

Commentary

What Is Life: A Biochemist's View

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The question of what defines life remains one of the most fundamental challenges in science and philosophy. While a consensus answer continues to elude us, we propose that organic life is best understood as an uninterrupted continuum of metabolic activity far from equilibrium—a continuous flow of matter and energy (including reducing power). This persistent metabolic continuity marks the vital boundary between living organisms and inanimate matter, including robots. Indeed, the absolute necessity of this unbroken flow is underscored by a simple truth: its interruption results in immediate and irreversible death.

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What is life? The question of what constitutes life has preoccupied philosophers and naturalists since classical antiquity. Since ancient times, many scientists and philosophers (such as Aristotle) have attempted to define the fundamental differences between the inanimate material world and living beings. These attempts largely relied on animistic concepts, which lacked empirical and scientific rigor.

Closer to us, during the first half of the 20th century, it was mainly the physicists who asked themselves the question, notably Erwin Schrödinger in a small book ("What is life?") published in 1944 ^[1]. While other great scientists such as Nils Bohr doubted that the functioning of living systems could be explained solely on the basis of the known laws of physics and chemistry, Schrödinger had a more reductionist approach and considered living beings as physicochemical systems with very particular properties but whose functioning obeys entirely the known laws of physics and chemistry.

This reductionist point of view has been adopted by the vast majority of biologists since the middle of the 20th century (see, for example, Monod, 1970 ^[2]). However, at present, the rigorous definition of living things is still the subject of much discussion and controversy (see references ^{[1][2][3][4][5][6][7]} for a non-exhaustive selection).

Some writers take an extreme reductionist approach, effectively negating life by reducing it to a mere physicochemical state ^[8].

Others conflate the notion of life with those of intelligence and consciousness ^{[9][10][11]}. We argue that these are three distinct concepts: while there is no doubt that a bacterium is alive, it possesses neither intelligence nor consciousness (until proven otherwise). Conversely, a chatbot equipped with highly advanced artificial intelligence (AI) cannot truly be considered alive.

Other scholars have proposed broader definitions of life. For instance, the renowned biologist Stanley Miller postulated that any system capable of reproduction and of adequately processing energy and information can be considered alive, regardless of its chemical composition ^[3].

However, the reproductive function must be understood through a temporal and evolutionary lens. A sterile hybrid (such as a mule) or a neutered animal is undoubtedly alive despite being unable to reproduce. On the other hand, the species as a whole, remains capable of reproduction and self-perpetuation.

Recently, William Brown of the International Space Federation proposed a particularly broad definition of life: "Within this study it is found that the requirements for abiotic matter to transition to a living system are only dependent upon a far-from-equilibrium thermodynamic low entropy state that enables animation of intrinsic universal awareness, a condition which generalizes the state of being alive to any configuration of matter and energy that can utilize information to intelligently manipulate matter and energy states for goal-oriented behavior and volitionally directed outcomes" ^[12]. Under this framework, any system—whether natural or artificial—that meets these conditions could be classified as alive.

Given that our era is defined by rapid advancements in robotics and AI, it is worth asking whether highly evolved robots could be considered living entities. They already share several key properties with living organisms, including a central processing system (AI), mobility, and complex behavior. One could even imagine a scenario where such robots build facilities to produce replicas of themselves (reproduction) or even design upgraded versions (evolution).

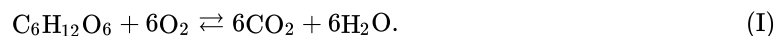
Critics might object that robots are composed of non-living components, whereas animals and plants consist of cells that are themselves living entities. For instance, spermatozoa and oocytes—both possessing all the fundamental characteristics of life—recombine to form a new organism, while isolated cells (such as mesenchymal stem cells) can be cultured in a laboratory and differentiated into various cell types ^[13]. However, a robot could also be compared to a unicellular organism, such as a bacterium or

yeast. If we examine life at a lower level of organization, the individual macromolecular components of a single-cell organism (membrane phospholipids, proteins, nucleic acids, etc.) are themselves non-living chemical entities—yet their collective assembly constitutes a living system.

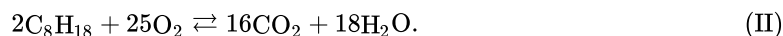
We can therefore imagine a scenario where robots equipped with advanced AI—and capable of reproducing by generating (more or less faithful) replicas—organize themselves into higher-order structures comparable to a biological society.

What, then, distinguishes such a system from a "classical" living entity—that is, one based on carbon chemistry as its structural backbone?

The latter exists in a state far from thermodynamic equilibrium ($dS_i > 0$), sustained by continuous fluxes of matter and energy (Fig. 1) derived from the combustion of organic substrates like glucose, which drives its metabolism:



However, one must not lose sight of the fact that such a robot also requires an energy source—such as a battery or fuel cell. This power storage must be recharged or replenished by an external energy input (e.g., light, electricity, or fossil fuels), effectively giving rise to a form of synthetic "proto-metabolism." Gasoline, for instance—primarily composed of alkanes such as octane—is combusted in the presence of oxygen through a chemical reaction remarkably analogous to the biological oxidation of glucose:



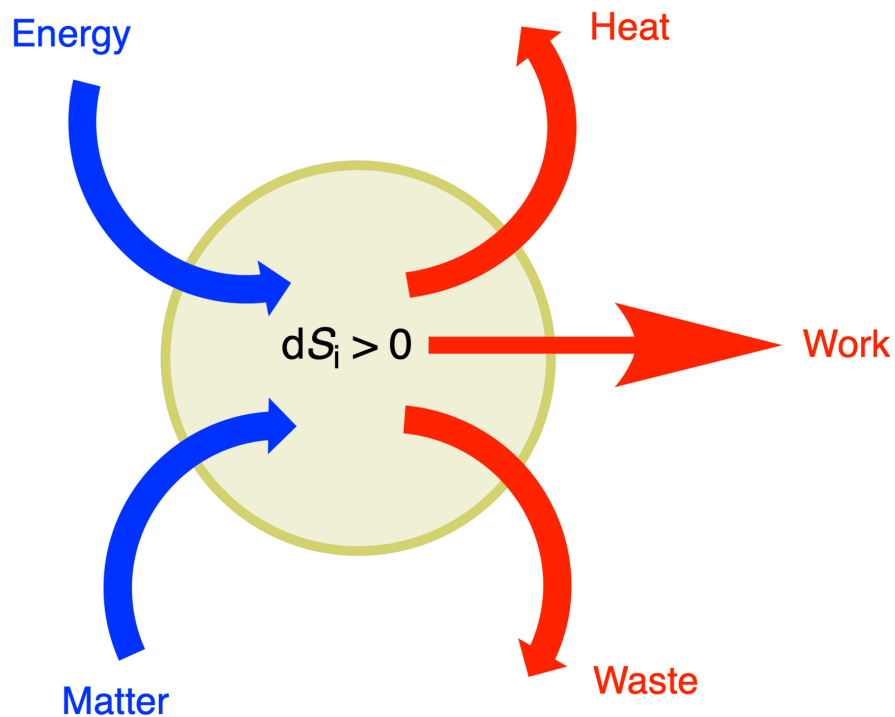


Figure 1. Living organisms are open thermodynamic systems traversed by flows of energy and matter (molecules). The energy supplied by the outside is converted into different forms of work with a minimum of dissipation in the form of heat. While some of these flows are vectorial (transport of molecules across a membrane, heat transfer), in others the flow translates in a chemical transformation (chemical reactions). These systems are therefore in a steady state meaning that the free energy remains relatively constant over time and are accompanied by an entropy production ($dS_i > 0$) ^[14]. (From ^[15]).

Alternatively, the battery could be charged—directly or indirectly—by solar energy. The ultimate outcome remains identical: the electrical energy supplied by the battery powers the artificial intelligence, mechanical actuators, and sensory sensors.

The primary distinction from organic life lies in how this energy is released. In a conventional fuel-powered system, combustion occurs rapidly and explosively (as in an internal combustion engine). In contrast, cellular metabolism operates through a gradual cascade of reactions, several of which occur near thermodynamic equilibrium. While reversible processes maximize useful work output (remember

that $\delta w_{\text{rev}} > \delta w_{\text{irrev}}$ [16]), complete equilibrium is incompatible with life—in thermodynamics, total reversibility is synonymous with death.

In cellular systems, the breakdown of glucose occurs through a multi-step pathway, enabling the controlled release and storage of energy as high-energy intermediates (such as ATP, thioesters, and redox equivalents). These compounds are subsequently used to synthesize the molecular building blocks essential for cellular maintenance and growth. This anabolic dimension is completely absent in current robotics: a robot must rely on an external, independently powered factory to construct a duplicate of itself. Consequently, a clear spatial and temporal discontinuity in metabolism exists between the parent robot and its offspring.

This distinction carries a corollary of paramount importance: a robot can be powered down and subsequently restarted without ill effect, whereas any severe disruption of cellular metabolism (such as anoxia or poisoning by cyanide or carbon monoxide) is synonymous with death—the system will never restart.

In a living cell, there is absolute continuity between the parent entity and the progeny, whether through sexual reproduction (via gametes) or asexual cell division. Indeed, both sperm and egg cells are fully alive and metabolically active prior to fertilization. Over the past four billion years, life on Earth has never “rebooted” between generations. The current metabolic flux is thus a direct, unbroken physical continuation of the primordial metabolic cascade initiated in the ancient oceans. This fundamental contrast alone erects a sharp barrier between the two worlds—one intrinsically discontinuous, the other continuous.

It seems plausible that robots could build a civilization and even supplant humanity (or any extraterrestrial equivalent), yet they would remain non-living entities in the metabolic sense due to their lack of a metabolic continuum. Another fundamental distinction lies in their origin: robots are artificial constructs that must be created by a pre-existing living entity. Unlike metabolic organisms—which, until proven otherwise, emerged naturally through a prolonged prebiotic evolutionary process—synthetic entities cannot arise spontaneously from within their own domain.

In view of this framework, it becomes relevant to re-evaluate the unique position occupied by viruses in the hierarchy of life. A virus particle (virion) consists merely of genetic material (DNA or RNA) enclosed within a protein capsid, sometimes accompanied by lipids and carbohydrates. Incapable of autonomous reproduction and completely devoid of metabolism, a viral particle is biochemically closer to a ribosome

than to even the simplest prokaryotic cell. Because an isolated virus exchanges neither matter nor energy with its environment, it behaves as an isolated thermodynamic system [17]. To reproduce, however, the virus must obligately parasitize a host cell (whether prokaryotic or eukaryotic). By hijacking the cellular machinery, the expression of the viral genome redirects host metabolism toward the assembly of new viral particles, turning the virus-host complex into a new, open, and living thermodynamic system. The virus thus represents a form of life that oscillates between a non-living inert state and a living state—a duality enabled exclusively through obligate symbiosis with an active living entity.

Consequently, we tentatively propose to define organic life as a continuous metabolic spectrum extending from the most primitive autonomous organisms to the most complex lifeforms. Any interruption of this metabolic continuum (where internal entropy production dS_i drops to 0) inevitably corresponds to death (Fig. 2). Ultimately, we argue that life is best defined as a thermodynamically open metabolic continuum expressed through an unbroken flow of mass, energy, and reducing power across the entire organism. Because living entities never exist in isolation but proliferate in tight interplay with one another, this metabolic continuum expands to encompass the whole biosphere.

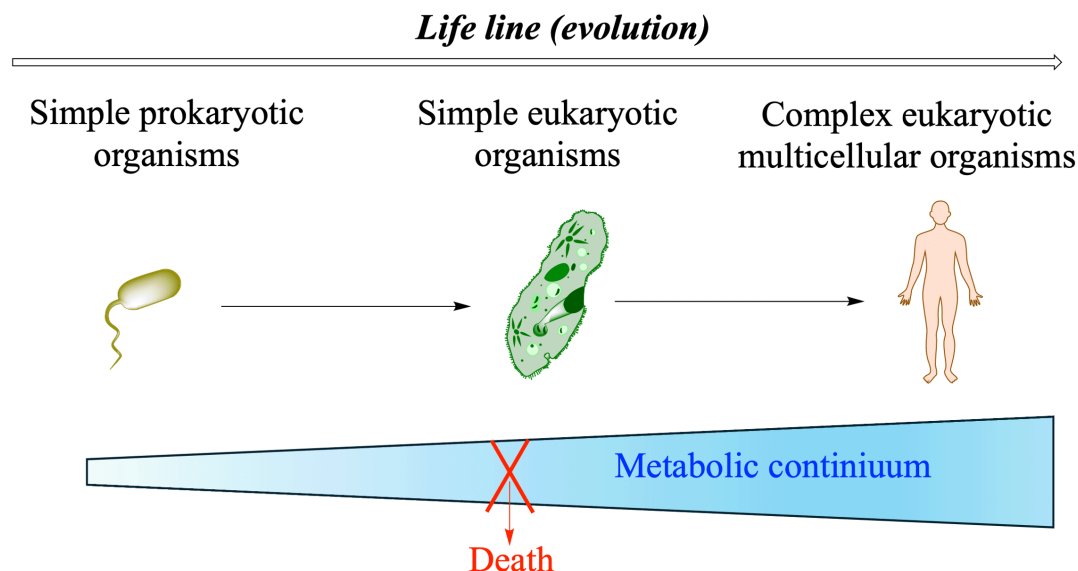


Figure 2. Unbroken lineage of germline cells passing active metabolism down through billions of years of evolution. Any interruption of cellular metabolism generally causes death within minutes. However, some cells, especially prokaryotes, can enter a state of dormancy, maintaining a minimal metabolic flux to survive prolonged environmental stress.

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Data Availability

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Author Contributions

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Declarations

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