Towards a taxonomy of life-like systems: An information theoretic view of life

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Abstract

Information plays a critical role in complex biological systems. This article proposes a role for information processing in life, life-like systems and intelligence. I hypothesize that carbon-based life forms are only one amongst a continuum of life-like systems in the Universe. Investigations into computational substrates that allow information processing is important and could yield insights into novel non-carbon based computational substrates that may have "life-like" properties.

I hypothesize that the key components of a computational view of life, life-like systems and intelligence are: 1) Information processing, 2) information storage (memory), 3) a physical substrate (hardware), 4) information transfer (across both physical space and time), 5) persistence of information across space and time (selection and heredity), and 6) availability of energy.

We know a lot about life as we know it (carbon based life)? How would we recognise life and intelligence as we do *not* know it? Life elsewhere in the Universe may be very different from what we see on Earth. Our conception of life and intelligence are very anthropocentric.

We present a taxonomy of life-like systems, ranging from computer viruses to supernovae, that lie on a continuum.

A computational view of life-like systems may allow us to recognise life in all its myriad forms in this Universe. We also present outreach resources that the general public and students can use to engage with some of these ideas.

Life may exist as a continuum between non-life and life, and we may have to revise our notion of life and how common it is in the Universe. Looking at life-like phenomena and intelligence through the lens of computation may yield a broader view of life and intelligence.

Introduction

What distinguishes life from non-life? Can life be radically different from the carbon-based life forms we see on Earth?

Answering these questions will require us to understand life at a computational level. Information plays a critical role in complex biological systems. I suggest that information processing capabilities distinguish life from other so-called non-living matter [1]. Information processing is possibly one of many key ingredients of life [1] and intelligence [2].

Investigating novel non-carbon based computational substrates may yield a broader understanding of "life-like" properties. Some of these life-like systems are described below:

1. Reaction-diffusion systems like the Belousov-Zhabotinsky (B-Z) reaction are chemical oscillators and also display complex properties reminiscent of life ("life-like" systems): persistent wave-like patterns that propagate are shown in Fig. 1.

2. Stars have an energy source and have compartments. Stars that undergo supernova (at the end of their life) cause disturbances in neighbouring galactic clouds, which ultimately leads to formation of new stars. This is conceptually similar to replication.

3. Weather systems like hurricanes persist for long times [1]; even weather systems on other planets like the Great Red Spot Jupiter have persisted for a very long time and display complex behaviour. These have persisted for a long time and are robust to perturbations. These weather systems can also merge with each other to "create" new weather systems like the Little Red Spot.

4. Clay (which is a crystal) can also replicate defects within it. Clay particles that are more "sticky" can preferentially attach to river beds and can attract other similar clay particles [3] [4]. When sheets of clay are cleaved off and then transported elsewhere, they can preferentially attract other similar clay particles and provide a template for producing similar clay particles (since clay is a crystal and can produce similar forms of itself). Hence, in this simple clay system, there may be some limited forms of "heredity" and "natural selection" [3].

5. Quantum systems are capable of transferring information like spin and have "life-like" properties.

Arthur C. Clarke wrote imaginatively about complex intelligent life arising from electrical currents in superconductors on a cold, seemingly lifeless planet [6]. He imagined the electrical currents being

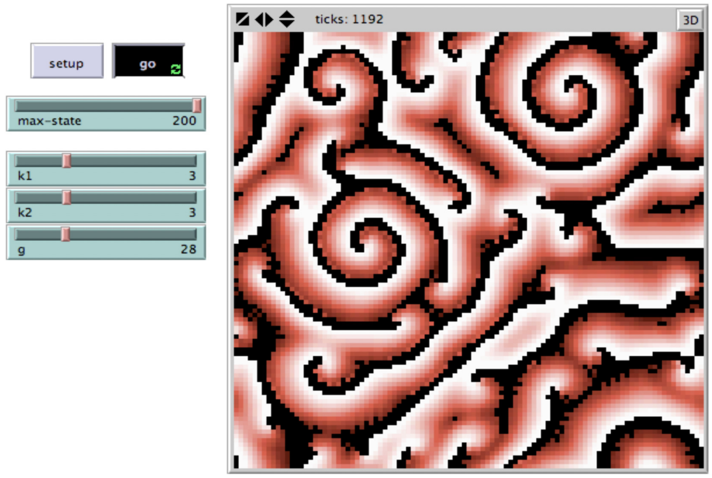

Figure 1. Screenshot from the NetLOGO simulation tool [5] for the Belousov-Zhabotinsky (B-Z) reaction showing wave like patterns that persist and propagate.

propagated endlessly in liquid helium (due to superconductivity). This ultimately led to neuron-like networks capable of intelligence.

He proposed a completely different computational substrate: electrical currents in superconductors at temperatures close to absolute zero. The story challenges our imagination and although unlikely to be feasible, challenges the very notions of life and intelligence.

We can develop a framework for an information-theoretic definition of life and intelligence that is independent of the subjective definitions of only carbon-based life.

What potential lifeforms might develop in our universe according to the established laws of physics? I propose that life based on carbon is just one among a spectrum of life-like systems in the cosmos.

A computational viewpoint of life, life-like systems and intelligence

Living systems are complex adaptive systems. Physical space plays an important role in life. Specialized structures, for example, cell membranes ("hardware"), serve both as an effective compartment and integrate information ("software") from extra-cellular and intracellular sources. The "software" and "hardware" of life and intelligence have co-evolved to achieve efficient information processing.

I hypothesize that the key components of a computational view of life, life-like systems, and intelligence are:

1. Information processing ("software").
2. Information storage ("memory").
3. The physical substrate ("hardware") and the role of physical space.
4. Information transfer (across both physical space and time).
5. Persistence of information (selection and heredity).
6. Availability of energy (energetic limits on information processing and life).

A requirement for life and life-like systems may be that the information should persist. This would result in selection of attributes that may also be "heritable". We note that conceptually, selection and heredity, and memory and persistence of information, are similar (and point to the survivability and robustness of these systems). Thinking about the Belousov-Zhabotinsky (B-Z) reaction, we note that certain model parameters that lead to persistent wave-like patterns (Fig. 1) may have a selective advantage: these patterns may become dominant in a population.

Our work is complementary to work suggesting that "selection" (broadly interpreted) can act on physical systems (such as stars and minerals) [7].

An overview of our approach is shown in Figure 3.

A step towards a taxonomy of life-like systems

We suggest a fruitful next step to be a taxonomy of life-like systems. These should include the following systems:

1. Oil droplets. Capable of self-preservation but may not be capable of replication.
2. Raleigh/Benard convection cells [8].
3. Clouds. Cannot replicate.
4. Stars. May not be capable of selection.

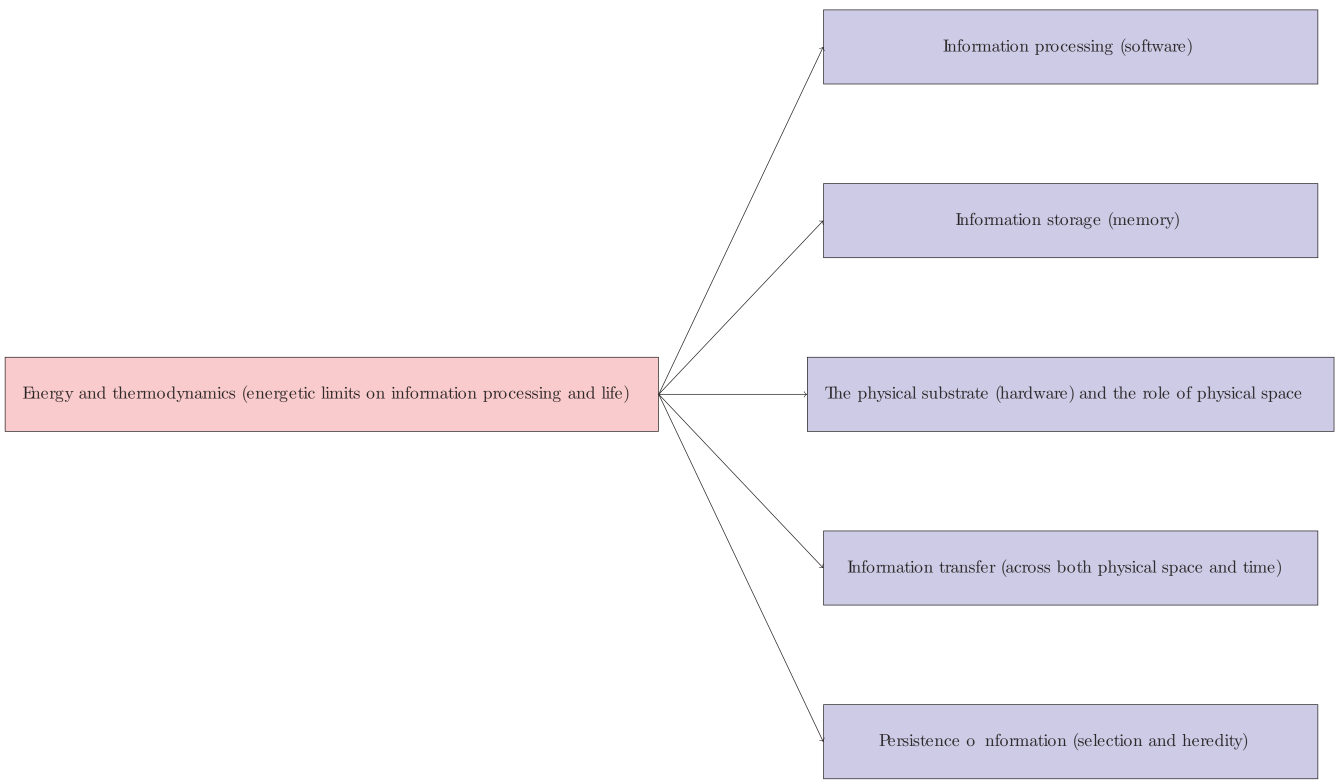

Figure 2. An overview of our approach and framework for life-like systems.

5. Clay. Can persist, Capable of some form of replication and capable of some form of selection and heredity.
6. Soap bubbles. Can persist, can merge
7. Solitons.
8. carbon-based life (life as we know it)
9. synthetic protocells.
10. innovations
11. mechanical and digital computers
12. Gaia [9] [10]
13. Memes
14. Biological viruses
15. ALife (Lenia [11], core war)
16. Computer viruses
17. Natural nuclear reactors [4]
18. Sand dunes (can replicate and move)
19. Rivers and other geological features. Rivers can move but cannot replicate. They are resilient and can maintain themselves over time.
20. Societies, cities and organizations. They grow over time and have some "lifespan". They also compete with each other. They do not replicate.

Self-preservation can arise naturally in some of these systems, convection cells and reaction-diffusion spots [8]. Some of these systems will be capable of persistence, heredity and selection. Some may have limited forms of selection. For example, clay [12] is capable of replication.

A naturally occurring nuclear reactor is also on this taxonomy. The natural nuclear reactor in Gabon (called Oklo) formed at least a billion years ago. As water seeped in through a naturally occurring band of uranium it would naturally moderate the reaction. As the reaction progressed, the water would evaporate making the reaction subcritical. This would allow more water to seep in which would further moderate the reaction. Water would further evaporate and then make the reaction subcritical again. In this way there would be many numerous cycles of operation of this naturally occurring nuclear reactor.

System	**Selection**	**Persistence**	**Heredity**	**Genes**	**Replication**
B–Z reaction systems	Limited	Yes	Limited	No	No
Natural nuclear reactor (Oklo)	None	Yes	None	No	No
Clay	Limited	Yes	Limited	No	Limited
Stars	Limited	Yes	None	No	Conceptual
Gaia	None	Yes	None	No	No
Artificial Life (e.g. Avida)	Yes	Yes	Yes	Yes	Yes
Innovations, ideas	memes	Yes	Yes	Yes	No
Yes					
Oil droplets	Limited	Transient	None	No	No
Rayleigh–Bénard convection cells	None	Yes	None	No	No
Clouds	None	Transient	None	No	No

Table 1. A tentative taxonomy of life-like systems, showing whether each system exhibits Selection, Persistence, Heredity, Genes, and Replication.

Many life-like properties arise from fundamental physical principles, such as energy minimization (for example, water flowing downhill), conservation of mass, and Le Chatelier's principle (providing a basis for the patterns we observe across scales).

Continuum between life and non-life, organic vs. inorganic

The boundary between "minerals" and "life" begins to dissolve when we look at organisms that build their bodies out of what we normally think of as purely geological materials. Two striking examples are brain corals and glass sponges. Though they belong to very different branches of the tree of life, both exploit the chemistry of seawater to precipitate sturdy mineral frameworks and in doing so they remind us that the living and the non-living are deeply entangled.

Brain corals secrete calcium carbonate (aragonite) to form ridged mounds whose folds give these animals their common name. Each individual polyp (a tiny, anemone-like creature) lays down successive layers of mineral skeleton as it grows. Over centuries and millennia, these layered deposits not only provide structural support for the coral colony but also build entire reef ecosystems that persist long after any one animal dies. In this sense, the "rock" of a coral reef is far from inert: it is literally the fossilized remains of countless generations of living polyps, and it continues to grow and remodel in response to biological and environmental signals.

By contrast, glass sponges produce a lattice of silica (opaline silicon dioxide) rather than calcium carbonate. Their skeletons can take on intricate, glass-like forms (sometimes looking eerily like delicate nets or shards of sculpted crystal). Unlike most sponges, glass sponges fuse their siliceous spicules into a continuous frame, creating what is essentially a living glass house. This silica comes from dissolved silicic acid in the water, which the sponges actively concentrate and polymerize into solid glass. What is remarkable is that they do so at ambient temperatures and pressures where synthetic glassmaking would normally require high heat; biology here finds a low-energy route to a material we usually associate with furnaces and laboratories.

Both examples illustrate biomineralization, the process by which organisms co-opt inorganic chemistry to build complex, functional architectures. Rather than drawing a hard line between the *organic* and the *inorganic*, biomineralizing species show us that life can appropriate elements of the mineral world (calcium and silica) and transform them into living scaffolds that grow, repair, and even sense their surroundings. In corals, the mineral skeleton becomes a habitat for hundreds of other species; in glass sponges, the transparent glassy skeleton channels water currents and supports symbiotic microbes deep on the ocean floor.

In blurring the distinction between mineral and living, these creatures invite us to rethink how we categorize nature. Their skeletons are geological, yet they form and maintain them through metabolism, gene expression, and cellular organization. They stand as a vivid reminder that, on Earth, life and the abiotic environment have co-evolved in an unbroken continuum: one in which the line between rock and organism is not a barrier, but a permeable membrane of ongoing chemical and biological exchange.

These mineral-wrought architects also challenge the neat separation of "objects" and "processes" in nature. At first glance, a brain coral colony or a glass sponge appears as a fixed, stone-like object: but each is in fact a living, dynamic factory of mineral production, constantly sensing its environment, depositing new material, and remodelling its own structure. In corals, the surface of the ridged rock, is not just a static skeleton but a record of ongoing polyp activity: with each ebb and flow of the tide, tiny animals extend their tentacles, secrete new calcium carbonate, and sculpt the shape of the reef. Likewise, the intricate lattice of a glass sponge is not a finished artifact but a living scaffold: its cells continuously extract dissolved silica, polymerize it into glass spicules, fuse them into new strands, and repair breaks.

Thus, what we might call the object of a coral head or sponge body is inseparable from the process of growth, mineral exchange, and self-maintenance. The organism and its seemingly inert shell are two sides of the same unfolding activity [13].

Discussion

Summary

In this work, we have proposed an information-theoretic framework for life, life-like systems, and intelligence, irrespective of substrate. Building on earlier ideas that information processing may be fundamental to both life and cognition, we identify six core components:

1. **Information processing** ("software"),
2. **Information storage** (memory),
3. **Physical substrate** ("hardware") and spatial compartmentalization,
4. **Information transfer** across space and time,
5. **Persistence of information** (selection, heredity),
6. **Energy availability** (thermodynamic constraints).

These elements co-occur in carbon-based life, but also manifest in diverse non-biological systems, from Belousov–Zhabotinsky reactions to stars and natural nuclear reactors, suggesting a continuum rather than a sharp life/non-life divide.

A continuum of life-like systems Our tentative taxonomy (Table 1) arranges systems by their capacity for selection, persistence, heredity, and replication. While classical living organisms score highly on all dimensions, other entities (clay crystals, convection cells, weather vortices, and even ideas or computer viruses) exhibit partial combinations of these traits. This perspective echoes Cairns-Smith's mineral-gene hypothesis and the Gaia concept, but extends them into a unified information-theoretic view.

Anthropocentrism and alien intelligence Our anthropocentric definitions, shaped by Earthly biochemistry and human cognition, may blind us to genuinely alien forms of life and mind. Clarke's thought experiment on superconducting currents and Nagel's reflections on the bat's subjective world [14] both caution that novel substrates could host intelligences beyond our conceptual reach. Philosophical rigour, alongside AI-driven pattern recognition (e.g. via neural cellular automata), may be needed to detect subtle life-like signatures in astronomical or geophysical data.

Artificial life and the search for extraterrestrial intelligence Computational models ranging from Conway's Game of Life to advanced ALife platforms offer testbeds for exploring emergent information dynamics and open-ended evolution. Integrating these with observational programs may broaden SETI strategies to include non-carbon targets, such as thermodynamic anomalies or persistent structural patterns in planetary atmospheres.

Toward a unified theory of life By viewing life as a continuum of information-processing phenomena, we open the door to a taxonomy that encompasses both the animate and inanimate. Future work should (i) refine metrics for quantitative comparison across substrates, (ii) experimentally test minimal computational life in chemical or physical media, and (iii) apply machine learning to detect universal signatures of information persistence and transfer. In doing so, we may arrive at a truly substrate-independent theory of life and intelligence.

Information processing is possibly fundamental to life [1] and intelligence [2]. I propose some key components of an information theory of life, life-like systems and intelligence.

These are rules we developed by observing life and life-like systems on Earth. There may be other life-like systems that we are yet to observe and that may be subject to other rules.

Arthur C. Clarke wrote imaginatively about complex intelligent life arising from electrical currents in superconductors on a cold seemingly lifeless planet [6]. He imagined the electrical currents as being only slowly attenuated (due to superconductivity) and ultimately leading to neuron-like networks capable of intelligence.

He proposed a completely different computational substrate: electrical currents in superconductors at temperatures close to absolute zero. The story challenges our imagination and although unlikely to be feasible, challenges the very notions of life and intelligence.

Are other computational substrates viable and energetically feasible? What forms of substrate capable of information processing could conceivably exist? Answers to questions like these may give us insights into non-carbon based forms of life and intelligence that we could search for outside Earth.

Our ultimate aim is to develop a framework for a computational definition of life that is independent of the subjective definitions of only carbon-based life. What life forms could conceivably arise in our known Universe subject to the known laws of physics? I hypothesize that carbon-based life forms and carbon-based intelligence are only one among a continuum of life-like systems in the Universe.

Energy may also lie at the heart of natural selection. Life-like systems can be characterized by how they acquire energy from the environment and use it to maintain itself and generate copies of itself [15].

For example, from the grand scale of stars to the microscopic oscillations of the Belousov–Zhabotinsky reaction, systems can exhibit life-like behavior at vastly different scales, echoing the Gaia idea that life exists on a continuum. Weathering patterns etched into stone, the self-replicating gliders of Conway's Game of Life, and the rolling currents of convection cells all demonstrate gradual gradations of self-organization, reproduction, and information transfer.

For a concrete application of how such a life-like system can be constructed, please see [16].

I propose a continuum of life-like systems and a continuum of selection like mechanisms. I suggest looking at these complex systems through the lens of information.

Methods from Artificial Intelligence (AI) can also be used to detect these kinds of signatures. For example, neural networks such as neural cellular automata can be trained on this data. These can they be used as "detectors" to recognize signs of such life-like systems from astronomic observational data.

We can use AI and human creativity to reimagine life (Figure 3).

ALife programs and computer programs like the Game of life can help us understand different kinds of intelligence. It can open our minds to different kinds of intelligence.

We need to keep looking for carbon based life but also keep our minds open. As Carl Sagan wrote in his novel "Contact" "... we are trapped by our time and our culture and our biology. How limited we are, by definition, in imagining fundamentally different creatures or civilizations. And separately evolved on very different worlds, they [alien intelligence] would have to be very different from us."

We hope these perspectives will challenge us to come up with alternatives to our current anthropocentric viewpoints of life. This may motivate novel ways to search for intelligence elsewhere in the Universe.

We hypothesize that persistence, heritability, natural selection and genes lie along a continuum. Hence the strict dichotomy and division between life and non-life needs to be revisited.

Graham Cairns-Smith [3] proposed that during the formation of a crystal of a mineral, particular types of lattice defects replicate as part of the crystallization process. Clay will dry and will get dispersed.

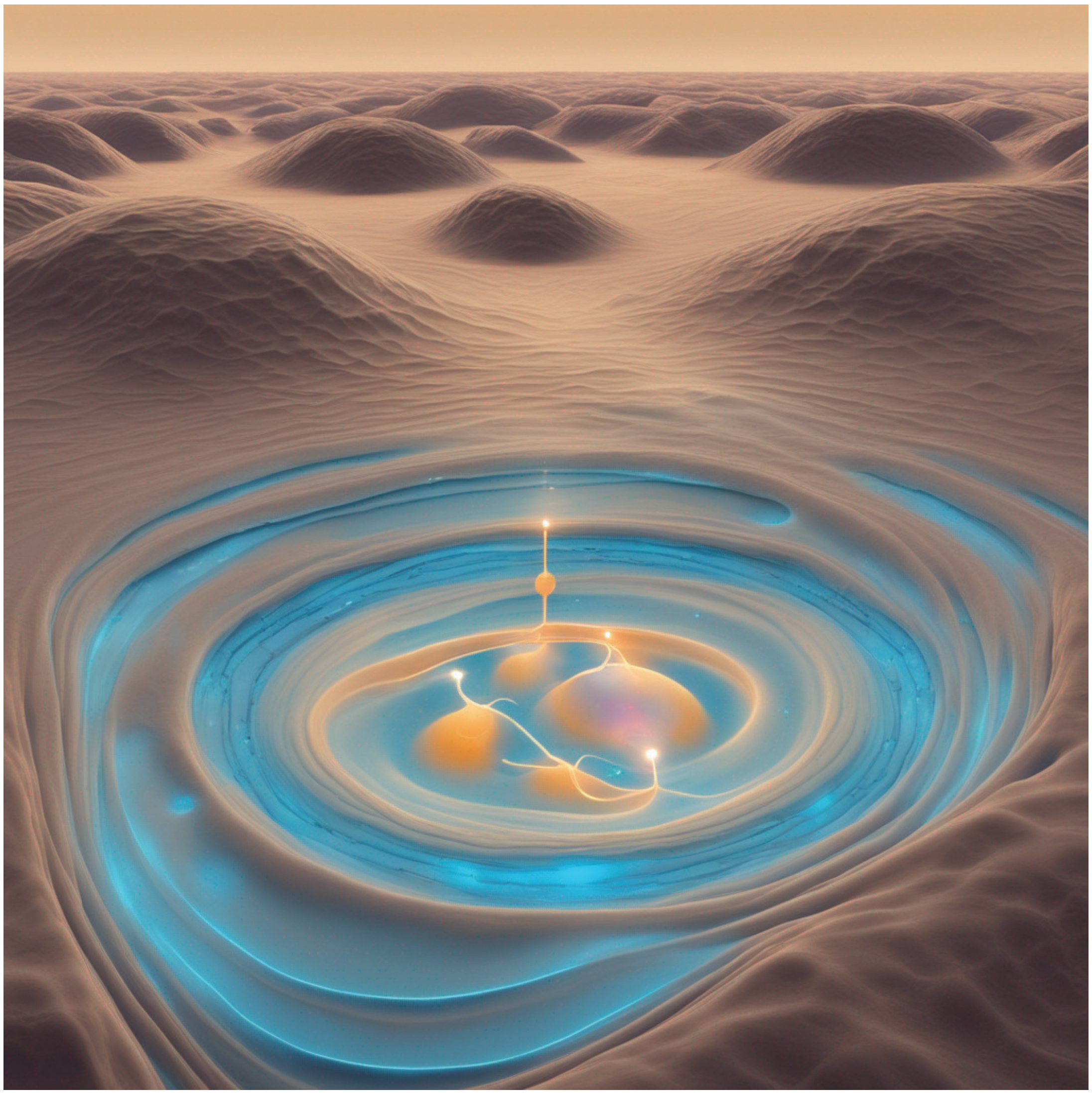

Figure 3. A visualization generated using generative AI of a hypothetical life-like made of ultra-cold liquid helium on a cold seemingly lifeless planet. Created by Soumya Banerjee using the DreamUp generative AI framework. The prompt used was the following: “Ultra cold liquid helium on the surface of a planet and electrical currents flow within it, currents and eddies form in liquid helium”.

The imperfections in the clay crystal will be propagated. Hence these imperfections seem to replicate themselves, they are thus self-selecting. This process is similar to a rudimentary form of evolution.

Stars are more likely to form near regions where supernovae have recently occurred. Over time, this leads to a concentration of star formation near past supernovae. A fixed proportion of these stars will eventually undergo supernova themselves, enriching the surrounding environment and further promoting new star formation. In this way, a kind of persistence emerges, where certain traits, such as exceeding a critical mass threshold (a kind of "gene"), increase the likelihood of supernova.

This illustrates that persistence, heritability, selection, and even genes can take many forms beyond biology. Recognizing and classifying these diverse manifestations allows us to better understand life-like processes across physical and cosmological systems.

Also persistence, heritability, natural selection and genes lie along a continuum. Hence the strict dichotomy and division between life and non-life may need to be revisited. Waves replicate and persist. Not on their own. But they and clouds persist because of shore and beach. The environment helps it persist. Similar conditions over time on a beach mean that waves will persist and keep on appearing on the beach. Hence this is like replication even though the genome is not in the cloud or wave but exists jointly on the wave and beach, i.e. it is a product of the cloud or wave and the environment. The organism and the environment are strongly coupled.

Organisms adapt their environment to suit their needs and they also specify the contents of the world they live in [17].

We suggest that living systems are amongst a continuum of evolving systems. Our work is complementary to other work suggesting that "selection" can act on physical systems such as minerals and clouds [7] [18].

There are also connections to the ideas of the "adjacent possible" [19] i.e., there are many systems where interactions between the constituents of the system lead to generation of new configurations.

I am not suggesting that we completely disregard what we see on Earth and abandon search for carbon-based lifeforms. However, I think we should complement current search strategies by keeping an open mind about non-carbon based life-like systems.

AI has the potential to accelerate the search for intelligence elsewhere in the Universe. Some have surmised that AI also has the potential to cause human extinction and hence act as a Great Filter for intelligence in the universe [20]. It seems likely that a prudent use about of AI along with international regulations may benefit humanity and its quest for intelligence in the Universe.

The organism also interacts with the environment and can modify it, for example, corals modify their environment [21]. Organisms also interact with each other. This forms the basis of different behaviour like mutualism, symbiosis, predation, etc. which leads to the emergence of collective intelligence.

It is conceivable that the “ghost in the machine” is related to collective intelligence and information processing in complex systems [2] [22].

Another idea to consider is that what we human beings define as life is very anthropocentric and also relates to concepts that are relevant only for a human. For example, an alien being might have a concept of a lightning. It may define lightning as electricity flowing from a cloud to the ground. However, this may not fully align with what the word lightning really means for a human being. The word lightning has many other connotations and many other concepts for a human being. For example, the word lightning for some human beings might conjure up images or being out for a walk in the wilderness and then being stuck outside while it is raining and there is lightning: a very dangerous but thrilling experience. If somebody is not a human being, then one may not fully appreciate the full concept behind water lightning actually means. Hence there are deeper philosophical implications here about what is life and whether we can even fully regard lifelike systems that are completely alien to us. This deserves further attention, potentially with the help of philosophers.

In “What is it like to be a bat”, Thomas Nagel [14] makes the following suggestions

“.. the general human weakness for explanations of what is incomprehensible in terms suited for what is familiar and well understood, though entirely different.”

“And if there is conscious life elsewhere in the universe, it is likely that some of it will not be describable even in the most general experiential terms available to us.”

It might be impossible to conceive of alien life-forms and intelligence.

We know a lot about life as we know it (carbon based life)? How would we recognise life and intelligence as we do *not* know it? Life elsewhere in the Universe may be very different from what we see on Earth [23]. Our conception of life and intelligence are very anthropocentric [24]. A computational view of life-like systems may allow us to recognise life in all its myriad forms in this Universe. There are also outreach resources that the general public and students can use to engage with some of these ideas [25].

These teaching and outreach resources are available here:

https://github.com/neelsoumya/deep_dali

We have also introduced a tentative taxonomy of life-like systems. Our hope is that this may lead to a unified theory of life-like systems.

The situation is similar to that faced by E.O. Wilson as he was attempting a unification of biology and sociology. He wrote in his book *Sociobiology* [26]: "This comparison may seem facile, but it is out of such deliberate oversimplification that the beginnings of a general theory are made. The formulation of a theory of sociobiology constitutes, in my opinion, one of the great manageable problems of biology for the next twenty or thirty years".

In summary, life may exist as a continuum between non-life and life, and we may have to revise our notion of life and how common it is in the Universe. Looking at life-like systems and intelligence through the lens of computation may yield a broader view of life and intelligence. We also suggest a taxonomy of life-like systems.

This is subject to further debate and verification (or falsification) using experiments in the true spirit of scientific enquiry. Viewing life as a continuum, we get a deeper appreciation of the immense beauty of life that exists in our Universe.

Declarations

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Conflicts of interests

All authors declare they have no conflicts of interest to disclose.

Ethics

No ethics approval was necessary.

Data accessibility

This study does not generate any clinical data.

Author contributions

SB carried out the analysis and implementation, participated in the design of the study, and wrote the manuscript.

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