(Toward) Discovery of Life beyond Earth and its Impact
Proceedings IAU Symposium No. 387, 2026
H. Landt, M. Dominik & C. Oliver, eds.
doi:10.1017/S1743921324002047

Re-evaluating Boundary Conditions of the Concept of Life

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Abstract. It is argued that a central challenge to the task of developing a foundational model for life lies within the implicit propositions of the Western scientific view. These propositions constrain thinking about the concept of life. Three implicit boundary conditions in particular - life as a property of a system, life as a purely biological phenomenon, and life as a binary concept - are identified, and it is suggested to replace them with three operational principles - synonymity of 'life' with 'processes of change'; the foundation of change upon interaction; the recursion and integration of change over boundary conditions.

Keywords. Life, Recursion, Boundary Condition

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1. Introduction

I attribute to Nature neither beauty nor ugliness, neither order nor confusion. For things can only be called beautiful or ugly, orderly or confused, in relation to our imagination. By the coherence of parts, I understand nothing but that the laws or nature of the one part so adapt themselves to the laws or nature of the other part that they are opposed to each other as little as possible. [...] From this it follows that every body, insofar as it exists modified in a certain way, must be considered as a part of the whole universe, must agree with the whole to which it belongs, and must cohere with the remaining bodies.

- Baruch de Spinoza 1665

Eight decades ago this year, Erwin Schrödinger published What is Life?, a seminal contribution in the quest to understand the concept of "life" (Schrödinger 1944). Whilst Schrödinger did not answer the question, precisely, in his book, he did lay a foundation of work building on and further developing an exploration of it. (Cleland & Chyba 2010; Cornish-Bowden & Cárdenas 2020; Trifonov 2011; Tsokolov 2009; Weber 2010; McKay 2004; Benner 2010; Jeuken 1975). Nonetheless, the question remains elusive.

There may, crucially, be a possible problem with the question *itself*, 'what is life?'. The word "is" relates to the stative verb "to be", which relates in turn to the condition of a given state at any given snap-shot in time. The implication then is that life is a quality or phenomenon which relates to "being", in the sense that a given system can be defined (in some way) as existing in a certain state (Musacchio 2005). This seems to run counter to all of our experiences of the phenomenon of life which have as their root, processes of change rather than states of being (Gómez-Márquez 2023). All biological organisms as we know it engage in the activity of change as a common theme and such changes are

https://doi.org/10.1017/S1743921324002047 Published online by Cambridge University Press

most commonly recognised through certain processes of change which we call variously; birth, death, ageing, evolution, mutation, selection, adaptation *etc.*

We must consider the way that we frame any such system. These frames are more commonly called boundary conditions (Paksi 2014; Polanyi 1968) and it seems logical to re-consider whether or not we have these frames set appropriately for the question(s) at hand; this work will reconsider such boundary conditions, to try and come to, at least, a better formulation of the question asked by Schrodinger.

2. Life as fundamentally a Boundary Condition Problem

We may re-express the problem of life as follows:

'Is there a meaningful, scientifically valid, and binary way to separate living things from non-living things, and to talk about why it is that life exists, and how it fits into the broader context of the world?'

This is clearly a two-part problem, and the two parts are not separable. It is of course possible to simply systematise the opinions of various observers on what is or isn't life, as the recent paper that distinguishes biosignatures using a neural network, ultimately trained on human judgement calls of such shows (Cleaves et al. 2023). But, in the first instance this approach is not completely consistent, as certain edge cases demonstrate (Cleaves et al. 2023). It doesn't really tell us what life is, independent of human perception. It just tells us what people, or rather some people, think life is.

Previous models of life have been incredibly useful, valuable, logical and well-constructed, and again, we by no means wish to cast aspersions on these works. But we are not the first to observe (Wolfram 1984; Persig 2014) that a binary definition of life may not be useful, or even possible. So, in un-asking the question of life, what are the assumptions, or boundary conditions, that we're objecting to? We identify three primary ones, which have proven particularly troublesome in trying to formulate a unified definition of life within the Western scientific cannon:

(i) Livingness is a quality, or property, inherent to a 'thing'; an object, a system, or an organism. (ii) Those things in proposition (i) are "biological things". (iii) There exists a binary distinction between livingness and non-livingness, such that 'things' can be identified as belonging in a category of either one or the other.

Let us consider each of these in more detail.

2.1. *Implicit Proposition #1*

It is fundamental that livingness be associated with "things" (objects, systems, organisms etc...) according to this proposition.

If this is true, how do we know this? On one level it seems perfectly reasonable to consider many material forms as "things" or "systems". Some of these things appear to be inanimate in that they do not seem to change, in any human perceptual sense, in response to some action taken by that thing. They do not appear to have agency (Moss 2024) associated with the thing itself but respond only to their environment. Inanimate things then are usually classified as non-living. Other things do possess what we call agency and appear to direct any response to their environment, towards certain outcomes and not to others. When such things are "biological" in nature (whatever that may mean), they are usually classified as animate and living. In the case of both animate and inanimate things though, we perceive a physical differentiation between the thing itself (the system) and their environments.

But note the wording here - we *perceive.* To view something as a singular, differentiated form is to see it as dis-attached in some way from its wider context. Consequently, connections that are definitely physically apparent and relevant are

https://doi.org/10.1017/S1743921324002047 Published online by Cambridge University Press

ignored. In categorising things, humans first break a node out of what is an otherwise connected and integrated whole. Once separated, we attach a specific meaning to that separated node; a meaning that is different to what is not the thing. Finally, we attempt to reconstruct those connections that were necessarily present before thing and environment were conceptually separated; without a full understanding of what connectivity has been disconnected.

2.2. *Implicit Propositions #2 and #3*

Now that we have reasonable grounds to doubt proposition (i), let's move on to proposition (ii) and proposition (iii), which are closely interwoven. The inherent assumption that biology is the sole province of life is baked into the etymology of the field's name. The word biology is derived from the Greek, bíos, life, and logía, field of study. By implication then, something non-biological, that does not operate in the same way as a blood-and-flesh owl, is not alive by definition.

Humans have come to define a set of systems as having livingness, and systems that operate in a different way to be perceived as non-living. Sagan spoke of 'carbon chauvinism' or 'water chauvinism' to describe the assumptions made about how the chemical makeup of terrestrial biology must be mirrored in extraterrestrial life (Sagan 1973). These ideas are encoded within proposition (ii). Life is that which functions like we do. That which does not function as we do is not life. Is this a warranted belief? Well, we have something of an easy time saying that all life on Earth is of one phenomenon, one class, as they all share certain characteristics as a result of being descended from a single common lineage. Every single biological organism on Earth shares a common ancestor; in the theory of panspermia, this may even be true of all life everywhere! But what if an organism was found, say an extraterrestrial, or even a terrestrial one, of different descent? That formed from, evidently, a completely separate abiogenesis? It has no reason to use the same processes as we do (Davis et al. 2009).

The fact that we cannot even agree that some apparent offshoots of this common lineage - viruses, prions, etc - are 'alive' displays a further flaw in this argument. What set of characteristics, exactly, makes something that is biological alive? There is a conflation here of the concepts *biological* and *living*. Now, this conflation quite often has value, but what is it fundamentally based upon? There are definitions that would enclose things that do not have our lineage, and ones that would exclude things that don't! From a historical perspective, there was a time when both animate and inanimate substances were thought to be composed of the same set of fundamental "elements" [earth, air, fire & water as laid out by Empedocles (Russell 1991) expanding to include the concept of space (vide infra) in the Pañca-Mahā-Bhūta of Hindu philosophy (Gopal 1990). As our knowledge of the natural world increased however, it became clear that the operational principles, the mechanisms, of animate and inanimate systems differed. These differences then, helped lay the philosophical foundations for a separation of what is considered living from what is not, on mechanistic grounds (Bucci et al. 2010). This in turn influenced our collective, conceptual thinking about our world, which lies at the heart of implicit proposition (iii).

Is there some foundational, Universal principle that maintains such a binary distinction between livingness and non-livingness; and if so, on what is such a principle based? Whenever some natural phenomenon is assigned a "name", we are constraining that phenomenon. How is this so? In effect, we are placing that phenomenon within some conceptual framework or category. Consequently, what is outside of that conceptual categorization is de facto, not the same as "name", but part of a different category variously called "environment", "society", "colony", "world" etc...

In truth, we are not making categorization decisions of life (or anything else for that matter) based on universal, foundational principles, but rather using heuristic concepts.

(Ippolitti 2015). Such decision-making has served humans well in many scenarios of life; but its value is in providing something that is functional and expedient for the human rather than a solution to a problem based on foundational principles.

To conclude this section, we contend that a central problem with answering the question 'what is life' is that it relies on assumptions that are not themselves objectively true. Life exists in a place, has a shape, has a mechanism and process of existing and being and continuing, has a name and an idea. But these are problematic assumptions which cannot be reasoned to be fundamental or objective. The universe doesn't seem to have a differentiated concept of life; but we humans have created one and in so doing have created those differences accordingly. So then, if we not at all sure that the three implicit propositions (i)-(iii) listed above represent foundational, universal principles, through which we may view the concept of livingness; what happens when we reject them from our concept of life?

3. Interactions Lie at the Heart of Conceptual Boundaries.

Once the above implicit propositions within the western concept of life have been identified as being subjective, we can then consider how to probe more fundamental features. Note we say, 'more fundamental', as we are speaking only of models here, not underlying reality itself.

As a starting point, there is the view within physics that a more fundamental representation for the fabric of existence is a distributed and universal field than singular objects such as particles (De Angelis & Pimenta 2018). Thus, the particulate electron for example only has meaning because of the presence of distortions within a field of subjective interactions (Kuhlmann 2013). Note this means both that the idea of a singular and localised form of 'an electron' is not fundamental, and that it only exists as a consequence of interactions with other parts of the universe; a result which emerges from many experimental observations, such as the suite of double slit experiments (Chang 2024).

Parallel examples of this kind of thinking can be taken from human experience. We can say that a game of tennis cannot exist in the absence of interactions between players. The concept, game of tennis, has meaning only when players are mutually engaged in an interaction field which connects them in some way. One player alone cannot create game of tennis, even if they have the balls, the racquets, the nets, an umpire, and an audience. Similarly, two tennis players, all set to play a match, but without tennis balls, or racquets for example, cannot create game of tennis, because the interaction between players and necessary tools (the ball and racquets) are not present.

The point we want to emphasize here is that the concept of something we might call an electron or a game of tennis exists due to the operation of fundamental interactions, interconnections between various "actors" or distortions with a conceptual interaction field (such as electrostatic, magnetic fields in the case of the former and tennis balls and tennis players in the latter scenario). This collection of interaction space, whether electrostatic, magnetic, probabilistic, gravitational, or human, represents an interaction field. One may then think of this interconnectivity between actors (whatever they may be) or distortions within an interaction field as what creates the "concept" or "experience" (charged particle, game of tennis). How then might this fundamental focus on interactions influence our idea of the concept "life"?

All of biology is built around cellular interactions; interactions which occur either within each biological cell and interactions between differentiated cells. So, right at the outset we may delineate two distinct concepts to biological life. One concerns what happens within a biological cell, in which the cell itself is the conceptual system. The second

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conceptual system exists at a level higher of abstraction in which individual biological cells are interacting components within a concept called cell population. These two concepts, biological cell and cell population are not the same, but they are deeply and recursively connected (Liu et al. 2018). Each of these two concepts have their own internal sub-sets of structural, mechanistic and conceptual boundary conditions. For example, individuated bacterial and archaeal cells have different cell wall and lipid membrane components (structural boundary conditions) and perform different suites of metabolic chemical reactions (mechanistic boundary conditions). Consequently, the use of different names to symbolize these two families of organism provides a conceptual boundary condition between them.

Cell populations also possess structural, mechanistic and conceptual boundaries, but they are not necessarily the same as those of individuated cells. From a chemical perspective, similar classes of chemical entity (molecules, macromolecules, ions etc...) and mechanism (messenger-receptor, signalling cascades etc...) are used across such boundaries, but the ways in which they manifest, and their integration are different (Gerdes & Pepperkok 2013). The result of these variations in boundary conditions is that cell populations can do things that individuated cells cannot, such as build structures we call organs, tissues, organ systems and organisms. They display what is called *emergent behaviour* (Cuenca et al. 2022).

What we have here is an integrated network of mutually connected, recursive subsystems, which function at different levels across the system as a whole. Therefore, at each level of the recursive structure, we can identify concepts (cell, cell aggregations, organs, tissues, organism etc...) which have operational meaning as a result of the interactions present within that concept and between that concept and adjacent conceptual structures. In some cases, the operational meaning of a concept will be closely associate with either structural or functional (mechanistic) features of that concept (eg: a human heart is fundamentally associated with its function to pump blood around the body). In other cases, that meaning will be more closely associated with its connections to other concepts eg: the system of Linnaean taxonomy that runs from the more specific concept, species, to the more general concept of kingdom (Kuntner & Agnarsson 2006).

It's worth noting that we are far from the first researchers to identify recursion, especially in the geometric context of fractal shapes, as a key idea in the structure and nature of life(Azua-Bustos & Vega-Martínez 2013; Grosu et al. 2023).

4. Interactions Lie at the Heart of how Concepts Change. This Dynamic Process of Conceptual Change is Livingness.

At this point, it is worth pausing to reflect on what we have tried to lay out above; that concepts result from interactions, connections or distortions within some interaction field (in whatever form that may be envisioned). How does this then relate to the concept of life or livingness?

Most scientific models of life focus on the concept itself as possessing the quality we call life. For example, the physical concept or system called, dolphin is said to possess the concept of livingness, whereas the physical concept paving stone is thought of as non-living, in a conceptual way (Amilburu et al. 2021). However, what we wish to emphasize here is that the cognitive concept life is perhaps better viewed as a variable which can be framed in different ways according to the question being asked or the level of complexity with which one wishes to explore this concept. Thus, the concept livingness reflects the process by which the cognitive concept life changes. In essence then, livingness can perhaps be viewed more fundamentally as the conceptual, mechanistic and physical processes of change; or put another way, the processes by which a system (however that is defined) changes against some variables (eg: time, informational input etc...). This is

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neither a new nor original idea as the dynamic nature of livingness resulting in change is embedded in thinking from classical Greek-Persian philosophy (Müller-Merbach 2006) to current scientific models such as natural selection (Gregory 2009), the constructal law (Bejan & Marden 2009); assembly theory (Sharma et al. 2023); dynamic kinetic stability (Pross & Pascal 2013) and more recently models of functional information (Wong et al. 2023).

All these wonderful approaches (and many other besides) have the concept of change at their heart; changes of form, changes of mechanism of operation, changes in energy or information content. They are, essentially, techniques of modelling or parametrizing, the processes and mechanisms of change and, as such, lie seamlessly within the overarching picture presented here. Interestingly, many of the above models go to significant lengths to draw out the connections between animate and inanimate systems.

Of course, when one talks about the concept of change, a logical question to ask is: what is actually doing the changing? One way to think of this is to adopt a systems-type of approach. So, the question what is changing can be answered by, the system is changing. Well then, a further question raises its head: what is the system? To which one may respond that a system is some collection of entities or components which are mutually linked together in some way and which operate in such a way as to influence the collective of that system (Wilkinson 2011). Processes of change, at their simplest, are frequently represented as mechanistic elements of an input-manipulation(or processing)-output-feedback cycle.

These mechanistic or non-material components may be connected to some material parts of a system, such as a biological form (eg: hermit crab), non-biological form (eg: pulsar) or a human-designed object such as a TV or suspension bridge. Together the material and non-material or operational elements comprise what we might call a system. An important point is that a system needs (by its very definition) to incorporate mechanisms by which that system can change. Conceptually, a system must integrate those mechanisms of change; they must therefore be part of the system. Now they can be external to the structural objects within the system, but they must be a part of the system as a whole. Anything that undergoes change by mechanisms which are not considered to be part of that system is, in reality, not a system at all but an object which is acted upon.

If we imagine a single wave crashing against a surf-line, billions of grains of sand will be disturbed by the force of the wave. The retreating of this wave creates patterns of sandbanks called bed-forms; patterns which are unique to each wave cycle and never repeated exactly in form, size or duration. The concept *beach* has undergone a physical change in form as a result of the wave dissipating itself on the shore. In systems language, the system *beach* has transitioned from one state to another state as a result of an energy-input event. In this view, the concept *beach* remains unchanged, but the physical changes to the system that have occurred are technical in terms of how the systems components (the grains of sand in this case) are distributed. This would be in line with the western scientific mechanistic or reductionist approach to change.

An alternative view to this would be to consider the concept *beach* after the wave-crash to be a newly created concept to that of *beach* before the wave-crash. This new concept is created out of the interaction between two other concepts, wave-crash and *beach* before the wave-crash. So now, just like the concept car is an object but car-with-driver is a system (which must technically also include, car ignition mechanism, fuel and many other constituent, integrated actors), so the concept *beach* is better considered as an object but the combined concepts wave-crash and *beach* before the wave-crash comprise a system. Now this may seem like semantics, but the power of this flexible

https://doi.org/10.1017/S1743921324002047 Published online by Cambridge University Press

conceptualization, a willingness to consider conceptual boundary conditions as fluid, allows us to view processes of change as integrative not just transformative.

Thus, not only does the physical object *beach* after the wave crash emerge out of the interactions between other physical objects wave-crash and *beach* before the wave-crash, but the concept of *beach* after the wave crash only exists as a consequence of the integration of concepts wave-crash and beach before the wave-crash. The conceptual boundaries of our system have changed. Now, of course this example of waves and beaches applies not only to that single wave and that momentary structure of the object *beach*. It applies to each connected sequence of wave-beach interactions that occurs over any given period of time (a temporal boundary condition).

Not only that, but when we consider the concepts wave-crash and *beach*, where exactly are we drawing the structural and mechanistic boundaries in order to frame those individuated concepts? Does the concept wave-crash include the building of the wave? Does it include immediately preceding and proceeding waves into which our wave merges? Does it include the backwash once the wave has crashed? Once we recognise that structural, and mechanistic boundaries associated with concepts are often not clearly delineated, we can see that concepts too should also be considered as similarly fluid and evolvable. Clearly, the examples that we have given above are not ones that focus on biological concepts and hence some readers may find themselves wondering what the relationship are between complex biological systems and complex non-biological ones. This is a logical question and one that scientists are engaged with as outlined above.

We propose that the foundational behaviour of any form of livingness is therefore, this recursive integration of all processes of conceptual change across any given set of (user-)defined boundary conditions.

5. The Life of Samantha

As a jumping off point from the previous section, we used examples of dynamic processes of conceptual change which are not directly or identifiably biological. So, you may rightly ask, where is biology in all of this?

Let us start with an individual human being; we introduce her here as Samantha. Samantha is a biological organism (which is a concept of course), so we might logically conclude that it makes sense to view Samantha as a physical, cognitive and emotional system. Now, Samantha is not a closed system (Wilkinson 2011) but one who exchanges physical matter and energy with her surroundings. The system we have called Samantha functions as an operationally interconnected network, of chemical reactions, control mechanisms, thought management, processing and communication units. Collectively, we refer to such an interconnected set of units as biological mind and body.

We envisage that most of us would be happy in considering the system Samantha to be a living system so long as the collective biological interconnectivity network remains operational, at least physically. Now, if we look at some of the various units, or components, of this physical biological system, we might identify other physical concepts such as heart, lungs, liver, central nervous system etc... Each of these may be considered as a system as well as being a sub-system component of the larger system Samantha. As an individual system, the heart for example, is not a closed one either, it takes in matter, processes it according to a set of interconnected instructions and then moves it on to other systems.

Within the heart itself, various structurally identifiable objects (concepts) are present, such as a heart valve for example. This too can be considered as a system. Not only does the heart valve have identifiable structural boundaries and mechanistic boundaries in relation to its role as a component of the heart network system, but it also operates as such due to its own internal composition and interconnectedness. For example, mature valves are composed of extracellular matrix (ECM) material divided across three main layers, the fibrosa, spongiosa and atrialis (for the atrioventricular valves) or ventirularis for semilunar valves (Chester & Grande-Allen 2020). If we move to increasingly smaller scales and explore the ECM as smaller sub-system within the heart valve, then we recognize how ECM is composed of a dynamic network if interacting molecules and minerals, including collagen, glycoproteins, hydroxyapatite amongst others.

Indeed, each component macromolecule within ECM can itself be considered as network of interacting molecules, and beneath the molecules, atoms, sub-atomic particles, quarks, etc. . . .each a recursively smaller scale of concept comprising networks of dynamic, interconnecting concepts.

This picture is of course not a new one; the whole edifice of cellular and systems biology is built upon such models of systems-within-systems; rather like a set of matryoshka dolls (Miller 1972). The significance of this recursive relationship between systems is that each dynamic system can be considered as an example of livingness within it's own set of user-defined boundary conditions. Importantly, it is not so much that the system possesses a quality we call living, but the system engages in living processes. It is, collectively, one contiguous spectrum of living processes, each with different sets of boundaries. When one recursively integrates each and every interconnected chemical system of livingness up to and including the structural, mechanistic and conceptual boundary conditions that we call Samantha; we begin to frame what we might colloquially call "the life of this organism".

Of course, what we have described above is only a limited framing of the full livingness of Samantha; both biologically and otherwise. What is outlined above represents only the internal biological systems, presented through some hierarchical biological architecture, for the bounded concept, Samantha. Additional biological systems can be identified which, whilst being partially internal to Samantha, nevertheless have components which are external to the organism. For example, the system of visual stimulus, heat-regulation, skin pressure sensing etc. . . . In effect, all physical systems with which Samantha regulates and modifies herself as a biological organism. The dynamic operation of each such system, on a material physicochemical level contributes processes of livingness which incorporate the biological organism Samantha, but which have external actors or elements. Examples include reflected/refracted light from the Sun, objects which Samantha touches and the flow of air over skin through which radiant heat is exchanged. In effect, the concept Samantha is now an element or actor in living processes which transcend the structural boundaries of the Samantha organism herself. Samantha is therefore a component in the operation of a larger scale system - perhaps she could be thought of as a cell within the wider Gaia organism (Stolz 2017).

We can also move beyond these physicochemical processes to look at other forms of system that Samantha, the organism and concept, is a component of but whose mechanism of operation are not only physicochemical but emotive and/or cognitive. Samantha has parents, siblings, friends, work-colleagues with whom collectively, Samantha engages in cognitive exchange via mechanisms which include both the physical senses and other processes such as language and emotions. The integration of all such physicochemical, emotive and cognitive processes across all boundary conditions for which Samantha is an actor (or element) becomes a representation of the complete livingness of the concept Samantha. We tend to condense this rather cumbersome mouthful of a phrase as "the life of Samantha". Therefore, from the perspective of Samantha, any way in which the concept Samantha or any concept of which Samantha is a part, actor or involved with, changes or is created; becomes integrated into the concept "life of Samantha". Of course, this begs the question as to what it means to say Samantha is alive, primarily because the concept of livingness that we have outlined above is not object-centric but

https://doi.org/10.1017/S1743921324002047 Published online by Cambridge University Press

process-focused. In effect, it is more accurate to say that Samantha (the human organismic concept) engages in multiple processes of livingness simultaneously and contiguously. We can play games of classifying those processes of livingness according to, for example, structural, mechanistic or conceptual differences using all sorts of different techniques and mathematics; one of which, Conway's game of life, is discussed in more detail in another article on these proceedings.

Acknowledgements

The authors acknowledge many colleagues for their time and good offices in wider discussions on boundary conditions in the context of life which helped shape this contribution; specifically Andrew Kirton (Leeds), Clément Vidal (VUB, Brussels), Kuhan Chandru (NUM), Inge Loes ten Kate (Utrecht) and especially Dirk Schulze-Makuch (TUB) and Juan Perez-Mercader (Harvard) for helping crystallize what is contained herein at the Kavli-IAU (IAUS387) symposium.

References

Amilburu, A., Moreno, Á.& Ruiz-Mirazo, K. Definitions of life as epistemic tools that reflect and foster the advance of biological knowledge. 2021 Synthese, 198, 10565.

Azua-Bustos A., Vega-Martínez C. The potential for detecting 'life as we don't know it' by fractal complexity analysis. 2013 International Journal of Astrobiology. 12(4), 314.

Bejan, A., Marden, J.H. The Constructal Unification of Biological and Geophysical Design. 2009 Physics of Life Rev., 6, 85.

Benner, S.A. Defining life. 2010 Astrobiology 10(10), 1021.

Bucci, M., Goodman, C., Sheppard, T.L. A decade of chemical biology. 2010 Nat. Chem. Biol. 6(12), 847.

Chang, D.C. A New Understanding on Wave-Particle Duality: Comparing the Quantum Wave Model with the Copenhagen In-terpretation and Other Alternative Models. In: On the Wave Nature of Matter. Springer, Cham. 2024.

Chester, A.H., Grande-Allen K. J. Which Biological Properties of Heart Valves Are Relevant to Tissue Engineering? 2020 Front. Cardiovas. Med., 7, DOI=10.3389/fcvm.2020.00063.

Cleaves II H.J., Hystad, G., Prabhu, A., Wong, M.L., Cody, G.D., Economon, S. Hazen, R.M. A robust, agnostic molecular bi-osignature based on machine learning. 2023 PNAS, 120(41), e2307149120.

Cleland, C.; Chyba, C. Does 'life' have a definition?. Ch 26 in Planets and Life: The Emerging Science of Astrobiology. Cambridge University Press, Cambridge, 2010.

Cornish-Bowden, A.; Cárdenas, M. Contrasting Theories of Life: Historical Context, Current Theories. In search of an ideal theory. 2020 Biosystems. 188 104063.

Cuenca, M.B., Canedo, L., Perez-Castro, C., Grecco, H.E. An Integrative and Modular Framework to Recapitulate Emergent Be-havior in Cell Migration. 2022 Frontiers in Cell and Developmental Biology, 8, 10.3389/fcell.2020.615759.

Davis, P.C.W., Benner, S.A., Cleland, C.E., Lineweaver, C.H., McKay, C.P., Wolfe-Simon, F. Signatures of a shadow biosphere. 2009 Astrobiology, 9(2), 241-249.

De Angelis, A., Pimenta, M. Understanding the Universe: Cosmology, Astrophysics, Particles, and Their Interactions. In: Intro-duction to Particle and Astroparticle Physics. Undergraduate Lecture Notes in Physics. Springer, Cham. 2018.

de Spinoza, B. Letter 15, to Oldenburg: 'A Worm in the Blood'.

Gerdes, H.H., Pepperkok, R. Cell-to-cell communication: current views and future perspectives. 2013 Cell Tissue Res. 352, 1.

Gómez-Márquez, J. Reflections upon a new definition of life. 2023 Sci Nat 110 53.

Gopal, M. in K.S. Gautam (ed.). India Through the Ages. Publication Division, Ministry of Information and Broadcasting, Govern-ment of India, 1990.

Gregory, T.R. Understanding Natural Selection: Essential Concepts and Common Misconceptions. 2009 Evo. Edu. Outreach 2,156–175.

Grosu, G.F., Hopp, A.V., Moca, V.V., Bârzan, H., Ciuparu, A., Ercsey-Ravasz, M., Winkel, M., Linde, H., Murean, R.C. The fractal brain: scale-invariance in structure and dynamics. 2023 Cerebral Cortex, 33(8), 4574.

Ippolitti, E. Heuristic Reasoning, Springer, Switzerland 2015.

Jacobs, S.A. The Scientific Consensus on When a Human's Life Begins, 2021 Issues Law Med., 36(2) 221.

Jeuken, M. The biological and philosophical definitions of life. 1975 Acta Biotheor. 24(1-2), 14.

Kuhlmann, M. Physicists Debate Whether the World is Made of Particles or Fields - or Something Else Entirely, 2013 Sci. Am., 303, August 1st.

Kuntner, M., Agnarsson, I., Are the Linnean and Phylogenetic Nomenclatural Systems Combinable? Recommendations for Bio-logical Nomenclature. 2006 Systematic Biology, 55(5), 774.

Liu, Q., Herring, C.A., Sheng, Q., Ping, J., Simmons, A.J., Chen, B., et al. Quantitative assessment of cell population diversity in single cell landscapes. 2018 PLoS Biol. 16(10), e2006687.

McKay, C.P. What is life–and how do we search for it in other worlds? 2004 PLoS Biol. 2(9), E302.

Miller, J.G. Living systems: The organization. 1972 Behavioral Science, 17(1), 1.

Moss, L. Normativity, Autonomy, and Agency: A Critical Review of Three Essays on Agency in Nature, and a Modest Proposal for the Road Ahead. 2024 Biol Theory 19 73.

Müller-Merbach, H. Heraclitus: philosophy of change, a challenge for knowledge management? 2006 Knowl. Manage. Res. Pract. 4, 170.

Musacchio, J.M. Why Do Qualia and the Mind Seem Nonphysical? 2005 Synthese, 147(3) 425.

Paksi, D. The concept of boundary conditions. 2014 Polanyiana, 1-2(23), 5.

Persig, R.M. Zen and the Art of Motorcycle Maintenance, 2014, Vintage Books, London.

Polanyi, M. Life's irreducible structure. 1968 Science, 160(3834) 1308.

Pross, A., Pascal, R. The origin of life: what we know, what we can know and what we will never know. 2013 Open Biol. 3, 120190.

Russell, B., History of Western Philosophy (2nd ed.), Routledge, London, 1991.

Sagan, C. The Cosmic Connection, Anchor Press/Doubleday, New York, 1973.

Schrödinger, E. What Is Life? The Physical Aspect of the Living Cell. Cambridge University Press, Cambridge, 1944.

Sharma, A., Czégel, D., Lachmann, M., Kempes, C.P., Walker, S.I., Cronin, L. Assembly theory explains and quantifies selection and evolution. 2023 Nature 622, 321.

Stolz, J.F. Gaia and her microbiome. 2017 FEMS Microbiology Ecology, 93(2), fiw247, https://doi.org/10.1093/femsec/fiw247

Trifonov, E.N. Vocabulary of Definitions of Life Suggests a Definition, 2011 J. Biomol. Str. & Dynam., 29(2), 259.

Tsokolov, S.A. Why is the definition of life so elusive? Epistemological considerations. 2009 Astrobiology. 9(4), 401.

Weber, B.H. What is life? Defining life in the context of emergent complexity, 2010 Orig Life Evol Biosph. 40(2), 221.

Westland, J.C. Information loss and bias in Likert survey responses. 2022 PLoS ONE 17(7), e0271949.

Wilkinson, L.A. Systems Theory. In: Goldstein, S., Naglieri, J.A. (eds) Encyclopedia of Child Behavior and Development. Springer, Boston, MA. 2011.

Wolfram, S. Cellular automata as models of complexity. 1984 Nature 311, 419.

Wong, M.L., Cleland, C.E., Arend Jr., D., Bartlett, S., Cleaves II, H.J., Demarest, H., Prabhua, A., Lunine, J.I., Hazen, R.M. On the roles of function and selection in evolving systems. 2023 PNAS, 120(43), e2310223120.