# 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 however has apparently emerged that entirely has been able to encapsulate life. Putting forward an adequate definition is not a simple matter to do, this despite many seems to believe they have an intuitive understanding of what it's meant when they state something is life. Yet it is important to do so, because we ourselves, individually and collectively, are life, entailing 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 though. 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 and 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 shared between all life, and demonstrate that the interconnected aspects of life are unique for precisely life, that it collectively does things other phenomena do not, and describe what life is. Thus, the following *ab initio* definition can be put forward: Life$_{\text{Terrra}}$ is a genome-containing, self-sustaining chemical dissipative system that maintains its localized level of organization at the expense of producing environmental entropy; that has developed its numerous characteristics through pluripotential Darwinian evolution.

**Keywords:** definitions of life, terrestrial life, extraterrestrial 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 amazed asked themselves what the numerous stars could be.

Curios children have turned their unbiased gaze upon them in the early evenings. The adults amidst their busy existence of food gathering, finding shelter, surviving and reproducing, has sat safe at the slowly fading campfire in the late evenings, their eyes irresistibly drawn to the majestic stars above. Some of the most curios, most dedicated among them, those filled with the inherent need and desire of humankind to explore, to understand, to improve, has walked afar from the safety of their fellow man for 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's what a star is. That's what a star does – a star like the sun.

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

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. But it is important to ask for many reasons. One is yet another innocent question, is there life elsewhere in the cosmos? But in order to answer that, we need to acquire an answer to the first one, because we need to understand what exactly we are searching for.

But this has proven to be harder than one at first sight could expect. But 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 a arbitrary division of nature, a human construct, where everything above that division is life and everything below is non-life? That no threshold of complexity exists at which a collection of molecules can be designated life? Many do seem to think that, 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 phenomena, from which everything else can be derived.

Thus, a star can be reduced to its elementary particles and the forces acting between them. But to scientists from virtually every discipline this view is not helpful. Because this do not remove the fact, that stars exists, and that a threshold do exist for them. The same is the case when it comes to life. Science works on different levels of description. Elementary particle physics concerns itself 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

Preprint published online 1.1.2019.

phenomena, this do 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 to put forward a definition, this despite many have an intuitive ability 'to instantly recognize life, discriminating the animate from the inanimate' [Gayon, 2010], or more accurately, many seems to believe they have an understanding of what it's meant when they state that something is life. Many people may for instance face a problem evaluating whether the slime mold *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 leave moved around by a 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 that 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 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, maintained by the combination of its waxes with $O_2$, 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 changes or is 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 in elimination of intuitive perceptions of nature that did not agree with reality. For instance, basically all 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 the 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 as seen 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 phenomena, but it is a natural phenomena, a part of the universe like 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 what's important is to demonstrate, that the collected aspects of life is unique for precisely life, that life collectively do things other phenomena do not. It is the interconnected cluster of aspects that is important to define, not the singular aspects in themselves. Furthermore, what life does, and what life is, seems to me to be the same from a scientific point of view. For example, a star is a spheroid of gas, which fuses hydrogen into helium, releasing radiation in the process. That's what a star does, that's what a star is. A division between 'does' and 'is' seems to diminish an understanding of the star.

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

## 2. Representative definitions

Many advanced definitions of life has 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 has (many of these overlap) been put forward [Trifonov, 2011], probably more, to 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 really have historical attributes, they do not need to record themselves in order to do physics and chemistry. But it has long been recognized, that biological phenomena do.

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

But there are some issues with Darwinian definitions of life. Because not all life are 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 such life is not 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, 'life' and 'living entities', appears to be more an ad hoc effort [Cleland and Chyba, 2002]. A definition must state this by itself.

But the fact remains that such definitions manage to stay clear of many of the counter-examples 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 environments. 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 groups of particles that move together to dissipate.

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

'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 produced within a organism as it maintain itself and metabolize far from thermodynamic equilibrium is compensated for by the increased entropy it create in its surrounding environment in the course of maintenance and metabolism. That observation is a powerful one indeed.

But there are some issues with entropy definitions of life. Because taking compounds from the environment, returning waste, and grow is something 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. But a fire whirl that emerges when rising heat and turbulent wind conditions joins together and create a tornado like vortex, also generate internal order as it dissipate 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 be able to steer clear of this or clarify the difference.

However, the fact remains, that although the entropy reduction point do 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, that some efforts are more fruitful than others. It is clear from physics that thermodynamics, with it's 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 attempt wisely 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 or steer clear of or 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. But that only life shares all these aspects at once is what a definition must give, and 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. Yet, some of these definitions do indeed encapsulate important single aspects of what life is, and what life does. But the sheer number of them and the lack of consensus among scientist have lead 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’.

But of course, such views may have their own problems. The philosophical distinction between propositions called analytic and synthetic propositions can be given 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 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 deposits, that there only exist analytic and synthetic propositions, and that anything else apparently is meaningless, then one can ask the obvious question, whether the proposition, ’that there only exist analytic and synthetic propositions’, is itself an analytic proposition?

If the answer is yes, then it is *ipso facto* not about the actual world, since it is just 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 absolute true, since it is just 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 seems of little relevance.

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

But again there seems to be problems with such views. The distinction between lexical and stipulative definitions can be given 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 deposits, that it must be defined the 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, whether the formulation, 'one should distinguish between lexical and stipulative definitions', is itself a stipulative definition?

If the answer is yes, then it is *ipso facto* not about the actual world, since it just 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 of little relevance for the scientific enterprise. Words are human-made, 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 relation between them, the chemical reaction, is not human-made. Thus, instead of this 'swamp of language' we might be better suited adhering to first principles.

### *3.2. First principles.*

A first principle, from which a demonstration begin are explanatory primitive [Gasser-Wingate, 2016]. It is a basic, self-evident proposition that cannot, or more accurately as understood in science, do not need to be demonstrated from any other proposition in order 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, life expanding in population size until constrained is a first principle etc.

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

First principles also exist in philosophy, albeit usually not realized as being such. For example have 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 on, 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' clarify a fact because the terms location, movement, distance, velocity and time stands in a certain interdependent relationship with each other in the actual world.

A similar situation goes 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 on, it's a first principle humans have clarified.

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

Consider 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 is attached. This is a fact independent of humans. When humans clarify a description, then it must first be established how the term time shall be used in relation to movement, velocity, acceleration etc. Clarifying such first principles is a scientific enterprise 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. in order to describe something. However, it is also unavoidable first principles in 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 the traffic, if he is not able to grasp, that the world do 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 is also 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* do not unambiguously clarify a relation at all, because the universe do not work that way.

If for instance this person is tasked with guiding another person in a car over the phone, and he guide 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 the traffic for long.

Thus, claiming that because words and terms is human-made, they then only inform about the meanings of words and terms in human language, rather than informing about nature, that they are a web of terms humans have constructed over the universe and thereby 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 evolutionary 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 extraterrestrial civilizations. Both are forced to act and communicate this same way.

Thus, first principles are not platonic forms, or analytic or synthetic propositions. They are not synthetic a priory 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 communication, regardless of our personal philosophical position, in order 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 putting forward a first strict formulation of a definition of life:

$\text{Life}_{\text{Terrra}}$ is a genome-containing, self-sustaining chemical dissipative system that maintains its localized level of organization at the expense of producing environmental entropy; that 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 emphasizing is not a mere word game, but is a crucial point for a stringent definition. A definition has to be both in present and past tense. We can once again take the example with the mule, 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 that 'has developed its numerous characteristics through pluripotential Darwinian evolution'.

All a mules predecessors has been able to reproduce, and have reproduced, meaning that reproduction has lead up to the present mules existence. But the mule is not itself able to reproduce. Thus, the mule fulfills all demands of Darwinian evolution in the past tense.

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

Because, we could easily come up with a thought experiment, a global event for instance, where 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. But 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 make biology so rich and complex. This has been acknowledged elsewhere. Already Bernal wrote that:

'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 posses 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, the coffee will cool down and the milk will warm up. Eventually both fluids will be at the same temperature as the area. They have come in thermal equilibrium. Repeat the experiment with the same conditions and you will with an extremely high probability 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, that is, take in energy internally and displace entropy externally in order 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 in order 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, but evolution requires obviously 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. But 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, 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 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 have demonstrated a remarkably rich diversity. Thus, the phrase 'pluripotential' in front of Darwinian evolution clarify the vast, but not infinitely open ended, capacity of life.

The definition steers clear of the counter-examples 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 descendents 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 from 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 (that is, inheritance of acquired properties) as well as Darwinian evolution [Cleland and Chyba, 2002].

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

However, it has been pointed out, that Lamarckian evolution can be considered more a complementation than a denial of natural selection since such RNA life can still undergo evolution through natural selection, even if Darwinian evolution are 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 mush to learn about major portions of the processes that lead to the appearance of the first life. But simply falling back on life as an emergent attribute of matter, appears not only alien for prebiotic chemistry research, but also to have little relationship to our current understanding of actual chemical and biological phenomena [Lazcano, 2010].

Nevertheless, if chemical evolution turns out to follow some first principles not shared by biological evolution, or requires some specific factors different from thermodynamics in order 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 in order to take place, and it has been demonstrated that in an open thermodynamic system the order of such a system will increase as 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 is part of living systems, but are not themselves life, such as in the autoorganization 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. But that is probably not a good distinction. Instead, chemistry is distinctive from biochemistry in that the latter has a history in it, a history that was developed through Darwinian evolution. It is the Darwinian evolution that evolved the functional molecules that transformed chemistry into biochemistry, and biochemistry into biology.

Thus, 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 accumulation of organic molecules into self-sustaining replicating systems, that is, life.

Thus, an extra phrase appears unnecessary, since abiogenesis subsumes into thermodynamics and Darwinian evolution, facilitated by both causality and probability. It does not require extra principles in order 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 en non-random process, the origin of life may a non-random process to, where ‘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]. But time will tell.

### *3.4. Dissipative system.*

Just like the phrase ‘Darwinian evolution’ expresses a long implicit list, then ‘dissipative system’ is also a phrase that is shorthand for a huge body of ongoing research. A dissipative structure is an open thermodynamic system, operating far from equilibrium, and which 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 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, where 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 the very mechanism that decrease entropy by displacing it to the environment. Thus, as long as Gibbs free energy flows through the mill-wheel, it maintains life far from thermodynamic equilibrium, that is, produce internal information content.

The phrase accompanied with the rest of the definition avoids some of the counter-examples listed in the introduction. It clarifies the difference between itself and non-life systems that can utilize far from thermodynamic equilibrium.

For example, a hurricane formation serves a fundamental thermodynamic purpose, which consist 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 increase the entropy of its surrounding environment. This is thus an example in which a complex structure arises and produces internal order as it dissipates energy to the environment [Schneider and Sagan, 2006].

However, the information or order in that system has not itself arisen through Darwinian evolution. That system use 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 a repetition in the definition. Metabolism is one of the numerous characteristics of evolution. Being able to metabolize is to be able to do energy transformation, which automatically implies thermodynamics.

Nevertheless, there is a dichotomy here. Because although evolution require thermodynamics in order to take place, thermodynamics do not require evolution in order to take place. On the other hand, thermodynamics is necessary for life, but it is not sufficient. Life requires evolution in order to arise and 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 that appeared to be analogous to reactions observed with terrestrial microorganisms. Thus one might conclude that life in the Martian soil were consuming nutrients and releasing $CO_2$ as a waste byproduct. However, it has become clear since then, that the Martian soil have a special chemistry where one or more inorganic oxidants present in the soil could produce a metabolic-like reaction [Klein, 1999]. Thus, a metabolic-like reaction can be a strong indication on 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.

But 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 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, hundreds or possibly even thousands, of years. Yet 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 dormant to this day. Thus, there is an interest in investigating, whether life from the Earth could survive in the present day conditions of Mars, which indeed seems to be the case, assuming that bacterial endospores is 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 do it with interruptions.

However, there is debate as to whether such life truly has a complete cease of metabolism, or whether there still is a extremely slow metabolism, that they so to speak still 'leaks', 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 designate an organism that has ceased to be living. But 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 internal order, 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 run to a halt on their own. The phrase refers to that the chemical system is self-sustaining in the way, that it does not require a scientist in the laboratory to keep it going, it only require external energy, and, very importantly, require information to do so.

Life contains its hereditary and messenger information in DNA and RNA, 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 implicit part of the phrase 'self-sustaining chemical system'. But that seems 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 possible in the cosmos enabling 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 capable of metabolism predated the development of genome based replication.

Thus, we might imagine life, on this planet in the past, and on other worlds in the universe, which do not contain its information as genetic information, but contain 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 to specific a demand. Writing 'information-containing' is a weaker, but also a more general definition. However, the fact is of course that all life on the 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 passing 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 '$\text{Life}_{\text{Terra}}$'. This probably goes counter to what is traditionally demanded of a general definition of life, but it is for now unavoidable.

All life on the Earth shares common properties. All life shares the same molecular models, 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*, all descends from a single instance of life, the origin of life, the single common ancestor to us all. This means that all data about life comes from only one example of life, one data point available: Earth based. Thus, a definition must stringently write '$\text{Life}_{\text{Terra}}$'.

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 goes that we don't know which features of terrestrial life that is 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, is 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 the hypothetical life in the solar system is found can the phrase be modified to '$\text{Life}_{\text{Solar system}}$', and only after all life in the galaxy is found, can we proceed to the phrase '$\text{Life}_{\text{Galaxy}}$'. Even then will it strictly speaking still be an inductive conclusion.

The phrase '$\text{Life}_{\text{Universal}}$' 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, and we in this respect is restricted, it is still without much relevancy regarding the formulation of a definition, since it is not immediately obvious, how we ever will 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 for 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:

$\text{Life}_{\text{Universel}}$ is an information-containing, self-sustaining physical dissipative system, capable of maintaining its localized level of organization at the expense of producing environmental entropy; that 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, is 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. But in order 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 addressed by astrobiology.

Life depends not only on local ecosystems. It depends on the very composition of the planet it's 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 the need and justification of 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 gains the characteristics progressively associated with objects designated life, or whether we already overall have that, but only need to do the right types of experiments to demonstrate how matter obtains the characteristics associated with co-called animate objects. But regardless of that, we can come a long way defining life using a first principle approach.

A first principle, from which a demonstration begin, start 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, a strict and a 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. Firstly, 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, all observations of course leading to the fact that evolution is taking place.

Secondly, the above listed attributes will however 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 'redox disequilibrium'.

Lovelock put emphasis on 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 if there is life or not 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 sufficient as an 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 leads to a problem involving observation of evolution, which is especially relevant for astrobiology, since it seems to imply a consequence of how long we must wait in order to record 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 on observable time frames.

Nevertheless, the definitions put forward here has the advantage in terms of time frames, that they do not require we look forward, but only that we in the present either can see a entropy reduction in a planet's atmosphere, or that we can see evidence of evolution in the present or the past on the planet. For example, it is possible, that life once existed on Mars but disappeared due to the planets transformation into a hostile environment for life [McKay and Stoker, 1989]. But 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 Earths 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 extraterrestrial life [Schulze-Makuch and Irwin, 2006].

It's a reasonably point. One could perhaps even argue, that all what the laws of physics allows 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 elsewhere with different genetic codes, more amino acids or amino acids with different chirality to exist [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 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, as a bacterium on the Earth might be able to [Wolfe-Simon et al., 2010]. Life on the Earth is based on a specific set of very complex chemical systems build on carbon. But it might be possible to have a silicon based instead [Pace, 2001].

However, it has been argued that biochemistry elsewhere in the universe will turn out to be the same as on the Earth, because some ways are more effective than others, carbon is better than silicon, 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, everywhere evolves in the same way.

But either way. Even if extraterrestrial 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 above mentioned constituent molecules.

The discovery of evolution represents a tremendous enrichment of humankinds understanding of itself and its place in nature, equal to the discovery of the solar systems place in the universe. However, it took humankind thousands of years to finally reach that insight, 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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