An *ab initio* definition of life pertaining to Astrobiology

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Abstract Many definitions of life have been put forward in the course of time, but none have emerged to entirely encapsulate life. Putting forward an adequate definition is not a simple matter to do, despite many people seeming to believe they have an intuitive understanding of what is meant when it is stated that something is life. However, it is important to do define life, because we ourselves, individually and collectively, are life, which entails an importance in itself. Furthermore, humankind's capability to look for life on other planets is steadily becoming a real possibility. But in order to realize that search, a definition of life is required. Progress has been made. Life is a complex, but natural phenomena that emerged and has been maintained under the dual demands of thermodynamics and evolution. Thus, any definition of life must include thermodynamics specifically, as well as evolution generally. A definition of life can be obtained through the application of first principles from physics, chemistry and biology. It must encapsulate the minimal properties that are shared between all life and demonstrate that the interconnected aspects of life are unique for precisely life and that it collectively does things other phenomena do not, as well as describe what life is. Thus, the following *ab initio* definition can be put forward: Life$_{Terra}$ is a genome-containing, self-sustaining, chemical dissipative system that maintains its localized level of organization at the expense of producing entropy in the environment; which has developed its numerous characteristics through pluripotential Darwinian evolution.

Keywords: definitions of life, terrestrial life, extra-terrestrial life, first principles.

1. Introduction

As far back in time as humankind has possessed the invaluable power of reflection, there have likely been those among them that, with unabridged wonder, have stirred up at the starry firmament and, with amazement, asked themselves what the numerous stars could be.

Curious children have turned their unbiased gaze upon the stars in the early evenings. Adults, amidst their busy existence of food gathering, finding shelter, surviving and reproducing, have sat safely at the slowly fading campfire in the late evenings, with their eyes irresistibly drawn to the majestic stars above. Some of the most curious, most dedicated among them, who were filled with the inherent human need and desire to explore, to understand and to improve, have walked afar from the safety of their fellow man, in solitude, to watch the beauty and sheer numbers of the stars. Overwhelmed, they have asked themselves what the stars above them all could truly be.

Now we know! 'A star is a luminous spheroid of hot gas composed mostly of hydrogen and helium, where the outward pressure of gas heated by nuclear fusion reactions in its core is balanced by the inward pull of the force of gravity, leaving the star in a long middle age of hydrostatic equilibrium, in which it steadily releases energy into outer space.' That is what a star is. That is what a star does – a star such as the sun.

The stars are so far away, while life is so nearby. However, the life that we are, the life that we are surrounded by, it lack a definition of its own. This is not due to a lack of trying. Many definitions have been put forward. However, none of the definitions that have emerged have been able to encapsulate life entirely.

This may seem odd. Just ask yourself the innocent question, what is life? You will quickly realize that this is not as obvious as it might seem. However, it is important to ask, for many reasons. One reason is yet another innocent question, namely, is there life elsewhere in the cosmos? To be able to answer that, we need to acquire an answer to the first question, because we need to understand what exactly we are searching for.

However, this has proven to be harder than one would initially expect. However, why is defining life apparently so demanding? Why is it so hard to define a set of properties that clearly distinguishes life from non-life?

Is it because definitions of life represent an arbitrary division of nature, a human construct, whereby everything above that division is life and everything below is non-life? Is there no threshold of complexity that exists by which a collection of molecules can be designated as life? Many do seem to think so and that such a definition has no place within biology [Luisi, 1998]. However, such a view would be naive. We already know that from the all-encompassing physicist's view, everything in the universe can be reduced to elementary particles and the forces acting between them. These again can probably ultimately be reduced to a single phenomenon, from which everything else can be derived.

Thus, a star can be reduced to its elementary particles and the forces acting between them. However, to scientists from virtually every discipline, this view is not helpful, because it does not remove the fact that stars exist and that a threshold does exist for them. The same is the case in regard to life. Science works on different levels of description. Elementary particle physics are concerned with the most fundamental building blocks. Biology concerns itself with the complex form of matter, the supra-molecular collection that exchanges matter and energy with its surrounding environment, life. Thus, even though everything probably can be reduced to a single

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phenomenon, this does not change that we, on one level of description, have stars, planets and life. It does not remove the demand for a definition.

However, it is correct that it is not a simple matter for which to put forward a definition, despite many people having an intuitive ability 'to instantly recognize life, discriminating the animate from the inanimate' [Gayon, 2010], or more accurately, many people seem to believe that they understand what is meant when they state that something is life. Many people may, for instance, face a problem in evaluating whether the slime mould *Fuligo septica* is vomit from an animal or is life. The moment we attempt to explain what life is, we realize that this is not a simple matter. This can be illustrated by the following definitions and their counter-examples:

(1) Life is an object that moves around in the environment! Do we mean that a dry leaf moved around by wind is life, while a tree is not?
(2) Life is an object that is able to move in the environment by its own force! Do we mean that a carrot is not life, but that a hurricane is?
(3) Life is a system that is able to react to its external environment! Do we mean that a mercury thermometer, which reacts to its external environment, is life?
(4) Life is a system that is able to metabolize! Do we mean that an automobile, which can be said to metabolize, is life [Sagan, 1970]?
(5) Life is an entity that feeds on compounds from the environment, returns waste, grows and moves! Do we mean that a wild fire, which feeds on compounds, returns waste, grows and moves, is life [Tirard et al., 2010]?
(6) Life is a system that uses energy to produce an internal order as part of its dissipative process! Do we mean that a hurricane, which generates internal order as it dissipates energy, is life [Benner, 2010]?
(7) Life is an object that exchanges some of its matter with the environment, but without changing its own general properties and boundary! Do we mean that a candle with a well-defined shape and boundary and that is maintained by the combination of its waxes with O_2, thus producing CO_2 and H_2O, is life [Sagan, 1970]?
(8) Life is an entity with the ability to reproduce itself! Do we mean that a reproducing fire is life, while mules and most honeybees are not?
(9) Life is a self-sustaining system with imbedded information that it can pass on to construct a new and similar system! Do we mean that a crystal of sodium chlorate with its right-handed or left-handed chirality features, which it can pass on to new and similar crystals, is life [Benner, 2010]?
(10) Life is a platonic form or a natural kind with intrinsic properties! Do we mean that a species, with its fuzzy boundaries and whose genotypic and phenotypic properties gradually change or are eliminated over time, is not life?

Thus, the statement 'I recognize when I see it' [Popa, 2010] is hard to justify. The history of science is one long display of the elimination of intuitive perceptions of nature that did not agree with reality. For instance, basically all of our intuitive views of the subatomic world are in conflict with that world. Humankind has indeed evolved some talent in differentiating life from non-life, but that might not help much when we search for life beyond Earth.

Another point here is that this common approach of listing life's characteristics, such as reproduction, growth, metabolism, etc., has been stated as being insufficient because these characteristics are seen as not unique for life [Benner, 2010]. Furthermore, this approach describes what life does rather than what life is.

However, I will say that the mere fact that characteristics of life are not unique for life is not an issue in itself. Life is a complex phenomenon, but it is a natural phenomenon that is part of the universe such as everything else. Thus, it should not be surprising at all that it shares its characteristics with other natural phenomena, or more accurately, incorporates natural phenomena.

Life is an interconnected cluster of aspects, and it is important is to demonstrate that the collected aspects of life is unique precisely to life forms, in that life collectively do things other phenomena do not. It is the interconnected cluster of aspects, not the singular aspects in themselves, that are important to define. Furthermore, what life does and what life is seem to be the same, from a scientific point of view. For example, a star is a spheroid of gas, which fuses hydrogen into helium, thus releasing radiation in the process. That is what a star does; that is what a star is. A division between 'does' and 'is' seems to diminish the understanding of the star.

A definition of life will be obtained in this work through first principles that stem from physics, chemistry and biology. The desirable definition must encapsulate the minimal properties that are shared between all life and connect physicochemical and biological first principles.

2. Representative definitions

Many advanced definitions of life have been put forward in the course of time by scientists from different disciplines holding a multitude of diverging interests and research traditions. In fact, more than 100 recorded definitions of life have (many of these overlap) been put forward [Trifonov, 2011], probably more, too many to be mentioned here.

Thus, I will mention only a couple, mainly those I consider representative and indeed incorporate single essential aspects of life. They will here roughly be divided into evolutionary definitions, thermodynamic definitions, and biophysical definitions.

2.1. Evolutionary definitions.

(i) Life is a material system that undergoes reproduction, mutation, and natural selection [McKay, 1991].
(ii) Life is a self-sustained chemical system capable of undergoing Darwinian evolution [Joyce, 1994].
(iii) Life (a living individual) is a self-sustaining object belonging to a set of elements capable of undergoing Darwinian evolution [Chodasewicz, 2014].

It is clear that such definitions indeed encapsulate characteristics for life. Such definitions focus essentially on life as a system with the capacity to perform a number of functions, such as, e.g., reproducing, metabolizing and growing.

Life follows the laws of physics and chemistry, but what sets biology apart is that it also has a history. Physics and chemistry do not truly have historical attributes; they do not need to record themselves to be physics and chemistry. However, it has long been recognized that biological phenomena do.

Thus, evolutionary definitions have, for good reason, become very influential. They shape our understanding of what life is, what it does and how it originated. One definition that has become highly influential is (ii). This definition, which is the result of a committee assembled in 1994 by NASA to discuss the possibility of extra-terrestrial life in the universe, is indeed a powerful one.

However, there are some issues with the Darwinian definitions of life. Not all life is capable of reproduction, despite obviously deriving from evolution. Mules are born sterile. Most honeybees do not reproduce. Cells such as human neurons do not divide. So not all life is capable of Darwinian evolution. Thus, organisms without the ability to reproduce are *ipso facto* inanimate objects in such definitions of life, which is obviously very counter-intuitive [Chodasewicz, 2014].

It has been attempted to clarify that single entities can be alive without themselves individually exemplifying life in such definitions. However, attempting to defuse this problem by creating two categories, namely, 'life' and 'living entities', appear to be more of an ad hoc effort [Cleland and Chyba, 2002]. A definition must state this by itself.

However, the fact remains that such definitions manage to stay clear of many of the counter-examples that are listed in the introduction.

2.2. Thermodynamic definitions.

(iv) Living systems maintain themselves in a state of relatively low entropy at the expense of their nonliving environments [Hitchcock and Lovelock, 1967].
(v) Living systems might ... be defined as localized regions where there is a continuous increase in order … at the expense of a larger decrease in order of the universe outside [Sagan, 1970].
(vi) Life emerges because thermodynamics mandates order from disorder whenever thermodynamic gradients and environmental conditions exist [Schneider and Kay, 1994].

It is clear that such definitions indeed encapsulate characteristics for life. Such definitions focus on life's ability to reduce its internal entropy at the expense of increasing it in the surrounding environment. Entropy is an exact measure of energy dispersal in a process at a specific temperature amongst particles, if not hindered from doing so [Lambert, 2006]. Furthermore, energy disperses spatially, making it possible for energy of a group of particles that move together to dissipate.

Lehninger (1982) argued in the same tradition as Boltzmann and Schrödinger, the following:

'Living organisms preserve their internal order by taking from their surroundings free energy, in the form of nutrients or sunlight, and returning to their surroundings an equal amount of energy as heat and entropy'.

Life is, thus, an entropy producing system; the organization that is produced within an organism as it maintains itself and metabolizes far from the thermodynamic equilibrium is compensated for by the increased entropy it creates in its surrounding environment during the course of maintenance and metabolism. That observation is a powerful one indeed.

However, there are some issues with entropy definitions of life. Taking compounds from the environment, returning waste, and growing are qualities that life has in common with fire. One can, of course, point out that fire only dissipates free energy, while life uses free energy to produce internal order as part of its dissipative process. However, a fire whirl that emerges when rising heat and turbulent wind conditions join together and create a tornado-like vortex also generates internal order as it dissipates free energy to the environment [Benner, 2010].

Thus, attempting to defuse such counter-examples to be minor or irrelevant exceptions appears to be ill-advised. A definition of life must steer clear of this or clarify the difference.

However, the fact remains that, although the entropy reduction point does not manage to avoid sharing this aspect with other non-life phenomena, it nevertheless still demonstrates an essential aspect of life.

2.3. Biophysical definitions.

(vii) All free-living organisms are autonomous agents … a system able to reproduce itself and carry out a least one work cycle [Kauffman, 2004].
(viii) A living being is any autonomous system with open-ended evolutionary capacities [Ruiz-Mirazo et al., 2004].
(ix) Life … is a complex, thermodynamically open, autopoietic system capable of undergoing Darwinian evolution [Tirard et al., 2010].

Such definitions demonstrate that progress has been made and that some efforts are more fruitful than others. It is clear from physics that thermodynamics, with its far-from-equilibrium and entropy displacement, must be included in a definition of life. It is equally clear from biology that evolution, with its concept of mutability, reproduction and natural selection, must be included in a definition of life. Any definition of life must include thermodynamics specifically; any definition of life must include evolution generally.

Thus, such definitions wisely attempt to include both. Nevertheless, the demand of generality and broadness has so far been at odds with them, and they do not manage to encapsulate life entirely nor steer clear of nor clarify some of the counter-examples.

As mentioned in the introduction, life is an interconnected cluster of aspects. These are shared by other natural phenomena. However, that only life shares all of these aspects at once is what a definition must give, and it must further avoid that obviously living organisms are not classified as non-life by it; a definition must also be logically self-consistent.

3. First principles

As seen with the definitions put forward, all of them have been insufficient to entirely define life. For either they have not been able to cover all aspects of life or have met counter-examples. However, some of these definitions do indeed encapsulate important singular aspects of what life is and what life does. However, the sheer number of the definitions and the lack of consensus among scientists have led to a critique of the whole enterprise [Bich and Green, 2018].

3.1. Philosophy of language.

A more philosophically grounded critique has also emerged. Thus, it has been claimed that definitions are limited conceptual tools; they inform about the meanings of terms in human language, rather than informing about nature. Thus, 'definitions specify meanings of terms by dissecting concepts that we already possess' [Cleland and Chyba, 2002]. Thus, Benner (2010) refers to the following correspondence:

'According to the classical philosophical understanding of ''definition,'' a definition must give both necessary and sufficient conditions, and must do that as a matter of the meaning of the term. For instance, the claim that water equals H_2O arguably specifies both necessary and sufficient conditions, but it doesn't do that as a matter of the meaning of the word ''water.'' The claim is a posteriori. A definition, on this classical understanding, must be a priori—at least its justification must be a priori (because it is supposed to be an analytic claim—true solely in virtue of the meaning of the terms involved). It turns out that, when understood this way, [a definition] is almost impossible to find'.

Of course, such views may have their own problems. The philosophical distinction between propositions called analytic and synthetic propositions can be given by the following definitions [Rey, 2010]:

(i) Analytic propositions are true by virtue of their meaning. Example: All triangles have three sides.
(ii) Synthetic propositions are true by how their meaning relates to the world. Example: All bachelors are alone.

A further distinction can be given between *a priori* and *a posteriori* propositions. These can be given by the following definitions [Kant, 1781]:

(iii) An *a priori* proposition is one whose justification does not rely upon experience. Example: 7 + 5 = 12.
(iv) An *a posteriori* proposition is one whose justification does rely upon experience. Example: All bachelors are unhappy.

However, if one posits that there only exist analytic and synthetic propositions and that anything else apparently is meaningless, then one can ask the obvious question about whether the proposition, 'that there only exist analytic and synthetic propositions', is in itself an analytic proposition?

If the answer is yes, then it is *ipso facto* not about the actual world, since it is only true by virtue of its meaning. If one asks whether it is a synthetic proposition, and the answer is yes, then it *ipso facto* cannot be held as absolutely true, since it is only true by how its meaning relates to the world.

The same can be inquired regarding *a priori* and *a posteriori* propositions, leading to similar results. Either way, it would appear that there are inherent problems in these well-known distinctions between propositions, and their implementation in scientific formalism, thus, seem to be of little relevance.

Other types of definitions critiques have also been put forward regarding them as being limited conceptual tools [Cleland and Chyba, 2002]. Thus, two kinds of definitions should be distinguished, namely, lexical and stipulative definitions. While the latter, especially, can possess great precision with its adoption of a rule, it is nevertheless still a limited tool in regard to providing a general definition of life in relation to specific scientific theories [Gayon, 2010].

Again, there seems to be problems with such views. The distinction between lexical and stipulative definitions can be given by the following definitions:

(i) A 'lexical definition gives or explains the meaning of a word by referring to the linguistic usage of this very word by certain people at certain places and time' [Malaterre, 2010].

(ii) A ‘stipulative definition deliberately assign a meaning to a word, for the purpose of clarifying arguments. It may agree with the common use of a word, but it may also contradict it’ [Gayon, 2010].

However, if one posits that it must be defined that way, that one should distinguish between lexical and stipulative definitions and that anything else apparently is meaningless; then, once again, one can ask the obvious question about whether the formulation, ’one should distinguish between lexical and stipulative definitions’, is in itself a stipulative definition?

If the answer is yes, then it is *ipso facto* not about the actual world, since it deliberately assigns a meaning to a word. If one asks whether it is a lexical definition, and the answer is yes, then it *ipso facto* cannot be held as absolute true, since it is just the linguistic usage of this very word at certain places and time.

Once again, it would appear that there are inherent problems in these distinctions, and their implementation in scientific formalism, thus, seems to be of little relevance for the scientific enterprise. Words are human-made, and terms are human-made, but this does not entail the conclusion that what they cover is human-made.

The words reactants and products are clearly human-made, and humans from a variety of different cultures can call them anything they like. However, the relationship between them, the chemical reaction, is not human-made. Thus, instead of this ’swamp of language,’ we might be better suited in adhering to first principles.

3.2. First principles.

A first principle, from which a demonstration begins, is explanatorily primitive [Gasser-Wingate, 2016]. It is a basic, self-evident proposition that cannot, or more accurately, as understood in science, does not need to be demonstrated from any other proposition to be applied.

First principles are well-known in physics, where theoretical work is stated to be from first principles or *ab initio* (from the beginning), if such work starts with the most essential facts.

First principles also exist in biology. Thus, evolution can, for example, be illustrated very well through the application of first principles without alluding to any theory or literature (see Varki, 2012). Thus, natural selection is a first principle, imperfect reproduction is a first principle, and life expanding in population size until it is constrained is a first principle, etc.

These last principles can all be explained on a deeper level, but the fact of the matter is that it is not necessary herein to grasp evolution. Throughout the history of science, many phenomena have been discovered and described without anyone knowing what is was. Thus, for instance, the Belousov-Zhabotinsky reaction was discovered by Belousov, who had no theory of it. Nevertheless, he could still describe this first principle [Taylor, 2002].

First principles also exist in philosophy, albeit they are usually not realized as being such. For example, humans made terms, such as stationary and movement, slow and fast, cold and warm. However, when such terms are used in communication, they must be applied in a certain way in relation to each other. This certain way is not, however, something humans have agreed upon; it is something dictated by the structure of the universe [Favrholdt, 1999].

Terms such as movement, distance, velocity and time are human-made, and different cultures have different designations for them. However, a first principle, such as ’the faster he (or anyone) moves from one location to another, the less time it takes’ clarifies a fact because the term's location, movement, distance, velocity and time stands in a certain interdependent relationship with each other in the actual world.

A similar situation occurs for the terms light and heavy. They are linguistic terms, but the relation ‘ten apples weighs more than five apples’ is not something humans have invented or agreed upon; it is a first principle humans have clarified.

There are many words for cold and warm. However, spontaneously going from warm to cold is a relation that is independent of the linguistic invention of words. Thermodynamics is formulated by using a long list of terms, which were all human-made. Nevertheless, the thermodynamic – and communicative – relation between them always stays the same.

Consider the first principles involving time. It is a basic human observation that there is a sequence of events to which the terms before, now and after are attached. This is a fact that is independent of humans. When humans clarify a description, then how the term time shall be used in relation to movement, velocity, acceleration, etc., must be established first. Clarifying such first principles is a scientific enterprise that is different from the cultural enterprise of inventing linguistic words for time.

One could say that this is only first principles in physics, where it is clarified how we necessarily must talk about movement, velocity, time, weight and temperature, etc., to describe something. However, they are also unavoidable first principles in the philosophy of language, although this might not follow the traditional formulations of first principles.

Thus, a human is entitled to believe that the faster he (or anyone) moves from one location to another, the longer time it takes. However, such a person will very likely not survive for long in the wild nature or in traffic if he is not able to grasp that the world does not work that way. The world forces him to act in a certain way regardless of his beliefs. This is not restricted only to obeying the reality of physics. It also involves obeying the reality of language usage. If someone states that the faster he (or anyone) moves from one location to another, the longer time it takes, then he *ipso facto* does not unambiguously clarify a relation at all, because the universe does not work that way.

If, for instance, this person is tasked with guiding another person in a car over the phone, and he guides the driver while watching from a distance, then his communication has to follow the descriptive relation between movement, distance, velocity and time; otherwise, the person in the car will not drive safely in traffic for long.

Thus, claiming that because words and terms are human-made, they then only inform about the meanings of words and terms in human language, rather than informing about nature, and that they are a web of terms that humans have constructed over the universe and, thereby, have given it a human-made structure, seems contrary to evidence.

First principles derive from the fact that the universe is structured in a certain way, and this certain way forces its inhabitants to both act and communicate in a certain way. Human elementary language is evolutionarily shaped by this certain way in order for humans to be able to communicate unambiguously with each other. This is also why humankind will be able to communicate with hypothetical extra-terrestrial civilizations. Both are forced to act and communicate this same way.

Thus, first principles are not platonic forms, nor analytic or synthetic propositions. They are not synthetic *a priori* propositions either, because this assumes that we structure the world with language, rather than it is the world that structures language. Why should we commit belief in any of these, when the justifications is so weak? We follow first principles both in acts and in communication, regardless of our personal philosophical position, to make ourselves understandable and to interact in the universe. That is their strength. That is the lesson of science.

3. An *ab initio* definition of life

Thus, on such an *ab initio* foundation, I can now proceed in putting forward a first strict formulation of a definition of life:

$\text{Life}_{\text{Terra}}$ is a genome-containing, self-sustaining chemical dissipative system that maintains its localized level of organization at the expense of producing entropy in the environment; which has developed its numerous characteristics through pluripotential Darwinian evolution.

3.1. Present and past tense.

Notice the present tense 'is' and the past tense 'has' in the full definition. This emphasis is not a mere word game but is a crucial point for a stringent definition. A definition has to be both in the present and in the past tense. We can, once again, take the example of the mule, which is a hybrid of a horse and a donkey, to illuminate why this is so.

A mule is clearly a living organism that 'is a genome-containing, self-sustaining chemical dissipative system that maintains its local level of organization at the expense of producing environmental entropy'. A mule is clearly a living organism which 'has developed its numerous characteristics through pluripotential Darwinian evolution'.

All mule predecessors have been able to reproduce and have reproduced, meaning that reproduction has led up to the present mule's existence. However, the mule itself is not able to reproduce. Thus, the mule fulfils all demands of Darwinian evolution in the past tense.

A mule's reproduction or lack thereof is something a definition has to account for, and not doing so is something that evolutionary definitions has been criticized for [Chodasewicz, 2014]. Attempting to save evolutionary definitions by differentiating life as a single individual entity and as a population, where it is the latter that makes the reproductive living system, is not satisfactory.

We could easily come up with a thought experiment, a global event for instance, wherein a human-made (or even a natural) genetically engineered virus makes all horses on Earth sterile, or that humankind wants to get rid of the entire species of mosquitoes by making them all sterile. This will, of course, mean that the whole population of horses or the entire species of mosquitoes will die out eventually. However, until they do, is the population or the species not life? Of course they are.

Evolution has a historical dimension. Biology is very much connected with its history, unlike (most) physics, which are one of the things that makes biology so rich and complex. This has been acknowledged elsewhere. Already Bernal wrote the following:

'Life involved another element, logically different from those occurring in physics at that time, by no means a mystical one, but an element of history. The phenomena of biology must be … contingent on events' [Bernal, 1959].

Thus, a definition of life requires both recognition of the ahistorical status of the laws of physics and chemistry as well as biology's historical contingency. To quote Stephen Jay Gould:

'Human evolution is not random; it makes sense and can be explained after the fact. But wind back life's tape to the dawn of time and let it play again–and you will never get humans a second time' [Gould, 1991].

This means that, although convergent evolution might lead to primate-like animals again, *Homo sapiens* will not emerge again, despite the fact that the laws of physics and chemistry, as well as the principles in Darwinian evolution, are the same.

Thermodynamics do not, in the same sense, possess a historical dimension; it is the outcome of more timeless first principles from physics and is, in that sense, simpler than biology. Place a cup of coffee with a specific high temperature and a cup of milk with a specific lower temperature in an area of uniform temperature between the coffee and milk temperature. Over time, coffee will cool down and the milk will warm up. Eventually, both fluids will be at the same temperature as the area, and, thus, will reach thermal equilibrium. Repeat the experiment with the same conditions, and there is an extremely high probability that you will obtain the same result. Biology is different from thermodynamics in that it is both a process and a record of history.

A mule has to maintain its internal organization at the expense of the surrounding environment, i.e., taking in energy internally and displacing entropy externally to maintain being a living organism. The moment it is not able to do that, it is no longer a living organism. However, a mule does not need to reproduce to stay a living organism. Although reproduction is a fundamental aspect in evolution, there is nothing in evolution that with absolute certainty enforces an organism to reproduce; however, evolution obviously requires that the predecessors of any organism have reproduced.

This emphasis in definition is, thus, not ad hoc. It is the clarification of a fundamental fact. We can only talk about a mule in the current here and now, and in the past.

3.2. Darwinian evolution.

Simply writing 'Darwinian evolution' could appear to be unnecessarily short. However, the phrase is actually shorthand for a process and mechanism that encompasses a vast body of ongoing research. Thus, writing 'Darwinian evolution' is sufficient, because it has a long-associated property list: it encompasses imperfect self-replication and reproduction, natural selection, sexual selection, neutral drift, purifying selection, mutability, heritability, and adaptability. It even reflects the composition and history of an ecosystem.

Darwinian evolution is an exceptional powerful way to structure matter. It is not only a process but is also a record of what has shown itself adaptive at the time. Thus, Darwinian evolution is by many considered as the best diagnostic feature of life [Popa, 2010].

Physics puts some restrictions on the possibilities that life can explore, although life, so far, has demonstrated a remarkably rich diversity. Thus, the phrase 'pluripotential' in front of Darwinian evolution clarifies the vast but not infinitely open-ended capacity of life.

The definition steers clear of the counter-examples that are listed in the introduction. The requirement for imperfect reproduction, where the imperfections are themselves reproducible, elegantly eliminates non-life chemical systems with the capability to reproduce.

Kondepudi et al. (1990) showed, for example, that a crystal of sodium chlorate can be powdered and used to seed the growth of new crystals, that is, reproducing. It is even capable of imperfect reproduction, as it contains many defects. However, the phrase steers clear of this otherwise profound counter-example in that the information in the crystal defects is not themselves inheritable via this process. It is not possible for the defects in the progenitor crystal to be passed along to the descendent crystals via this process, and adapted descendants do not emerge this way. Thus, the sodium chlorate system is not capable of supporting or competing with Darwinian evolution [Benner, 2010].

The phrase also clarifies an essential difference between fire and life, since the first one is not capable of Darwinian evolution either.

Nevertheless, there have been suggested exceptions to Darwinian evolution. It is possible that early life on the Earth went through a period of reproduction without replication, in which Darwinian evolution was not yet in place [Dyson, 1985]. In Dyson's double-origin theory, protein-based beings capable of metabolism predated the development of nucleic acid-based replication.

Thus, it has been suggested that a world of naked RNA molecular life is possible, in which such life would conflate phenotype with genotype, thereby allowing limited Lamarckian (i.e., inheritance of acquired properties) as well as Darwinian evolution [Cleland and Chyba, 2002].

This issue could, of course, easily be solved by writing 'has developed its numerous characteristics through pluripotential evolution', by using evolution in a more relaxed and general sense.

However, it has been pointed out that Lamarckian evolution can be considered more a complement to than a denial of natural selection since such RNA life can still undergo evolution through natural selection, even if Darwinian evolution is assisted by other types of evolution. Thus, the naked RNA molecular life can be included in the Darwinian framework if they are capable of undergoing the Darwinian process too [Chodasewicz, 2014].

3.3. Chemical and biological evolution.

In the definition of life, the origin of life, abiogenesis or chemical evolution, should perhaps also have been mentioned in form of an extra phrase. Thus, the phrase 'that has developed its numerous characteristics through chemical and pluripotential Darwinian evolution' should be present.

However, this would imply that there is a fundamental difference between the first principles in chemical evolution and biological evolution, or between thermodynamics and chemical evolution. It is correct that there is still much to learn about major portions of the processes that lead to the appearance of the first life. However, simply falling back on life as an emergent attribute of matter appears not only alien for prebiotic chemistry research but also has to have little relationship with our current understanding of actual chemical and biological phenomena [Lazcano, 2010].

Nevertheless, if chemical evolution turns out to follow some first principles that are not shared by biological evolution or requires some specific factors different from thermodynamics to take place, then the introduction of this phrase is needed. Strictly speaking, until the first truly living cell arises in a laboratory and provides us with an answer, it is not clear whether there should be such an extra phrase.

However, chemical reactions demand thermodynamics to take place, and it has been demonstrated that in an open thermodynamic system, the order of such a system will increase as the energy flows through it [Prigogine and Stengers, 1984]. Furthermore, this occurs through the spontaneous development of cycles in the system. One example is the cyclic chemical phenomena known as the Belousov-Zhabotinsky reaction [Taylor, 2002]. Thus, biological cycles may merely be an exploitation of thermodynamic cycles that already existed before life arose [Sagan, 1970].

In fact, self-assembly and complexification do exist in a wide range of systems that are part of living systems but are not themselves life, such as in the auto-organization of lipidic molecules in bilayers, micelles, and liposomes [Farmer, 2005].

A difference between non-life and life could, perhaps, be said to be the difference between chemistry and biochemistry. However, that is probably not a good distinction. Instead, chemistry is distinctive from biochemistry in that the latter has a history that was developed through Darwinian evolution. It is Darwinian evolution that evolved the functional molecules that transformed chemistry into biochemistry, and biochemistry into biology.

Thus, the consensus in the prebiotic research community appears to be that life is seen as the evolutionary transition between chemical systems and biomolecular networks. An evolutionary continuum exists where thermodynamics and evolutionary processes in the proper environmental conditions facilitate prebiotic synthesis and the accumulation of organic molecules into self-sustaining replicating systems, that is, life.

Thus, an extra phrase appears to be unnecessary, since abiogenesis subsumes into thermodynamics and Darwinian evolution, which is facilitated by both causality and probability. It does not require extra principles to have taken place. The first definition will, thus, be sufficient.

In fact, just as natural selection among those individual organisms whose variations were most beneficial under the given circumstances is a non-random process, the origin of life may be a non-random process by which ‘the origin and evolution of life … can be understood as resulting from the natural thermodynamic imperative of increasing the entropy production of the Earth in its interaction with its solar environment’ [Michaelian, 2011]. Time will tell.

3.4. Dissipative system.

Just as the phrase ‘Darwinian evolution’ expresses a long, implicit list, ‘dissipative system’ is also a phrase that is shorthand for a huge body of ongoing research. A dissipative structure is an open thermodynamic system that operates far from equilibrium and is characterized by a spontaneous structural and functional order and by a low value of entropy [Prigogine and Lefever, 1968].

Such a system in which energy is continuously imported from and entropy is released into the surrounding environment is thought to be essential for biological processes [Prigogine and Stengers, 1984].

A more intuitive way to grasp energy and entropy in terms of life may be to imagine a type of generalized water-mill, in which free energy is flowing from higher quality to lower quality, that is, energy dispersal, and during the flow of energy, the mill-wheel is turning, producing internal organization in the mill. This mill is life, and the turning-wheel is the very mechanism that decreases entropy by displacing it into the environment. Thus, as long as Gibbs free energy flows through the mill-wheel, it maintains life far from thermodynamic equilibrium; that is, it produces internal information content.

The phrase that is accompanied by the rest of the definition avoids some of the counter-examples that are listed in the introduction. It clarifies the difference between itself and non-life systems, which can be utilized far from the thermodynamic equilibrium.

For example, a hurricane formation serves a fundamental thermodynamic purpose, which consists of a movement of moist air up to higher altitudes, where condensation occurs, thus markedly accelerating the transfer of heat from the warm ocean waters to the cooler layers of the atmosphere. In that way, the hurricane elegantly acts to reduce a temperature gradient and, thereby, increases the entropy of its surrounding environment, which is, thus, an example in which a complex structure arises and produces an internal order as it dissipates energy into the environment [Schneider and Sagan, 2006].

However, the information or order in that system has not itself arisen through Darwinian evolution. That system uses free energy to produce order as part of its dissipative process, but it has not developed this characteristic through Darwinian evolution, and the information is not itself inheritable. Therefore, the system cannot support Darwinian evolution.

It might be objected that there is repetition in the definition. Metabolism is one of the numerous characteristics of evolution. Being able to metabolize involves being able to do energy transformation, which automatically implies thermodynamics.

Nevertheless, there is a dichotomy here. Because although evolution requires thermodynamics to take place, thermodynamics do not require evolution in order to take place. On the other hand, thermodynamics are necessary for life, but they are not sufficient. Life requires evolution to arise and to develop. Thus, there is not a reciprocal relationship. It is possible to differentiate between metabolism and thermodynamics.

For instance, while metabolism is a characteristic of life, it is not a narrow enough guideline as an indicator for life elsewhere. The Viking Landers on Mars in 1976 tested for metabolic clues to life in the soil [Klein, 1999]. They found a reaction in two of the experiments, which appeared to be analogous to reactions that were observed with terrestrial microorganisms. Thus, one might conclude that life in the Martian soil was consuming nutrients and releasing CO_2 as a waste by-product. However, it has become clear since then, that the Martian soil has a special chemistry wherein one or more inorganic oxidants that are present in the soil could produce a metabolic-like reaction [Klein, 1999]. Thus, a metabolic-like reaction can be a strong indication of the presence of life, but it is not sufficient, while the absence of one is a strong indication that life is not present on a planet.

Furthermore, an entropy reduction is an essential characteristic of life, meaning that the chemical composition of a planet's atmosphere is far from thermodynamic equilibrium if there is life on it [Hitchcock and Lovelock, 1967]. However, the existence of an entropy reduction on a planet is not sufficient as an indicator of life, since other factors might create a redox disequilibrium, while the absence of one is a strong indication that life is not present on a planet.

However, if there is both a metabolic-like reaction in the soil and an entropy reduction in a planet's atmosphere, then it is a very strong indicator of life. Thus, again it is possible to differentiate between them.

3.5. Maintains vs. maintaining.

It is well-known that there exist many forms of healthy life that are capable of existing deep within the ordered regime of thermodynamics, as evidenced by hibernation and dormancy in plants, and life, thus, can reduce or postpone its utilization of energy and displacement of entropy to the surroundings [Macklem and Seely, 2010].

Spores are capable of staying dormant and ceasing to have metabolic activity at low temperatures for extremely long periods, such as hundreds or possibly even thousands of years. However, these spores can return to life when being subjected to more fitting conditions suitable for germination, growth, and reproduction [Sagan, 1970].

Mars appears to have once been a more hospitable place for life [McKay and Stoker, 1989]. If life arose there in the past, then some of it could have survived but is dormant to this day. Thus, there is an interest in investigating whether life from Earth could survive in the present-day conditions of Mars, which indeed seems to be the case, assuming that bacterial endospores are sufficiently shielded from solar irradiation [Wassmann et al., 2012].

Thus, instead of writing 'maintains its localized level' in the definition, I should instead write 'capable of maintaining its localized level'. The first phrase means that life continuously maintains it, while the latter phrase means that life can maintain it with interruptions.

However, there is debate as to whether such life truly has a complete cease of metabolism, or whether there still is an extremely slow metabolism that, so to speak, still 'leaks' and that a sufficiently sophisticated experiment could find. There is some evidence that there is, indeed, minimal metabolism of exogenous or endogenous compounds in the dormant spores of *Bacillus* species [Ghosh et al., 2015]. There is also evidence that there is rRNA degradation in the spores of *Bacillus subtilis* held at physiological temperatures, as well as indications of some gene expression taking place in them [Ghosh et al., 2015].

Thus, whether there are spores that truly can put metabolism to a complete halt is still a debated question. If they can, then it is, of course, remarkable, since this generally designates an organism that has ceased to be living. However, if they do have a metabolism, then they does not possess an inert immortality, the second law of thermodynamics will be in effect, and the first phrase is sufficient.

3.6. Genomes and information.

The phrase 'self-sustaining chemical system' is already well-known from earlier definitions [see Joyce, 1994]. Life is a chemical system, but there exist many chemical systems that obtain an internal order and undergo cycles and non-retraceable trajectories that are not life [Brack and Troublé, 2010].

The latter systems are not truly self-sustained of course. They eventually come to a halt on their own. The phrase refers to the chemical system as being self-sustaining in a way that does not require a scientist in the laboratory to keep it going; it only requires external energy, and, very importantly, requires information to do so.

Life contains its hereditary and messenger information in DNA and RNA, which are collectively designated the genome. Stating a distinction between 'genome-containing' and 'chemical system' in the definition could, perhaps, be considered a repetition, since one may argue that information is already an implicit part of the phrase 'self-sustaining chemical system'. However, that seems to be ad hoc. A definition should clarify this on its own.

Nevertheless, a definition requiring embedded instructions in the form of DNA and RNA may be too narrow. Thus, there may be other systems of molecular memory that are possible in the cosmos and enable life that do not contain information in this form. As mentioned earlier, it is possible that early life on the Earth went through a period of reproduction without replication

[Cleland and Chyba, 2002]. In this double-origin scenario, protein-based beings that are capable of metabolism predated the development of genome-based replication.

Thus, we might imagine that life on this planet in the past and on other worlds in the universe does not contain its information as genetic information but contains it in a different kind of structure. The demand is fundamentally only this, that all of the information necessary for a collective system such a life to undergo evolution necessarily must be present within that very collective system.

Thus, writing that life is 'genome-containing' might then be too specific a demand. Writing 'information-containing' is weaker but is also a more general definition. However, the fact is, of course, that all life on Earth has its heredity information in a genome, a molecular habitat of expanding and mutating simple tandem repeats, which evidently is a highly efficient way to maintain and pass on information.

Thus, for present day Earth-based life, the definition should stay true to that fact.

3.7. Specific vs. general.

Notice that the definition writes 'Life$_{Terra}$'. This probably goes counter to what is traditionally demanded of a general definition of life, but it is, for now, unavoidable.

All life on Earth shares common properties. All life shares the same molecular models and the same macromolecules [Raulin, 2010]. Thus, all terrestrial life use virtually identical DNA for hereditary information, all life use proteins to control biochemical reaction rates, and all apply identical ATP molecules to store energy. Thus, we see the same fundamental biochemistry in organisms such as bacteria and *Homo sapiens*.

This is hardly surprising at all, since all terrestrial life, ranging from bacteria to *Homo sapiens*, descend from a single instance of life, the origin of life, which is the single common ancestor to us all. This means that all data about life comes from only one example of life, one available data point that is Earth based. Thus, a definition must stringently write 'Life$_{Terra}$'.

Given just one data point makes it difficult to distinguish which properties of terrestrial life are unique and which properties of life are truly universal. Thus, the concern is that we do not know which features of terrestrial life are just accidents of history [McKay, 2004]. This can only change if we find life on a different world. Astrobiology could, thus, help solve this debate by finding potential alternative life forms that have evolved independently beyond the Earth.

This point is entirely valid. However, even if we find life on Mars, Europa, Titan, Enceladus or even in the clouds of Jupiter and Saturn, or when we, hopefully, begin harvesting data about life on diverse exoplanets, the validation or modification of my definition will still not lead to a truly universal definition.

This is due to the fact that all definitions so far, my own included, are inductive; that is, a conclusion from the specific to the general. While the conclusion of inductive reasoning may be probable, based upon the available evidence, it cannot be logically certain. Only when all of the hypothetical life in the solar system is found can the phrase be modified to 'Life$_{Solar\ system}$', and only after all life in the galaxy is found, can we proceed to the phrase 'Life$_{Galaxy}$'. Even then, it will still be an inductive conclusion.

The phrase 'Life$_{Universal}$' will only be deductive, that is, a logical conclusion from the general to the specific, where the conclusion is necessarily true, when all life on all planets in all the galaxies of the universe is carefully examined.

Thus, even though the point is valid and it is limiting to generalize from a single example, or examples, it is restricted in this respect, and it is still without much relevancy regarding the formulation of a definition, since it is not immediately obvious how we will ever be able to obtain knowledge of all the possible life that exist in this vast universe.

Life on other planets may modify the definition of life, although I am inclined to think that life on the Earth is representative of life. Nevertheless, from a deductive point of view, we cannot simply criticize a definition just because we lack data points, and it is just important to keep this in mind.

3.8. Summery considerations.

If we choose to take all these *pro* and *con* points into consideration and relax the requirements, then the following second formulation can be put forward:

Life$_{Universal}$ is an information-containing, self-sustaining physical dissipative system, capable of maintaining its localized level of organization at the expense of producing entropy in the environment; which has developed its numerous characteristics through pluripotential evolution.

4. Summary

Why attempt a definition of life? There are two reasons in my mind. The first one is that we, ourselves, individually and collectively, are life, and it seems strange that we cannot provide a definition of what we are. The second reason is that humankind is on the verge of becoming a space-faring species. Life on this blue planet may be only one in the grand cosmic tree of life. Our capability for searching or encountering life on other planets is steadily becoming a real possibility. To realize that search, we have to know what we are looking for, and that requires a definition.

The study of life has, understandably, taken place within a terrestrial perspective in biology. Evolutionary biology explains life very well, but we have steadily become aware that life is intrinsically linked together with the very solar system it arises in, perhaps even with the very galaxy. Thus, a wider perspective is required, one that is addressed by astrobiology.

Life depends not only on local ecosystems. It depends on the very composition of the planet it is on, of the very location of the planet in the solar system, the habitable zone, and on the very star the planet orbits. Life itself is assembled of elements that originated in the cores of stars far away in time and space. Thus, there is a need and justification for astrobiology.

There are many definitions of it. Personally, I tend to define it as: 'Astrobiology is evolutionary biology in a solar system context (or more ambitiously: Astrobiology is evolutionary biology in a galactic context)'. Astrobiology will, in all likelihood, with time, be able to explain life even better in the cosmic perspective to which it belongs.

It can be discussed whether we still lack a general theory of how matter progressively gains the characteristics that are associated with objects that are designated as life, or whether we already have that overall and only need to do the right types of experiments to demonstrate how matter obtains the characteristics that are associated with so-called animate objects. However, regardless of that, we can come a long way in defining life by using a first principle approach.

A first principle, from which a demonstration begins, starts with the most essential facts and relations and can utilize physics, chemistry and biology very well without needing to be demonstrated from any other proposition or alluding to any theory. Thus, two definitions, one that is strict and one that is more relaxed, have been put forward on this foundation.

These definitions provide two operational ways in which we can search for potential life on other planets. First, a visiting observer on an exoplanet will see the attributes of life in the form of the diversity of species in ecosystems and the competition and synergism of species, which are all observations that lead to the fact that evolution is taking place.

Second, the above-listed attributes will not be seen by an observer positioned far outside the exoplanet. He will see life as the process of taking free energy from its surroundings and returning entropy, which affects the very atmosphere of the exoplanet. Thus, it is a well-known fact that the chemical composition of the Earth's atmosphere is far from equilibrium, which is designated as 'redox disequilibrium'.

Lovelock emphasizes this, stating that 'the entropy of living systems is low relative to that of their nonliving environments in that there will always exist an entropy gradient between the two', when he, along with a group of researchers, proposed a life detection system to look for life on Mars [Hitchcock and Lovelock, 1967]. The state of disequilibrium has, thus, been proposed as a biosignature, albeit not the only one, that can tell us whether there is life on exoplanets [Schwieterman et. al., 2018]. This is due to the fact that the simultaneous and persistent existence of CH_4 and O_2 in the Earth's atmosphere, which should otherwise rapidly oxidize to CO_2 and H_2O, is an indication that life continually resupplies these gases.

However, the existence of an entropy reduction on a planet is not a sufficient indicator of life, but the absence of one is a strong indication that life is not present on a planet, since an entropy reduction is an essential characteristic of life.

The definitions put forward also provide other possibilities. Thus, it has been postulated that evolutionary definitions lead to a problem involving the observation of evolution, which is especially relevant for astrobiology, since it seems to imply a consequence of how long we must wait to record the effects of natural selection on exoplanets and under what conditions [Luisi, 1998].

However, it is indeed possible to observe the process of natural selection happening relatively fast due to the fact that the rate of change in a population is related to the duration of an organism's life cycle [Carroll et al. 2007]. Thus, many organisms can experience phenotypic evolution in only a few generations, and noticeable differentiation among populations within species can take place within observable time frames.

Nevertheless, the definitions put forward here have the advantage in terms of time frames in that they do not require that we look forward but that we in the present either can see an entropy reduction in a planet's atmosphere or that we can see evidence of evolution in the present or in the past on the planet. For example, it is possible that life once existed on Mars but disappeared due to the planet's transformation into a hostile environment for life [McKay and Stoker, 1989]. However, if life once existed on the red planet, then evidence of it and its evolution will probably still be there.

Life arose relatively quickly after the Earth's formation, which may be an indication that life, with some certainty, will arise on planets in possession of the right conditions. Thus, if life is common in the universe, then there is the possibility that life elsewhere could be built differently than their terrestrial counterparts and that we may be too restricted when looking for extra-terrestrial life [Schulze-Makuch and Irwin, 2006].

It is a reasonable point, and one could perhaps even argue that all that the laws of physics allow to arise, will arise. Thus, the real question is whether the laws of physics allow life on other planets to function in other ways than we know on the Earth. A plenitude of life not only in biological diversity, but in chemical construction.

Thus, we can perhaps expect life to exist elsewhere, with different genetic codes, more amino acids or amino acids with different chirality [Cleland and Copley, 2005]. It may be the case that water does not define life, but just happens to be an aspect of the Earth's environment. Thus, it is possible to conceive of solvents such as ammonia, sulfuric acid or methane-ammonia mixtures [Pace, 2001]. It may also be possible for life to use arsenic in the place of phosphorus to build its DNA [Wolfe-Simon et al., 2010]. Life on the Earth is based on a specific set of very complex chemical systems build on carbon. However, it might be possible for life forms to have a silicon-based system [Pace, 2001].

However, it has been argued that biochemistry elsewhere in the universe will turn out to be the same as that on the Earth, because some processes are more effective than others; carbon is better than silicon, and water is better than ammonia [Pace, 2001]. Thus, natural selection will ensure (assuming there is an initial diversity of molecules to select from) that life, in terms of biochemistry, evolves in the same way everywhere.

However, either way, even if extra-terrestrial life with such alien biochemistries exists, they are still easily encapsulated by the definitions put forward in this work, since these are independent of the abovementioned constituent molecules.

The discovery of evolution represents a tremendous enrichment of humankind's understanding of itself and its place in nature, which is equal to the discovery of the solar systems place in the universe. However, it took humankind thousands of years to finally reach that insight, which is an insight that is yet relatively easy to comprehend when first encountered. Thus, it is perhaps not so strange that an adequate definition of life is still in the making; after all, barely any time has elapsed after these profound advancements.

Perhaps life is a question with a billion answers. Or perhaps the opposite is true: life is the single answer to a billion questions. Time will tell.

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