Finding or Creating a Living Organism?
Past and Future Thought Experiments in Astrobiology Applied to Artificial Intelligence

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Abstract. This is a digest of how various researchers in biology and astrobiology have explored questions of what defines living organisms—definitions based on functions or structures observed in organisms, or on systems terms, or on mathematical conceptions like closure, chirality, quantum mechanics and thermodynamics, or on biosemiotics, or on Darwinian evolution—to clarify the field and make it easier for endeavors in artificial intelligence to make progress. Current ideas are described to promote work between astrobiologists and computer scientists, each concerned with living organisms. A four-parameter framework is presented as a scaffold that is later developed into what machines lack to be considered alive: systems, evolution, energy and consciousness, and includes Jagers operators and the idea of dual closure. A novel definition of consciousness is developed which describes mental objects both with and without communicable properties, and this helps to clarify how consciousness in machines may be studied as an emergent process related to choice functions in systems. A perspective on how quantization, acting on nucleic acids, sets up natural limits to system behavior is offered as a partial address to the problem of biogenesis.

Keywords: definition of life; Darwinian evolution; biosemiotics; thermodynamics; quantum mechanics; chirality; systems; ecology; artificial life; consciousness; nucleic acid; Axiom of Choice.

1 Introduction

A scientific description of *living organisms* that is based in theory ought to make testable predictions about those organisms. The critical point—of whether features of biology and living organisms are consistent with what is known of artificial models and computational intelligence—is in how one conceives of a definition of living organisms. At this point, there is a growing movement towards a novel, cogent theory.

The academic literature on this subject spans a myriad of concepts: definitions of life based on functions or structures observed in organisms, or on systems terms, or on mathematical conceptions like closure, chirality, quantum mechanics and thermodynamics, or on biosemiotics, or on Darwinian evolution for analysis. These will all be explored herein, but for clarity, four distinct contexts will be highlighted more closely: systems, evolution, energy, and consciousness. In the process of understanding these four contexts, the reader will see that an idea of emergent properties of systems will be a consistent thread, with recourse to a theme: large-scale characteristics arising from small-scale processes (Schrödinger, 1944). Along the way, there will also be an introduction to Jagers' operator theory, which posits that dual closure, of both functional and structural elements, is the building block of a class of systems called *operators*, and these culminate in living organisms (Jagers op Akkerhuis, 2010).

The first of these four contexts, *systems*, is a general term that includes organisms. All organisms are systems, but not all systems are organisms. The other three terms (*evolution*, *energy*, and *consciousness*) are each features of systems that arguably may confer status as a living organism. The NASA definition of life, for example, says that living organisms are chemical systems that undergo Darwinian evolution (Mullen, 2013). Later in this work there will be a chance to see how this definition arose, and why it is useful. Other features of systems, such as chirality, will also be explored.

These four major themes are presented here in Table 1, and include standard definitions that highlight how systems thinking is fundamental to understanding the process of defining life in a useful way. In succeeding sections, living organisms will be more closely defined in terms of structure as a *system*, in terms of the potential for *evolution*, in terms of flows of *energy*, and finally in terms of a measure of *consciousness* which emerges from a system. Each of these is incomplete but offers tools from which to build and refine a future definition that is falsifiable and leads to predictions that can be applied, for example, to the question of how a living machine might be built.

Table 1. Four Major Tools for Defining Living Organisms

Concept	**Definition**
Systems	Systems are comprised of elements, relationships between the elements, and an inherent functionality.
Evolution	Populations of living organisms change genetic composition and phenotypes over time.
Energy	Energy is a measure of a system's ability to do work.
Consciousness	Conscious systems are self-aware.

Now, one practical purpose of the paper is to highlight a hypothetical roadmap to living machines. Along the way, some of this process will be based on induction, and some on deduction. Notably, deduction is introduced early with the operator theory (Section 3, paragraph five), and this and the deduction present in the Banach-Tarski paradox described (Section 9, paragraph five) lead to a novel result: nonconstructive mathematics emerges in systems that order systems functions. A system with overdetermined operations attains this. The ability to articulate these hypotheses strongly highlights the importance of deductive processes in this project.

Section 2, below, presents an overview and introduces systems concepts. Subsequent sections treat topics ranging from the physical (i.e. systems boundaries, chirality, and quantum mechanics) to the biological (i.e. biosemiotics, and Darwinian evolution), with thermodynamics forming a bridge between the two. This is not by chance. The importance of energy and thermodynamics in describing how living systems behave is one of the most useful tools that scientists have. Energy is the language of life.

2 Review – Systems

Consider what makes a computer operating system or a language notation system or a thermodynamic system or an ecosystem or any other types of system coherent. Each of these systems is comprised of *elements* that work together. They are in some *relationship* to each other that defines how these elements work. But a system isn't simply a list of elements and their relations, a database, or a stack. The original conception by Carnot was of thermodynamic systems put together in order to do work. This is still the current model: The elements of systems and their relations perform *functions*, as does the system itself.

Perhaps it is good enough to stop here. The idea of a function implies an intention, a will, and perhaps that is enough to ascribe to life. A poetic reading of the universe, with its systems of stars and galaxies, of moons and planets, with various organized systems, such as riverine patterns in watersheds, erosional contexts, climate, weather, orogenies, glacial advances and retreats—these can all be read as systems, with inherent functionalities among elements. But the step from function to will and intention seems a huge one. Perhaps intention and will here, in the broadest sense possible, allow for a connection between physical processes and a teleology to which the reader will rebel.

Functions can be something as simple as a transformation in shape or something more complex, for example, a chemical feedback loop in a series of chemical reactions that may happen in a specific environment. The most strikingly useful feature of a system to a scientific approach, one that aims to be predictive and falsifiable, however, is its *boundary*, that which separates inner from outer. Boundaries or membranes are a dimensional ladder to the creation of environments and spaces. They create the process by which elements are retained or expelled, and the ideas of *here* and *there*. Boundaries thus allow for a system itself to create and perform mathematics, to structure and restructure both environments and themselves. This raises a further series of questions: To what extent does a system itself create *here* and *there*, or *in* and *out*? Or is it the researcher who makes these distinctions? And is the functionality of the boundary, and the mathematics that it generates, generated by the system or by the researcher who asks about this functionality?

Before jumping too far ahead, it makes sense first to look at systems functions and how systems concepts relate to living organisms and their origin. To start with boundaries: Leeuwenhoek's early micrographs of plant tissue, whose most obvious feature was of the walls between cells, and microbial and other organismal forms wherein boundaries between cells—these highlight the importance of boundaries and membranes. In more recent work, Morowitz (1992) writes about amphiphilic compounds (e.g. fatty acids) as having been essential in creating a membrane for early organisms, and Deamer (1986), as well, picked up on this notion, visiting geologic sites and running experiments *in situ*. The idea is that there ought to be an environment where living organisms naturally start to occur. The architecture of the cell might exist easily (and naturally) in some environments. As a vacuole may hold some special chemistry to work a process, already this is a start to a locally independent system.

Notably, in the field of microfluidics which looks at how membranes and vacuoles form, experiments explore useful properties of materials and flows, and promise to innovate chemical and engineering processes which take advantage of this local independence (Whitesides, 2006). Many reactions can proceed simultaneously in close proximity, a “lab on a chip” (Kitson et al., 2012). One may envision natural processes occurring with similar fecundity in an environment where conditions are favorable.

Boundary formation is an important systems function, and is not far off from a system assembling itself, a process referred to in the literature as *autopoiesis*. For example, Walde et al. (1994) demonstrated that a system of fatty acids could self-catalyze to form new vesicles under certain (alkali) conditions. This type of self-assembly, which, in chemical systems, relies on self-catalysis, can also include micelles, i.e. two-layered vesicles (Bachmann et al., 1992; Luisi et al., 1988; 1999). Bourgine and Stewart (2004) concisely summarize this idea with the definition of an autopoietic (self-assembling) system: that it has a semi-permeable boundary; that the boundary is produced within the system; and that the system acts to reproduce itself via its relations and components.

Prions, for example, reproduce their structure in other proteins they contact. The system assembles itself—though lacking a semi-permeable boundary, the prion system is not an autopoietic system. It is akin to crystal formation from a melt, wherein seed crystals allow for the propagation of the mineral species. In contrast, prokaryotic cells are true autopoietic systems, i.e. engaged in both boundary creation, maintenance and reproduction. The leap from autopoiesis to autopoietic system is not just important in understanding abiogenesis, the formation of life from nonliving matter. Each step, such as seed formation, surface templating, morphogenesis, which themselves can be used artificially to run a rich panoply of biomimetic reactions (Mann, 1995; Mann & Ozin, 1996) is an additional function that can be adapted within a system to take on other functions itself. Thus, autopoiesis may be critical in tracing the developmental histories of the very first living organisms.

Some systems can do more than reproduction, boundary creation and maintenance. The systems that we call living organisms undertake a varied set of functions to maintain their proper existence—birth, responsiveness to the environment, assimilation of nutrients, metabolism and catalysis, excretion, homeostasis, adaptation, growth, reproduction, consciousness, death—and these comprise an *ad hoc* definition of life. Yet this is only a rough concept, with exceptions such as: seeds and spores are not environmentally responsive to a range of conditions but are alive; or, mules are not able to reproduce themselves but are alive. This is clearly only a set of general observations based on induction, and this functional definition lacks predictive power.

3 Review – Four Broad Categories for Defining Living Organisms

Observational (inductive) definitions of living organisms fall into four broad categories, and these reprise the categories from Table 1. Empirical definitions of each are listed in the last column of Table 2, which includes the earlier entries of Table 1 for clarity. These four categories are listed in an approximate order of historical significance for the first three; the fourth and final is not much present in the discourse but is important for future work. The first of these four broad definitions is based on observed processes that all organisms seem to embody, like the eleven *ad hoc* functions mentioned in the paragraph above.

Tirard et al. (2010) give a clear summary of early work here, including the debates of Lamarck and Darwin, as well as recent historical description of developments in the definitions of life. They focus on recent work by Cleland and Chyba (2002) which questions whether the transition from nonliving to living organism can be well defined. If not, perhaps there will be a continuum between the two. This refinement is helpful. It might mean that a scientific definition will differ from various folk definitions, as a continuum is decidedly not what a typical folk definition of life describes. This may be useful for prediction. But currently this approach is at a dead end. Observation of gross systems functions is not a current area of research interest.

Table 2. Four Broad Categories for Defining Living Organisms Based on Induction

Concept	Definition	Specific Feature	Empirical Definition of Living Organisms
Systems	Systems are comprised of elements, relationships	Systems	Systems which include a set of functions as

	between the elements, and an inherent functionality.	functions	defined by observation in nature.
Evolution	Populations of living organisms change genetic composition and phenotypes over time.	Darwinian evolution	Systems subject to speciation through natural selection via competition, survival and reproduction.
Energy	Energy is a measure of a system's ability to do work.	Thermodynamics	Systems whose chemical reactions produce a local decrease in entropy.
Consciousness	Conscious systems are self-aware.	Consciousness	Systems where consciousness can be inferred from actions.

The second of these four broad categories is based on how systems undergo Darwinian evolution, that is, how systems are subject to speciation through natural selection via competition, survival and reproduction. This topic is important currently for research including projects related to exploration in our solar system, and will be taken up in the next section of the paper, Section 4.

The third of these four broad categories looks at thermodynamics, and draws on chemistry and physics models. Here, life is defined as systems whose chemical reactions produce a local decrease in entropy. A crystal, as it forms, produces a local decrease in entropy, but it is not a living organism. Notwithstanding, current work such as England's (2015) "Dissipative adaptation in driven self-assembly" focuses on how small-scale deviations from equilibrium can produce new functional relations on the large-scale system via changes in entropy, and provides new tools as well for modeling systems evolution. More discussion of this example, and of the thermodynamic definition of life will be explored in Section 6 of the present paper.

The fourth of these four broad categories is based on cognition as a feature of organisms, and is inferred from their actions. Bourgine and Stewart (2004), for example, define a cognitive system based on sensory structures that trigger actions for the maintenance of unique boundary conditions: “A system is cognitive if and only if sensory inputs serve to trigger actions in a specific way, so as to satisfy a viability constraint." In short, a cognitive system is a system that takes actions to stay alive. These actions can be both internal and external. Actions triggered by a sensory system reinforce adaptive choices that the system makes for its viability. Bourgine and Stewart (2004) here define the basis of living organisms as a combination of autopoiesis and cognition. Regulation of boundary cases distinguish living organisms from non-living dynamical systems. Thus, what distinguishes living organisms from non-living systems could be seen as an (albeit abstract) question that bridges both life sciences and computational sciences. More of this will be explored in Section 7, which derives cognition from constraints imposed by the quantization process arising in quantum mechanics.

The preceding discussion and set of four broad approaches to defining life are each based on observation and induction. In contrast to this inductive approach, one may examine, for example, deductive work by Jagers (2010; 2016) and Jagers and van Straalen (1999) that explore both the *function* and *structure* of systems in a mathematically rigorous framework. Recall that systems may be open or closed depending on how their boundaries are defined and whether energy can cross that boundary. Jagers (2010; 2016) and Jagers and van Straalen (1999) define two additional closures. With *functional closure*, the functional elements of systems must comprise a mathematically closed set; and with *structural closure*, there must be a structure that physically encloses the object (mathematically: topological closure) for a thing to qualify as an *operator*. Their model is called the Operator Theory, and operators that are at least as organized as the biological cell are termed organisms. This raises the question how to determine, express and compare levels of organization, and provides a framework and reason to do so. It is an active area of research (Georgiev & Chatterjee, 2016). The two criteria that define an operator are termed *dual closure* for ease, and it is clear that operators (e.g. multicellular organisms) can be distinguished from groups of operators (e.g. groups of cells lacking plasma connections) on this basis. Results here are promising. The rigor allows one to distinguish virus (not an organism, as it lacks *functional closure*) from cell (an organism) and flock of seagulls (not an organism, as it lacks *structural closure*) from seagull (an organism) in an unequivocal and internally consistent fashion.

It also raises further questions. These notions are topology-related, and topologies on sets can be defined in many ways. It therefore may happen that a system for one topology satisfies a closure condition, and in the other topology it does not. Perhaps the topology common on Euclidean spaces is the one that is meant by Jagers' work and others involved in the Operator Theory project. The issues raised are informative, and highlight the importance of rigorous definitions in developing usable theory.

One may also wed a deductive approach to the concept of consciousness, and define living organisms as self-sustaining or state-based systems. This approach looks at how a system maintains itself or its internal state, or is based on a state. A flame is a state-based system that is nonliving, but living organisms are certainly also state-based systems. They are subject to dying, and that is a change of state. Recent work in this area includes Gleiser & Walker (2008), who chart the homochirality in living organisms as resulting from an early phase transition; Mathis et al. (2017) who look at how the origin of life can be modeled as a phase transition; and Walker (2014) who looks at how information flows in early systems underwent a change of state that defines living organisms. These state-based models all focus on transitions that occurred as systems went from nonliving to living, and this historical perspective provides tools for further research in defining life using the mathematics of state-based systems functions. This state-based mathematical approach will be visited again in Section 8 of the present paper, which discusses information, information entropy and biosemiotics.

4 Review – Darwinian Evolution

Living organisms as a category are those systems that undergo evolution as Darwin described it (Mullen, 2013). This is a political position. The scientific literature on evolution has progressed from what Darwin described, and the concept of evolution itself is still evolving. The *NASA definition* is that a living organism is a self-sustaining chemical system capable of Darwinian evolution. This definition lacks a rigorous description of the term *Darwinian evolution*. Thus it is also an *ad hoc* observational form. The NASA definition arose out of an advisory panel within the NASA Exobiology Program that was working through the state of knowledge at the time, trying to anticipate future trends in the field in order to help with strategic planning for future missions (Mullen, 2013). The definition is useful in planning remote sensing for living organisms. It is left to the researcher to describe a reasonable chemical system of interest that could be seen as self-sustaining. Thus, the definition allows for NASA to do its work: by finding a class of chemicals off-planet and inferring the presence of living organisms.

If one considers a living organism as a self-sustaining chemical system capable of Darwinian evolution (with the further requirements that the system exists at temperatures wherein chemical bonds are possible) and includes several additional features: a process to lower entropy; a partition (separation) from the environment; physical scaffolding for optimizing chemical processes; energetic chemical pathways; and a solvent to host chemical reactions (Benner et al., 2004), even this definition is yet *ad hoc* and falls short of being a theory. Notwithstanding, it is a very useful definition for solar system research. Missions to other planets can look for chemical markers, evidence for systems functions that imply living organisms based on this definition. The detection of these chemicals form mission protocols and an operative strategy to learn new things, and it falls within a standard of scientific rigor. The assumptions are explicit and specific.

Let us look more deeply at this definition. Since the chemical system in question is to be self-sustaining, it precludes certain types of objects as living organisms. It is not the individual chemicals that are living, but rather the system of chemistry in the environment that lives. And this relation between environment and system is important.

Heredity records the interactions between environment and systems it hosts. These interactions affect populations over time. Diverse heredity can arise out of population expansion, and lack of diversity from depopulation (Lande, 1988). Heredity, as it transmits a current population code, also contains a record of success and challenges in its various markers which determine phenotype. A history can be teased out in hindsight from these specific markers. The variation can be measured and be used to estimate the timing of events in the population (Orlando & Cooper, 2014).

The environment can also be queried for causes of population dynamics, notably, with ice cores that record stable isotope data showing rainfall and other climate data (Rozanski et al., 1997); or in the geologic record to find evidence of an asteroid impact, via a shocked quartz layer or an anomalous metal (e.g. indium) in the stratigraphy (Alvarez et al., 1995; Goderis et al., 2021), or other environmental data, for example, in a change in oxidation state over time. Heredity preserves records of the coupling between a population and its environment over time. It is an internal boundary layer. Darwinian evolution records boundaries that shift over time.

In addition to environmental factors as a basis for evolution, selection can also occur due to chemical (genetic) changes which lead to lower *species entropy* and higher information complexity (Brooks & Wiley, 1984; Collier, 1986). Essentially, species entropy can be measured as the sum of reductions of entropy in all the populations of a species, at the expense of free energy in the environment. Brooks-Wiley evolution also includes a measure of information, that is, how efficient the genetic information is at recording all the possible combinations of heredity which are present. Thus the chemical system subject to Darwinian evolution can also be subject to information measures.

If this be the case, then it is not clear what may separate an ecosystem from computer code which likewise undergoes Darwinian selection, mutation and propagation as it is run *in silico*. Individual life forms under a computer code definition are not chemical systems, and are not Jagers operators, as they lack structural closure—but they do behave as evolving systems. Some endeavors have created computer code with architecture that has structural closure (Tamulis et al., 2004), and these are generally chemical systems as well, even made from DNA (LaBean, 2003). Thus the "chemical systems" part of the NASA definition of life, at this point in scientific progress, is not completely arbitrary.

As Lovelock and Margulis postulated in the Gaia hypothesis (1974), a larger planetary system itself can be defined as a living organism, but it is notable that a population size of one falls afoul of Darwinian evolution. Lovelock is a chemist, and his work in this area has focused on changes to the atmosphere brought about by living organisms. For example, Earth's atmosphere hosts chemical biomarkers such as phosphine. From space, one may draw a conclusion that there are living organisms here. The atmosphere contains markers of life. But a single living organism is not going to evolve as a population unless it may reproduce. Yet this possibility exists. Terrestrial spacecraft may carry microbes to Venus or Mars, or to one of the Jovian or Saturnian moons, and then there may be a larger population size in the future. Terrestrial life may also have been seeded from some other place, what is called *panspermia* (Ginsburg et al., 2018; Horneck et al., 2001). Then this Earth would be part of a larger population size, with interactions between individual living solar system objects. Each contains a unique set of ecosystems within a larger frame.

If ecosystems are then the focus of the concept of life, one could say that Earth or other planets, or other astronomical bodies, that host interacting organisms represent instantiations of a level of Jagers operators that is higher than the organism level. As a host of various ecosystems, planets could be seen as similar to living organisms that host symbionts and parasites, but planets reproduce asexually via material transfer (space travel and panspermia) of organisms, so their lifepath is unique. The structural closure of a planet (in space) distinguishes it from an ecosystem, as well.

Finally, we learn from the above descriptions that the NASA definition of life and its reliance on Darwinian evolution are useful for making decisions about what is living and what is not, and that the Jagers operator likewise helps to clarify these decisions. But there is more to the story. What would life be without its unique chemistry?

5 Review – On Chirality

Nearly every terrestrial life form exclusively uses a distinct subset of the chemistry available: levorotary amino acids and dextrorotary sugars. Handedness (also termed *chirality* from the Greek word χειρ for "hand") refers to forms that are mirror images of each other, and can occur as a feature in any molecular structure with four atoms or groups of atoms, owing to the three-dimensional character of space. If three points determine a plane, four can break its symmetry. Since shape can influence action on the molecular level, chirality influences chemical reactions. It has a functional role to play in DNA and RNA processing, in protein folding, chelation and other chemical processes. The *homochirality* of amino acids and sugars used by organisms likely preserves some early choices made by the first chemical systems.

Rates of chemical reactions are influenced by chirality. Living organisms use enzymes; and catalysts and enzymes allow for the fast running of chemical reactions present in metabolisms. See, for example, Buckel & Thauer (2013) who describe four chemical pathways of multienzyme complexes in anaerobic bacteria and archaea. In natural systems, chemical species analogous to those in organisms may be present, but reaction kinetics are often very slow. It takes a metal catalyst, for example, with its unique shape, to form a template on which a chemical species can adsorb and react in a short time frame. An enzyme is a protein that has incorporated a chemical catalyst.

Shape is a functional parameter for catalysis in chemical systems. The shape of the catalyst determines its functionality. Catalysts and enzymes make various chemical reaction kinetics favorable that otherwise would be slow. Thus, chirality is likely favored in self-sustaining chemical systems. The systems evolve to favor available catalysts. Further, chirality (handedness) in organic chemistry is probably a consequence of the prevalence of enzymes, as Mellersh (1993) has suggested for RNA's action on peptides.

Consider a system that includes suspension in a fluid. If the flow reverses direction, the handedness of the flow (clockwise or counterclockwise) remains the same even as the flow direction is opposite. This extra parameter (clockwise or counterclockwise flow) is an indication that systems with chiral elements tend to be more sensitive to kinetic rather than thermal stability; there is this extra parameter related to motion. Thus, systems with chiral elements may not reach thermal equilibrium as readily as non-chiral systems (Gilat, 2002). Thermal instability may provide a setting for dynamic (and living) systems to self-organize. A thermal gradient is certainly important for differential chemistry processes to occur in an environment. In summary, chirality both arises from catalysis (and enzymes) and promotes thermal gradients in chemical systems as they evolve.

In living organisms, chiral molecules exist to help with metabolic processes. A chiral system can also be at lower entropy than a symmetric one, because chiral forms present more system states. Thus an autocatalytic chemical system will be favored thermodynamically over a chemical system that is simply autopoietic. And this is what is observed. The transition to homochirality as chemical systems became organisms was a consequence of polymers' differential reaction and diffusion rates in what has been called a period of *punctuated chirality* until a phase transition occurred (Gleiser et al., 2008; Gleiser & Walker, 2008; Walker, 2010).

A similar state is true in organismal evolution. Mitochondria (the organelle of power conversion in eukaryotes) are highly conserved over time, as are the genetic materials that code for these structures. The history of their origin is striking. Mitochondria and chloroplasts in animals (and protists) and plants (and algae) respectively, are endosymbionts, earlier organisms that were incorporated into the workings of an earlier prokaryotic host. Margulis (1981) introduced this idea of evolution where competition is not the fundamental principle for fitness, but rather cooperation. The evidence for this cooperation is still present in the genetics of the organism, preserving, for example, thousands of genes from cyanobacteria within chloroplasts (Martin et al., 2002). Symbiosis and endosymbiosis form the basis for species survival in eukaryotes, based on optimizing energy flows within the framework of ecological change over time. Chirality, catalysis, enzymes, cooperation—these all lower entropy over time.

6 Review – On Thermodynamics

To look at these ideas more clearly, let us look at what Schrödinger presented in *What is Life?* (1944) as a primary feature of living organisms, the local reduction of entropy. For background: *thermodynamics is the study of the flow of energy within and between systems*. It makes use of the concept *entropy.* Heat flows from hotter to colder objects. Power is the rate, with respect to time, that this energy flows. Entropy flows as a consequence of this flow of heat, and in the opposite direction of any work done. It is a dissipative process whose measure gives information about system parameters. *Entropy is a measure for the potential number of states* (linked to quanta of energy) *of the system*. Reduction in the number of states available to a system reduces the entropy. As with heat, it is simply a measure of energy. The word entropy itself is related to the word *trope*, used in music to denote a melody. In a poetic frame: entropy may be thought of as a melody inside a system, wherein all the subatomic particles in that system are playing through their possible microstates.

At this point, it may be useful to explore what is meant by a *phase* within a system. In a dynamical system (i.e. one that changes over time), a phase is a distinct element that is stable at the present conditions but may be transformed if the conditions change. In a chemical system, liquid water, ice and steam are each considered to be separate phases. Likewise, liquid water and liquid hydrogen peroxide are each separate phases. The *state* of a system includes a description of the phases present.

The entropy of a system is also measured by the number of equivalent arrangements of quantum information (i.e. descriptions of the quantum states or energy levels) available for the elements of that system. A higher entropy system means that more equivalent arrangements are available, but large sets of equivalent arrangements are often composed of states whose energy difference is low. A reduction in entropy locally can mean that the states available to a system are high-energy states, with large differences between them. These differences in energy levels can help to explain why macroscopic events in a system are often irreversible.

Goldstein (2001) provides a detailed summary of an argument (i.e. Bolzmann's Argument) for why macroscopic events are irreversible generally, and the total entropy of systems tend to increase. System equilibria are stable because there are no accessible lower energy states for the system. Equilibrium states are low-energy compared to other local alternatives, and thus systems tend to find equilibria. Bolzmann's Argument is that on a microscopic level, there are more phase states available for the particles when the system is at a higher entropy, i.e. approaching equilibrium. Thus, systems in disequilibrium initially tend towards irreversible macroscopic processes but for equilibrium (as entropy increases) depend on reversible microscopic processes. This thermodynamic evolution of a system can affect how much free energy is available to it to do work.

Perunov et al. (2014) describe how particle-systems evolve over time using a model of free energy available in a system, the Helmholz free energy: $F = U - TS$, where U is the internal energy of the system, and T and S are the temperature and entropy, respectively. While system evolution can be a stochastic (random) process, the various terms in the equation provide different pressures on the system as it adapts to an environment. This model is a quantification of how systems adapt to environmental change, and can be applied to living systems. As an example, Davies et al. (2013) model the local reduction in entropy in a living cell, and show how information reduction plays a role in protein synthesis that mirrors how entropy is involved in heat conservation. England (2015) describes how this process works for organisms, and Schneider and Kay (1994) model the chemical states of ecosystem functions. For the latter, their work addresses chemical, cell, organism, and ecosystem levels. Here, the second law of thermodynamics (i.e. that entropy increases globally) acts with local chemical equilibria to dissipate gradients. The work points out that chemical systems underly macro structures. Living systems are defined by Schneider and Kay as having a rebirth-growth-death cycle, and are distinct from non-living entities in this regard. Notable is the cyclical evolution of a phase-state system. Growth occurs as entropy decreases locally.

Rapp (1987) expands on this idea, showing how these cycles are functionally beneficial to the systems themselves. Oscillations can create advantages for temporal organization; for spatial organization; to allow for prediction; efficiency; and information processing. Temporal coordination is a hallmark of biological systems. All organisms exhibit oscillatory processes, and these range from milliseconds to years in frequency. Major biological processes on the organismal level are all periodic.

Within this framework, living systems may be subject to disruptions. Aluminum, for example, is the most abundant metal in Earth's crust, but has no observed role in biological processes. Likely this is due to the single +3 oxidation state available to the aluminum atom, which means it is not part of any redox reactions (Shaw et al., 2014). Instead, it disrupts organism cycles by replacing iron atoms, to which it is similar, and drives local dissipative processes. Cycles in neurons and the nervous systems in vertebrates, for example, are disrupted by the presence of aluminum (Shaw et al., 2014).

Cycles are important to living systems. The information complexity seen in the process of protein synthesis as DNA codes for RNA—which in turn codes for the structural (and information) complexity of proteins—depends on the assembly, copying and coding processes here, and influences how various states of these macromolecules are available in cycles (Milnes et al., 2012). Periodicity is fundamental to heredity and the architecture of the cell. The work done depends on both the energy and information. Some of this energy and information is separated in space, and some in time. Quantum mechanics is a description of these states and information, and that is the subject of the next section.

7 Review – On Quantum Mechanics and Consciousness

The text so far has explored living organisms as related to systems, evolution and energy, and has introduced how information and energy can be coupled. The present section explores quantum mechanics and its relation to living organisms. For this, it is worth summarizing some important aspects of quantum mechanics. First, historically, quantum mechanics arose from the finding that electron energies are at discrete levels within the atom. Unlike, say, satellite orbits around a planet, which are subject to radial inertia and can occupy any position in space, so long as their orbital energy supports the trajectory, electrons in atoms and ions and molecules behave differently. Electron orbitals can only have discrete amounts of energy. Photon emission caused by an electron moving from a higher energy orbital to a lower one is restricted to energy magnitudes specific to the type of atoms and orbitals. The orbitals are *quantized* and quantum mechanics is the model of these phenomena.

Electrons also do not gain nor lose radial inertia when they are bound to a nucleus. Their travel is unlike the satellite orbit of a planet, and instead is subject to wave-particle duality. In some situations, a billiard ball is an accurate model for the electron; in other situations, a wave (that can travel through a diffraction gradient) is more accurate. Both features are inherent in the electron. And both are subject to quantization.

This quantization has fundamental implications for modeling. Euclidian space is flat, and mappings between Euclidian spaces are smooth. They have continuous partial derivatives of all orders. Quantum mechanics, with discrete quanta of energy, imposes restrictions on how interactions of system elements can occur. Models for quantum mechanics are based on space with restricted symmetries, Lie groups, and their associated Lie algebras. On a macro scale, organisms exist in a flat (Euclidian) space, but the inner workings are in this restricted space.

Davies (2004) offers a detailed, critical history of quantum mechanics' relation to biological processes. Many quantum-mechanical models of systems serve only to define the unique shapes of molecules, but have little to do with biology beyond this shape analysis, a kind of ball-and-stick reductionism. All chemical reactions, including those wherein metabolism occurs, depend on entropy for their dynamics, but the quantum-mechanical basis of entropy, and the centrality of entropy in metabolism is ignored historically. Electrostatic charge and chemical bonding are the more important determiners of reaction dynamics and entropy.

Notwithstanding, Davies does go on to make some additional points about the existing literature: living organisms are involved in information processing, and life processes are divided into two classes: informational and metabolic. Some processes do utilize quantum effects for particles, e.g. protein folding is constrained by an uncertainty principle; but decoherence of particle relations is common, so any possible reliance on quantum effects or quantum computing are not widespread within the cell.

Quantum coherence is an active maintenance of relations between particles, even if they become separated. Two electrons that had been occupying a single orbital will still be spin-up and spin-down, respectively, even as one is removed, so long as quantum coherence is maintained. The qbits of quantum computers rely on this quantum coherence for computation, as do natural systems (Buluta et al., 2011). Again, Davies' (2004) review of the cell literature suggests that quantum decoherence is common in the cell and quantum computing is not widespread. However, because of the existence of quantum levels in molecular chemistry generally, quantum computing may speed processes in the cell that utilize quantum effects, by limiting the number of possible choices available when it does exist, and he suggests that long-lived quantum coherence in living systems should be experimentally tested to demonstrate whether it exists, perhaps in localized subunits.

Two issues seem to be at work here: the first is the use (and potential use) of quantum-mechanical features by the cell; and the second is whether quantum mechanics has a relationship to a definition of life. The first is the primary focus of Davies' article, and one hopes for experimental testing of his listed questions. Igamberdiev (2008) attempts to go further with the second. Quantum mechanics is based on the wave equation. His work asserts that the system function of quantum mechanics involves a history of the state of that system. Thus, a quantum system is a historical system, even though quantum processes are entirely probabilistic.

Igamberdiev attempts to generalize this to the biological cell: The collapse of the superposed wave function in a quantum-mechanical system is also what occurs in the internal processes of state within the biological cell. The collapse of potentiality—as competing morphologies or states of the cell reconcile as a system—is the history of the states of the system. Igamberdiev asserts that since the mathematics of this collapse in the cell can be modeled as the collapse of the wave function—the same wave function used to model particle relations—quantum mechanics in the universe at large is simply a special case (or subclass) of living organism. Analogy is taken as homology: Anything which has a historical process of state whose workings can be modeled with a wave function is defined as living. It is not clear whether this definition is falsifiable via experiment, but I cannot initially think of one to do so. In general, the state of any system can be defined from the history of that system. We are back to looking at systems.

The following extended treatment is the author's contribution. Systems are comprised of elements, relationships between those elements, and functionality—that maintains either elements or relationships or both. It is hypothesized that one of these system functions is a mathematical set-selection process: systems choices are made not as binary (yes/no) decisions but rather as a ranking of competing options. The ranking maintains the system. Selection of system functionality is thus from a set of (potentially) infinitely many options. It is from this special relationship to ranking that the life of living systems arise. Here, briefly, is a pointed hypothesis: systems choices are made not as binary decisions but rather as a ranking of competing options, implying a change from measurable to nonmeasurable systems functions, which in turn implies internal representation or consciousness.

The above hypothesis is a deduction based on how systems operate. Systems functions may be made explicit in a model, e.g. in a chemical system that includes an acid, that acid may function as a proton donor for some reactions, a set of chemical species may serve as proton receptors, and there may be feedback loops which specify certain stabilities and outcomes. If any of the functions in a system are found to employ free choice sequences (i.e. sequences wherein no future value can be known in advance) and if the initial conditions for these sequences are not explicitly specified, then a mathematical set-selection process can be deduced to have occurred if the system is stable. In short, if there is no basis for ranking systems functions, and yet they are ranked, then there must be some other (internal) feature or history at work here. Otherwise, the system would be unstable.

To get a stronger sense of this concept of *internal* feature, let us explore the idea of consciousness briefly. Human consciousness makes use of two distinct types of objects which it contemplates. There are mental objects which have communicable properties, and these are the subject of language, and more distinctly, are also subject to mathematical modeling. One can readily perceive that language allows for the communication of mathematical objects distinctly. If someone asks you to imagine three non-collinear points, you can close your eyes and imagine them. If they ask you to imagine lines connecting them, you can do so, and will now have in mind a triangle. For some, mathematics is itself the study of mental objects with communicable properties (Borovik, 2009).

Notwithstanding, another class of mental objects lacks the ability to be communicated effectively. For example, personal experience cannot be distinctly communicated in its entirety. Only certain features are communicable. This communication involves an internal process of figuring out how to communicate mental objects. Personal thoughts, such as romantic interest, cannot be distinctly communicated. These exist primarily in the mind of the person holding that interest. They don't have a strict correlation with the person's environment.

Like human consciousness, a living system is hypothesized as one which has both explicit (communicable) and implicit (non-communicable) operations involved in its ranking functions. More is developed on this in Section 9. Before we get there, let us look more deeply at definitions of life that refer to conscious systems, so that the foundation for the analysis will be well-informed.

The feature *consciousness* is remarkably difficult to work with. Like *life*, consciousness has not been given a definition from deduction that allows for falsification. We are left looking for inferences from observing organisms that may embody it. Hameroff (1998), for example, looked at an increase in the complexity of sensory organs in fossils, and presents an argument that the Cambrian revolution visible in the fossil record (i.e. the increased diversity of life forms occurring during the Cambrian Period) resulted from something that was newly evolved—consciousness. For Hameroff, the demarcation is in the sensory and motor apparati. He attributes a few features to these sensory and motor apparati as having been advantageous, namely, the presence of unpredictable choice processes; the presence of memory and an inner life; and abundant neural networks. His hypothesis is based on both inference and deduction, but it is not clear how one would falsify it.

The author's view, which is a reasoned speculation: Consider the dual closure of the atom described in Jagers' (2016) operator theory. His theory denotes organisms as operators, but there are other, nonliving operators defined in his system. Recall that Jagers operators are defined by dual closure, and only operators that are at least as organized as the cell are defined as living. Atoms, for example, are nonliving Jagers operators. According to cosmology, the level of operator (i.e. both functional and structural closure) for the atom was attained shortly after cosmogenesis and the Big Bang. In the early moments of the universe, there was a "soup" of high energy particles (Deltete & Guy, 1997; Frampton & Volovich, 1990). Atoms became Jagers operators once space had cooled enough for hadrons (in the nucleus of atoms) so that leptons (e.g. electrons) became bound to them. Their orbit provides a structural closure to the atom. Electrons became bound to protons and neutrons, and the atom becomes an operator.

Now, imagine a quantum effect for an electron. And then imagine how it can pass across the limit of the next dual closure, the molecule. One sees that the pathway to chemical reactions, which lead from atomically bound electrons to molecularly bound electrons, is a narrow one. Yet thermodynamics and, especially, entropy provide the structure by which molecular systems form and evolve. Quantum thermodynamics is a robust field that uses entropy calculations to predict chemical reactions successfully (Levine et al., 2009).

One next wonders about the biological cell functions, and how thermodynamics operates on the level of the cell. The hypothesized aim here is to look for system functions that are quantized in the cell in a manner that allows for a type of restriction on future paths akin to entropy. It ought to create an internal set-selection process so that systems functions are ranked.

Following this aim, perhaps the place to focus is on the genetic material of the cell. Base pairs, at their simplest, are complementary molecules whose bonding surfaces are congruent only to their complements. Thus a surface is quantized either to 0 or 1, that is, unattached or attached, within a system of other base pairs whose surfaces are also quantized either to 0 or 1. Molecules formed from these base pairs can grow only if these nucleotide quanta are the same. This process is similar to crystal growth, but it is distinct from other types of crystallization because, herein, the nucleotides form a closed set that consists of two closed subsets. Typical crystal lattice systems are open sets which admit target ions but also impurities.

The development of heredity (genetic patterns, functionalities and permutations) can be seen as a consequence of nucleotide quanta. Optimization processes come into play to maximize the uptake of nucleotides into the nucleic acid, with RNA, the first of these nucleic acids, acting as an enzyme for protein catalysis as well as for RNA formation itself (Cech, 1986). The result is an infinite set of permutations as well as a structure for information reduction (coding) that may have features of a set-selection ranking process. But first let us look at information processing and related concepts, such as information entropy.

8 Review – On Information, Information Entropy and Biosemiotics

Thermodynamics has a measure of internal freedom of systems called entropy. It takes into account the number of states available to the system. Information theory also has a measure that makes use of mathematical relations nearly identical to those used in statistical thermodynamics. It is called information entropy or Shannon entropy, and measures how new a piece of information is (or surprising, as per Shannon's original text) compared with the number of possible outcomes within the information setting (Shannon, 1948). It uses a logarithmic scale, like thermodynamic entropy: $-P(x) \log P(x)$, where P is the probability of some outcome x. Events with many possible outcomes have higher Shannon entropy, just as systems with many possible states available to them have higher thermodynamic entropy.

Like energy in a thermodynamic system, information in an information system follows flows that build up a state history to increase or decrease the novelty of information. These flows work in the same way that chemical reactions in systems either increase or decrease thermodynamic entropy. Flows of novel information tend to increase the number of possible outcomes in an information system in the same way that flows of energy tend to increase thermodynamic entropy. It is a special kind of information system where flows will reduce the number of possible outcomes.

Since an information system is similar to a thermodynamic system, let us look at how information is treated in living systems. Perhaps we will find some structures common to both. *Semiotics* is the study of symbols, and is related to the English word *sign. Biosemiotics* is "the study of living systems from a semiotic (i.e., sign-theoretical) perspective", wherein signs are distinguished from information. A sign needs an interpreter to become information (Hoffmeyer, 2008).

Barbieri (2008) suggests that living systems are those based on signs and codes. Life is defined as having two functions: copying and coding. Copying is an individual process, one of reproduction. A *copy* is made during *copying*. In contrast, coding is an organizational process—one that includes environmental interaction. Elements are *organized* into a code during *coding*. In the living cell, genes, for example, are copied, while proteins are coded from an environmental repository.

Natural selection operates on copying processes, while *natural conventions* operate on coding processes. A semiotic system (such as the cell) has a code, a codemaker, signs and meanings. According to Barbieri, living organisms manufacture and use signs. They are a locus of information processing.

This definition can be expanded to a cosmological scale. Thomas et al. (2006) model the evolution of the early universe (with the presumption that it had a non-uniform distribution), and define four processes for their model: *steady state*, *periods*, *chaos* and *bios*. The latter term, *bios*, is a semiotic concept. It is a type of feedback mechanism that includes two populations (along with population members), recursion, trigonometry and a connection to an earlier state. It is an interesting contribution to mechanistic systems modeling—a proto-biosemiotic treatment. Bios could easily have been defined within biosemiotic parameters, and the model would not be changed by much. But the semiotic systems of Barbieri (2008) and of Thomas et al. (2006) can each be seen to lack dual closure. In the case of Barbieri, while a cell has a structural closure, other semiotic systems may not. In the case of Thomas et al., a structural closure for the universe is not defined. Instead, their models offer insight into how physical systems perform functions on information.

With these tools in hand, the NASA definition of life here will be translated by the author to (perhaps unwieldy) information-centric language: A self-assembling chemical system capable of Darwinian evolution can be seen as a self-assembling information system capable of generating a shared architecture recording a history of low-probability outcomes that capture present and past environmental conditions. This definition includes information transmission, a shared architecture, and relationships to the environment. It also includes a nod to the decreasing species entropy concept discussed in Brooks & Wiley (1984) and Collier (1986) and Section 4 of this work. Note that there is nothing denoting structural closure in this information-centric definition, and also no term that is strongly analogous to Darwinian evolution. Yet it does generalize the NASA definition to be useful for examining information systems that are not chemical systems. It allows for looking at computer-based systems.

9 Analysis

If computers can be built to become a self-assembling information system capable of generating a shared architecture recording a history of low-probability events that capture present and past environmental conditions, the following ideas may be helpful as a guide. They are listed in Table 3 and described herein.

Table 3. What Machines May Lack to be Considered Alive.

Concept	What Machines Lack
Systems	Structural closure Maintenance of boundaries
Evolution	Heredity, including general relations to the environment, a process for self-assembled, shared architecture between machines, and a clear connection between machine history and the environment A process to lower Shannon entropy Opportunities for competition and cooperation to lower species entropy
Energy	Searching out and harvesting their own energy A process to lower thermodynamic entropy

Consciousness	Function processing that includes overdetermination Micro-scale binary processes that result in a macro-scale ranking processes Exhibiting gross changes in state space

First, as systems, machines (or software) will need to have some kind of structural closure to qualify as a Jagers operator. For autopoietic systems in an environment, this requirement of a boundary or membrane does not have an obvious path to success. But one may take a cue from living organisms, as Damer and Deamer (2020) have done. They place amphiphilic compounds in geothermal (hot spring) environments to see how they can self assemble as membranes. The hot springs provide a gradient for protometabolic processes. The amphiphilic compounds provide the boundary. These are molecules with both polar (hydrophilic) and nonpolar (lipophilic) regions. They have both, hence *amphi-* is used as a prefix in the term. In practice, these molecules can align within the environment. This process of independent alignment of potential membrane material can also be generalized.

In our hypothetical computer system, a boundary can be created from some substance (or code) that has regions of opposing properties, and can align itself in physical (or code) space. An autopoietic boundary would allow for it to be maintained easily over time. This would allow for structural closure.

Machines also lack complexity, as a system, such that operations are not as complex as those of a cell. The level of complexity is a critical feature of living systems according with Jagers' (2010) ideas. But his treatment of what constitutes a living operator is an inferred position, rather than one arrived at by deduction. There is no mathematics behind his assertion that complexity transforms an operator into a living system. To understand more about complexity and its role in systems functions, consider the proposed hypothesis, that the ordering of systems functions wherein a mathematical set-selection process occurs and systems choices are made not as binary (yes/no) decisions but rather as a ranking of competing options, and where this (macro-scale) process is an emergent property of (micro-scale) binary decisions. This will be discussed below, but first, evolution and entropy are calling.

As systems, machines (or software) will need to have some kind of heredity process for there to be a mathematical, biosemiotic system; and a local reduction in both thermodynamic entropy and Shannon entropy to create a state space wherein this kind of macro-scale ranking system can emerge from bulk processes. It is worth the effort to see why.

To cite an example: The main point of the Banach-Tarski (1924) paradox is that the bounded subsets *A* and *B* each contain congruent partitioned subsets.

> Given any two bounded subsets *A* and *B* of a Euclidean space in at least three dimensions, both of which have a nonempty interior, there are partitions of *A* and *B* into a finite number of disjoint subsets, $A = A_1 \cup \ldots \cup A_k$, $B = B_1 \cup \ldots \cup B_k$, such that for each *i* between 1 and *k*, the sets A_i and B_i are congruent.

It is an interesting feature that *B* can contain two translated copies of *A*, but more interesting is that the congruent partitioned subsets are nonmeasurable. It all comes down to how the index *i* is chosen, and the fact that the space is at least three-dimensional while the indices are one-dimensional. That allows for additional freedom in choosing partitions.

For clarity, that is the same kind of freedom that exists in a structure that is overdetermined, whether it is a crystal that is growing from a seed, subject to both crystal lattice entropies and symmetry; or to a thermodynamic system with enough functional choices that maintenance is assured. *Overdetermination*, where an observed effect is determined by multiple overlapping causes, produces a reduction in the state space and entropy. The complexity that Jagers (2010) demands is here hypothesized as an overdetermination of states so that thermodynamic entropy, species entropy and Shannon entropy can be reduced. It is what Walker and Davies (2013) have called the algorithmic origin of life. wherein system functions (and a causal structure) on the macro-scale arise from the micro-scale as a phase transition.

At this point it makes sense to introduce mathematical tools to measure overdetermination in the thermodynamic entropy, species entropy and Shannon entropy of various systems, and determine by observation how these values change with different levels of Jagers operators. One idea is to model a system and its elements and functions with a system algebra, and this is an active area of research (Wang, 2006; Zadeh, 1973). One could also use the tools of computational intelligence to find this set of empirical relations from systems data. Determination of a *divergence measure* to show the overdetermination for these three entropies is also a current area of research, with no consensus (Chen & Frid, 2001; Griffith & Koch, 2014; Harder et al., 2013). There are now tools that can build high level estimates of information dynamics from classical information-theoretic measures like Shannon entropy, e.g. to assess information flows from websites (Lizier, 2014). But for a general system, this is a future goal.

To be clear, the crux of the paper is that overdetermination is a testable preliminary hypothesis for describing how the various types of entropy are reduced, and also for finding a mechanism that corresponds with what is called consciousness, i.e. that which is generated as internal (noncommunicable or nonmeasurable) features in a system. It is testable, but not yet ready to be tested. Relevant tools are presently being developed by researchers in three different fields: astrobiology/origin of life, quantum mechanics, and computer science.

It is notable at this point to look at where Cleland and Chyba (2002) take the definition-of-life debate. They overview several definitions of life, including the Darwinian-evolution definition. They conclude that none of these are theoretically satisfactory, though some have practical applications. They infer that life will not have a satisfactory definition until there is a new theory of life. They make the analogy of trying to define water before the discovery of the periodic table. They imply that we are in a sort of dark ages. Thus, Cleland and Chyba in presenting their challenge have highlighted the importance of deductive work by Jagers (2016). They have also opened a door to computer science informing astrobiology.

What has been done historically to define life has been empirical rather than theoretical. The history is one of practical applications of *ad hoc* implementations. What constitutes a living organism and how to push computational-intelligence research forward will lead from behind. It is hoped that the ideas presented herein will aid in practical implementations, and that the questions that arise herein will find answers in professional practice. This new deduction is very close at hand.

10 Conclusion

Interest in how living organisms are identified as alive has steadily provided new insights for those studying the field. Some conceptions have been inferential, providing *ad hoc* definitions that are liable to exception. Organism functions, such as reproduction, growth and metabolism, and the like provided a basis for study but no deductive framework. Focus on entropy and state space have done more in this regard, even allowing for the analysis of Darwinian evolution as a change in species entropy. Likewise, deductive frameworks like Jagers' operator theory provide the concept of dual closure that is helpful for identifying both functional and structural parameters within systems.

Entropy is a measure of microstates available to systems. Macro-scale systems functions are hypothesized to be a result of overdetermination in this state space, and thus works to lower entropy for some systems. A living system is also defined by an analogous concept of Shannon entropy, which measures the probabilities of novel information available to information systems, and which also is hypothesized to give rise to consciousness. Tools to test these hypotheses are currently being developed in astrobiology, quantum mechanics and computer science.

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