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A Valid Theory of Life: Introduction to the Special Issue

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Abstract

What constitutes a valid theory of life? This paper opens a special issue of *Organisms* devoted to that question. It proposes criteria for evaluating competing definitions of life and establishes a critical framework for assessing claims about living and non-living objects. Mapping the intellectual terrain from Aristotelian and Cartesian causality to thermodynamics and contemporary information theory, the paper identifies recurring conceptual errors — above all, a covert dualism that persists across otherwise opposed positions — that theorists of life would do well to correct. It links these academic debates to practical challenges in ecology, medicine and technology, arguing that the question of life carries genuine civilizational urgency.

Keywords: life, agency, evolution, negentropy, biology, thermodynamics

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This special issue addresses an enduring question: what is life? For most of history, recorded or otherwise, the answer has remained philosophic, but it now holds the key to addressing the so-called polycrisis—simultaneous crises in ecology, economy and technology arising from the sprawl of industrial civilization.

Organisms launches this special issue with a written symposium on the vital question. Convened by four researchers in engineering and life sciences, the symposium provided data for a meta-analysis of how 68 experts seek to define life. Using statistical techniques often applied in digital humanities, they wrote "What Lives? A meta-analysis of diverse opinions on the definition of life" (https://link.springer.com/article/10.1007/s13752-026-00544-9), a paper that identifies zones of agreement and divergence in scientific theories of life (Bender, Kofman, Agüera y Arcas, & Levin 2025). I recommend reading "What Lives?" alongside this special issue.

As editor, I shall not favor any of the approaches in the following symposium. Instead, I offer criteria for validating a theory of life, and what such a theory should accomplish, as a propaedeutic to a bracing discussion, and to subsequent installments of this special issue. This introduction is also an invitation. *Organisms* will publish this special issue on a rolling basis, and readers are invited to respond to the question of life. Responses may come in any reasonable format, including formal or informal writing, audio, video or visual arguments. *Organisms* and I aim to convene future symposia to continue the discussion.

The question of what life is leads naturally to the indexical question, "Is that alive?" Which, after discussion, may lead to the answer, "I know life when I see it". Reasoning from appearances can be misleading. Simulations such as clockwork or electronic automata may be mistaken for organisms, and many contemporary accounts of life reveal, upon examination, assumptions that underdetermine or even deny the phenomena of life—or at least their uniqueness in the physical universe. These are not classroom issues. Shortcomings in healthcare, engineering and ecosystem management reveal gaps in our understanding of life, and growing threats in practical applications lend urgency to discussions of theory.

To help close these gaps, and form a practical consensus, I propose three conditions for judging a valid theory of life. These conditions draw on Western philosophic and scientific traditions that began with Aristotle, and they relate to the primary observables of life. They set the ground for a discussion of widely circulated biological paralogisms that concludes this introduction.

A successful theory of life should explain the following properties.

Materiality

Life is a material expression. As such, biologists should not have recourse to immaterial causes, a category that includes essences ranging from souls to formal abstractions. Do architectural plans cause buildings? A theory of life should define the energetics of life. There is no controversy that geophysical sources of energy fuel the biosphere. A theory of life should answer the question of what material formations enable organisms to harvest energy from their environment, and to persist over time despite opposing thermodynamic gradients.

Novelty

Life exhibits a mix of stability and novelty that suspends physics. Despite the seeming frailty of individuals, organisms have persisted for billions of years, many with archaic features. Yet life shows an equal capacity for novelty. Some forms of life, notably bacteria, specialize in metabolic innovation. Others, such as humans, innovate their behavior, and, for all species, innovation is expansive, producing new as well as adaptive categories of exploitation. Life is conservative, as the pathways of heredity show, but its expression over time is prolific, inventive and sometimes profligate. How does life navigate the practically infinite realm of possible chemistries? How does life create new realms of possibility—new chemistries, new symbioses, and new economies—which bear no traces in earlier phases? And how does life maintain stability despite the astronomical potential for error as it produces novelty?

Agency

To ground the science of life, we might begin by establishing a minimal unit of analysis, namely the fundamental biological object. As in mathematics, a biological object may incorporate other objects, which form a set, and it may interact with other objects under functional constraints. Not to presume a schema, but the science of biology should look something like this. And it does. Why, then, do we lack an effective theory of life, or, at the least, a theory of life that is universally convincing? To do this, we do not need to undermine the foundations of Western science, or project a world beyond its reach. Presuming that mathematics is useful, and observations tell us something about the world, we could interrogate our conceptual frame, starting with the unit of analysis.

Let me now recast the question of life with more precision: what is the fundamental unit of analysis in biology? It should be the leanest structure, or category of structures, that exhibits properties of life. In other words, the unit of analysis should be alive. And its properties, especially those which make it alive, should be observable and, from the standpoint of logic, necessary and sufficient. This assertion begs the question of life. What are our criteria for judging whether something is alive or not? We know life incorporates non-living resources, and that it self-assembles complex physical structures; but it is given that life subsists in a geophysical world, and we should not confuse chemical inputs or sub-systems with life.

Here semantics can be misleading. To maintain neutrality to competing theories of life, I called the fundamental unit of biology a structure; but living beings, which change structures over time, are closer to systems of dynamic flow. On this point, the writing of Conrad Waddington is instructive. To remain at the level of meta-theorizing, I suggest that the word "agent" encapsulates the phenomena of life, and it can be used to reference the fundamental units of biology—whatever those are. Once we distinguish the legal and technical meanings of the word, agency captures the self-organizing, self-interested and self-perpetuating nature of living creatures. Life possesses an agenda—if only to stay alive.

The definition of life, and who defines it, has always stirred controversy. It has also inspired extraordinary leaps of faith, denial and dogma, stretching the capacity of natural philosophy to extremes. Is life, or at least human life, an eruption of spirit into a material plane? Or is the biosphere with its inhabitants a kind of mechanism, whether clockwork or informatics? Though not directly addressed in the following symposium, these extremes should be mentioned for the following reasons. They bookend popular discourse on life; large swathes of humanity accept one of them; and, beneath them, we can find the foundation of errors that resonate throughout less extreme positions in the life sciences.

Spiritualism and reductionism have more in common than we normally think. Both rely on an impoverished dualist causality that explains life away. Immaterial souls are obviously dualist, but dualism persists in the modern evolutionary synthesis and also in other theories that attribute life's unique properties to information. Take Richard Dawkins' description of organisms as giant lumbering machines controlled by "selfish genes" (Dawkins 1976). Ascribing agency to inert molecules—in fact, molecules selected by evolution for inertia, in the form of structural durability—seems as valid as ascribing agency to immaterial puppet masters. Why? Nucleic acids are chemical templates with no inherent metabolism. When extracted from a cell, DNA does nothing, and, though some versions possess catalytic properties, RNA does not form cells.

While nucleic acids are part of life's story, when taken alone, they hardly constitute a theory. Theories must possess explanatory power, that is, they need to attribute causation, and, from a theoretic perspective, saying ribonucleic acid complexes cause life parallels the claim that architectural plans cause buildings. In Aristotelian terms, nucleic acid templates are formal causes. They are necessary (we think) to cause organic phenomena; but to explain organic phenomena, they need to be embedded in a causally rich theory. The toolkit for developing such a theory lies within the heritage of Western thought, but it requires recovering concepts of causality suppressed by modernism, specifically the physics of René Descartes.

Writing in the 17th century, at the cusp of the modern era, Descartes foresaw the power of rational analysis, much of it due to his innovations in mathematics and physics. To close the door on medieval tendencies, he reduced the rich taxonomy of causation in Aristotelian physics to mechanism. Plants, animals and the solar system became components of a clockwork universe. Then he confronted the reality of human experience. Falling back on his foundational phenomenology, with its confident ground in self-perception, Descartes reasserted the realm of spirits when he proclaimed, *cogito, ergo sum*. This contribution to the culture of science persists to this day: conceptual muddles that have undermined alternative cultures of ecology that could have started with Alexander von Humboldt in the 19th century or Lynn Margulis in the 20th.

The source of these muddles lies in the confusion of sentience, narrowly conceived as rational thought, with agency. Antonio Damasio calls this "Descartes' error" (Damasio 1994). While rational thought can be conducted in material media—see research on distributed cognition to demystify how this happens—it does not explain agency (Hutchins 1995). Nor does it explain life, the only observable phenomenon that exhibits agency. In fact, the attempt to explain agency via rationality—and here I include information-based theories of sentience and cognition—contains an implicit dualism. In a seeming perversion, rationality and its mental double of information are nothing more than desiccated souls dressed as matter. Just as DNA is inert outside a cell, abstractions are inert outside an operating environment.

Information-based theories are not wrong as much as incomplete. To be effective, abstractions require, to revive Aristotle's terms, an efficient cause, that is, an agent. Though it is up to biologists to decide, that ensemble seems to correspond to nucleic acids and cells. Nevertheless, let us be clear: codes and other abstractions are representations developed for human knowledge, communication and social coordination; they do not subsist in an independent realm where, like Platonic forms, they effect change in the material world. To see the implications of this statement, and its utility in validating a materialist theory of life, let us consider the role played by emergence and complexity in many theories of life or, in what amounts to a proxy for life, theories of cognition.

No less than Descartes, contemporary scientists view the definition of life through the lens of rationality. We start with observation that life emerges from matter. The characterization of life as emergent is a category distinction, but it is not an explanation. When we ask how life emerged from matter, the question shifts to complexity. Matter "complexifies" until it reaches a take-off point, or singularity, where it comes to life. The combination of emergence with complexity is appealing because it offers an account of how life develops in a continuum that includes dissipative structures, active matter and other phenomena, which can be modelled quantitatively. However, whatever singularity gave rise to life was not a phase transition. Life displays a certain *kind* of complexity, and its kind is visible in cellular structure. We can contrast cells with viruses, noting that the latter is a kind of information bomb, not a viable entity. A valid theory of life should offer precise definitions, even algorithms, of how life organizes matter to exhibit viability.

Viability opens the door to thermodynamics. My last paragraph concluded with a comment on the microscopic structure of life. Left alone it might imply that life is a procession of material states, and that organic activities can be charted through appropriately parameterized state spaces. Though Waddington may well have agreed with the previous statement, I mentioned his concept of homeorhesis, dynamic state, to erode optimism about cybernetic, and currently popular Bayesian, approaches to metabolism, a category which includes individual cognition. The stability of an organism is not the same as stability of any group of well-ordered atoms. In the latter, which includes the aperiodic crystals of nucleic acids, order is an emergent property which is completely described by the mathematics of phase transitions. Complexity describes the continuum from the geometric patterns of, say, crystals (which are intuitively visible), to the topology of proteins. However, it does not bridge the discontinuity between cells and the rest of the universe. Does anything?

Now I shall turn to two texts, both by towering figures in science, that are conveniently named *What is Life?* The first, written by Erwin Schrödinger in the 1940s, makes a radical proposal: that the ability of life to avoid heat death, at least in the conditions offered by its terrestrial environs, might be called negentropy (Schrödinger 1944). Schrödinger wants to explain the persistence of biological order over eons of geophysical time—an extraordinary feat that the most durable non-biological substances can hardly match. He presciently attributes the heritable characteristics of living substances to aperiodic crystals, and, in keeping with Darwin's theory of evolution, he cites mutation as the source for novelty. Unfortunately, Schrödinger does not account for the amount of time required for life to explore the state space of possible mutations—a figure that exceeds astronomical time by orders of magnitude (Kolmogorov complexity may make this problem more tractable [Dingle, Camargo & Louis 2018; Johnston *et al.* 2022]). It is equally unfortunate that Schrödinger's discussion of order led many to conflate thermodynamic entropy with the recently established theory of information entropy. I am aware of recent proposals that information may constitute a quasi-physical force at the quantum level, or under extreme gravitation, but, for now, linking these effects to macroscopic phenomena requires a speculative leap. While such a leap may lead to a comprehensive understanding of the universe, I argue we can ground biology with existing concepts, as long as we do not exclude suppressed legacies.

Half a century later, in an eponymous volume, Lynn Margulis and Dorion Sagan dispel the need for a negentropic force. What appears as negentropy is a local phenomenon, albeit one that requires a particular material constellation. Living beings export entropy into biophysical environments; this is a metabolic process that generates the organic order we observe as agency (Margulis & Sagan 2000, p. 229). As long as we do not commit category errors, e.g., separating cognition from other metabolic functions, there is nothing mysterious about the phenomena of life. Life is inherently diachronic, and it is not just complex: life is a particular kind of complex. In biology, whatever analytic unit we choose is the simplified foreground, isolated for convenience, of an energetic system, and the order exhibited by living things is produced—and reproduced—by self-organization. I use the last term not as an explanation but as an observation awaiting a theory.

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