is not an impossible problem (Scott 1986, Morowitz 1992, Bedau 1998, Lahav 1999, Brooks 2001, Buiatti and Buiatti 2001). Overwhelmed by life's incredible complexity, some scientists prefer to consider definitions of life as uninteresting, or even doubt the scientific need for them, or the chances of ever finding, a satisfactory definition for life (Gilat 2002). But if we cannot describe life on Earth, how will we be able to understand life as a general concept. That represents biological and nonbiological life, terrestrial and extraterrestrial life, material and cybernetic life.

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Four major questions are generally formulated in exploratory astrobiology, the origin of life and artificial life:

- Is life a unique thing, or is it a unique collection of common features?
- Is the origin of life mere probability, or is it the result of some special circumstances?
- Is life a physical necessity?
- Is it possible to formulate a representation of life on Earth in a way that will address life elsewhere?

Understanding life is not just a theoretical exercise; it is a quest directly connected with its origin and has many practical applications (Bedau 1998, Kuhn 2002, Russell 2002, Lacey et al. 2002). Future explorers of the outer space (either man or machine), challenged with facing life forms unlike anything on Earth (Friedman 2002, Nealson 2002), have to be 'armed' with accurate guidelines capable of discriminating the essence of life from its composition and from its physical appearance. Many things in nature might seem related to life, whereas they are simple natural phenomena or complex processes, and conversely, many things that may seem lifeless, might be alive or even dangerous (to us). The creation of artificial life (making fully fledged autonomous systems) cannot advance without understanding its general properties and the circumstances leading to life and supporting it (Langton 1989, Ronald et al. 1999, Ruiz-Mirazo et al. 1999, Standish 1999). The assessment of successful early life simulations involves identifying specific and interconnected objectives derived from the essential attributes of life (Ronald et al. 1999, Korzeniewski 2001) or from the logic behind its self-organization (Boden 1996). Finally, anticipating the overall consequences of life on another planet will become an important part of mission planning for all extraterrestrial exploration (Brack 2000, Reichhardt 2001) and the terraforming of other planets.

Several approaches are commonly used to represent life: mechanistic–reductionist, dialectic–materialism, holism, and vitalism (Pályi et al. 2002). The mechanistic–reductionist approaches interpret all life-related phenomena through physicochemical processes but explain little about the origin of life. The dialectic–materialism views describe the origin of life as a set of qualitative changes (jumps) driven by quantitative (gradual) accumulations. Holistic views interpret life as a collective property, while vitalist theories attribute life to a hidden (vital) force. Although these approaches might sound different from each other, it is not always easy to tell where one ends and the other begins. An extensive collection of definitions of life has been formulated using such approaches (Maynard Smith and Szathmáry 1995, Muller 1935, Gánti 1975, Lahav 1999, Pályi et al. 2002, Szathmáry 2002, Appendix B). Some definitions of life are subjective and depend upon an individual standpoint and religious subconscience (Hennet 2002), ranging from pure materialism to pure spiritualism (Apte 2002; Appendix B). A committed materialist defines life in terms of matter and energy, denying the need for a spirit, while a pure spiritualist would only consider the reverse. Although some address major requirements of life, many definitions do not identify the essentials of life, while others focus heavily on features that are particular to the terrestrial type of life. A comprehensive interpretation of life must address issues and identify properties that are independent of its physical nature (Dix 1983, Kauffman 2001), otherwise the model becomes flawed with exceptions and liable to unanswerable criticism. A correct interpretation of life must address the essential properties of life, must be capable of relating them to the early history of life, and must help reveal the forces driving its emergence and evolution.

Holistic and Mechanistic Definitions of Life

Two scientific approaches dominate modern theoretical debate about how life should be interpreted: holistic (as opposed to reductionist) and mechanistic (as opposed to vitalist) (Tamponnet and Savage 1994, DeLoof and Broeck 1995, Buiatti and Buiatti 2001, Nevo 2001, Rosslenbroich 2001).

Holistic interpretations of life are function- and purpose-related descriptions. The classic example of holism is “nothing is alive in a cell except the whole of it” (Olomucki 1993). In holism, life is viewed as a collective property. It was suggested that an appropriate approach to obtaining a holistic definition of life is to address questions such as:

- How are different forms of life at different levels of the vital hierarchy related to each other (Bedau 1998)?
- Is there a gigantic hiatus or a phenomenological continuum between life and non-life (Bedau 1998)?
- What is more important for life: the form, the shape or the composition (Bedau 1998)?
- Are life and matter intrinsically related (Von Liebig 1868)?
- Are life and mind intrinsically connected (Bedau 1998)?

Holistic approaches show considerable limitations in experimental practicality because they often neglect the particular properties of living entities.

Reductionist interpretations of life try to demystify the explanation of some very complex activities otherwise thought by some to have a non-material explanation (Arrhenius 2002). One of the paradigms of modern molecular evolution is that minimal life consists only of molecules and their mutual interactions (Luisi 2002). Despite the popularity of reductionism, many scholars agree upon the existence of some emergent properties of matter, i.e., properties that appear only at certain levels of complexity. The structure at each level of organization is made of the components of a lower level, but the lower levels cannot explain some of the qualities of a higher level. Thus, structures may be considered the subject of a reductionist approach while some properties cannot (Luisi 2002).

The mechanistic interpretations of life are pragmatic approaches. They describe living forms as complex machines, whose parts function in a thermodynamic direction that is somehow fortunate for the survival of the overall system (Prigogine 1980, Schrödinger 1944). This need for thermodynamic justification feeds most mechanistic interpretations of life. Most mechanistic descriptions of life tend to explain it as a probabilistic paradigm. When this philosophy is taken to its extreme (i.e., interpreting the origin of life strictly as a collection of chance-like events), it fails to identify any meaning for life in general, to understand life as a concept or even to consider the need to look for attractors that might have 'pushed' life into physical existence. The purely mechanistic interpretations are closer to 'not seeing the forest for the trees' than any of the other approaches.

Vitalism is an ancient belief that living entities exist due to a mysterious force called the 'vital force', 'perfecting principle', 'entelechy', or 'mneme'. Although modern science generally dismisses this stand, vitalism has never been scientifically demonstrated as erroneous. However, vitalism has fallen behind in the ranks of approaches to describe the origin of life because of its non-scientific belief in a transcendental principle. On the other hand, because modern science is still unable to provide an articulate model for the origins of life, vitalistic ideas still surface now and then. After all, vitalists can always claim that they said nothing more than 'the force(s) behind life is (are) unknown', and on this issue they are perfectly right. Vitalists would be wrong only if they claimed that the situation would remain so forever. Finding a physical attractor for life would actually provide some reconciliation between modern science and the old-fashioned vitalism.

Generalist vs. Minimalist Definitions of Life

Although the need to represent life in a simultaneously broad and detailed manner seems obvious (Dix 1983), some descriptions of life use a conceptual generalization to an excessive degree. These descriptions either use an obscure language with disguised meanings and thus become eclectic to any non-specialist, or else they render themselves useless by providing insufficient information to discriminate life from non-life. They sometimes even go beyond what life actually is (Hotchkiss 1956, De Loof 1993, Baltscheffsky 1997, Korzeniewski 2001, Hennet 2002, Appendix B). Notable examples are:

- "Life is a historical process of anagenetic organizational relays" (Valenzuela 2002).
- "Any system that creates, maintains and/or modifies dissymmetry is alive" (Krumbein 2002).

The minimalist approach considers that life can and must be defined on the least amount of information (necessary and sufficient) to distinguish it from inanimate matter (Korzeniewski 2001). This approach was defended as an attempt to avoid dogmatic assumptions and arbitrary requirements about life (Hennet 2002). However, the products of this approach are not by design meant to explain how and why life emerged. Although sometimes praised as being intellectually challenging, minimalist approaches are often irrelevant or unable to convey true illumination. They do not make life clearer to whoever or whatever (observer or instrument) has already experienced life, nor are they insightful to whoever (or whatever) has never seen life before.

It has been claimed that a minimalist description of life would also implicitly address the problem of its essence (Korzeniewski 2001). According to such an interpretation, a minimal and sufficient dictionary-type description of an object or a phenomenon (such as growing crystals, fire, clocks, hurricanes, wars or religious cults) must implicitly explain the forces and circumstances behind their emergence. A theoretical attempt has been made to describe life through the definition of a minimum unit of life (Szathmáry 2002). Apart from using the word 'minimalist', this interpretation reaches far beyond the dogma of a minimalist type of definition. It is rather an attempt to find a generalist interpretation of a minimal unit. The objection here is that the individual level of existence might not be enough to fully explain the meaning of life in general (at the supra-individual level). Life as an overall phenomenon has a considerable bearing on the understanding of its essence. Explaining life requires both individual and collective attributes. Generalist approaches to life are nevertheless valuable tools because of their built-in tendency to ignore the composition of individual life forms and address general concepts. They are the closest to a non-Earth-centric interpretation of life.

Cybernetic Definitions of Life

Cybernetic definitions of life are a product of the belief that it is possible to derive a definition of life from computer simulations, thus describing life entirely as a cybernetic 'thing' (Emmeche 1992, Milosavljevic 1995, Clark and Kok 1998, Bedau et al. 2000, DeBeer and Kourie 2000, Korzeniewski 2001). Yet caution must be exercised when using them. Statements such as "a living individual is as a network of inferior negative feedbacks (regulatory mechanisms) subordinated to (being at the service of) a superior positive feedback (potential of expansion)" (Korzeniewski 2001) are so unconstrained that many otherwise lifeless 'things' can fit the profile and be considered alive. Examples are not only plasmids and viruses but also the development of cloud systems, liquids at boiling point, fire, fluid vortices, magmatic extrusions, or uplifts associated with plate tectonics. Many of these 'things' display some form of intrinsic expansive tendency and use some form of regulatory feedback to adjust themselves to the tolerance limits of their available space and resources, thus apparently 'avoiding' functional collapse. If such things are alive, why not so consider other things such as the capital market, art, religion, or other phenomena related to the field of psychosociology such as the dispersion of news, lies, and gossip? They all display regulatory mechanisms at lower levels supporting the need for an expansion.

Cellularist vs. Genetic Definitions of Life

Cellularist and genetic definitions are descriptions based solely on experimental knowledge of life on Earth. Most classical interpretations of early life were either cellular or genetic (Luisi 2002). A 'cellularist' believes that the formation of a cell (a semi-permeable physical enclosure or a compartment) represents the relevant turning point toward life and that all other properties of life are consequent. In contrast, a 'geneticist' considers replication and variability as being the true starting points for life. In the last few years it has become more and more obvious that these two visions are not actually antagonistic to each other, but rather entangled, complementary and temporally connected. They are different facetes of the same thing. Although cellularist and genetic definitions of life are no longer much favoured, they are often used for teaching purposes.

Parametric Definitions of Life

Parametric (or criterion-based) definitions of life try to identify a list of the most relevant features of life (Appendix B). The most extreme (and most mistaken) parametric approach tries to identify one single feature of life as explaining everything including its origin. So far this attempt has proven fruitless and it is likely to remain so. One single step toward life is extremely unlikely. It is no different from viewing life as an extraterrestrial experiment, a miracle, alchemistry or magic. The philosophy of most criterion-based definitions is to gather the smallest bundle of features of life, features that in each author's mind are the most striking, the easiest to perceive (or to measure) and the most comprehensive. The most popular parameters used in parametric definitions are replication, metabolism and evolution (Eigen et al. 1981, Gánti 1974, Békés 1975, Jibu et al. 1997).

Despite their analytic appeal, parametric interpretations of life fail to discriminate between properties of life that are primeval or causal and properties of life that are derived (i.e., consequential and therefore subsequent). Some features from the physicochemical world such as electrical charge, the notion of spin from quantum mechanics, the electromagnetic force, mass and gravitation are considered more fundamental than others such as temperature, energy, viscosity, the strength of a chemical bond or the shape of a crystal. The latter are generally considered derived because they can be explained as consequences. Analogously, life also displays some features that are fundamental (either causal or phase transitions) and others that are derived (deterministic or emergent). This separation is not trivial, especially when early life is discussed. Although features such as energy balance, preservation of molecular and cellular architecture, metabolism, replication, reproduction, complexity, Darwinian evolution, homeostasy, motion, genetic blueprints, response to stimuli or intelligence are excellent discriminators for life (Oparin 1924, Schrödinger 1943, Gatlin 1972, Gánti 1974, Eigen and Winkler-Oswatisch 1981, cited by Dyson et al. 1997, Horowitz 1986, Fontana 1992, Joyce 1994, Dyson 1997, Hazen 2001), they are not primordial. These features are deterministic consequences of other preexisting circumstances, outcomes of the way living nature functions and are often not a confirmation that life is present.

Numerous lifeless physical realities display some life-analogous properties. Computer programs are capable of replication, fire is capable of growth, oceans have boundaries, the economy displays a means to achieve homeostasy, and the arts have an evolutionary history. Simply assembling such features indiscriminately, without regard for their type, meaning and interdependencies would be superficial. An endless plethora of overlapping combinations of parametric definitions of life can be (and have been) formulated (Appendix B). Although never completely wrong and usually not mutually inconsistent, they have no special merits in themselves and often tolerate each other. All these definitions are snapshots of the same multidimensional 'thing' we call life, viewed from different angles. The biggest caveat of the definitions of life that use exclusively derived properties is their inability to relate to the early history of life. This is because, instead of viewing life as a qualitative accretion punctuated by stepwise probabilistic novelties, a thing in harmony with its surrounding universe, parametric definitions contemplate life as a mere collection of unusual attributes, a spatiotemporal coincidence of remarkable properties. They tend to ignore the conditions and the factors that lead to these properties. A potential trap for a purely parametric description of life using exclusively derived properties is that of failing to recognize prelife forms as relevant. This applies especially when elaborate features such as hierarchical networking, oxidative phosphorylation, semi-conservative replication, or Darwinian evolution are used as criteria to formulate a definition for life.

Material-Related Definitions of Life

Although "living organization is ... characterized by a deep interrelation between form and materiality" (Patee 1977, Emmeche 1992, Moreno et al. 1994), the universal properties of life are probably independent of its material nature (Maturana and Varela 1980, Langton 1989, Emmeche 1992, Morán et al. 1997). Despite the fact that life on Earth should only be used as one possible example of life, many descriptions of life are Earth-centric (Farmer 2002). The extension of this bias is also known as the 'weak anthropic principle' or the 'anthropic cosmological principle' (Barrow and Tipler 1986). The anthropic mentality implies that some very restrictive conditions are required for the existence of life, such as the particular properties of water at terrestrial temperatures (Jibu et al. 1997), the properties of the carbon atom (Benn 2001, Altstein 2002), or the critical events of phase transitions (Glassman and Hochberg 1998).

A common downside consequence of this vision is to impose Earth-related physical and chemical limits on where life may exist in the Universe and even to establish theoretical habitable zones based on material composition (Gonzalez et al. 2001, Lineweaver 2001, Kasting 2002). In a few cases particular types of molecule such as nucleic acids and proteins are used to describe life (Kunin 2000). As far as we know, life on Earth might be the only type of life in the entire Universe using proteins and nucleic acids. Not only do protein/DNA-centric visions put any other possible form of life out of scale, but they interfere with a fundamental goal in exobiology, which is to understand life as a general concept. On the basis of an Earth-centric 'policy', an extraterrestrial flying to Earth, its body made of tar, its blood liquid ammonia and breathing chlorine gas, should be treated no more than as a bag of chemicals, irrespective of how complex its technology, how efficient its metabolism, or how elaborate its mathematics and its music. The 'Earth-centrist commission' would declare the 'extraterrestrial bag' to be 'a non-living thing' because it did not have ribosomes or DNA and it was too much unlike us. They would then draw some fluid from it with a syringe, make a chemical analysis and put the 'thing' in a freezer. How does this differ from the Amazonian indians killing explorers simply because they were unlike anything they had ever seen before in the jungle?

What is Needed to Explain Life?

"Definitions are usually like a fisherman's net: too small to encompass Leviathan, but with a mesh too large to hold many of the denizens of the deep" (Lauterbur 2002). Contemplative visions such as "the mystery of life isn't a problem to solve, but a reality to experience" (Herbert 1965), approach life as something that cannot be understood, considering the subject too magnificent for our tiny brains. This mentality denies the spirit of the scientific method, portraying scientists as lost beings, doomed to wander forever in seas of incertitude and jungles of paradox. Most scientists believe that even though we may not yet be up to the task, life and its origins remain decipherable natural phenomena. Although life appears very complex, it may be simple in its basic principles. The main objective in exobiology is to find a way to approach the Gordian knot of life? Without cause–effect events regulated by the laws of chemistry and physics, there can be no science of the origin of life (DeDuve 1991). It appears obvious that one should start from simple physical principles and follow their causality until lifelike properties are achieved.

The most common approach used by modern science to explain the origin of life is molecular Darwinism. Chemical simulations may be able to tell us