The Challenge of Distinguishing Living from Non-Living Entities

Abstract

The complexity and diversity inherent in living organisms have long been regarded as significant challenges to the formulation of a universally accepted definition of life. Life is manifested across diverse forms, characterized by properties such as growth, reproduction, responsiveness, adaptation, and homeostasis. However, these traits are not exclusively confined to living systems; they have also been observed, to varying extents, in certain non-living entities. As a result, the conceptual boundary between the living and the non-living has been rendered increasingly ambiguous. In this study, the transformation of non-living matter into living systems is investigated, and it is demonstrated that this process lacks a precise temporal threshold that clearly marks the emergence of life. Through mathematical analysis, it is shown that no comprehensive definition of life captures a distinct separation within the chemical continuum that leads from inanimate to animate matter. The absence of uniquely defining features that unequivocally distinguish living organisms from non-living entities is thereby revealed. This analysis challenges traditional assumptions regarding the definability of life, emphasizing the need for a revised conceptual framework that accounts for the continuum between non-living and living systems.

Keywords: Definition of Life; Living vs. Non-living Systems; Continuum of Matter; Emergence of Life; Abiogenesis; Biological Complexity; Cognitive science; Dynamic Kinetic Stability. Chemical Evolution; Philosophy of Biology.

1 Preliminaries and Introduction

Defining life remains a persistent scientific and philosophical challenge, as no single criterion adequately captures the full range of biological complexity. Traditional definitions, based on metabolism, growth, reproduction, and responsiveness, are rooted in our intuitive understanding shaped by familiar life forms such as animals and plants. However, such definitions falter when applied to borderline cases like viruses, viroids, and prions, which exhibit some but not all traits of life (Jianhui, 2019)[37]. Broader frameworks incorporate molecular inheritance (DNA/RNA), evolutionary adaptability, and systemic organization (Luisi, 2006[57]; Koshland, 2002[48]). Yet, the continuum between non-living and living states challenges rigid boundaries, emphasizing the need for an interdisciplinary approach that integrates biochemical, evolutionary, and philosophical perspectives (Cleland and Chyba, 2002[12]; Walker et al., 2017[104]).

The objective of this article is to highlight the absence of a conclusive definition of living organisms based solely on their observable characteristics, one that can unequivocally separate them from non-living entities. The concepts of living beings and life phenomena have long been intertwined with manifestations of conscious experience. From the perspective of human cognition, newborn infants embark on a developmental journey during which they gradually learn to differentiate entities exhibiting movement or responsiveness from those that do not. This gradual process of categorizing living and non-living entities occurs within the cognitive frameworks of individuals and is shaped by observable behavior and interaction with the environment. At its core, the differentiation between living beings and non-living entities finds its roots in human conscious experience. It is our subjective awareness and perception that attribute specific qualities and characteristics to entities in our environment. Markers such as growth, reproduction, metabolism, and responsiveness to stimuli are often associated with consciousness, as they imply a level of sentience and subjective experience unique to living organisms.

Despite intuitive distinctions between living and non-living entities, the philosophical and logical foundations of such classifications remain unresolved. A central question persists: is there a necessary and sufficient condition that definitively distinguishes life? Some philosophical perspectives argue that consciousness, marked by subjective experience and self-awareness, is the essential criterion, making life inseparable from mind (Damasio, 1994[22]). This view contrasts with more mechanistic definitions based on metabolic or genetic traits, highlighting the ongoing tension between empirical frameworks and ontological interpretations of life.

According to Hueck (2025)[33], the self-organizing capacity of organisms must be empirically accessible to serve as a basis for scientific explanation. Yet, the underlying forces of life processes cannot be directly perceived, only their outcomes are observable. For this reason, concepts such as purposiveness and self-generation were regarded by Kant as heuristic rather than ontological constructs (Kant, 1790[41]). This epistemic limitation continues to shape debates on biological agency and teleology in contemporary philosophy of biology (Walsh, 2015[105]; Nicholson, 2018[72]).

Alternatively, other thinkers argue for a more nuanced and gradational understanding of the living/non-living distinction. They suggest that cognition and life may exist along a continuum rather than as binary categories, allowing for degrees or levels of cognition that blur traditional boundaries. This view gains traction as complex systems, including advanced artificial intelligence or robotic entities, begin to exhibit behaviors and adaptive capacities reminiscent of living organisms, thereby challenging classical criteria and prompting a reevaluation of the parameters that define life (Pascal and Pross, 2022[76]; Varela and Thompson, 1991[103]).

Such perspectives resonate with contemporary philosophy of science, which emphasizes relational, systemic, and emergent properties over static, essentialist definitions (Deacon, 2012[23]; Moreno and Mossio, 2015[66]). Life appears not as a single definable trait but as the result of complex interactions among biochemical, cognitive, ecological, and evolutionary factors. This complexity complicates any attempt at rigid classification and aligns the life, non-life distinction with broader metaphysical questions concerning identity, continuity, and emergence. The challenge reflects the classical problem of the one and the many, how to reconcile the unity of the concept of life with its diverse and often overlapping manifestations. In response, many scholars advocate a shift from reductionist models to holistic, systems-based frameworks that view life as an ongoing process or pattern rather than a fixed state.

In this manuscript, it is posited that life fundamentally emerges from physicochemical processes. A wide range of organic molecules has been successfully synthesized under laboratory conditions designed to mimic prebiotic environments, based on extensive scientific expertise and diverse experimental approaches. In the subsequent sections, the specific sources and methodologies employed in these efforts will be examined in detail. The mathematical concepts presented in this article are conveyed using straightforward methods and can be understood with only a basic level of mathematical knowledge.

2 The History of Lifes Definition: From Philosophy to Biology

The question of what constitutes life has long occupied thinkers across disciplines, from early philosophical inquiry to contemporary biological science. Despite significant advances in empirical understanding, the fundamental nature of life remains unresolved. The transition from inert matter to self-organizing, adaptive systems represents a critical yet insufficiently understood juncture in this inquiry.

Numerous definitions of life have been proposed, emphasizing characteristics such as self-replication, metabolism, cellular organization, and the capacity for evolution. However, none of these criteria, either individually or in combination, has yielded a universally accepted or fully explanatory definition. This persistent ambiguity suggests that life may not be adequately captured by a fixed set of properties, but instead requires a more integrative framework capable of accounting for its dynamic and emergent nature.

Stewart (1995)[96] advances the strong thesis that cognition is coextensive with life (cognition = life), treating cognition as a constitutive feature of living systems and thereby supporting approaches that define life in cognitive terms; however, this identification introduces a significant conceptual difficulty. If cognition is understood in broad functional or dynamical terms, such as information processing or adaptive responsiveness, then certain non-living systems, including artificial or self-organizing structures, may also qualify as cognitive. This creates a demarcation problem, as the attempt to unify life and cognition risks overextending the concept of life or undermining its explanatory precision. The issue, therefore, lies not in the importance of cognition for life, but in the strength of their equivalence, suggesting that cognition must be constrained by additional criteria, such as autonomous self-maintenance or dynamic kinetic stability, to preserve a coherent definition of life.

Classical criteria emphasize growth, reproduction, and responsiveness (Koshland, 2002[48]), while others define the cell as lifes minimal unit (Luisi, 2006[57]) or highlight homeostasis and dynamic regulation (Gánti, 2003[29]). Each approach reveals a facet of life, but none encompasses it entirely. Ancient thinkers invoked vitalism or soul-like essences, only for such ideas to be displaced by biochemical models as science matured. Today, many researchers and philosophers view the boundary between living and non-living not as a sharp divide, but as a gradient shaped by emergent complexity and far-from-equilibrium processes (Cleland and Chyba, 2002[12]; Walker et al., 2017[104]; Deacon, 2012[23]). Life, it seems, lies not in static definitions but in dynamic becoming.

By the early 20th century, a novel hypothesis quietly began to crystallize within the scientific community: the concept of managed metabolism as the foundational precursor to life. Stewart (1918)[98] was among the first to challenge the traditional organism-centric view, proposing instead that lifes origins lay not in fully formed cells or organisms but in the complex, self-sustaining interactions of molecular networksprimitive catalysts that formed, reacted, and persisted. This hypothesis marked a significant epistemic shift in the philosophy of biology and science more broadly, emphasizing processes over entities and dynamic systems over static structures.

From a philosophy of science standpoint, this paradigm shift illustrates a move away from classical reductionism, which seeks to explain biological phenomena solely by their constituent parts, toward emergentism, which holds that novel properties and causal powers arise at higher levels of organization that cannot be fully predicted or explained by reference to lower-level components alone (Anderson, 1972[4]; Kim, 1999[44]). The idea that metabolic networks emerge from the nonlinear interactions of simple chemical reactions reflects an appreciation of complexity, self-organization, and the importance of systemic context.

This shift also challenges the classical mechanistic worldview that dominated earlier scientific thought, where life was often understood as a machine composed of discrete parts. Instead, the managed metabolism hypothesis points to a dynamic, far-from-equilibrium system that maintains itself through continuous energy flow and chemical transformations (Prigogine, 1967[83]). Such systems exhibit properties that are explanatorily irreducible to their components, prompting reconsideration of causal explanation and the role of teleology in biological systems.

Kolb (20152016)[46, 47] later elaborated on this evolutionary narrative, tracing the lineage of metabolism from its humble molecular beginnings to the elaborate biochemical networks that sustain life today. This trajectory highlights not only a scientific discovery but also a philosophical reflection on the nature of scientific explanation, causality, and emergence: how simple physico-chemical interactions can give rise to self-organizing, adaptive systems that blur the boundaries between living and nonliving, structure and function, and cause and effect.

In the mid-twentieth century, the physicist Erwin Schrödinger entered the domain of biology with his influential work What is Life? (Schrödinger, 1944[88]). In this seminal contribution, Schrödinger posed a fundamental question: how can highly ordered biological systems persist in a universe governed by the second law of thermodynamics, which predicts increasing disorder? He proposed that living systems maintain their organization by importing what he termed negative entropy from their environment. In contemporary terms, this idea corresponds to the intake and transformation of low-entropy energy and matter, enabling organisms to sustain structural and functional order while exporting entropy to their surroundings. Although Schrödingers argument was largely conceptual and lacked formal mathematical development, it proved highly generative, contributing significantly to the emergence of biophysics and shaping subsequent theoretical approaches to the origin and maintenance of life.

The managed metabolism hypothesis can be understood within this broader intellectual trajectory, illustrating how scientific theories develop through the interplay of conceptual innovation and empirical refinement. It reflects central themes in the philosophy of science, particularly the dynamics of theory change as articulated by Thomas Kuhn (1962[51]), as well as enduring challenges such as the demarcation between living and non-living systems. Moreover, it highlights the reciprocal relationship between empirical investigation and metaphysical interpretation in advancing scientific understanding. In this sense, the hypothesis underscores that progress in science is not solely driven by the accumulation of data, but also by the critical re-examination and reformulation of foundational concepts.

In time, another voice entered the dialogue, Shanta (2015)[89], who insisted that life was not only reactive but cognitive. All life, from the simplest bacterium to the complex human mind, shared a thread of awareness. Even the lowly cell, stripped of its nucleus, retained surprising resilience. It could adapt, survive, respond. Was it possible, then, that cognition was not a product of brains but a property of life itself?

Pascal and Pross (2022)[80] compellingly demonstrate that Darwins theory of evolution transcends the traditional boundaries of biology, extending its explanatory power to non-living chemical systems. Building upon their insights, this paper explores the notion that the distinction between biological and non-biological states is not sharply defined. Rather, it proposes a fluid continuum of evolutionary development that seamlessly spans both domains.

This continuity echoes Aristotles concept of hylomorphism, wherein matter (hyle) and form (morphe) are inseparable, and life is understood as the actualization of potentiality within matter through form (Aristotle, Metaphysics). Rather than viewing life as an abrupt or isolated phenomenon, Aristotles framework invites us to consider the transition from non-living to living entities as a gradual process of complex organization and dynamic actualization. This notion aligns with a metaphysics of emergence, where biological form progressively unfolds through interaction and self-organization.

Contemporary philosophy of mind and cognitive science further develop this insight. Thinkers such as Francisco Varela and Evan Thompson advocate the enactive approach, emphasizing the embodied, situated, and dynamic nature of cognition (Varela, Thompson, and Rosch, 1991[103]; Thompson, 2007[100]). According to this view, life and mind co-emerge through continuous reciprocal interactions between organism and environment, dissolving rigid separations between subject and object, or living and non-living. Cognition is not merely computation but active sense-making, grounded in the organisms embodied engagement with its world.

The emergence of cognitive chemical systems endowed with adaptive capacities marks a pivotal milestone in the trajectory of life. These systems explore new structural and organizational possibilities, enhancing their resilience in fluctuating environments. This resonates with the enactive emphasis on autonomy and self-production (autopoiesis), where cognitive systems are not passive information processors but agents actively shaping and being shaped by their surroundings (Maturana and Varela, 1980[62]). Such systems blur classical boundaries, illustrating how life and cognition are intertwined processes embedded within broader ecological and thermodynamic contexts.

Yet, this unfolding transition resists discrete categorization, challenging any sharp ontological divide between non-living and living states. This continuity recalls the classical philosophical problem of the one and the many, how the unity of life as a concept reconciles with the manifold and gradated forms it manifests (Graham, 2014[31]). It foregrounds a central philosophical challenge: the problem of demarcation. How can we specify the precise criteria that definitively confer life upon an entity, especially when these criteria appear to emerge gradually and relationally? Philosophers such as Susan Oyama have argued compellingly that life is better understood as a developmental system rather than a fixed category (Oyama, 2000[74]). Her developmental systems theory underscores the inseparability of genetic, environmental, and organismal factors in the emergence and sustenance of living beings, thereby rejecting simplistic genetic determinism and categorical divides. This approach aligns with the recognition that the properties we attribute to life are relational and historically contingent.

In this context, the gradual chemical evolution from non-living to living forms further complicates the quest for definitive boundaries. The absence of a singular, predetermined moment of becoming alive highlights the elusive and processual nature of this transition (Pascal and Pross, 2022[76]). Attempts to establish a fixed temporal or structural boundary encounter the inherent fluidity and interdependence of biological and chemical organization. Moreover, the lack of exclusive, inherent features uniquely characterizing living systems adds to the ontological ambiguity.

Consequently, the boundary between living and non-living remains permeable and indeterminate, defying reductionist categorizations and inviting ongoing philosophical reflection on lifes fundamental nature. This ontological fluidity challenges the tendency in both philosophy and science to seek strict taxonomies, encouraging instead a systems-oriented perspective that appreciates the emergent, dynamic, and relational qualities of living systems (Noble, 2012[73]; Kauffman, 2000[42]).

3 Exploring the Chemical and Physical Processes of Emergent Life

To advance our understanding of lifes chemical origins, researchers often delineate the defining attributes of cells into distinct hallmarks, including growth, division, information processing, and compartmentalization (Luisi, 2006[57]; Deamer, 2017[24]; Morowitz, 1992[67]). However, elucidating the precise mechanisms by which these fundamental features emerged from non-living molecular mixtures remains one of the most profound enigmas in cognitive science and origins-of-life research (Szostak, 2012[99]; Pascal and Pross, 2016[78]). Consequently, this question continues to be a vibrant and interdisciplinary area of inquiry, spanning chemistry, biology, and philosophy (Cleland and Chyba, 2002[12]; Deacon, 2012[23]; Walker, 2017[104]).

A key area of scientific inquiry focuses on how complex molecules essential for life arose under early Earth conditions. Experiments simulating ancient environments, featuring reducing atmospheres, volcanic activity, lightning, and high temperatures, have shown that basic organic compounds like amino acids, nucleotides, and lipids can form from simpler chemicals. Researchers also investigate settings like hydrothermal vents and clay-rich areas that may have supported the chemical reactions needed for lifes emergence by providing energy, nutrients, and protection. Understanding how non-living matter transitioned into living systems remains central to defining life, prompting questions about what first catalyzed this transformation and how early molecules gained self-sustaining and adaptive capabilities.

In a follow-up study, Kolb (2015-2016)[46, 47] explores essential topics related to the chemical origins of life, underscoring the importance of philosophical approaches in defining life and understanding the transition from abiotic to biotic systems. A key model examined is Oparins, which suggests the spontaneous formation of coacervates, structures that encapsulate chemical matter, demonstrate primitive self-replication, and facilitate early metabolic activity. Kolb also discusses recent experimental advances that build on Oparins framework and considers possible selection mechanisms that may have influenced these early systems.

The transformation of non-living chemical compounds into living organisms has long been a central question in origin-of-life research. This process, often referred to as abiogenesis, has been explored extensively by Kepa et al. (2017)[43], who analyzed key transitional steps from simple molecules to biologically relevant structures. Cooper (2019)[19] further elaborates on the plausibility of simple organic molecules forming and spontaneously polymerizing into complex macromolecules, such as proteins and nucleic acids, under the environmental conditions believed to have existed on primitive Earth. During this era, Earth's atmosphere was markedly different from todays, lacking free oxygen and consisting predominantly of carbon dioxide (CO_2) and nitrogen (N_2), with trace amounts of hydrogen (H_2), hydrogen sulfide (H_2S), and carbon monoxide (CO). These reducing conditions, in combination with energy sources such as ultraviolet radiation, volcanic activity, and electrical discharges, created favorable settings for the abiotic synthesis of organic compounds.

In addition to atmospheric and surface-based hypotheses, geochemical environments deep beneath the ocean's surface have garnered increasing attention. According to Belthle and Tüysüz (2022)[9], under-sea hydrothermal vents represent one of the most plausible settings for prebiotic chemistry. These vents emit hot, mineral-rich fluids containing hydrogen gas (H_2), which can act as a powerful reducing agent to drive the synthesis of reduced carbon compounds essential for early metabolic networks. The unique conditions in these environments, including stable temperature gradients, catalytic mineral surfaces, and continuous chemical flux, could have supported the stepwise evolution of increasingly complex molecular systems, eventually leading to the first self-replicating entities.

Together, these studies underscore the complexity and multidisciplinary nature of the origin-of-life research. Understanding how inert chemical matter could transition into self-organizing, adaptive, and evolving life forms remains a profound scientific challenge, one that bridges chemistry, geology, biology, and planetary science. Baum (2018)[8] explores a generic description of life and uses it to explain how the chemically unusual life forms we observe today could have emerged. One of the most remarkable features of life is its apparent ability to defy the second law of thermodynamics and become increasingly out of equilibrium with its environment over time. To understand this phenomenon, Baum proposes a conceptual framework in which tendencies can be analyzed in relation to the expected equilibration point of the environment. He suggests that living entities correspond to metastable attractor states that tend to remain out of equilibrium with their surroundings. Baum applies this framework to investigate the emergence of life from non-life, its evolutionary trajectory towards complexity, and the causes and impacts of cellular encapsulation. By viewing life as a metastable attractor state, Baum provides a novel perspective on how living organisms can persist in a state of disequilibrium with their environment, and how this disequilibrium may have contributed to the development of complex life forms.

According to Pascal and Pross (2016, 2017)[78, 85], life can be understood not as a mysterious anomaly within nature but as a phenomenon grounded in a rigorous physico-chemical framework, specifically, in an extrathermodynamic or kinetic foundation that arises from mathematical and logical considerations. At its core, life is characterized by a self-sustaining network of chemical reactions capable of replication, and its origins can be traced to a primordial chemical system that emerged under early Earth conditions. Though the precise identity of this initial replicative system is lost to time, its appearance marked a pivotal transition in the history of matter: the crossing of a threshold from chemistry to biology.

From a philosophical perspective, this view challenges traditional dualisms between the living and the non-living by proposing a continuous, well-defined process through which life emerged from non-life, driven by identifiable kinetic forces. Life, in this sense, is not a category apart but a complex expression of far-from-equilibrium chemical systems governed by thermodynamic and kinetic laws. Pross and Pascal argue that this transition was not arbitrary but contingent on specific environmental and molecular conditions that enabled self-replication, persistence, and exponential growth, principles that gave rise to increasing complexity in both individual protocells and their emergent networks.

Their account places life squarely within the scope of natural science, reframing its origin as an inevitable outcome of the material organization of matter under particular conditions. It suggests that the boundary between biology and physics is not one of kind, but of degree, a shift in organizational complexity governed by continuous processes rather than discrete leaps. In doing so, their work offers a scientifically grounded response to long-standing philosophical questions about what distinguishes living systems and how novelty emerges from underlying physical laws.

4 Tracing the Evolution from Non-Living to Living Systems

Origins-of-life research has long grappled with a fundamental question in both biology and the philosophy of science: how were the proteinaceous side chains and the protein backbone selected during the early stages of evolution? Frenkel-Pinter et al. (2019)[28] investigated the oligomerization reactions of a group of positively charged amino acids, including both proteinaceous and non-proteinaceous types. Remarkably, these amino acids were found to spontaneously oligomerize under mild, hydroxy acid-catalyzed dry-down conditions, without the involvement of enzymes or activating agents.

The findings reported in this study are critical for the experimental evaluation of early protein evolution models and contribute significantly to our understanding of lifes chemical origins. While several models propose that unactivated amino acids could have directly condensed into polypeptides through chemical evolution, these models encounter substantial challenges, some of which have been partially addressed by recent experimental evidence. Protocells are cell-like compartments that mimic certain characteristics of living cells and are considered potential precursors to modern life. According to Cornell et al. (2019)[21], the initial protocells on early Earth likely developed with self-assembled membranes composed of fatty acids. However, a significant obstacle in comprehending the origin and resilience of protocells lies in the instability of fatty acid membranes when exposed to high salt concentrations or divalent cations, which would have been abundant in the early oceans.

During the process of converting a non-living chemical compound into a living organism, there is an intermediate state known as the ”pseudo-alive” state. This state is characterized by the sensitivity of the chemical composition to the environment, which gives rise to properties that are characteristic of both living and non-living matter. In the pseudo-alive state, the chemical compound exhibits several characteristics that are typical of living organisms, such as the ability to undergo self-replication and to respond to external stimuli. However, it also retains certain features of non-living matter, such as a lack of metabolic processes. The pseudo-alive state represents a transitional phase in the evolution of life, in which non-living matter begins to exhibit properties that are characteristic of living organisms. By studying this intermediate state, researchers can gain insights into the fundamental nature of life and its emergence from non-living matter.

The concept of self-sustaining protometabolic cycles and self-multiplying protocellular compartments stands as a pivotal aspect in our understanding of the origin of life. These processes are believed to have played a crucial role in the emergence of the earliest living entities. Self-multiplying protocellular compartments are structures capable of replicating themselves through simple physical mechanisms. These compartments likely served to protect and replicate the self-sustaining protometabolic cycles, which represent the chemical reactions necessary for sustaining life-like processes.

The integration of these two fundamental processes, self-sustaining protometabolic cycles and self-multiplying protocellular compartments, is thought to have led to the formation of the first living systems. This integration facilitated the exchange of energy and materials between the protometabolic cycles and the protocellular compartments, enabling the development of more complex and efficient metabolic pathways. While the exact mechanisms by which these processes unfolded remain the subject of ongoing research and debate, the concept of self-sustaining protometabolic cycles and self-multiplying protocellular compartments provides a valuable framework for understanding the initial stages in the origin of life and the emergence of primitive living entities, for more informations see Monnard et al., (2015)[65] and Nader et al., (2022)[70].

Pross, in his (2021)[84] work, proposes that a cognizant chemical system that was capable of evolving and adapting to better exploit its environment would discover new possibilities for structural and organizational complexity, leading to the emergence of increasingly persistent forms. This process ultimately culminated in the emergence of the bacterial cell, which represented a significant milestone in the evolution towards greater persistence. Over the course of several billion years, this process led to the emergence of animals with neural systems and, ultimately, to the discovery of mind. Throughout this evolutionary process, the drive towards increasing persistence governed the development of life. Pross's perspective offers a unique way of thinking about the origins and evolution of life on Earth, emphasizing the role of persistence in driving the emergence of increasingly complex organisms. By viewing life as a conscious chemical system, Pross highlights the importance of adaptation and evolution in the development of life on our planet. Overall, Pross's work provides valuable insights into the fundamental nature of life and its relationship with the environment.

The process of chemical sensitivity to the environment triggers molecular transformations within the pseudo-alive state, enhancing its responsiveness. As this process unfolds, the system of chemical synthesis gradually transitions into a living organism, imbuing it with distinctive characteristics that we perceive as the hallmark of living beings. This experiential distinction underscores a fundamental delineation between living and non-living entities. It's noteworthy that evolution manifests across all three stages ”non-living, pseudo-alive, and living”although discerning precise boundaries between these stages proves challenging. In Section 9, mathematical methodologies are employed to illustrate the absence of rigid distinctions between living and non-living entities. This perspective underscores the pivotal role of chemical sensitivity in the evolutionary trajectory of life, highlighting the continuum that exists between non-living, pseudo-alive, and living states.

In contemporary theoretical biology, life is increasingly understood as the result of a coupled organization of matter, energy, and information. Information is not merely a descriptive abstraction but a physically instantiated and dynamically operative component of living systems, governing their structure, function, and adaptive capacity. Genetic information enables the storage, transmission, and variation of traits across generations, thereby playing a central role in evolutionary dynamics (Lazcano, 2008[52]; Sharma et al., 2023[95]). At the same time, living systems continuously process environmental information through regulatory, metabolic, and behavioral networks, which allows them to maintain autonomy and respond adaptively to changing conditions (Barandiaran et al., 2009[7]; Froese and Stewart, 2010[27]).

From this perspective, the organization of matter and energy cannot be separated from informational constraints and causal structures. The concept of downward causation highlights how higher-level informational organization can influence and regulate lower-level physical processes, thereby shaping system dynamics across scales (Farnsworth et al., 2017[26]). This view is further supported by approaches emphasizing self-organization, autopoiesis, and requisite variety, in which informational structure emerges from and simultaneously constrains dynamic processes (Gershenson, 2015[32]; Ruiz-Mirazo and Moreno, 2004[87]).

Moreover, studies on protocells and artificial life systems demonstrate that even minimal living-like systems rely on the interplay between material organization and infor-

mational processes, particularly in the emergence of agency, behavior, and individuality (Rasmussen et al., 2008[86]; ejková et al., 2018[11]; Egbert et al., 2023[25]). These findings suggest that the transition from non-living to living systems is not solely a matter of energetic or material complexity, but also of the emergence of structured information and its functional integration into system dynamics (Muñuzuri and Pérez-Mercader, 2022[69]; Kauffman and Roli, 2021[39]).

Accordingly, evolution can be interpreted not only as a process of energetic expansion and material reconfiguration (Judson, 2017[38]), but also as the progressive accumulation, transformation, and selection of information within dynamically stable systems. This perspective aligns with views that emphasize open-endedness, autonomy, and the co-evolution of informational and material organization in living systems (Pattee and Sayama, 2019[75]).

Extending this framework, information assumes a dual role in living systems: it functions both as a repository of historical constraints and as an active driver of future system trajectories. In evolutionary terms, biological systems can be understood as information-processing entities that encode past environmental interactions in their structural and functional organization, while simultaneously generating novel informational configurations through mutation, recombination, and developmental plasticity. This recursive interplay between stored and newly generated information enables cumulative evolution, in which complexity arises not merely from increased material organization, but from the hierarchical structuring and integration of information across multiple levels of organization.

Furthermore, the evolution of living systems involves a progressive shift in the modes of information storage and processing. Early prebiotic systems likely relied on distributed and transient informational patterns embedded in chemical reaction networks, whereas more advanced organisms developed stable symbolic encoding mechanisms, such as the genetic code, which allow for high-fidelity replication and long-term information preservation (Maynard Smith and Szathmáry, 1995[63]). This transition marks a critical increase in evolvability, as it enables the decoupling of information from immediate physical dynamics and facilitates the emergence of complex regulatory architectures.

In addition, higher-level biological organization introduces new layers of informational integration, including epigenetic regulation, neural processing, and social communication systems. These layers expand the informational capacity of organisms beyond the genome, allowing for context-sensitive adaptation and the transmission of acquired information across both biological and cultural timescales. Consequently, evolution operates not only on genetic information but also on epigenetic, behavioral, and symbolic forms of information, *leading to a multi-level selection process that integrates diverse informational domains.*

Ultimately, the evolution of life can be viewed as the emergence of increasingly sophisticated informational regimes, in which matter and energy are organized in ways that enhance the acquisition, processing, and utilization of information. This perspective reinforces the idea that the defining characteristic of living systems is not solely their material composition or energetic throughput, but their capacity to generate, maintain, and evolve structured information that sustains adaptive, autonomous, and open-ended dynamics.

5 Understanding Lifes Foundations: Toward a Definition of Living Systems

In their work, Bartlett et al. (2020)[6] propose a reframing of the definition of life, aiming to encompass a broader range of possibilities while acknowledging the need to differentiate the specific kind of life observed on Earth. To achieve this, they introduce a new term called “lyfe”. Going forward, they use ”life” to refer to life as we currently understand it, while “lyfe” represents the potential forms life could take in a more general sense. The two designations are defined as follows:

1. Life, as we currently understand it on Earth, is characterized by specific disequilibria and classes of components. It involves an autocatalytic network of organometallic chemicals present in an aqueous solution. These life forms are capable of recording and processing information about their environment in molecular form. One of the key features of life is its ability to achieve dynamic order by dissipating various types of disequilibria. These disequilibria can include redox gradients, chemiosmotic gradients, as well as visible and thermal photons. These processes contribute to the maintenance and functioning of living systems on Earth.

2. Lyfe, on the other hand, encompasses any hypothetical phenomenon in the universe that exhibits the fundamental processes associated with the living state. It is not limited to specific disequilibria or components and can manifest in diverse ways. Lyfe refers to any hypothetical phenomenon that maintains a low-entropy state by dissipating and converting disequilibria. It utilizes autocatalytic networks to achieve nonlinear growth and proliferation, similar to life as we know it. Additionally, lyfe employs homeostatic regulatory mechanisms to maintain stability and counteract external disturbances. It also acquires and processes functional information about its environment, enabling it to interact and adapt to its surroundings. By defining lyfe in this way, it allows for the exploration and consideration of potential forms of life beyond our current understanding and observations on Earth.

Gaining a precise understanding of the distinction between living organisms and non-living matter necessitates a comprehensive examination of the evolution of living beings and their origins. According to Kamila et al. (2020)[68], the initial phase of life's emergence involved a primitive nonenzymatic form of metabolism catalyzed by naturally occurring minerals and metal ions. This perspective, known as the ”metabolism first” hypothesis, suggests that a primitive version of metabolism capable of synthesizing and breaking down ketoacids, sugars, amino acids, and ribonucleotides would be required for continuity with modern metabolism. In their review, Kamila et al. provide accessible insights for chemists into the metabolic pathways relevant to the origin of life. The review also highlights experiments that propose several pathways may have originated from prebiotic chemistry. By exploring these pathways, we can gain valuable knowledge about the chemical processes that may have contributed to the emergence of life.

Any scientific explanation of the origin of life must account for a driving force that can clarify how intermediate forms can remain stable over extended periods of time in a state that is far from equilibrium (Pascal et al. (2013)[77]). In order to solve the question of life's origin, it is necessary to explain how states, which are considered unstable from a statistical and thermodynamic perspective, can acquire an alternative form of stability that enables further improbable changes. Pascal et al. introduced a concept called dynamic kinetic stability, which is specific to entities capable of self-reproduction. This new form of stability provides a satisfactory explanation for the processes governing transformations in both inanimate and animate systems. Each form of stability is supported by its own unique mathematical logic.

One form of stability is thermodynamic stability, which dominates the regular chemical world and has been understood since Boltzmann (Boltzmann (1896)[10]). It involves the tendency of physico-chemical systems to move towards more probable states. In contrast, dynamic kinetic stability is a distinct form of stability that is specific to persistent replicating systems. It arises from the dynamic persistence associated with exponentially driven self-replication. Understanding the interrelation between these two distinct forms of stability, each with its own mathematical logic, is crucial for explaining the essence of biology.

These findings have direct implications for scenarios in which early evolution is driven by environmental heterogeneity. The trade-offs imposed by network topology are likely to have played a significant role in shaping the evolution of early life forms, determining which organisms were better suited to their environment and which were not. By understanding the relationship between network-level structures and the emergence of properties at the chemical level, researchers can gain valuable insights into the fundamental nature of life and its origins. In the study by Ameta et al. (2021)[3], prebiotic scenarios like Dynamical Kinetic Stability reveal a nuanced interplay crucial for evolution. This process hinges on the delicate balance between the persistence of chemical compositions, ensuring robustness to environmental changes, and the exploration of novel compositions, allowing for susceptibility to perturbations. These evolutionary trade-offs, combined with the connectivity rules dictated by network topology, indicate the presence of an optimal ”Goldilocks” range. Within this range, the density of catalytic interactions neither exceeds nor falls short, providing the conducive conditions for evolutionary progression.

6 Exploring the Topological Foundations of Lifes Emergence

Researchers can explore the interplay between network topology and the emergence of chemical properties using a combination of theoretical modeling and experimental studies, as demonstrated in the works of Winterbach et al. (2013)[107] and Somarakis et al. (2016)[97]. Theoretical models can be used to simulate the behavior of complex networks and their impact on the emergence of properties at the chemical level. These models can take into account various factors such as the connectivity of the network, the chemical reactions that occur within the network, and the environmental conditions that affect the network's behavior. By using theoretical models, researchers can explore the impact of different network topologies on the emergence of properties at the chemical level and gain insights into the constraints and trade-offs that shape the evolution of living entities.

Experimental studies can also provide valuable insights into the interplay between network topology and the emergence of properties at the chemical level. Researchers can design experiments to manipulate the connectivity of chemical networks and observe the resulting impact on the emergence of properties such as growth, variation, and resilience to environmental changes. By conducting these experiments, researchers can test the predictions of theoretical models and gain a more comprehensive understanding of the fundamental mechanisms that underlie the origins and evolution of life. In summary, investigating the interplay between network topology and the emergence of properties at the chemical level requires a combination of theoretical modeling and experimental studies. By using these complementary approaches, researchers can gain deeper insights into the complex interplay between matter and consciousness that underlies the nature of existence.

The dynamics observed in the system under investigation highlight the non-obvious role of self-assembly in driving self reproduction. While self-assembly has been previously demonstrated to drive self reproduction in other systems, such as tubular assemblies of molecules, its role in the system under investigation was not immediately apparent. The robustness of self-assembly as a mechanism for driving self-reproduction is due to its ability to create organized structures from simple building blocks. This process can occur spontaneously, without the need for external energy input. The resulting structures can then serve as templates for the formation of new structures, leading to self-replication and self-assembly. In the system being studied, the role of self-assembly in driving self-reproduction was not initially clear. However, the observed dynamics suggest that self-assembly may play a critical role in driving the emergence of self-replicating structures. By understanding the underlying mechanisms that drive self-assembly and self-reproduction, researchers can gain valuable insights into the origins and evolution of life, for more informations see Pross and Pascal (2017)[85]; Merindol and Walther (2017)[68] and Muchowska et al. (2022)[68].

In line with the ”metabolism-first” hypotheses regarding the origin of life, the initial stages involved the emergence and evolution of proto-metabolisms, which are organizations of molecular species. Unlike the involvement of self-replicating RNA, these proto-metabolisms are believed to have emerged independently. They are characterized as self-producing and self-amplifying because the formation of each member of the metabolism is catalyzed by at least one other member within the metabolism. Additionally, they have access to a suitable source of free energy and other necessary resources. As a collective network of molecular species, they exhibit autocatalytic properties.

The constituents of the proto-metabolism work together to amplify the formation of each other. This metabolic organization can include catalytic polymers, small-molecule autocatalytic cycles, and processes. Under specific conditions, these components cooperate to facilitate the emergence and evolution of the proto-metabolism. For more detailed information on this topic, refer to the manuscript by Stewart (2018)[98].

7 The Ontological and Methodological Challenges of Defining Life

The definition of life has long remained a central philosophical and scientific problem, situated at the intersection of biology, chemistry, and epistemology. Despite advances in molecular biology and origin-of-life studies, no single, universally accepted definition has been established. Instead, multiple conceptual and methodological tensions have been identified that challenge both theoretical coherence and practical application.

From an ontological perspective, life is often approached as either a fixed category defined by essential characteristics or as a process defined by dynamic organization. Essentialist definitions typically cite features such as metabolism, reproduction, and evolution as necessary and sufficient criteria. However, such characteristics have also been observed in non-living systems to varying degrees, thereby undermining their exclusivity. This has led some philosophers to adopt a processual view, in which life is regarded not as a discrete entity but as a set of continuous, self-sustaining interactions maintained over time (Nicholson & Dupré, 2018[72]).

Methodologically, efforts to operationalize a definition of life, particularly in fields such as astrobiology and synthetic biology, have encountered significant limitations. For instance, NASAs working definition, which identifies life as ”a self-sustaining chemical system capable of Darwinian evolution,” is widely used but has been criticized for excluding certain borderline entities such as viruses and prions (Cleland & Chyba, 2002[20]). Moreover, this definition presupposes terrestrial biochemistry, potentially overlooking alternative life forms that might exist under non-Earth-like conditions.

The existence of entities that blur the boundary between living and non-living, such as viruses, viroids, and synthetic protocells, has further complicated the definitional landscape. These systems exhibit some features of life, such as replication or structural complexity, while lacking others like metabolism or autonomy. As a result, the boundary between the living and the non-living is increasingly viewed as a continuum rather than a binary divide (Luisi, 1998[56]).

Philosophical pluralism has been proposed as a response to this definitional impasse. According to this view, different definitions of life may be context-dependent, serving distinct explanatory or pragmatic functions in diverse scientific disciplines. Trifonov (2011)[102], after surveying over a hundred definitions, proposed a minimal consensus definition: Life is self-reproduction with variations. While this captures the evolutionary dimension of life, it remains insufficient for encompassing systems that resist neat categorization.

The definitional problem is not merely semantic but reflects deep epistemological and ontological uncertainties. Rather than seeking a single, universal definition, it may be more productive to frame life as a family of overlapping processes, defined relationally and contextually. This approach accommodates the diversity of living systems, acknowledges the transitional nature of prebiotic chemistry, and aligns with ongoing efforts in synthetic and astrobiological research.

Life arises not ex nihilo, but from the transformation and organization of matter under specific thermodynamic and kinetic conditions, conditions that enable increasing complexity, self-organization, and dynamic persistence. This emergence reflects a relational and process-oriented ontology in which living systems are inextricably linked to their ecological, energetic, and molecular contexts. Organisms are not isolated substances but dynamic nodes in a continuum of interactions that shape and are shaped by their environments (Pascal and Pross, 2016[78]; Deacon, 2012[23]).

Within this ontological and evolutionary continuum, the philosophical challenge of defining ”life” remains deeply contested. The longstanding effort to demarcate living from non-living entities has generated significant methodological and conceptual inquiry. Cleland and Chyba (2007)[15] argue that definitions of life often conflate descriptive generalizations with essential properties, thus masking the deeper ontological ambiguity of the term. Malaterre and Chartier (2021)[59] further highlight the circularity involved in defining life either by identifying shared features of known living systems or by first postulating a definition and then applying it to select instances. This problem points toward a fundamental ontological tension: does life constitute a distinct natural category, or is it a gradational construct shaped by context and perspective? The absence of a clear threshold between non-living and living systems underscores the philosophical and scientific complexity of the issue, prompting continued exploration into whether the concept of life is best grounded in biology, metaphysics, or both.

Physiological attributes of organisms, growth, metabolism, adaptation, are not isolated features but are dynamically interwoven with their environmental matrices. As such, life must be understood not as a static state but as a sustained process of interaction and integration. Organisms engage their surroundings through networks of exchange, including chemical signaling, energetic uptake, competition, and cooperation, thereby actively shaping and being shaped by their ecological niches (Lenton et al., 2020[53]).

The extension of Darwinian principles beyond the biological domain, as advanced by Pascal and Pross (2022)[80], profoundly shifts our conceptual boundaries. Their work illustrates that the principle of selection for persistence, central to evolution, applies not only to biological organisms but also to non-living chemical systems governed by dynamic kinetic stability. In this framework, evolution becomes a general principle of matters self-organization under far-from-equilibrium conditions, dissolving the rigid boundary between biology and chemistry.

The emergence of what Pross refers to as cognizant chemical systems, systems capable of environment-sensitive responses and structural adaptations, marks a pivotal point in the evolutionary continuum (Pross, 2021[84]). Such systems exhibit rudimentary forms of information processing and self-modification, properties traditionally attributed only to life. Their appearance suggests that cognition and adaptive complexity are not exclusive to biological life but may be inherent potentialities of organized matter.

Yet, the transition from non-living to living systems is not defined by a singular threshold. Instead, it represents a gradational evolution, what some describe as a continuum of increasing persistence, organization, and adaptability (Walker, 2017[104]; Shapiro, 2006[90]). This continuum challenges the ontological distinction between life and non-life, as no set of attributes appears to be both necessary and sufficient across all contexts to define life unambiguously (Cleland and Chyba, 2002[12]).

The philosophical implications are profound. If the criteria for life are context-dependent, provisional, and overlapping, then life cannot be ontologically separated from non-life through essentialist definitions. Rather, the concept of life must be approached as an emergent phenomenon, an outcome of specific organizational thresholds within chemical and thermodynamic systems (Deacon, 2012[23]). This shifts the inquiry from ”what is life?” to ”how does life emerge and persist under given conditions?”

Furthermore, as Pavlinova et al. (2022)[81] argue, the emergence of life may have depended on intermediate chemical states capable of limited heredity and catalytic recombination, which allowed for proto-Darwinian evolution before full biological systems took form. This suggests that life did not begin at a sharply defined moment but evolved gradually through increasing functional and organizational complexity.

Similarly, Ameta et al. (2021)[3] demonstrate that the topology of molecular interaction networks imposes constraints on evolutionary pathways. These structural trade-offs between growth, variation, and robustness further reinforce the notion that life is not a substance but a process, shaped and bounded by underlying principles of connectivity and information flow.

Many philosophers various aspects of the definition of living organisms have been investigated. Cleland (2012, 2019)[16, 17] presents a comprehensive and nuanced argument in favor of pursuing universal biology despite the complex and diverse nature of life on Earth, which William James vividly described as a ”blooming buzzing confusion”. In her work, Cleland advocates for the exploration of universal biology, which involves studying the possibility of life forms and processes that may exist beyond Earth. She acknowledges that the study of life on Earth can be intricate and bewildering, with its vast array of species, ecosystems, and biological phenomena. However, instead of viewing this complexity as a deterrent, Cleland sees it as a motivation to expand our understanding of life in a broader context. Cleland argues that by solely focusing on Earth-based life, we may limit our understanding of the potential diversity and complexity of life forms that could exist elsewhere in the universe. She emphasizes the importance of interdisciplinary approaches and collaboration between scientists from various fields, including biology, chemistry, physics, and philosophy.

Knuuttila and Loettgers (2017)[45] have studied on the comprehensive definition of living being, but they did not reach a general conclusion to separate living beings from non-living. Malaterre (2010)[58] proposed two arguments: first, that the roots of the tree of life extend well beyond the commonly recognized ”ancestral organisms” and include much simpler, minimally living entities that can be referred to as ”protoliving systems”; and second, that these roots gradually dissipate into non-living matter along several functional dimensions. Between non-living and living matter, there exist physico-chemical systems that exhibit a ”lifeness signature.” This signature could also explain a variety of biochemical entities that are considered to be ”less-than-living” but ”more-than-non-living.

Based on the sources we've discussed, the difficulty in distinguishing between living and non-living entities stems from two primary reasons. Firstly, certain organisms can exhibit characteristics of both life and non-life at different times or under varying conditions. For example, they may enter a state of dormancy or suspended animation where typical signs of life, like metabolism or reproduction, are absent, only to resume their living state later. This fluctuation makes it challenging to definitively classify them as strictly living or non-living. Secondly, there is no single defining characteristic that unequivocally separates living organisms from non-living entities. While living organisms display a combination of features such as organization, metabolism, growth, reproduction, adaptation, and response to stimuli, non-living entities may exhibit some of these traits individually but not in a coordinated manner. As a result, drawing a clear boundary between living and non-living entities becomes problematic.

Thus, the categorization of certain entities as living and others as non-living is arbitrary and lacks substantive meaning. By assigning beings to distinct groups based on specific characteristics, we implicitly suggest that those outside the designated category lack these attributes. However, this assumption is flawed due to the absence of a precise definition of the distinguishing characteristics of living beings and a comprehensive understanding of other entities that may possess or lack these attributes. Consequently, our categorization remains incomplete and potentially inaccurate.

8 Cognitive systems are defining features of living organisms

The transition from non-living chemical compounds, such as γ, to living organisms is intricately tied to the evolution of cognitive systems within these compounds. Initially rudimentary, these cognitive systems exhibited basic information processing and adaptability.

However, through a gradual process of evolution, these systems became increasingly sophisticated. As these cognitive systems evolved, they facilitated the emergence of more complex structures and functions, ultimately giving rise to living organisms. This evolutionary progression of cognitive systems within non-living compounds laid the groundwork for the development of biological life. Numerous factors contributed to this phenomenon. Firstly, the innate capacity for adaptation and information processing enabled these cognitive systems to effectively interact with their environment, thus enhancing survival and reproduction. Additionally, the accumulation of genetic variation, driven by processes like mutation and natural selection, fostered diversification and complexity within these cognitive systems. Furthermore, environmental pressures and selective forces played a pivotal role in propelling the evolution of cognitive systems towards greater complexity. Organisms with more advanced cognitive abilities were better equipped to navigate and thrive in their environments, thereby outcompeting others and proliferating.

All material systems, whether living or non-living, exhibit responses to external perturbations, albeit in distinct ways. Non-living matter, for instance, responds to perturbations through the directing effects of the Second Law of Thermodynamics. For example, heating a physical object can cause it to expand or undergo a phase transition. Similarly, perturbing a chemical system at equilibrium, such as introducing an additional reagent or altering the concentration of its constituents, leads to the system seeking to re-establish its equilibrium state. In both physical and chemical cases, the system's response to the perturbation can be explained using thermodynamic principles (Pascal and Pross (2022)[80]). In contrast, living systems demonstrate different behaviors. While they adhere to the physical laws of nature, they primarily operate according to biological principles and respond to perturbations through a phenomenon known as adaptation. Organisms adjust to perturbations in a manner that aligns with their own agendas or survival strategies.

Pascal and Pross (2022)[80] introduced an intriguing concept of a non-equilibrium state of matter called an energized dynamic kinetic state, which challenges the prevailing understanding of the emergence of life from non-life. They demonstrated that certain chemical systems, when activated into this dynamic kinetic state, can exhibit rudimentary cognitive behavior. This proposition challenges the conventional notion that life emerged solely from non-living matter. The exploration of the energized dynamic kinetic state by Pascal and Pross suggests the existence of alternative pathways for the emergence of cognitive behavior. It challenges the traditional view that mental capabilities are exclusive to living organisms. By activating specific chemical systems into this state, they propose that basic cognitive processes could manifest, blurring the line between the living and non-living.

On the other hand, drawing on Shapiro works (2007 and 2021)[92, 93], it is posited that every living being possesses a cognitive system that gives rise to a unique form of consciousness. Primitive organisms, under specific conditions or chemical states, can develop such cognitive systems. From this perspective, the chemical evolution of life can be seen as a complex kinetic process that engenders a distinct state within our consciousness system. This state allows us to map the emergence and evolution of life as a cognitive system, which can be understood as a thermodynamic phenomenon. Thus, a comprehensive understanding of the functioning of cognitive systems in various organisms can enrich our comprehension of the human consciousness system.

Shapiro argues that all living organisms, including plants, possess cognitive systems. However, the prevailing assumption is that plants lack consciousness, primarily due to a top-down perspective that employs human consciousness as the benchmark for assessing consciousness in other beings. This approach fails to consider the fundamental differences between plants and animals, resulting in the rejection of plant consciousness based on criteria derived from animal consciousness. Shapiro's argument is rooted in the belief that cognition extends beyond the boundaries of the central nervous system and can be found in a wide range of organisms. He proposes that cognition should be understood as a distributed phenomenon, where various parts of an organism interact and process information to guide adaptive behavior. In the case of plants, this distributed cognition manifests through complex physiological processes, such as signal transduction, environmental sensing, and response mechanisms.

The field of biology has shifted from a DNA-centric perspective, as represented by the central dogma, to a cell-centric viewpoint. Within this cell-centric framework, some biologists propose that cells exhibit behaviors resembling those of sentient beings, and they draw comparisons to information processing or computational models. However, these explanations often neglect the sensory aspect of cellular behavior. These advancements imply that cells possess a cognitive nature, suggesting the presence of a mind, which challenges the traditional concept of genetic determinism. The existing scientific evidence compels scientists, philosophers, and scholars to reevaluate their understanding of cognition in the context of life (Shanta (2015)[89]). Shapiro (2011)[91] highlights how molecular biology has identified specific components related to cell sensing, information transfer, and decision-making processes. This molecular perspective provides detailed descriptions of cell cognition, ranging from bacterial nutrition to mammalian cell biology and development. It presents a cognitive and informatic view of how living cells operate and utilize their genomes, which fundamentally differs from the perspective of genetic determinism.

9 Mathematical Methods for Distinguishing Living and Non-Living Entities

The web grew increasingly intricate with the discoveries of Ameta et al. (2021)[3], who demonstrated how the very architecture of chemical networks influenced their evolutionary trajectories. Systems characterized by tight connectivity tended to favor stability, growth, and robustness, whereas more loosely connected networks embraced variation, flexibility, and exploration. These dynamics revealed inevitable trade-offs, the seed of complexity was sown in the delicate balance between order and chaos. Somewhere within this shifting landscape, between entropy and structure, between cognition and chemistry, the story of life began. It was not a sudden spark but a gradual ignition; not a divine breath but an unfolding equation written in the language of nature. Yet, despite all progress, the fundamental question persisted: Where, precisely, does life begin?

In this section, I undertake a systematic examination of this question in its full depth and complexity. I demonstrate, drawing on mathematical concepts, that defining living systems in terms of a fixed set of intrinsic characteristics that purportedly distinguish them from non-living entities is fundamentally problematic. More precisely, no set of biological, chemical, or physical properties appears sufficient to partition living and non-living entities into two strictly disjoint and well-defined categories.

Kolb (2015)[46] offers a thorough analysis of the critical stages in chemical evolution that contributed to the emergence of life, highlighting the complex interaction between environmental conditions, chemical pathways, and growing molecular complexity. He emphasizes that life's origin was not a singular event but rather a gradual sequence of chemical transformations sustained by specific conditions and continuous energy input.

Pavlinova et al. (2022)[81] explored this ghostly middle ground, suggesting that life may not have emerged in a single moment, but through a gradual sequence of increasingly complex states. Evolution itself, they argued, might have begun before life as we know it, in the form of catalytically guided recombination within chemical systems teetering on the edge of biology. Regarding the transition from a non-living to a living chemical state, extensive research has been conducted, as an examples see Merindol and Walther (2017)[64]; Lehn (2007)[54]; Ziemann et al. (2009)[108]; Liang (2016)[55]; Agozzino et al. (2020)[1]; Greer et al. (2016)[30]; Krämer et al. (2022)[13]; Kaklauskas et al. (2022)[40]; Jeziorski et al. (2022)[36]; Slootbeek et al. (2022)[94]; Stewart (2019)[98], Trefil et al. (2009) [101], Jeancolas, et al. (2020)[35], and Pascal and Pross (2022)[80].

The emergence of living systems can be attributed to internal chemical and physical changes, denoted by γ, in response to environmental factors. The γ cognitive system evolves not only within living organisms but also from non-living chemical states. This suggests that the evolution of life represents a continuum, from non-living matter to living biological states, rather than a sharp division. In essence, biological evolution is a distinctive expression of broader chemical and physical processes governed by the laws of matter and energy. Using mathematical methods, it is demonstrated that no comprehensive definition can clearly separate living from non-living entities based solely on characterizations.

Entities in the universe are typically classified into two categories, living (A) and non-living (B), according to a set of characteristics attributed to living systems. This classification is based on the assumption that such characteristics can be reliably identified and defined. For the distinction to hold, it must be ensured that none of these traits are exhibited by members of group B. However, due to the universes scale and diversity, a complete identification of all non-living entities is infeasible.

Additionally, transitions between groups A and B are observed over time, further obscuring categorical boundaries. This ontological fluidity complicates any effort to establish a definitive concept of life. Nonetheless, living beings are still regarded as systems, examples of which include humans, animals, plants, bacteria, and possibly viruses.

In defining living organisms, two general cases can be considered. First, one may assume that all living beings share at least one common characteristic. Second, it may be supposed that each category of living beings possesses a characteristic common to that particular subgroup. To analyze the problem mathematically, let us assume a finite set of properties associated with living organisms, denoted by

$$q_1(x), q_2(x), q_3(x), \cdots, q_n(x),$$

where some of the properties $q_1, q_2, q_3, \cdots, q_n$ holds for a living being x. On the other hands, if some of the properties $q_1, q_2, q_3, \cdots, q_n$ holds for x, then x is living creature or $x \in A$.

Put

$$A = \{x \in U : \quad q_i(x) \text{ holds } \exists i (1 \leq i \leq n)\}. \tag{1}$$

As mentioned, A encompasses all living creatures. The properties represented by q_i delineate the members of A, or conversely, the presence of members in A determines property q_i for some $(1 \leq i \leq n)$. However, a significant issue arises with this definition: certain organisms identified as non-living may still qualify as members of set A. For instance, could artificial intelligence machines, viruses, or amino acids belong to A?

In this scenario, we define the set A to encompass all entities sharing at least one common characteristic. Defining living organisms necessitates a comprehensive collection of samples representing various living beings. For this purpose, we gather samples categorized into groups A_1, A_2, ..., A_k, where A_1 might represent mammals, A_2 insects, A_3 plants, and so forth. This collection constitutes a complete sample of living organisms, denoted as $A = \cup_{i=1}^{k} A_i$.

Let $q_1, q_2, q_3, \cdots, q_n$ represent a finite sequence of special characteristics defining all organisms within set A. Consider $\Omega \subseteq q_1, q_2, q_3, \cdots, q_n$ as a non-empty subset, where all living beings satisfy each characteristic in Ω. Let $\Omega = q_{k_1}, q_{k_2}, q_{k_3}, \cdots, q_{k_t}$, with $1 \leq t \leq n$.

Our aim is to determine if an element x satisfies the properties of Ω, which is equivalent to verifying if x satisfies each property $q_{k_1}, q_{k_2}, q_{k_3}, \ldots, q_{k_t}$ individually. Thus, x belongs to set A if it satisfies all properties in Ω.

Let U denote the collection of elements in the world. We define $b_{(k_1,k_2,\cdots k_t)}$ as $q_{k_1} \wedge q_{k_2} \wedge q_{k_3} \cdots \wedge q_{k_t}$. Therefore, $b_{(k_1,k_2,\cdots k_t)}(x)$ indicates that x is a living being, or equivalently, x belongs to set A.

The set A can be represented as:

$$A = \{x \in U : \ x \text{ satisfies \ in \ the properties } \Omega\}.$$

Now let $b_{(k_1,k_2,\cdots k_t)} = q_{k_1} \wedge q_{k_2} \wedge q_{k_3} \cdots \wedge q_{k_t}$. So $b_{(k_1,k_2,\cdots k_t)}(x)$ holds means that x is a living being or equivalently $x \in A$. It is clear that we can display the set A as below

$$A = \{x \in U : \ \ b_{(k_1,k_2,\cdots k_t)}(x) \text{ holds } \}.$$

For the existence of set A, it is necessary that $\Omega \neq \emptyset$. The characteristics attributed to living organisms are inherently tied to the selection of samples, particularly complete samples. Thus, the characteristics of living organisms and the selection of a complete sample are interdependent. Therefore, sets A and Ω are mutually dependent on each other.

Based on the gathered information, it is presumed that a chemical compound, denoted as γ (for illustrative purposes, let's assume it represents a zygote like an egg or a plant seed), lacks the characteristic traits associated with living organisms and therefore does not belong to the set A. However, it is postulated that through environmental processes involving chemical, physical, and biological factors (such as incubation or other transformative processes), γ undergoes a conversion into a living entity, thus becoming a member of set A. Let's denote the physical, chemical, and biological attributes of γ as a, and the corresponding attributes of the transformed entity as b.

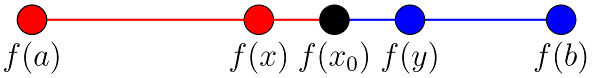
Now we define a function f from $[a, b]$ onto $[0, 1]$, where $f(a) = 0$, $f(b) = 1$, and $f(x)$ represents the relative distance between simple γs and a particular stage in embryo formation for $a \leq x \leq b$. More precisely, let t_a denote the start time of γ incubation, and let t_b represent the moment the chick hatches. Then the position a corresponds to time t_a, the position x corresponds to time t_x, and the position b corresponds to time t_b.

So, we define $f(x) = d(a, x) = \frac{|t_x - t_a|}{|t_b - t_a|}$ where d is a distance from a to x for all $x \in [a, b]$. The function f is continuous, and so we cannot determine when the number $f(x)$ must be in order for x to be living in our definition. If we define the set

$$\omega = \{f(x) : \ x \text{ is a living organism}\}.$$

Then $1 \in \omega$. So ω is non-empty and bounded below. Let $\inf \omega = \alpha$. Then there is $x_0 \in [a, b]$ such that $f(x_0) = \alpha$. It follows that for all $x, y \in [a, b]$ with $f(x) < \alpha < f(y)$, the position of x indicates that the γ is not alive (or $b_{(k_1,k_2,\ldots k_t)}(x)$ not holds) and the position of y indicates that it is alive (or $b_{(k_1,k_2,\ldots k_t)}(y)$ holds).

Consider the following diagram:



We can take $f(x)$ and $f(y)$ (or t_x and t_y) sufficiently close so that the contradiction between x and y disappears with respect to the common characterizations mentioned in Ω, resulting in $\Omega = \emptyset$.

In contrast, in the subsequent scenario, if a γ (zygote) possesses the attributes of living organisms (i.e., it belongs to set A) but is not subjected to incubation, it will eventually transition into a non-living entity. Now, let's contemplate the moment when the γ is excluded from set A. In this instance, if we revisit the previous argument, we can deduce that Ω becomes empty.

According to the elucidations provided in the preceding chapter, the process of transitioning a non-living chemical compound into a living organism, or vice versa, adheres to this argument. However, if the members of set A lack a common characteristic, we encounter definition (3,1). Nevertheless, these arguments can engender a contradiction, underscoring the challenge of precisely delineating the boundary between living and non-living entities. Consequently, discerning the moment when a non-living chemical compound transforms into a living organism becomes a formidable task. For instance, contemplate the transformation of water from a liquid state to solid ice. There is no fixed moment, denoted as t_0, at which the water definitively transitions from liquid to solid (ice). This illustration underscores the continuous and dynamic nature of the shift from non-living to living systems, further complicating the endeavor of defining the attributes of living beings. Based on the aforementioned argument, the establishment of a comprehensive definition of living organisms solely predicated on their distinguishing characteristics would yield a contradiction symbolized by a black dot in the diagram above, a logically untenable scenario.

Given that the living state of matter arises from the non-living through a gradual and continuous transformation, lacking any sharp ontological boundary, as argued above, the distinction between living and non-living matter becomes a matter of degree rather than of kind. This aligns with the philosophical perspective that life should not be treated as a discrete category, but rather as a dynamic, emergent organization of matter shaped by thermodynamic and kinetic constraints (Schrödinger, 1944[88]; Deacon, 2012[23]; Pascal and Pross, 2016[78]). The so-called 'living state' is thus better understood not as a fixed ontological class, but as a transitional phase in the continuum of complex systems, marked by features such as self-maintenance, adaptive responsiveness, and far-from-equilibrium behavior. These characteristics form a loosely defined cluster that resists rigid classification, reflecting the limitations of classical taxonomies when applied to evolving, process-based phenomena.

10 Corollary

Living organisms emerge from the intricate interplay of chemical and physical processes embedded within nature. Within this complex framework, physiological characteristics intricately intertwine with the ecological dynamics of their environment. Living beings are deeply connected to their surroundings, engaging in myriad interactions that mutually shape and are shaped by their habitats. These interactions span across various realms, encompassing not only chemical and physical processes but also ecological dynamics like resource competition, predation, and symbiotic relationships. Pascal and Pross (2022)[80] have convincingly shown that Darwin's theory of evolution transcends the confines of biology, extending its reach to non-living chemical systems. Building upon their work, this paper delves into the notion that the demarcation between biological and non-biological states is not sharply delineated. Instead, it suggests a fluid continuum of evolution spanning across both domains.

The arrival of cognitive chemical systems, imbued with the remarkable ability to evolve and adapt within their environment, marks a significant milestone in the journey of life. Leveraging their cognitive faculties, these entities traverse new structural and organizational avenues, enhancing their sustainability and resilience in the face of environmental challenges.

Yet, the transition from non-living to living entities eludes a discrete demarcation, unfolding instead as an uninterrupted continuum. This inherent continuity poses a philosophical quandary, challenging our ability to delineate the precise attributes that confer the status of living upon an entity. Consequently, the quest for a definitive and comprehensive definition of living organisms, capable of unequivocally distinguishing them from their non-living counterparts, remains an enduring philosophical endeavor. In the unfolding chemical evolution from non-living to living entities, the absence of a singular, predetermined moment underscores the elusive nature of this transition, complicating attempts to establish a fixed temporal boundary. Moreover, the absence of inherent, exclusive features further complicates the ontological distinction between living beings and non-living entities. Thus, the delineation between these ontological realms remains fluid and indeterminate, defying facile categorization and inviting continued philosophical inquiry into the nature of life itself.

In principle, the living state of matter constitutes a dynamic condition arising from continuous physico-chemical transformations within environments far from equilibrium. Although properties such as self-maintenance, reproduction, and responsiveness can be used to approximate this state, they constitute a loosely associated cluster rather than a strict set of necessary and sufficient conditions. As a result, no definitive boundary can be drawn between living and non-living matter based solely on observable traits. This ambiguity highlights the inherent complexity of emergent systems and supports the view that life is best understood as a continuum, shaped by thermodynamic constraints and kinetic stability, rather than as a sharply delineated category grounded in metaphysical or abstract definitions.

Availability of data and material. The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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