

What is life? Definitions, controversies, ontological perspectives, and implications for biology education

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Abstract

Despite major advances in biology and sustained debate in the philosophy of science, the question “What is life?” remains unresolved. Biology education, particularly through textbooks, continues to rely on non-consensual lists of characteristics that persist in students’ thinking, even when several have been revised or abandoned in contemporary science. To address this conceptual and pedagogical tension, we propose an ontological shift from understanding life as a set of properties to conceiving of it as a process. We show that both scientific fields—such as synthetic biology and origins of life research—and philosophy of biology increasingly converge on a process-oriented account. This framework accommodates challenging cases such as viruses, avoids essentialist interpretations, and supports more systemic and dynamic perspectives. Engaging students with the philosophical question “What is life?” may foster deeper conceptual change and contribute to a more integrated and reflective biology education.

Keywords definition of life, ontology of life, philosophy of biology, biological education

Biology, since its origins as a discipline, has been defined as the study of life (e.g., Mayr 1996, Campbell et al. 2001, Raven et al. 2023). This definition is supported by its etymology, from the Greek words *bios* (life) and *logos* (study). Despite the extensive biological knowledge accumulated thus far, questions such as “What is life?” or “What differentiates living from non-living objects?” remain unresolved and lack consensus (e.g., Popa 2004, Trifonov 2011, Kauffman 2013, Cleland and Zerella 2014, Ferreira Ruiz and Umerez 2018, Dupré 2020, Fernau et al. 2020, Vidal-López 2020, Amilburu et al. 2021, Gómez-Márquez 2023, Pierce 2023). Although certain areas of biology, such as those that study the origin of life (e.g., Kauffman 2013) or the synthesis of biological elements (e.g., Fernau et al. 2020), have contributed to developing a more contemporary view of life, these proposals seldom permeate into biology itself, and even less so into biology education. For example, in biology textbooks (table 1), life is often depicted as a list of properties aimed at capturing its essence (Mayr 1996, Pierce 2023) or at characterizing living organisms (Vidal-López 2020). When these properties are overly rigid, they are frequently challenged by counterexamples or contentious cases, prompting many scholars to revise

classical property lists and propose more robust definitions. For instance, Ferreira Ruiz and Umerez (2018) advocate for definitions that transcend life as it exists naturally on Earth. Similarly, Cleland and Zerella (2014) emphasize the practical significance of addressing the question “What is life?,” highlighting its relevance to research on the origin of life, the search for extraterrestrial life, and synthetic biology experiments.

Thus, such inquiries demand a more precise examination of what biologists recognize as a definition of life, as well as the scope and implications of the life definitions we use in research and education.

In this regard, reflection on the ontology of life might offer pathways toward a consensual understanding of life and its nature. Yet, a common ontological classification of life remains elusive. Historically, philosophers like Aristotle conceptualized life as a material substance or object (Marcos 2017). Contemporary philosophers of biology debate whether life should be understood as an emergent property—or a cluster of properties—and whether these properties are individual or systemic (Ferreira Ruiz and Umerez 2018). Others advocate for a processual and systemic perspective (e.g., Pross 2012, Ferner and

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Table 1. Samples of definitions of life based on cluster of properties.

Book title/authors	Properties												
	O	Rep	M	G	A	S	H	D	I	Reg	Com	Con	Mo
Biology (Raven et al. 2023)	X	X	X	X	X	X	X	X			X		
Campbell Biology (Hillis et al. 2021)	X	X	X	X	X		X	X		X			
Life: The Science of Biology (Hillis et al. 2020)	X	X	X	X	X	X	X	X	X	X			
Biology (Brooker et al. 2020)	X	X	X	X	X	X	X	X	X		X	X	
Biological Science (Freeman et al. 2017)	X	X	X		X	X	X	X	X	X	X	X	
Biology: Science for Life (Belk and Maier 2015)	X	X	X	X	X	X	X		X				X
Biology: The life in the earth (Audesirk et al. 2013)	X	X	X	X	X	X	X						
Concepts in Biology (Enger et al. 2012)	X	X	X	X	X	X	X	X	X	X	X	X	
Biology (Solomon et al. 2011)	X	X	X	X	X	X		X					X
Biology (Robinson 2002)	X	X	X	X		X							
Total frequency	10	10	10	9	9	9	8	7	5	4	4	3	2

Note: The properties are as follows: O = organization (the composition of one or more cells as the fundamental structural and functional unit of life); Com = complexity (a high degree of ordered structural and functional organization emerging from interactions among components across multiple levels); Con = control (the presence of regulatory mechanisms that coordinate internal processes and responses to maintain functional integration); S = sensitivity (the ability to detect and respond to internal and external stimuli through specialized molecular and cellular mechanisms); G = growth (an increase in size and/or cell number); D = development (a genetically programmed process of change in form and function over an organism's life cycle); Rep = reproduction (the biological process by which organisms produce offspring); Reg = regulation (the coordinated adjustment of physiological activities to sustain stable internal functioning); H = homeostasis (the dynamic maintenance of relatively constant internal conditions despite external fluctuations); A = adaptation (the evolutionary process by which heritable traits that enhance survival and reproduction become more common in populations over generations); I = information (the capacity to store, transmit, and express genetic information encoded in DNA, directing structure, function, and inheritance); M = metabolism (the sum of all chemical reactions through which organisms obtain, transform, and use energy and matter); Mo = movement (the capacity of organisms or their internal components to change position, enabling function, interaction, or survival).

Padreu 2018, Dupré 2020, Gómez-Márquez 2023, Pierce 2023). However, these rich epistemological and ontological discussions have seen limited integration into the training of biologists and biology teachers.

Therefore, this essay aims to illustrate the advantages of engaging with these debates within biology and to highlight how adopting alternative ontological perspectives could benefit both biology and biology education. To this end, the discussion will encompass insights from biology and the philosophy of biology, proposing ontological and pedagogical solutions to the enduring challenge of defining life. In this paper, as several other authors have done, we understand life as a process, state, or property (or a “collection” of properties) that emerges, whereas living systems or living organisms are understood as objects, entities, or structures that possess the property of life or undergo this process (e.g., Fernau et al. 2020, Pierce 2023).

The problem of life: How does biology define its object of study?

Trifonov (2011) identified over 100 definitions of life and, through semantic synthesis of 123 definitions, proposed that life could be defined as “self-reproduction with variation.” A similar perspective is adopted by the United States National Aeronautics and Space Administration (NASA), which defines life as “a self-sustained chemical system capable of undergoing Darwinian evolution.” On the other hand, other researchers such as chemist Addy Pross (2012), have defined life as “a self-sustaining kinetically stable dynamic reaction network derived from the replication reaction” (p. 164). In a similar approach, evolutionary ecologist S. Pierce (2023) defined life as “a self-regulating process whereby matter undergoes cyclic, uniplanar conformation state

changes that convert thermodynamic disequilibria into directed motion, performing work that locally reduces entropy” (p. 9).

In contrast, a search of widely used general biology textbooks reveals a tendency to describe life as a property of biological entities that evolve, adapt to their environment, develop, and reproduce (Raven et al. 2023, table 1). For instance, Curtis and Barnes (2000), in the sixth edition of *Biology*, state that “there is no simple definition of what life is; life does not exist in the abstract—there is no life, only living beings—and no simple or singular way to demarcate the living from the non-living” (p. 12). Curtis and Barnes (2000) conclude that no single property is exclusive to the living world. In the same vein, Hillis and colleagues (2020) write: “The phenomenon we call life defies a one-sentence definition. We recognize life mainly by what living things do.” To define life, they highlight some of the properties and processes humans associate with it, such as evolutionary adaptation, regulation, energy processing, or reproduction (see table 1 for a summary of examples of life definitions based on cluster traits). Therefore, although these texts often assert that biology is the study of life or “the living,” they frequently fail to provide a definition of life. Moreover, many do not reflect on the historical complexity and ongoing challenges faced by the scientific community in establishing a singular, universally accepted definition of life. At best, they acknowledge the historical debate within the scientific and philosophical communities or emphasize the complexity of addressing this question. The most typical approach to define life involves listing certain properties that all living organisms are expected to possess. However, no consensus has been reached on these properties to date (table 1).

Various criteria have traditionally been proposed to characterize life (Farmer 1992, Emmeche 1994, Luisi 1998, Koshland 2002, Dupré and O'Malley 2009, Benner 2010, Ferreira Ruiz and Umerez 2018, Fer-

nau et al. 2020), with some of these properties closely interconnected or partially overlapping. As table 1 shows, in biology books used in undergraduate biology education, at least 13 characteristics can be found that are usually given as typical of living beings. Some of the most recurrent are (i) **cellular organization** or being composed of one or more cells, which serve as the unit of life and the minimum structure supporting vital activity; (ii) showing the ability to increase in size or number of components in a regulated manner (**growth**); (iii) having the capacity to produce similar compositional systems (**reproduction**); (iv) reproducing with hereditary variation that may lead to differences in fitness (**evolution and adaptation**); and (v) engaging in complex biochemical reactions that utilize free energy and environmental nutrients to produce compounds necessary for maintaining organization (**metabolism**) (table 1; Pierce 2023). However, this list of properties is not universally adopted, and some traits are absent in specific biology textbooks (table 1) or definitions, and counterexamples often accompany these proposals, further complicating efforts to establish a singular definition (e.g., Solomon et al. 2011, Pierce 2023, Raven et al. 2023). For example, there exist some contemporary perspectives on the role of information in the definition of life (see table 1) emphasizing not merely its complex chemistry but also the manner in which life actively manages and processes information (Karp 2019, Bartlett et al. 2025). Moreover, some theorists have proposed that the origin of life can be understood as a transition in which information shifts from being a passive attribute of molecules to exerting causal efficacy over matter, thereby enabling hierarchical regulation within biological systems (Walker and Davies 2012).

According to Pierce (2023), this kind of definitions of life using clusters of traits fail because “they focus on secondary phenomena or emergent properties without successfully discerning the underlying mechanism” (p. 2). Furthermore, this type of definition falls short in terms of being able to encompass all the definitions that can be proposed and used by scientists who study life. For example, Fernau and colleagues (2020) studied how scientists working in the field of synthetic biology defined life, concluding that there are four basic concepts of life, including life as a stage model based on a list of properties of living matter. The other three definitions were life as a continuous process starting with the origin of life; life as a general principle; and life as a relational concept.

If we stay for a moment on the definition of life as the process that begins with the origin of life, it is not surprising that it is the researchers working on this subject who in recent years have most strongly proposed the idea of understanding life as a “process” and not as a “thing”; such as the passage from chemistry to biology, or the process by which chemical material decreases entropy (e.g., Pross 2023, Kauffman 2013, Pierce 2023). In fact, in his seminal work, *What is Life*, Schrödinger (1944), was one of the first trying to answer this question asking for the main trait of life; “What is the characteristic feature of life?” (p. 69), giving some of the traits in table 1 (e.g., moving, exchanging material with its environment). However, it was in this work that the proposal that life, unlike the inanimate universe, is the process by which entropy is reduced was also conceived; “Life seems to be orderly and lawful behavior of matter, not based exclusively on its tendency to go over from order to disorder, but based partly on existing order that is kept up” (p. 68).

In the most contemporary version of defining life as a unique chemical process, Pross (Pross 2012, Pross and Pascal 2023) proposes that life is a kinetically stable dynamic reaction network. He introduces the concept of dynamic kinetic stability (DKS), the process by which

life originates and persists over time through replication. According to this proposal, natural selection would be a chemical consequence of kinetic competition between replicators (Pross 2012). Meanwhile, Pierce (2023) defines life as a dynamic process sustained by networks of kinetically coupled chemical reactions far from thermodynamic equilibrium. According to this proposal, life operates far from thermodynamic equilibrium, but its definition does not focus on kinetics, nor on thermodynamics, but rather on the creation of structures (organization) through the generation of work and movement (Pierce 2023). Both propositions, in which life is understood as a continuous process, are in line with contemporary philosophical suggestions, some of which we will review in the next section.

How does the philosophy of biology define life?

In the philosophy of biology literature, there exists a wide range of definitions of life, spanning from perspectives that advocate refraining from defining life altogether (e.g., Machery 2012, Cleland 2019), to processual approaches that conceptualize life as a dynamic process (e.g., Gómez-Márquez 2020, 2023), and to more classical system-based proposals (e.g., Razeto-Barry and Ramos-Jiliberto 2013) that attribute life to one or more properties distinguishing it from inert matter (e.g., Diéguez 2013, Ferreira Ruiz and Umerez 2018). However, even among the system-based proposals, no consensus has been reached. Table 2 provides a compilation of definitions of life proposed by various authors in the fields of philosophy of biology as well as biology and biochemistry. All current definitions of life emphasize specific life-giving properties. Some definitions prioritize functional criteria, such as metabolism and reproductive autonomy, whereas others focus on evolutionary criteria, like continuity or the ability to evolve, alongside metabolic or organizational characteristics as the most critical considerations (Popa 2004).

For example, Maturana and Varela (1973, 1994) said that a living system is defined by a particular organization: a network of molecular processes that continuously produces and maintains itself. Life consists of the ongoing realization of this organization, preserved through a constant molecular flow. A living being exists as long as this organization is conserved, and its autonomy emerges from this operational closure. Moreover, in the formulation developed by the authors, this idea is articulated through the concept of autopoiesis. Living systems are characterized by a circular organization of molecular productions that regenerate the very network that produces them. Thus, life is not something that an entity possesses, but the continuous realization of a self-producing and self-delimiting organization. A system remains alive insofar as it conserves this autopoietic organization, which defines its identity and autonomy as a living system.

Later, Hooker (1981, 1987, 1995) developed the notion of autonomous systems and “organizational autonomy” as a basis for defining life, arguing that (i) living organisms are autonomous systems, that is, cohesive systems whose components are bound together by “dynamic linkages” that distinguish them from their environment; (ii) they are thermodynamically far-from-equilibrium systems, requiring the import of energy and matter in order to maintain their organization, support their vital processes, and interact with the environment; (iii) moreover, it is not sufficient for them to preserve their internal processes, as they must also engage with their surroundings and even modify their own processes in response to contextual demands—a capacity referred to as “organizational autonomy,” which characterizes life itself; and (iv) finally, they embody a normative

Table 2. The definitions summarized in this table originate from philosophers and scientists and represent distinct theoretical, ontological, and methodological approaches to understanding life.

Authors	Definition of life and/or characterization of living organisms
Maturana and Varela (1994 [1973])	Living is the continuous realization of molecular dynamics in a molecular autopoietic system, preserved through a constant molecular flow. The dynamic itself constitutes the living entity, providing autonomy without the entity using the dynamic to regenerate or sustain itself
Shapiro and Feinberg (1990)	Life is the activity of a “biosphere,” that is, the activity of “a highly ordered system of matter and energy characterized by complex cycles that maintain or gradually increase the order of the system through an exchange of energy with its environment”
Emmeche (1994)	Intuitive notions of life imply that living systems result from a continuous evolutionary process producing autonomous organisms that are highly organized, open, and thermodynamically far from equilibrium systems
Joyce (1994)	“Life is a self-sustained chemical system capable of undergoing Darwinian evolution”
Hooker (1995)	Life is defined by organizational autonomy, cohesive systems that regenerate themselves while remaining thermodynamically far-from-equilibrium. Living beings require constant exchange with the environment, actively adapting and modifying internal processes. They also embody a normative dimension, evaluating changes by internal criteria and exercising self-direction
Luisi (1998)	Life is defined as a system self-sustained by utilizing external energy and nutrients, with an internal process producing components coupled with the environment through adaptive changes persisting through the system’s history
Koshland (2002)	Defines life based on the acronym PICERAS: Program (genetic), Improvisation (genetic adaptability), Compartmentalization (spatial confinement), Energy (open metabolic system), Regeneration (component renewal), Adaptability (behavioral response), and Seclusion (metabolic isolation)
Ruiz-Mirazo et al. (2004, 2010)	Two key properties of living systems are (basic) autonomy and open-ended evolution
Di Paolo (2005)	A self-producing process that not only conserves itself but also regulates, evaluates, and makes sense of its own existence, generating agency, historicity, and values
Dupré and O’Malley (2009)	They note: “Our central argument is that life arises when lineage-forming entities collaborate in metabolism. So, our vision of life is a continuum of variably structured collaboration systems”
Benner (2010)	Life is described as a self-sustaining chemical system capable of Darwinian or “supra-Darwinian” evolution
Pross (2012)	A self-sustaining kinetically stable dynamic reaction network derived from the replication reaction
Diéguez (2013)	Defines life as a natural type based on homeostatic properties: structural and hierarchical organization, self-reproduction with heritable variation (enabling evolution), genetic information storage, metabolism, and interaction with the environment
Forterre (2013)	Life is the mode of existence for ribosome-encoding organisms and capsid-encoding organisms and their ancestors. Organisms are defined as integrated molecular/cellular systems producing individuals that evolve through natural selection. The origin of life is tied to the emergence of the first organism meeting these criteria
Razeto-Barry and Ramos-Jiliberto (2013)	Life is argued to be an autopoietic system operating at multiple levels, transcending the molecular level
Bickhard (2016)	Life is conceived within a processual rather than a substantial framework. The author does not provide a straightforward definition of life; rather, his writings delineate the defining features of a living system, such as interactive autonomy, the condition of being far from thermodynamic equilibrium, and the capacity for self-maintenance. Furthermore, the organism exhibits normativity as an emergent property, representation as anticipatory function, and recursive self-maintenance
Dupré and Guttinger (2016)	Key properties of living systems include metabolism and collaboration
Ferner and Pradeu (2018)	Life is viewed as a process , not a substance. Developmental trajectories and stage differences are generative and not adequately captured by the traditional substance-based view
Ferreira Ruiz and Umerez (2018)	Life is characterized by cluster properties such as cellular organization, metabolism, equilibrium state, autonomy, spatial limitation, reproduction, responsiveness, common molecular constitution, growth, and evolution
Dupré (2020)	Life and organisms are processes with varying properties over time, analogous to objects undergoing changes
Gómez-Márquez (2020)	Proposes seven principles (Vital Order, Principle of Inexorability, reformulated Central Dogma, Tyranny of Time, Evolutionary Imperative, Conservative rule, Cooperating Thrust) as rules for explaining life as an evolutionary process . Life is metaphorically described as a never-ending race with changing runners and evolving rules
Gómez Márquez (2023)	Life is defined as an interactive process that occurs in entropy-producing, adaptive and informational (organic) systems. Life must create order by continually producing disorder and exporting it to the environment, so that we move and stay in the phase transition between order and chaos, away from equilibrium, thanks to the input of energy from outside
Pierce (2023)	Life is a self-regulating process whereby matter undergoes cyclic, uniplanar conformation state changes that convert thermodynamic disequilibria into directed motion, performing work that locally reduces entropy

Note: For the preparation of this manuscript, we conducted a structured search in ERIC, Web of Science, and Scopus using the keywords “life” and “definition of life,” without temporal restrictions. The results were manually screened to exclude works that did not directly address the conceptual definition of life. Only publications that explicitly proposed or analyzed a definition of life were included in this table and in the corresponding philosophical discussion, enabling engagement with diverse authors and research traditions within the philosophy of biology and related fields.

dimension, in that they can evaluate their changes according to internal criteria (autonomy), thereby responding with a certain degree of self-direction. Another philosopher of biology, Bickhard (2001, 2008, 2009, 2016), does not provide a straightforward definition of life;

rather, his writings describe the constitutive characteristics of living systems, which he refers to as autonomous or interactive autonomous systems. These systems are characterized by their maintenance of processes endowed with emergent normative properties (Bickhard 2016).

For Bickhard (2008, 2009), a living system must remain open and engage in regulated interactions with its environment, thereby preserving a stable form in the face of environmental perturbations—what he considers self-maintenance. Within the broader function of sustaining life and autonomy, Bickhard (2001) highlights the anticipatory nature of action: Life presupposes certain favorable environmental conditions that may or may not obtain, thereby introducing the possibility of representational error—representation as anticipative function (Bickhard 2001).

From a segment of the philosophy of biology, it has been argued that our current biological knowledge is insufficient to generalize a definition of the nature of life. Cleland and Zerella (2014) contend that it would be a mistake to base a universal definition of life solely on the example of life on Earth. Nevertheless, other philosophers of biology argue that the perceived futility of defining life stems from an overemphasis on the classificatory function of such definitions, overlooking other epistemological purposes (Knuuttila and Loettgers 2017). For example, Amilburu and colleagues (2021) assert that defining life is a necessary and valuable endeavor because it is a complex, historical, and multidimensional phenomenon, for which sufficient empirical evidence and scientific theory have been developed.

On the other hand, Gómez-Márquez (2023) distinguishes between conventional and non-conventional definitions of life. Within conventional definitions (see table 2), Dupré and O'Malley (2009) propose that metabolism and reproduction are the most widely accepted criteria for defining a living being. Metabolism, as a fundamental means of survival, is often regarded by many scientists as the most essential biological process and the key distinction between living and non-living entities (Luisi 1998). However, some authors disagree that reproduction, whether at the organismal or cellular level, is a valid criterion for classifying life. If reproduction were a necessary condition for being alive, infertile organisms would fail to meet this criterion (Ferreira Ruiz and Umerez 2018). Similarly, reproduction can also occur in non-living systems, such as crystals, which grow and replicate (Benner 2010, Pierce 2023).

The case of viruses is particularly challenging for conventional definitions of life because viruses have some traits of life but not others. Viruses, composed of nucleic acids capable of replicating, mutating, and evolving, are typically classified as infectious subcellular agents. Conventional biology does not consider viruses as living beings because they lack the autonomy required for reproduction and metabolism, relying entirely on host organisms for these processes (Alberts and Bray 2011, Curtis and Barnes 2000, Van Regenmortel 2016). Dupré and O'Malley (2009) argue that this lack of autonomy is not exclusive to viruses but is also seen in other organisms, including humans. Conversely, some exceptions among viruses challenge this classification. For example, the *Alicidius* virus can develop flagella outside its host cell, and “Mimiviruses” exhibit sophisticated, independent replication mechanisms. Similarly, Forterre (2013, 2016) introduces the concept of the virocell, the infected cell hosting a virus, as the unit of life for viruses. In this framework, the virocell represents the “life form” of the virus, while virions function analogously to seeds or bacterial spores, lying dormant until conditions are suitable for activity (Forterre 2013). This perspective positions viruses as “hybrid entities” straddling the boundary between life and non-life (Vidal-López 2020).

A rarely discussed yet significant criterion for defining life is the **capacity to collaborate**. Collaboration, both at the intracellular and intercellular levels, is arguably one of life's central characteristics

(Dupré and O'Malley 2009). For instance, although humans are considered discrete biological entities, derived from a lineage of cells originating from a single zygote, they also consist of a vast number of symbiotic bacteria. These microbial cells, which constitute approximately 50% of the total cells in the human system, play critical roles in physiological processes associated with digestion (Sender et al. 2016). This collaboration is essential for maintaining systemic functionality. Without such symbiosis, humans, as discrete entities, would not autonomously sustain the metabolic processes vital for survival. Dupré and Guttinger (2016) argue that most eukaryotic organisms, including humans, rely on symbiosis with other organisms to achieve homeostasis, reproduction, and survival. Consequently, it can be asserted that life emerges at the collaborative intersections of many lineages, where entities work together to sustain living systems.

The ontology of life: a key element for research and understanding

The first philosophical text on biology is found in Book I of Aristotle's *On the Parts of Animals*, where Aristotle is often regarded as the first philosopher of biology to apply empirical knowledge to the study of “the living” (as he referred to living organisms). Using an articulated body of theories and concepts far advanced for his time, Aristotle argued that living beings are substances. Although he did not explicitly define life, he sought to explain it by defining what constitutes a living being. According to Aristotle's ontology, the world is populated by **substances**—what we today understand as **material objects**—and among these, living beings are the quintessential substances (Marcos 2017).

Much later, approximately 300 years ago, many biologists adhered to vitalism, a theory positing that living organisms possessed a “vital spirit,” a unique **property** enabling them to perform activities impossible for inert matter. Vitalists argued that this essence distinguished living from non-living systems. In contrast, mechanists, led by René Descartes in the seventeenth century, proposed that reality, including life, consisted merely of inert particles colliding and interacting (Razeto-Barry 2018). Mechanists contended that life was not fundamentally different from inanimate systems, reducing the explanation of life to characterizations of properties in living beings. By the 19th century, reductionism emerged, proposing that the **complex properties** and operations of life could be simplified and understood through basic principles (Curtis and Barnes 2000). However, reductionists, like vitalists and mechanists, failed to provide a definition of life, instead focusing on the characterization of **properties** in living entities.

In modern biology, it is widely accepted that life obeys the laws of chemistry and physics, and belief in a vital principle has been abandoned. Yet, as Vidal-López (2020) notes, biologists still have not reached a consensus on a definition of life. Instead, they continue to describe the **properties** of living organisms or propose that life itself is merely an emergent property of certain entities defined as living. Naturalism offers an alternative framework, treating living beings as a natural type with flexible boundaries, where members need not exhibit all properties but rather a “cluster” of defining characteristics (Ferreira Ruiz and Umerez 2018).

Building on Aristotle's views, some philosophers of biology, such as Hull (1992), have rejected the notion of individuality based on substance or material objects, emphasizing that living beings do not retain unchanged material substance throughout their existence. Living entities undergo maturation, metamorphosis, and other

transformations, demonstrating that what we perceive as “constant things” are merely temporary stabilities within a continuous flow of change (Ferner and Pradeu 2018). Moreover, Dupré (2012, 2020) argues that understanding organisms as autonomous substances is misguided, as multicellular organisms—and even most unicellular ones—are inherently symbiotic. The stabilization of an organism depends on external and internal factors, undermining the autonomy implied by substance-based ontologies.

Dupré contends that our understanding of life has been constrained by metaphysical perspectives that view the world as composed of static things and their properties. Instead, he proposes that life is better understood as a **process**. Organisms’ life cycles, encompassing transformations in form and function, align with the view that life is a **series of interacting processes**. These interactions regulate balances such as cell division, differentiation, and death, shaped both by internal cellular dynamics and the organism’s larger structural context (Dupré 2020). Ferner and Pradeu (2018) argue that the shift toward a **processual vision** of the living world—where organisms are conceptualized as processes rather than static “things” or “substances”—is both dramatic and necessary. They contend that this **processual ontology** is more appropriate because it accounts for the developmental trajectories of organisms and the substantial differences in properties between stages of their life cycles, which traditional substance-based views fail to address. Similarly, Gómez-Márquez (2023) concludes that life is inherently a process and that living beings are the systems through which this process unfolds. This perspective, according to Gómez-Márquez, is fundamental to developing an adequate and comprehensive definition of life.

This perspective also resolves the ongoing controversy regarding the specific properties a material object must exhibit to be considered alive. It addresses debates within the scientific community about the classification of hybrid entities that exist in a gray area between living and non-living systems—entities that exhibit only certain properties from the cluster typically associated with life. For instance, viruses could be classified as life when forming the virocell, as life would now be understood as a process. Furthermore, this alternative ontology is more open to recognizing the emergence of new forms of life beyond those known on Earth. A similar point of view on viruses is proposed by Pierce (2023) based on his definition of life as an emergent organizational process. According to this author: “in their free state they [viruses] are aggregates of molecules (a non-living state), but when they encounter cell membranes and are then intimately incorporated into metabolic machinery, they actively participate in the directed motion network (share the living state of the cell), which reduces entropy by converting simple resources into more complex copies of virus particles.” Much the same point of view on viruses would be inferred from the definition of life by Pross (2012), who conceives it as a replicative chemical process. From a coherent reading of Pross, it could be said that, during replication, the viral genome is part of a chemical system that exhibits DKS and Darwinian evolution, so it participates in the process of life.

Table 3 summarizes a comparison of different biological, philosophical, and pedagogical dimensions that can be inferred when we understand life as a state associated with one or more emergent properties or as a process. In the following section, the educational and learning aspects associated with the definition of life are described and reflected upon. The comparison developed here makes visible how the choice between a property-based and a process-based understanding of life reorganizes explanatory priorities across levels of

analysis. A trait-centered framework tends to privilege categorization and boundary setting, whereas a process-oriented perspective foregrounds mechanisms of organization, conservation, and transformation over time. This shift has implications beyond the definition itself: it influences how biological phenomena are interpreted, how borderline cases are approached, and how coherence between molecular, cellular, and systemic levels is conceptualized. Rather than offering mutually exclusive alternatives, the contrast clarifies how each framework frames problems differently and reveals what becomes conceptually salient within each ontological stance.

Learning challenges and implications for teaching the concept of life

It has been suggested that biology employs far more concepts in generating knowledge compared to disciplines like chemistry and physics (Mayr 1996). This may influence students’ perceptions of biology as a difficult subject and affect their ability to learn it effectively at school and university levels (e.g., Wandersee 1988, Nehm 2019). Currently, hundreds of concepts are utilized in biology education, presented either through textbooks or teachers’ discourse in classrooms (Nehm 2019), with the concepts of life and living beings being no exception. Despite the importance of understanding biological concepts (Kampourakis 2021), researchers in science education and teachers themselves have observed and documented several poorly understood topics and concepts, including life and living beings (e.g., González-Weil and Harms 2012, Martínez-Lozada et al. 2013, Reiss and Kampourakis 2018, Cofré et al. 2023). On the other hand, the concepts of life and living beings are foundational in biology curricula and textbooks, serving as structural pillars for other topics taught at various educational levels, from preschool to university (Harlen 2010). For example, in the *National Curriculum in England* (2015), second-year primary students are taught to “explore and compare the differences between living things, dead things, and things that have never been alive,” whereas sixth-grade students are tasked with “describing how living things are classified into large groups based on common observable characteristics, including microorganisms, plants, and animals.” Similarly, in the US teaching standards (NGSS Lead States 2013), the central idea in life sciences, LS1, “From molecules to organisms: structures and processes,” focuses on the key characteristics of living beings. This idea emphasizes explaining how the complex systems of living organisms grow, develop, reproduce, and function to thrive. However, educational research suggests that this curricular emphasis does not always translate into an integrated understanding of the concept of life, partly due to the ways in which it is introduced and developed in curricular materials.

In this regard, Medina and Quiroz (2025) show that school textbooks tend to introduce life and the functioning of living beings through **implicit ontological assumptions**, predominantly holistic in nature, which privilege global descriptions of organs and functions while failing to make explicit the cellular mechanisms and interactions that give rise to emergent properties. This approach hinders students’ ability to move across levels of biological organization and to construct coherent explanations of what it means to be alive, thereby fostering fragmented and weakly articulated understandings. From this perspective, learning difficulties associated with the concept of life cannot be attributed solely to individual cognitive deficits, but must also be understood in relation to the underlying ontologies that structure curricula and school textbooks.

Table 3. Overview of definitions of life as a process or as a list of properties and their underlying distinguishing dimensions.

Dimension	Life as a stage model based on a list of properties of living objects	Life as a diverse-definable, continuous process (starting with the origin of life)
Question that answers	What traits does something have to be alive?	What dynamics and relationships occur in the process of life?
Ontology	State/object's feature (e.g., Raven et al. 2023)	Processual-chemical (e.g., Pross 2012); Processual-systemic (e.g., Pierce 2023)
Conceptual consequence	Separates the living from the non-living	Integrating life within the physical-chemical continuum
Consequences for studying the origin of life?	Difficult to studying and understand the origin of multiple properties	The origin of life is implicit in the definition since life as a process is a bridge between the inert and the living
Viruses status	It is not life (uncertain) because it does not have some properties (metabolism), but it does have others (it evolves)	During replication, the viruses enters a dynamic replicative process that meets the life criterion
Differentiation between living and non-living	Not clearly possible to draw a line by defining different traits (e.g., viruses)	Difficult but possible to draw a line due to fluid transitions and processuality of life
Positive aspects to understand what life is	It is concrete, it reduces complexity	Avoid essentialism. Promotes systemic and dynamic thinking
Negative aspects to understand what life is	It promotes preconceptions such as associating life with macroscopic movement. It can complicate the understanding of evolution as a process	It is more complex to understand

In pedagogical terms, Kampourakis and Stern (2018) emphasize the importance of clarity in the meanings of scientific concepts, as these are central to both science and science education. This raises the question: how can this lack of consensus about the ontology of life or the definition of life be addressed in biology education? One possibility is to transform this challenge into an opportunity to teach students about the construction of scientific knowledge, the nature of science, and the ongoing controversies within the scientific community. Highlighting biological concepts and definitions that are not always universally agreed upon can illustrate the dynamic and evolving nature of science (Harlen 2010, Oreskes 2019, Cofré et al. 2023). The core objective of science education is to help students understand scientific facts, principles, and theories while fostering critical thinking and an appreciation for science as a continuous process of inquiry (Kampourakis 2016, Lederman et al. 2024). Using the controversy over the definition of life as a teaching tool could expose students to the challenges biologists face in their research and demonstrate how science progresses amidst empirical uncertainty and persistent disagreements (Cleland and Zerella 2014).

Furthermore, given the documented difficulties in understanding the concept of life at all educational levels, including science teachers and university students (e.g., Babai et al. 2010, González-Weil and Harms 2012, Martínez-Losada et al. 2013, Kurt 2013, Skelling-Desmeules et al. 2021, Galera-Flores et al. 2024, Harada and Hino 2024), offering a new ontology for the concept of life can be seen as an opportunity to respond to this difficulty in understanding. Multiple studies have described how movement is the property most associated with life across various educational levels (see also table 1). Babai and colleagues (2010) analyzed response times and accuracy among secondary school students when classifying living and non-living entities, showing that students experienced greater difficulty when they were required to recognize immobile organisms, such as plants, as living, compared to moving animals. These results suggest that, even when students are familiar with formal scientific definitions, movement operates as a dominant intuitive criterion for judging life. Skelling-Desmeules and colleagues (2021) extended this analysis to undergraduate students using experimental tasks combined with electroencephalographic recordings, showing longer response

times and neural activation associated with conflict detection and resolution when participants were required to identify non-moving living organisms as alive in contrast to moving inanimate objects. This pattern indicates that the association between life and movement persists into adulthood and that responding in accordance with biological criteria requires the active regulation of this intuitive response. Taken together, these studies suggest that defining life through lists of properties is insufficient to promote a deep understanding of the concept, given that certain perceptual criteria continue to operate automatically. These difficulties have also been documented in initial teacher education. In a design-based study, Galera-Flores and colleagues (2024) showed that future primary school teachers hold fragmented conceptions of the living being model, with structural and descriptive approaches prevailing over systemic and dynamic understandings. Their results reinforce the need for pedagogical proposals that enable the integration of structural, functional, and process-oriented dimensions of the concept of life, particularly in teacher education.

From a cognitive and neuroeducational perspective, recent research has contributed to explaining why these conceptions persist over time. Neuroimaging studies suggest that scientific learning involves the detection and regulation of conflicts between intuitive and scientific representations. Clark and colleagues (2025) showed that undergraduate life sciences students activate brain regions associated with executive control and error detection when evaluating incorrect biological models, and that such activation is related to greater long-term conceptual retention. These findings are consistent with other studies indicating that even advanced learners maintain active intuitive representations that must be regulated in order to reason scientifically (Skelling-Desmeules et al. 2021, Harada and Hino 2024).

In line with contemporary theories of conceptual change, these results support the view that scientific learning does not involve the elimination of intuitive ideas, but rather their coexistence and context-dependent regulation (e.g., Vosniadou 1994, diSessa 2006, Chi et al. 2012, Potvin 2013, Parraguez et al. 2023; see also Vosniadou 2019 for a review). From this perspective, proposing an ontological shift in how life is conceptualized (from a set of properties to life understood as a

process), as reviewed in this work, may yield better learning outcomes and promote a more enduring understanding.

Conceiving life as a dynamic and organized process therefore constitutes a relevant pedagogical opportunity for biology education. This approach makes it possible to articulate different levels of biological organization, to render explicit the mechanisms that sustain living systems, and to move beyond reductionist views based on the mere enumeration of isolated properties. From a science education perspective, approaching life as a process supports modeling practices, systems thinking, and an understanding of biology as an explanatory science focused on mechanisms, thereby contributing to the development of more integrated, durable, and epistemologically informed learning (table 3). Although this hypothesis requires empirical testing, similar ontological changes have already been applied to address alternative conceptions in other areas of biology, such as evolution, which students often mistakenly perceive as a static state rather than as a dynamic process (Chi et al. 2012).

Concluding remarks

Although biologists have amassed extensive knowledge about life on Earth, and philosophers of biology have long reflected on the subject, there remains no consensus on the nature of life. This paper argues that traditional biology instruction, particularly as conveyed through textbooks, transmits to school students, future biologists, and prospective biology teachers a definition of life based on a non-consensual list of characteristics. Many of these characteristics have been abandoned or significantly revised within contemporary science, yet they persist in students' beliefs across educational levels. This approach is further weakened by the lack of agreement regarding these defining traits and is complicated by the existence of hybrid entities that blur the boundary between the living and the non-living. Such entities pose significant challenges to the formulation of a robust and universally accepted definition of life.

To address both this conceptual and pedagogical gap, we propose defining life in classrooms and textbooks according to an alternative ontological framework: understanding life not as a set of properties, but as a process. Over the past two decades, several scientists and philosophers have advanced process-oriented accounts of life, suggesting a growing ontological convergence on this issue, despite differences in how the relevant processes are characterized (e.g., Pross 2012, Gómez-Márquez 2023, Pierce 2023). Recognizing life as a process that natural entities undergo shifts the focus toward its inherently dynamic character. Although adopting this perspective would entail a paradigmatic shift in the definition of life—and perhaps in parts of the biological sciences—it offers multiple benefits and opens new avenues for research and reflection.

A processual understanding of life appears particularly fruitful for disciplines such as astrobiology, synthetic biology, and origin-of-life research (Kauffman 2013, Cleland and Zerella 2014, Fernau et al. 2020, Pierce 2023), as it provides greater conceptual flexibility when investigating the emergence of life and its potential existence beyond Earth. At the same time, this framework may prove equally valuable for biological disciplines that study processes involving viruses—such as microbiology, molecular biology, epidemiology, medicine, and evolutionary biology (Ferreira Ruiz and Umerez 2018, Dupré 2020).

Moreover, in biology education, engaging explicitly with the scientific and philosophical question “What is life?” may encourage stu-

dents to appreciate the complexity of scientific inquiry under conditions of deep conceptual uncertainty. Integrating philosophical perspectives on the nature of life—grounded in empirical findings, theoretical principles, and explanatory frameworks from diverse biological disciplines—could significantly enrich biology education. Finally, the persistence of alternative conceptions, such as the association of life with movement—even among adults with some knowledge of the characteristics of living beings—warrants further investigation. In particular, future research could explore how an ontological paradigm shift in the definition of life might influence learning processes and facilitate the conceptual change necessary to foster a deeper and more durable understanding of life as a process.

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Author contributions

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