First principles of terrestrial life: exemplars for potential extra-terrestrial biology

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Abstract The search for life elsewhere in the universe represents not only a potential expansion of our knowledge regarding life, but also a clarification of the first principles applicable to terrestrial life, which thus restrict the very search for extra-terrestrial life. Although there are no exact figures for how many species have existed throughout Earth's total history, we can still make inferences about how the distribution of this life has proceeded through a bell curve. This graph shows the totality of life, from its origin to its end. The system enclosing life contains a number of first principles designated the walls of minimal complexity and adaptive possibility, the fence of adaptation, and right-skewed extension. In this discussion of life, a framework will be formulated that, based on the dynamic relationship between mesophiles and extremophiles, will be imposed on exoworlds in order to utilize the graph's predictive power to analyze how extra-terrestrial life could unfold. In this framework the evolutionary variation does not depend on the specific biochemistry involved. Once life is 'up and running,' the various biochemical systems that can constitute terrestrial and extra-terrestrial life will have secondary significance. The extremophilic tail represents a range expansion in which all habitat possibilities are tested and occupied. This tail moves to the right not because of the biochemistry constitutions of organisms, but because it can do nothing else. Thus, it can be predicted that graphs of terrestrial and extra-terrestrial life will be similar overall. A number of other predictions can be made; for example, for worlds in which the atmospheric disequilibrium is approaching equilibrium, it is predicted that life may still be present because the extremophilic range expansion is stretched increasingly farther to the right. Because life necessarily arises at a left wall of minimal complexity, it is predicted that any origin of cellular life will have a close structural resemblance to that of the first terrestrial life. Thus, in principle, life may have originated more than once on Earth, and still exist. It is also predicted that there may be an entire subset of life existing among other domains that we do not see because, in an abstract sense, we are inside the graph. If we view the graph in its entirety, this subset appears very much like a vast supra-domain of life.

Keywords: astrobiology, extremophiles, evolutionary variation, exoplanets.

1. Introduction

How can we imagine the unimaginable? How do we conceive that which we cannot conceive? How can we search for unknowns hiding beyond these mental restrictions? In the search for potential extra-terrestrial life elsewhere in the solar system and indeed elsewhere in the galaxy, these are important questions to consider.

One way to proceed could be to avoid trying to imagine the unimaginable, avoid trying to conceive that which we cannot conceive, and simply rely on pure observation: we observe life that we have not known before and agree that it is indeed life. Although it is crucial to maintain an open mind in science, another way to proceed is to stretch the existing theory to its limits to determine whether the unimaginable becomes imaginable or whether predictions we had not conceived are conceived. This approach is relevant in our current situation. The search for life elsewhere in the galaxy not only represents a potential expansion of our knowledge of life, but also represents a clarification of life on Earth, as the conditions that apply to terrestrial life represent restrictions on that very search.

Astrobiology has many research directions; however, in recent decades, an important area relevant to the search for life elsewhere has been the study of extremophiles. An extremophile can be defined as 'an organism that is tolerant to particular environmental extremes and that has evolved to grow optimally under one or more of these extreme conditions, implicitly implying the existence of adaptive responses and survival thresholds to pressure, temperature, pH, salinity and desiccation extremes etc.' [von Hegner, 2019].

Thus, extremophiles show that a far greater range of possibilities exist for life than previously thought, and it is reasonable to assume that potential analogues to terrestrial extremophiles could thus exist on worlds that were previously considered hostile to life. Some restrictions exist however for their use as analogues. Evolutionary processes are important to consider as well as processes addressed in other disciplines such as

planetary science. Because once life is 'up and running,' then it is not only physics and chemistry that apply, but also biology.

Despite the remarkable and fascinating capacities of extremophiles, they are still within evolutionary biology. For example, as discussed here, life necessarily arises at the simplest possible complexity, which is a first principle for life. One peculiar consequence of this is that organisms such as extremophiles under certain circumstances do not exist in a world that otherwise possesses the right conditions for extremophilic life. Although extremophiles can exist in an extreme environment here-and-now if they are placed there, no native extremophiles can exist there if the environment has always been extreme [von Hegner, 2019]. Seemingly paradoxically, it is the very extreme environment itself that ensures that there are no (native) extremophiles in this environment. Therefore, a theoretical framework is desirable to guide research within extremophiles.

In astrobiology, a familiar phrase exists: 'life as we know it' and, as a natural corollary: 'life as we do not know it.' There is a huge diversity of life forms on Earth, yet all of these life forms have a shared biochemistry due to their common origin. However, does a different biochemistry imply the existence of other evolutionary principles? Can a different biodiversity be expected if life arises in another world with a different biochemistry? These important questions in the search for extra-terrestrial life can be formulated in a weak and a strong version.

The weak version emphasizes that universal characteristics of terrestrial life may be universal either because they were merely inherited through a common origin or because they are indeed necessary features of life *per se* [Domagal-Goldman et al., 2016]. In essence, no new kind of biology is required here, as we remain within 'life as we know it,' only examples of extra-terrestrial life are potentially required to conclusively differentiate between these two possibilities.

The strong version emphasizes that terrestrial life provides only one kind of biology and that we are severely limited by studying only this single kind of biology [Sagan, 1980]. Here, the issue is not to differentiate between characteristics already familiar from terrestrial life, but to relate to a potential other fundamental kind of biology. In essence, searching for 'life as we do not know it' is not just about finding extra-terrestrial life that may have counter-examples among terrestrial life, but finding a whole new kind of life. The crucial word here is 'kind,' which signals a fundamental difference.

How do we proceed to look for the unknowns beyond? As mentioned above, one way to proceed is by stretching the existing theory to its limits to see what it tells us, which is the focus of the present work. Some of the existing theory I build on here was originally introduced by Gould (1996). Here, I will expand this framework, applying it to an analysis of mesophiles, extremophiles, and the first principles that restrict terrestrial life in order to formulate a framework guiding the discussion and search for potential extra-terrestrial life.

2. First principles of terrestrial life

Although there are no figures for how many species and individual organisms have existed on Earth in its totality, one can still make inferences regarding how the distribution of life has proceeded. Thus, something can be said about what the bulk of this terrestrial life has been, what it mainly still is, and what it will theoretically continue to be. Importantly here, something can be said about the physico-chemico-biologico conditions that inevitably apply to this life. This distribution can be described by a bell curve, as shown in Figure 1. This graph, in a sense, illustrates the totality of life throughout Earth's entire history, from its origin until the moment when the sun will end it.

This graph is dictated by a number of first principles of life. It is framed by restrictions that will here be designated the walls of minimal complexity and adaptive possibility, the fence of adaptation, unbiased random walks, and right-skewed extension.

A first principle from which a demonstration begins is explanatorily primitive [Gasser-Wingate, 2016]. It is thus a basic, self-evident proposition that cannot, or more precisely does not need to, be demonstrated from any other proposition to be applied. First principles are well-known in the physical sciences, where theoretical work is stated to be from first principles if such work starts with the most essential facts [von Hegner, 2020]. First principles also exist in the biological sciences, through which, e.g., evolution can be stated without alluding to any theory [Varki, 2012]. For example, natural selection is a first principle, imperfect reproduction is a first principle etc.

Thus, while the walls, fence, unbiased random walks, and right-skewed extensions can indeed be further reduced in terms of physics, chemistry, and biology, such reductions are not needed to be able to benefit from the predictive power of these principles.
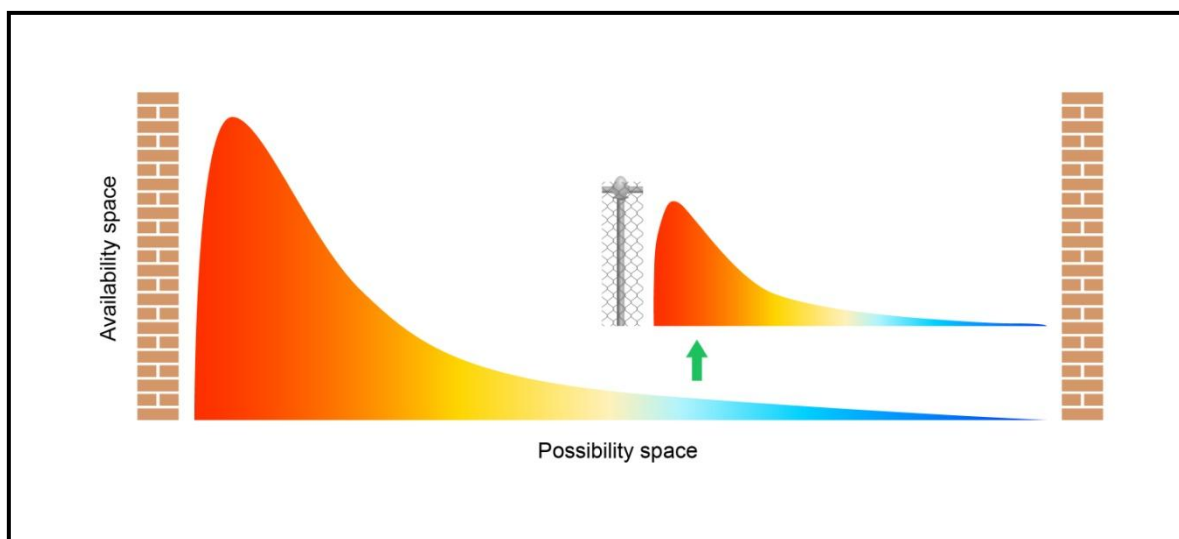

Figure 1. The totality of life throughout a world's entire history, from its beginning at a left wall of minimal complexity to its end at the right wall of adaptive possibility. The full spectrum of evolutionary variation in the entire system unfolds over time and space between these walls, where life moves through rows of fences of adaptation. The mesophilic mode occurs just to the right of the left wall, with its mesophilic peak, while a marked skewness arises to the right, designated the extremophilic tail. The color change in the graph is symbolic of environments that gradually move from mesophilic to extremophilic with increasing temperature. Credits: partially adapted from Gould (1996).

While the given bell curve for life is framed by motionless walls and appears to be a frozen image, the given graph is not static; rather, the graph is changing and dynamic, representing the full spectrum of evolutionary variation in the entire system over time and space. As will be shown, this figure represents a coherent interdependent whole. One cannot just consider biology without also accounting for chemistry or physics.

2.1. Walls of minimal complexity and adaptive possibility
Figure 1 shows two walls, the first two principles between which the evolutionary variation of terrestrial life is, in a sense, enclosed.

The first is a full wall on the left, which can be designated the left wall of minimal complexity. This concept comes from the Full House model, which posits that due to constraints imposed on the origins of life from chemical evolution and physical principles of self-organization, the first terrestrial life form necessarily came into existence at the lower limit of life's conceivable and preservable complexity [Gould, 1996]. Thus, the first terrestrial life form is constrained to have begun at the simplest starting point right next to a lead wall of complexity. Because virtually no space exists between this left wall and the initial cellular mode, life cannot move left. Only one spatiotemporal direction exists, which is toward the right. Of course, the left wall is simply an abstraction, being helpful for chemistry and physics. It represents a physicochemically constrained point, with no biology existing before it; rather, biology escapes, in a sense, to the right of this wall.

The figure also shows a full wall to the right. Within limited use in the Full House model, this wall was called the wall of human limitations [Gould, 1996], but here, I will here extrapolate the wall to be a limitation for all life *per se,* designated as the right wall of adaptive possibility. The right wall also represents a physicochemical restraint toward which life can move but not pass through. Thus, biology ends at the right wall, where chemical and physical possibilities no longer exist; therefore, this wall can also be designated the right wall of structural possibility. The right wall is also an abstraction, yet it differs from the left wall. While chemistry and physics lie behind the left wall, it is important to realize that there is nothing behind the right

wall. Even the term 'the other side' does not make sense here. This wall is an abstraction of the inevitability of nature.

Easily understandable walls, such as the light barrier, are not located in a specific place and are not physical structures; rather, they arise from the very nature of the universe. The more one accelerates, the more one's mass increases, requiring more energy for acceleration. Thus, infinite energy is required to achieve the speed of light, resulting in infinite mass, which is not possible. Another wall is absolute zero on the Kelvin scale. Here, molecules stand completely still with no movement; thus, to say 'further down' on the scale makes no sense.

More subtle walls exist, such as the components of an individual cell experiencing losses in molecular fidelity over time [Hayflick, 2007] or experiencing changes in cell integrity when encountering temperatures above a certain threshold, primarily due to the instability of macromolecules above such temperatures [Merino et al., 2019].

For terrestrial extremophiles, it is not yet known where these more subtle walls are located. An important point that will be addressed is that there may be different right walls of adaptive possibility, depending on the environmental stressors involved, such as acidity or temperature for example.

2.2. Mesophilic peak

Figure 1 shows a high and wide curve standing just to the right of the left wall of minimal complexity. The top of this curve can be designated as the mesophilic peak. As can be seen, no numbers have been set for the figure. There are several reasons for this. The two axes represent different entities. While the x-axis represents possibility space, where terrestrial life has stretched increasingly farther to the right to explore the possibilities of habitats, the y-axis represents availability space.

Strictly speaking, the graph represents the entire history of terrestrial life, from its origin 4.1–3.5 billion years ago [Bell et al., 2015] until the sun leaves the main sequence in the Hertzsprung–Russell diagram in approximately 5 billion years and begins turning into a red giant star [Schröder and Connon Smith, 2008], ultimately ending all life on Earth in the process.

Quantifying the number of life forms in this figure is challenging. It has been hypothesized that more than 50 billion species have arisen since life emerged [Mayr, 1995]. For the current life on Earth, it has been estimated that more than 30 million species may exist [Mayr, 1995], while others estimate that there are ~ 8.7 million species globally for all kingdoms of terrestrial life, while acknowledging that the majority of species await description [Mora et al., 2011]. The current number of prokaryotes has been estimated at $4–6 \times 10^{30}$ cells [Whitman et al., 1998].

While such approximations may be questioned due to their restricted empirical basis and inherent subjectivity, these approximations also overlook the point. Evolution is not given by a single value, but by the variation in the whole system. Immediately after the emergence of life, this estimate of the number of prokaryotes would be one number, yet would differ after a billion years etc. This crucial insight is represented in Figure 1. Although we do not have exact numbers, the shape of the graph has remained broadly constant throughout life's history, with a tail extending further to the right and a mesophilic peak varying but remaining in place. The mesophilic mode, i.e., the value for terrestrial life, which occurs most frequently, has not changed position on the figure; rather, it has grown higher, that is, more abundant, over time.

Treated in purely mathematical terms, the mesophilic peak will never reach zero because the tail of the curve never touches the horizontal axis. Theoretically, life could indefinitely continue to grow more abundantly, possessing the potential for unlimited growth. Thus, only walls to the left and to the right exist, not at the bottom or top of the figure. However, pragmatically, the size and composition of the world will set a limit to this potential, as many factors come into play, such as limited space and limited resources. Thus, the curve will pragmatically represent the abundancy space for terrestrial life.

Interestingly, as will be discussed in Section 2.5, the mesophilic peak can become an extremophilic peak, indicating that the overall environment has become increasingly more extreme, and then return to a mesophilic peak, indicating that the overall environment has become more relaxed.

2.3. Extremophilic right tail

The figure shows a marked skewness to the right, possibly the most prominent feature on the bell curve. This right skewness will be designated the extremophilic tail, which represents the crucial point of this discussion. While the y-axis represents availability space, the x-axis represents available possibility, terrestrial life has stretched farther to the right to explore the possibilities of habitats. While the x-axis can be considered to represent a continuum of time, extending from the origin of life until the moment when the sun will end it, it is more informative to consider this axis as a representation of how far the limits of extremophile potential extend. Thus, we predict the existence of a tail, designated the right extremophilic tail.

This tail represents an extremophilic range expansion going to the right, where habitat opportunities are being tested and occupied. It represents encounters with increasingly challenging environments, i.e., encounters with increasing environmental stressors. This extremophilic front of terrestrial life inevitably exists. Life moves in an unbiased random walk, meaning that the right tail inevitably moves, exploring available space. Thus, the extremophilic right tail represents not only an ecological range expansion into new habitats, but also an encounter into increasing hostile environments.

This movement should not be perceived as a tendency of evolution towards progress, implying that extremophiles are 'higher' organisms than mesophiles. An extremophile is merely an organism that is tolerant to particular environmental extremes and that has evolved to grow optimally under one or more of these extreme conditions [von Hegner, 2019].

Thus, the extremophilic tail moves to the right not because of a preference for progress, but because organisms are initially unable to do otherwise. Life necessarily arises at the simplest complexity. Because virtually no space exists between the left wall and the initial mesophilic mode, nothing can move left. Only one spatiotemporal direction exists, which is toward the right, an unbiased random walk, a purely physical phenomenon occurring in an available space over time.

The fact that virtually no space exists between this left wall and the initial mesophilic mode leads us to a crucial point. On a general bell curve, there would be tails in both directions; however, because this curve is restrained on one side, there is only a right skewness. Here, skewness denotes a coefficient of asymmetry, i.e., information is given regarding the tendency of deviations from the mean (finding an approximate central value of a given set of values) to be larger in one direction than in the other. Thus, although a preferred direction does not exist, terrestrial life can initially only move to the right, i.e., an extremophilic tail will appear to the right, representing an ecological range expansion in which possibility space is explored and occupied.

It is not yet known where the limits of all extremophile adaptations are, which is one of the reasons why no numbers or units are included on the figure. Treated in purely mathematical terms, a normal distribution will continue on to infinity. The extremophilic tail of the curve will never touch the axis because it is asymptotic to this axis; thus, regardless of how far the curve extends, it will never touch the horizontal axis, although it will become increasingly closer. Furthermore, although different factors (e.g., temperature) are involved, with extremophiles adapting to new conditions (e.g., lower or increased temperatures) in new habitats, the right skewness has no physical units: it is a pure number.

There can also be different right walls depending on the extreme stressor. For example, stressors for acidic environments may be numerically different from stressors for environments with increased temperature etc. Thus, different numbers exist for different possibilities and, in reality, are better represented by different graphs. However, pragmatically, the extremophiles represented herein will eventually reach a point at which they do not move any further, i.e., they reach the ultimate right wall. However, there are different right walls, and the roads leading to these walls are evolutionarily long and winding.

Thus, evolution is not described by a single value, but by the variation in the entire system. The shape of the graph has remained broadly consistent throughout life's history, with a mesophilic peak varying but remaining in place, and an extremophilic tail extending increasingly farther to the right.

2.4. Fence of adaptation

Besides the left and right walls, there is another first principle that applies to life. While these walls are full walls, there is a semi-wall between them; more precisely, there is a fence of adaptation between the walls, acting as a threshold for terrestrial life, as shown by the smaller graph in Figure 1.

This fence differs from the walls. Here, life is not directly prevented from moving on, as the fence of adaptation can be bypassed. While only chemistry and physics lie to the left of the left wall, biology exists on

both sides of the fence of adaptation. Organisms can move slowly both to the left and to the right of this fence. However, although biology exists on both sides, the fence of adaptation presents an asymmetry.

Extremophiles will be destroyed if they suddenly move to the left, as crossing the fence of adaptation means entering a different environment. Moving to the left basically means that they will no longer be adapted to their given environment. For example, if a thermophile cannot tolerate a given temperature (lower or higher than that to which it is adapted), it will not survive.

Thus, natural selection will keep extremophiles on the right side, and the majority can accumulate only on the right side of the fence as a new mode; meanwhile, others continue in the right tail as new extremophiles, and those who remain to the right of the fence adaptation in reality turn into new mesophiles. In contrast to the walls, the fence does not represent an inevitable restriction due to the laws of nature, but instead represents environmental stressors that maintain this situation.

It is still possible for organisms to move to the left of the fence, where they will be absorbed within already occupied space. Extremophiles cannot move left towards the mesophiles without being destroyed, as they are not merely extremotolerant towards the extreme environment: they are extremophilic towards it. However, extremophiles can move back if there is time for such adaptation (just as there must be time for adaptation if they are moving to the right), becoming mesophiles in the process. Such extremophiles will not become the former species again, but they can move toward mesophilicity.

Thus, once terrestrial life has passed through the fence of adaptation, a new graph will in an abstract sense emerge, shaping a mode to the right of the fence. The organisms that have now emerged to cope with the environment in question will again be able to increase in number on the y-axis, while a new extremophilic right tail along the x-axis will explore available habitats for those organisms that have gained increased capabilities after crossing the fence. As adaptation to a more extreme environment occurs gradually over time, there are in an abstract sense many rows of fences of adaptation through which life moves.

In the Full House model discussing the relationship between unicellular and multicellular life, life moves entirely freely in an unbiased random walk, bouncing off the left wall, but otherwise having no preference, with the majority of life remaining in the unicellular mode [Gould, 1996].

Contrary to this assumption of a free reign of unbiased random walks, I posit that there is a restriction in the form of the fence of adaptation. Thus, although the initial movement is indeed unidirectional, it is still restricted by the interplay between environmental stressors and adaptation, which influence the direction.

While the x-axis can be considered to represent possibility space, where terrestrial life can indeed move both ways toward the mesophilic or extremophilic direction, the sides of the fence represent an obstacle that can only be circumvented with some effort. Hence, life tends to remain on one side of the fence of adaptation due to biological constraints. From a genetic viewpoint, this phenomenon equates to the tendency of species to remain genotypically or phenotypically similar in the same environment over long periods of time. New mutational variants are mostly harmful and will not be positively selected; hence, they will not be fixed in the gene pool, and the average population will remain in place. New variants can take effect, e.g., by organisms' expansion into peripheral areas, through mutual competition, or through forced encounters with major environmental changes, where variants provide benefits that cause them to be eventually fixed in the gene pool by natural selection. Thus, the fence represents an asymmetry, with mesophilicity being favored over extremophilicity, but not due to an intrinsic preference. However, the case in which terrestrial life tends to remain to the right of the fence of adaptation is only temporary. Sooner or later, such an equilibrium will be broken, and life will change due to the dynamics of the environment.

Here, it is important to note that while organisms that pass through the fence can become a new species, the species from which they originate can still exist and continue in the original environment. While many organisms bounce off the fence, with their species thus potentially going extinct, some species continue to exist in their environment for a long time. They continue, so to speak, on the original graph, while the new species, so to speak, rises up on a virtual new graph. Hence, there are many different individuals and species at stake. Many curves arise on the same overall graph, and the fence of adaptation can provide an abstraction for natural restrictions.

Identifying the walls and the fence between them is not necessarily as straightforward as it may seem. Thus, finding the right wall may not be easy in all cases. In some cases, it is easy. A true wall, such as the above-mentioned light barrier, cannot be breached, and regardless of the adaptation, be it biological or

technological, organisms will never be able to pass or even come near the wall. While this is a trivial fact, there are other non-trivial ones.

Do the components of an individual cell experience random losses in molecular fidelity over time, leading to changes in molecular structure and, hence, function over time? Yes [Hayflick, 2007]. Does the integrity of some cells change under rising temperatures, decreasing due to the instability of macromolecules above a certain temperature? Yes [Merino et al., 2019]. Do information-containing polymers such as DNA and RNA experience changes over time, in the form of mutations? Yes. Do the repair and replacement systems that maintain fidelity in most molecules until an organism reaches its reproductive capacity, themselves suffer the same fate as their substrate molecules over time? Yes, this appears to be case [Hayflick, 2007].

Individual components always eventually impact the right wall of possibility, but it does not necessarily follow that the overall adaptation strategies do, because an organism or a species is more than its constituents. An organism can replace individual components, and a species can evolve different mechanisms. The fact that individual components degrade over time does not mean that species degrade over time.

Extremophiles themselves are a good example of adaptation extending beyond the components themselves. The freezing point of water is 0 °C; yet, extremophiles capable of growth and reproduction exist below such temperatures, not because they possess a cytoplasm with a different freezing point, but because they have managed to adapt, e.g., they can prevent stiffening of their lipid cell membrane [Chattopadhyay and Jagannadham, 2003] or maintain their internal space liquid below water's freezing point [Chattopadhyay, 2006]. If we considered this behavior solely from the viewpoint of water, it would not be possible; however, adaptation makes it possible. Thus, perhaps surprisingly, temperatures below the freezing point of water are initially not a right wall for all terrestrial life, but only a fence of adaptation for some.

It is not yet known where the limit lies for adaptations overall and how far the right tail can be stretched before the fence becomes the right wall, which is one of the reasons why no numbers are set on the x-axis. Just as there are different fences, there can also be different walls, depending on which extremophile adaptation is involved. Thus, extremophilic adaptation to an acidic environment may be numerically different from that for increased temperature, etc. Different numbers for different possibilities exist. Furthermore, adaptation is complicated by the existence of contingent evolution. The adaptation of a given species with or without a contingent event may proceed differently, separating biology from the more deterministically oriented chemistry.

The ultimate right wall is probably determined by available energy. The universe sets a limit, as there will no longer be free energy available in the very distant future; instead, all energy will have become entropy.

2.5. Distinction between mesophiles and extremophiles

One might argue that the distinction between mesophiles and extremophiles is artificial, that all prokaryotes can be viewed as extremophiles, and that they have always been the dominant organisms on this planet. Thus, the mode on the right of the left wall could equally well be considered as extremophiles.

First, in favor of this viewpoint, evidence suggests that the oldest common terrestrial life was thermophilic or hyperthermophilic [Gaucher et al., 2010]. Second, while extremophiles were once considered to be relatively rare, confined to overtly extreme environments on Earth, it is now known that extremophiles are in fact far more prevalent than previously thought [Low-Décarie et al., 2016].

With respect to the first point however, terrestrial life began next to the left wall at the simplest possible complexity. As this first life was fragile compared with extremophiles, we can predict that this first life in the Earth's overall extreme environment must have existed in a semi-protected environment, with its descendants in the peripheral areas adapting to the surrounding extreme environment over time, thus becoming thermophiles [von Hegner, 2020].

Thus, if extremophiles became the mode in the early expansion of life, they represented a new virtual graph in Figure 1, having passed through the fence of adaptation and started a new curve, moving to the right of the fence. These extremophiles will now be mesophiles in relation to the new right tail. In fact, it may be predicted that this must have occurred at least once in the history of life due to the evidence of thermophiles. Hence, the first terrestrial life may have gradually disappeared, leaving only thermophiles. However, life can move to both sides of the fence of adaptation. After environments have become generally relaxed, some of these thermophiles have subsequently returned to being mesophiles again, stopping at the wall. In other

words, after the fence of adaptation, the peak will be composed of extremophiles, but the right extremophilic tail on the new graph will continue to explore the possibility space. Upon successful establishment in an extreme habitat, the peak could also be termed the mesophilic peak in comparison with these new extremophiles, although this peak is more extremophilic than the peak on the large graph.

Thus, due to environmental stressors, the first mesophilic peak may have been replaced by an extremophilic peak, which subsequently became the mesophilic peak observed for Earth today, indicating that the overall environment has become more relaxed. Expressed less abstract, for a time, we will have a low variation, i.e., a small standard variation on the bell curve. However, as the tail moves further to the right, we will again have a high variation, i.e., a large standard variation.

With respect to the second point, the distinction between mesophiles and extremophiles must necessarily exist. Thus, the extremophile tail is inevitable. Life moves in an unbiased random walk restricted by the fence, meaning that the tail inevitably moves and explores available space, i.e., available habitats. The tail represents an extremophilic range expansion; as it moves to the right, organisms become more extreme. In comparison with this extremophilic front, organisms to the left of the tail are mesophiles. Because the organisms in the tail belong to the minority, mesophiles must necessarily be the majority, even if the survival capacity of these mesophiles is impressive.

Thus, although extremophiles are far more prevalent than previously thought, the majority of terrestrial life should not be considered extremophiles, as the right tail will always be the extremophilic front.

3. Applications for potential extra-terrestrial biology

As discussed thus far, Figure 1 represents of course the situation of the Earth. This figure tells us that one should not focus on individual datasets in a particular era, nor should one focus too narrowly on individual values, on single individuals and trends, but rather on the full spectrum of evolutionary variation throughout the entire system in time and space. This full system is the reality reflected by the interdependent relationship between physics, chemistry, and biology in the figure.

In the forthcoming discussion of potential extra-terrestrial life, this evolutionary variation, i.e., the dynamic relationship between the y-axis and x-axis and between mesophiles and extremophiles, will be imposed on exoworlds in order to analyze how life could behave on such worlds. Thus, imposing this relationship on worlds similar to or different from the Earth is more a deductive approach than an inductive one, which adds to the framework's predictive power.

3.1. Exoworlds: alternative biochemistries

Figure 1 shows the first principles that govern life. As one of the forces in this graph, the evolutionary variation does not depend on the specific biochemistry. Different types of biochemistry are likely to play a role in chemical evolution – the processes leading up to the first life form. However, once life is 'up and running' to the right of the left wall, the various biochemistries that can constitute differences between terrestrial and extra-terrestrial life will have secondary importance.

Several types of alternative biochemical systems have been proposed that could potentially apply to exoplanets and exomoons around the galaxy, such as alternative chirality biomolecules [MacDermott and Tranter, 1994], silicon atoms serving as the backbones of molecules to carry biological information [Pace, 2001], DNA molecules consisting of 8 bases rather than 4 [Hoshika et al., 2019], or life existing in liquid methane on the surface of Titan [McKay and Smith, 2005] etc.

Rather than focusing on a specific hypothetical alternative biochemistry, for the sake of simplicity, I will be generic and use 'potential alternative biochemistry' (PAB) as a variable representing different biochemistries. If one imagines an exoworld in which PAB-based life has arisen rather than the familiar terrestrial life, how would this extra-terrestrial life unfold? It can be predicted that such life would in fact unfold in the same manner illustrated in the figure for life on Earth.

The extremophilic tail moves to the right not because of the biochemistry constitutions of organisms, but because the organisms can do nothing else. Life necessarily arises at the simplest complexity. Because virtually no space exists between the left wall and the initial mesophilic mode, only one spatiotemporal direction exists, aimed toward the right via an unbiased random walk, a purely physical phenomenon that simply occurs in an available space over time.

If PAB-based life arises on an exoworld, then PAB-based extremophiles will arise on that world as well because, although extremophile capacities seem impressive, extremophiles do not evolutionarily differ from life *per se*. Hence, life expands into new habitats, gradually adapting to these habitats. As some environments will always be more extreme than others, mesophiles and extremophiles will be present. Thus, regardless of the specific biochemistry comprising PAB-based life, the extremophilic tail will still move to the right, exploring possibility space, i.e., habitat possibilities will be tested and occupied on the given world.

The mesophilic abundance to the right of the left wall does not arise from the organisms' biochemistry constitutions, but arises because some organisms necessarily represent the mode, i.e., the majority of life forms, this is what data in a bell curve represents. In a traditional bell curve, for example, there are humans on the left that are shorter and humans on the right that are taller than the majority of humans, the mode, in the middle. In the given graph, the left tail is virtually absent, but there is necessarily a mode of majority organisms that differ from the extreme organisms moving toward the right. Thus, regardless of the specific biochemistry comprising PAB-based life, extra-terrestrial life will still organize itself with a major portion of life depicted in the mode of the given world.

The fence of adaptation is not caused by the biochemistry constitutions of organisms, but by individual variations among organisms in relation to each other. If a multitude of PAB-based life exists, then evolutionary variation will also exist; thus, fences of adaptation will be in place as well. Consequently, due to environmental stressors and competition for limited resources (stronger within a species, weaker between species), natural selection to circumvent the fence of adaptation between a multitude of organisms will be in effect. Regardless of the specific biochemistry comprising PAB-based life, evolutionary variation will exist, and thus, natural selection between organisms will occur in the given world.

Hence, what happens between the walls do not depend on the specific biochemistry. If PAB-based life exists, then the graph for these life forms and terrestrial life will be broadly similar. The graph peak may be higher or lower than that of Earth's, and its right tail may be shorter or longer, but a bell curve will still arise for this variation.

Here, an interesting question arises. While PAB-based life, such as silicon-based organisms, seems to be possible, such organisms may have a different adaptive range possibility than carbon-based organisms. Thus, the adaptive responses and possibilities will differ between a PAB-based species and a carbon-based species. For example, will a different biochemistry mean that PAB- or carbon-based organisms reproduce more slowly or rapidly relative to each other? Will a PAB-based hyperthermophile reach the right wall before a carbon-based hyperthermophile, or vice versa? Viewed purely from a chemical viewpoint, PAB-based life and carbon-based life have different possibilities. Thus, it seems reasonable to extrapolate that silicon-based life and carbon-based life also have different adaptive range possibilities.

In a first consideration, if PAB-based life and carbon-based life existed simultaneously in one world, they would compete for space and resources. Here, the biochemistry differences could presumably prove crucial in the long term, with one of the species potentially being outcompeted by the other. Yet, on Earth, both bacteria and archaea exist. Although they are both carbon-based organisms, they are quite different in many ways. Although bacteria are dominant, archaea has managed to remain. This may be due to the fact that contingent events play an important role in evolution, allowing one species to remain on the stage of life, even when another species seems to have the advantage. Thus, if one species disappears, it is not necessarily due to the different range of possibilities caused by biochemistry constituents or the possibility that one species reached the right wall before the other.

If the focus is not on different species outcompeting each other, but only on whether PAB-based and carbon-based life can bypass the fence of adaptation better than each other or reach the right wall faster than each other, then it still seems reasonable to extrapolate that PAB-based and carbon-based life have different adaptive range possibilities.

However, once PAB-based life and carbon-based life are 'up and running' after originating at the left wall, this perspective does not necessarily apply. From a chemical viewpoint, the components of PAB-based and carbon-based life could, for example, break down faster or slower than each other when encountering the same type of stressors, such as the same increased temperature, radiation level, or acidity etc. However, from a biological viewpoint, an organism or a species is more than its constituents. Life is not a passive cargo, but responds actively and dynamically to its environment.

Of course, if organisms were immediately exposed to an extreme environment, then the components would matter, in which case they would break down, one biochemistry constituent faster than the other. Yet adaptation is a gradual step-by-step process. An organism can replace individual components, and a species can evolve new environmental responses. The fact that individual components break down over time or due to stressors does not mean that species break down.

Thus, the possibilities of chemistry differ from the possibilities of biology. For this reason, evolutionary considerations must be taken into account. As mentioned in Section 2.4, terrestrial extremophiles provide a good example of adaptation extending beyond the components themselves. The freezing point of water is 0 °C; yet, there exist extremophiles such as *Deinococcus geothermalis* DSM 11300, capable of surviving at -25 °C [Frösler et al. 2017], and extremophiles such as *Planococcus halocryophilus* Or1, capable of growing at -15 °C with 18% salinity [Mykytczuk et al., 2013]. Adaptations among such extremophiles also include vitrification (without intracellular freezing) [Clarke et al.2013]. Some organisms can overcome membrane stiffening by incorporating lower-melting-point fatty acids, such as unsaturated, short-chain, or branched-chain fatty acids, which provide a fluidizing effect on the cell membrane [Chattopadhyay and Jagannadham, 2003]. At the opposite end of the scale, there exist extremophiles such as *Geogemma barossii* 121, which can live at temperatures up to 130 °C [Kashefi and Lovley, 2003]. If the outcomes were solely determined by the individual components themselves, these organisms would not exist; yet, they do exist, having managed to adapt to the environment.

We must also consider that the same fence represents different challenges, with different adaptation possibilities for the same fence, even for organisms from the same species. Thus, members of the same species are confronted with the same situation in the form of the fence of adaptation, which seemenly paradoxial indicates that the individual members face different obstacles due to their variation, thus, the fence are passed by only a few. For this reason, not all individuals have offspring. This condition applies strongest within a species, but can also apply if different species compete for the same environment. Different species have different challenges with the same fence of adaptation, even in the light of convergent evolution. Sometimes, species cannot get past the fence and become extinct. However, the fact that they become extinct is not necessarily due to their components, but their variation.

Thus, both PAB-based and carbon-based life continue to bypass the fence of adaptation, each with its own challenges, which are not necessarily based on their biochemistry constituents. Yet, it is not easy to predict how fast or how efficiently the evolutionary variation of these organisms unfolds. This difficulty is not solely due to the obvious lack of data, but also due to the inherent unpredictability of evolution that comes from the versatility of adaptation and contingent events.

However, will the fence of adaptation more quickly become the right wall for one set of life forms if they follow the same story on both worlds? This may be the case. The right wall is independent of adaptation and contingent events, but just as we do not yet know the limits of terrestrial extremophiles, it is also currently not possible to determine the strength of the relationship between PAB-based and carbon-based extremophiles or to predict which one will arrive at the wall first. One obstacle to such predictions is the fact that an organism consists of more than just a single biochemistry constituent, such as membrane lipids or molecules of RNA or DNA. A multitude of components are involved in even the simplest organism, rendering such predictions even more complex.

Although possibilities may vary due to different biochemistries, the overall graph will remain the same. The evolutionary variation remains and unfolds between the two walls. Thus, if Titan is indeed teeming with life living in methane rather than water, then the overall graph for this extra-terrestrial life will still be the same as that for Earth life. This life will still be constrained by the first principles discussed thus far.

Until now, we have adhered to the fact that life arises in its simplest form at the left wall. However, could life on other worlds arise in a simpler form than what is known for terrestrial life? It is not easy to see how life can be simpler or more fundamental than the most rudimentary functional bacterium. Yet, in recent years, nanobes have been discussed. The existence of nanobes has long been considered, but only relatively recently have they been verified as indeed being organisms [Luef et al., 2015].

These organisms are significantly smaller than bacteria and could potentially constitute a vast independent domain only recently considered. However, much evidence suggests that nanobes are adapted from bacteria and, in fact, depend on them for survival, as nanobes may lack some necessary organelles to survive on their

own. Yet, even if terrestrial nanobes are an independent domain, they will still be within the framework reviewed. They will have arisen at the left wall and will have followed all of the steps undertaken thus far. Consequently, mesonobes and extremonobes should exist on Earth, and their extra-terrestrial analogues could potentially exist elsewhere in the cosmos.

3.2. Earth and Mars: exemplars of evolutionary variation

The manner in which evolutionary variation proceeds for a world like Earth has been reviewed in Section 2. Here, Figure 1 showed that in a habitable world like Earth, mesophiles arise on a curve to the right of the left wall, which rises and broadens, i.e., the number of mesophiles has increased throughout life's history. Meanwhile, an extremophilic range extension is also observed moving to the right, where all habitat possibilities are being tested and occupied.

These two facts are important to keep in mind because each extension could be considered as an indication of healthy habitability in a world. The term healthy is not meant as a geocentric violation of the Copernican principle, but to indicate that evolution has the free opportunity to explore a world's habitats. In other words, the planetary ecosystem has not collapsed on a healthy world. On Mars and exoworlds like Mars the situation will be different.

If life did indeed occur on Mars in the past, then it can be predicted that the extremophilic tail for this life would have moved to the right because the Martian organisms could not do anything else. For this life, the mesophilic abundance to the right of the left wall would be present because some Martian organisms necessarily represent the mode, i.e., the majority of life. The fence of adaptation will have been in place due to individual variation among Martian organisms in relation to each other. Thus, the graph of that world may have varied relative to the Earth's graph, but would still be similar overall, demonstrating a healthy habitability in the Noachian era.

However, if extra-terrestrial life once originated on Mars and thrived there for some time, then the Martian ecosystem has long since collapsed. Here, the initial increase in life is stopped, while the extremophilic range expansion is stretched even further to the right as life seeks to survive on this world. This situation could be considered as unhealthy habitability in a world.

Here, it might be intuitively expected that the curve peak would either simultaneously move downward and flatten (platykurtic distribution) or that the curve peak would simultaneously increase and become thin (leptokurtic distribution). Indeed, these situations are possible because, for many distributions encountered in practice, a positive kurtosis (a measure of the thickness or heaviness of a tail) corresponds to a sharper peak with higher tails than seen in a normal distribution. Yet, the correspondence between kurtosis and peakedness is not valid in a strict mathematical sense [Westfall, 2014]. Thus, a distribution with a flat top may have an infinite kurtosis excess, whereas one with an infinite peakedness may have a negative kurtosis excess [Weisstein, 2020]. Consequently, the kurtosis excess provides a measure of greater extremity in deviations (i.e., the presence of heavy tails) in a distribution, not the degree of peakedness [Westfall, 2014]. As a result, the dataset has more in the tail, that is, a heavier and longer tail, than a normal mesokurtic distribution.

On Earth, the mesophilic mode has not changed position on the bell curve, but has only grown over time, while the extremophilic tail has stretched increasingly farther to the right, owing to the fact that the Earth's conditions are favorable for mesophilic life. Thus, while the figure does indeed represent universal restrictions, the shape of the graph is due to the Earth's own characteristics. It is a healthy world.

In contrast, for a world like Mars that is gradually shifting to being unhealthy, the bulk of extra-terrestrial life will move to the tail of the distribution rather than remaining near the mean, corresponding to greater extremity. Thus, the important point here is that the number of mesophiles is declining on the planet, while the number of extremophiles is not necessarily increasing; rather, the extremophiles are enduring by stretching increasingly farther to the right, becoming more extreme.

The movement of life occurs in an unbiased random walk (albeit with a restriction in the form of the fence of adaptation), where life sometimes moves to the right, thus extending the tail in the distribution of extremophilicity, or to the left, becoming absorbed within already occupied space. In a healthy world like Earth, extremophiles can return to being mesophiles. However, on worlds like Mars, life cannot go back to the mesophilic end of the x-axis without being destroyed. They remain standing to the right of the fence of

adaptation and, from there, will continue to extend farther to the right on the x-axis (provided there exist environments in which extremophile analogues can exist), becoming more extreme.

Viewed purely as a mathematical function, this extra-terrestrial life will approach zero; however, the curve will never actually reach zero, hitting the end of an adaptive potential, because a normal distribution continues on to infinity. The extremophilic tail of the curve will never touch the x-axis, as it is asymptotic to this axis; thus, mathematically speaking, regardless of how far the curve extends, it will never touch the horizontal axis. One can go as many standard deviations away from the mean as one wants, but the area contained in these regions will be very small. Pragmatically, extremophile analogues under such conditions will reach a point at which they cannot survive on such worlds. They will eventually hit the right wall.

However, until an organism reaches the right wall, their survival presupposes that they can continue to bypass the fence of adaptation. This extra-terrestrial life will continue to stand to the right of the fence of adaptation on a virtual new graph, forming a new right extremophilic tail. Eventually, there will no longer be any active life, as life will reach the right wall of possibility and will no longer be able to adapt to the rising extreme environment. Thus, rather than a binary choice between habitability and uninhabitability, one can speak of healthy and unhealthy ecosystems lying on a gradual habitability scale.

As a further obstacle, although first considerations indicate that organisms can continue for a long time to increase their extremophilic capacity for accommodating the increasing uninhabitability of a world, life in a healthy ecosystem does not exist in isolation. Consequently, life in a collapsed ecosystem, such as that on Mars, will additionally face ever greater difficulties, due to increasingly existing in fragmented ecological pockets, where life will find it harder to draw on the resources required to bypass the fence of adaptation. Life in such pockets could potentially endure in the form of an analogue to *Halorubrum lacusprofundi*, which is both a halophile and a psychrophilic organism, in principle capable of living in pockets of Martian brines [Reid et al., 2006]; yet, such life will face increasingly greater challenges.

The given graph presents expectations for a world like Earth, where the curve represents a dominant presence of mesophilic life. It is important to realize that although evolution is enclosed by the walls, i.e., the restrictions of physics and chemistry, the biology lying between these walls is not a passive entity. Thus, it can be predicted that when the mesophilic curve becomes high and wide, it can potentially transform the environment of the given world into habitable environments and bring the planetary atmosphere out of equilibrium.

Life itself inevitably has an effect on the environment in which it exists. Thus, every organism utilizes free energy in order to live and releases heat or waste products to the surrounding environment, i.e., it lowers its internal entropy by increasing the entropy of the external environment [von Hegner, 2020]. Hence, organisms do not merely form a passively varying curve or extension to the right. The products in the mode and tail, i.e., the organisms, can actively act on the abiotic environment in which they exist. Such an atmosphere far from equilibrium will be maintained by the massive number of mesophilic life forms in the graph.

Organisms are known to have transformed the entire atmosphere of early Earth [Domagal-Goldman et al., 2016]. Thus, the atmosphere can provide a biosignature; if purely chemical factors can be disregarded, the atmosphere can show whether extra-terrestrial life may be present in a given world [Hitchcock and Lovelock, 1967], with the world's life behaving as in the terrestrial graph, exhibiting a high and wide curve of life. Here, the extremophilic right tail itself has a negligible effect due to the modest amount of life it represents.

These considerations are non-trivial because they allow one to predict extra-terrestrial life on worlds like Mars and its analogues, even though signs of life, such as an atmospheric disequilibrium, have disappeared again. Even though the figure does not depict a linear relationship, for worlds in which the mesophilic abundance decreases and the atmospheric disequilibrium approaches equilibrium, we can still deduce that life may be present as the extremophilic nature of life becomes more profound. Contrary to the original idea behind an atmosphere in disequilibrium, where the absence of an atmosphere in disequilibrium indicates the absence of life, the relationship of the figure shows that even if the content of the graph is not sufficiently high and wide to affect the atmosphere, the right tail can be stretched so far that life can still be present in a world that once had such an atmosphere.

After all, such an atmosphere is a by-product of life, but it is not initially a prerequisite for life. The first terrestrial life, and the first modest population of life, evidently existed without such an atmosphere; thus, this framework provides the important insight that a modest population of extra-terrestrial life can again survive without such an atmosphere. Consequently, used as a biosignature, the figure can tell us whether a world is healthy, but not whether life has disappeared.

However, as will be discussed in the next section, there will inevitably be a time when extra-terrestrial extremophiles disappear on such an exoplanet, as life continuously adapts to the increasingly extreme environment and is pushed faster towards the right wall than its analogues on Earth.

3.3. Extremophiles and endospores

Due to its stellar development, the sun will leave the main sequence in approximately 5 billion years and start turning into a red giant star [Schröder and Connon Smith, 2008]. At this point, the sun will destroy (or will have already destroyed) all life that could potentially have remained on Earth. Thus, from a purely physical viewpoint, it is a star that will one day eliminate life, terrestrial as well as extra-terrestrial, regardless of whether the star becomes a supernova.

Still, there are a number of subtleties worth exploring from an astrobiological viewpoint, which can reveal interesting dynamics occurring in the graph. Before a star like the sun finally ends life on a world like the Earth, gradual changes will have taken place. Due to the sun's changes, Earth's planetary environment will become increasingly more extreme, and life will continue to adapt. However, seemingly paradoxically, it is the increasing extreme environments themselves that will prevent extremophiles from surviving long before the sun sheds its outer layers and becomes a white dwarf. As discussed above, from the astrobiological viewpoint, terrestrial and extra-terrestrial life will end because it is gradually pushed towards the right wall and cannot move any further.

It is not yet known where the limits are for extremophiles. As mentioned above, for certain situations, extremophiles can adapt beyond the purely physical parameters applicable to their individual components. However, in a world that is becoming more extreme and more environmentally uniform, one can expect that the number of graphs for the fence will gradually shrink to only one, indicating that only one extremophilic species has managed to 'hold on' to this world. This one species will also eventually reach the right wall, remain there, and, if the environment continues to become more extreme, disappear as a consequence of not being able to adapt further.

Yet, we can predict that life will eventually move from extremophiles to endospores. In this adaptation, an organism can enter dormancy as an endospore, the toughest (dormant) life known. Thus, it is possible that endospore analogues could still currently be present on a world like Mars.

In this last phase of life on a world, a right tail will initially extend on the x-axis. However, this situation will be different from the cases discussed thus far. In terms of activity and reproduction, life will have impacted the right wall. The extreme environment will prevent endospores from emerging from their dormancy and becoming active, as there will be no suitable environment for them; if they somehow become active, they will be destroyed by the environment. Thus, life itself will not be able to actively contribute to its movement on the graph, and adaptive dynamics will not be seen here.

Initially, extremophiles and endospores will exist simultaneously, but when the last extremophiles are gone, only endospores will remain. Thereafter, no new endospores will be created in this phase. There will be only a selection of already existing endospores, consisting of the hardiest ones, while the environment rises in extremity. Thus, unless the endospores escape their world through lithopanspermia [von Hegner, 2020], they represent an evolutionary trap, as the evolutionary variation has disappeared. Evolution is active and dynamic, but in this case, only external factors will be responsible for the events. Consequently, endospores will become the tail, a virtual line around which the endospores will cluster, and their numbers will inevitably decrease over time along the x-axis as the environment extremity increases.

Thus, in a world, life begins with a single fragile organism and ends with a single organism: the toughest of them all.

3.4. Multicellular life: a remark

One area that has not yet been touched upon here is multicellular life. While conditions for life and its distribution *per se* are the primary topic in astrobiology, the question of multicellular life is still relevant. The

relationship between unicellular and multicellular life was the subject of the original Full house model [Gould, 1996]. In this work, the author argued that although multicellular organisms appear to be the pinnacle of adaptation and although evolution appears to be moving toward increased complexity, such organisms are simply one end of the complexity distribution. The author argued that the full system of variation is the reality and that multicellular life, which first emerged relatively late in life's history, actually constitutes only a modest proportion of life, while, by any measure, bacteria have remained the most common and most successful life form from the beginning to the present [Gould, 1996]. Thus, multicellular life is thoroughly discussed therein, and only certain considerations new to this discussion will be mentioned here.

Intense debate has focused on whether life can be said to move towards complexity. Based on the Full House model, it is not clear that it does. Contrary to the Full House model's original proposal for free reign of unbiased random walks, I propose that the fence of adaptation represents a certain obstacle to this walk, as discussed in Section 2.4. Thus, while the unbiased random walk is unidirectional, i.e., life can indeed move towards complexity or simplicity, life tends to stand on one side of the fence. Although unicellular life will certainly be present in a world where life has arisen, as all cellular life begins at the left wall, there is no obvious reason why multicellular life should also arise. However, if multicellular life does occur, it tends to remain in existence due to the fence of adaptation.

Another emerging relationship is the asymmetry between unicellular and multicellular life. If the story of multicellular life were played back, it is not certain that multicellular life would arise again. If it did occur again, we would not see the same species as those seen since the Cambrian explosion, which is a consequence of contingent events, the historical dimension that separates biology from chemistry and physics [Gould, 1996].

This aspect of multicellular life is in contrast to unicellular life. Figure 1 shows that some regularity in evolution is indeed applicable to unicellular life. If the story of life were played back and started over at the left wall, a graph very similar to the one shown would be expected. Convergent evolution plays a role here, as it is well known that widely differing species in the same type of environment can achieve common structural features that are beneficial in those environments.

However, we observe asymmetry here, with convergent evolution becoming more random as one more closely approaches multicellular life. That asymmetry is not given by a straight inclined line. Rather, it is a sharper transition, as convergent evolution is profound among unicellular life, while being more arbitrarily distributed among multicellular life. If the right tail is interpreted as multicellular life with complexity increasing as one moves to the right, then it follows that convergent evolution also decreases as one moves farther away from the unicellular mode.

However, regardless of these aspects, multicellular life arose much later than extremophiles and has not extended, nor will it never extend, as far as extremophiles. This result is due to their fragility. Multicellular life has a very limited range compared with unicellular life. If we view evolution in the form of reproductive success and range expansion into new habitats, then the unicellular style of life has remained most successful by any measure, while multicellular life is far behind. In one sense, such multicellular life is at the mesophilic end of the axis, although it can produce extremotolerant life such as the tardigrade, which can withstand certain extreme environments but has a life cycle only in mesophilic environments.

Thus, the figure for mesophilic and extremophilic life shows a much more fundamental relationship than that between unicellular and multicellular life, and the corresponding graph can be understood as multicellular life appearing on a new and smaller virtual graph given by the fence of adaptation.

4. Discussion

Some points arise from the previous discussion. One point is that 'life as we know it' is evidently a phenomenon on a planetary body, and as discussed, that life is the full spectrum of variation unfolding between restrictions of minimal complexity and adaptive possibility – or shorthand, life is the evolutionary variation unfolding between two enclosing walls. But do these two statements necessarily follow each other? Are they mutually dependent? Must the situation on the graph necessarily be imposed on a planet or moon?

Let us consider the following statements: 'Φ is an extremophile,' mean 'Φ descends from an extreme habitat.' Hence, 'Φ is an extremophile' but 'Φ does not descend from an extreme habitat' is false as per

definition; further, if 'Φ is an extremophile,' 'Φ descends from an extreme habitat' and 'if Φ descends from an extreme habitat,' 'Φ is an extremophile' are tautologies [von Hegner, 2019].

However, 'θ is the evolutionary variation unfolding between two enclosing walls' but 'θ does not exist on a planetary body' is not false per definition because 'if θ is the evolutionary variation unfolding between two enclosing walls,' then 'θ exists on a planetary body' and 'if θ exists on a planetary body,' 'θ is the evolutionary variation unfolding between two enclosing walls' are not mere tautologies. Hence, 'life is the evolutionary variation unfolding between two enclosing walls' does not mean 'there is life on a planetary body.' These two statements do not have the same semantic meaning in astrobiology.

Of course, this is simply a semantic argument, not a logical or evidence-based argument. However, if this argument has some merit, then there could be a scale on which the probability of life falls outward, with rocky worlds having the highest probability of life, followed by the outer atmospheric layers of gas giants [Sagan and Salpeter, 1976] and then perhaps even complex self-organized living plasma structures in outer space [Tsytovich et al., 2007]. The central point of this discussion will always be the left wall: how the first life forms can arise and how evolutionary variation can unfold in such environments.

Another point focuses on the debate regarding probabilities involved in chemical evolution. Is life a natural consequence of certain types of star formation and the self-organization of matter? Or are a wide range of probabilities at stake for the occurrence of life? While this debate has not yet been settled, it is important to note that Figure 1 does not represent probabilities for biological evolution. Once life is 'up and running,' it will proceed with a mesophilic mode, a right extremophilic tail, and fences of adaptation. Life cannot do anything else.

This debate is about the course of events in biological evolution. Yet what about the course of events of chemical evolution? What are their probabilities? As life beyond Earth has not yet been located, rather than seeking answers to this probability among a variety of worlds, one solution could be instead to seek answers at home.

An important consequence of the established framework is that because life necessarily arises at a left wall of minimal complexity, then any origin of cellular life that hypothetically arises on other worlds will have a close structural resemblance to the first terrestrial life. Thus, the hypothesis can be put forward here that bacteria and archaea may represent two independent origins of life on Earth.

Their mutual similarities may firstly be due to the fact that the left wall represents a blue print for life: cellular life can only arise in this way, with a modest space for structural variation. Their similarities may secondly be due to the fact that they have subsequently transferred genes among themselves through lateral gene transfer, thus recombining new genes into their respective DNA, and/or through the spreading of viruses, thus blurring genetic analyses of their true origin.

Thus, in principle, it is possible that archaea did not branch off from the bacterial domain, as is the current consensus, but that bacteria and archaea originated from two independent origins of life on this planet, with archaea probably emerging later. From this viewpoint, bacteria and archaea are initially not cousins but became so later and represent not only different terrestrial domains, but two independent life forms sharing this planet. Although these life forms are not extra-terrestrial life occurring elsewhere, they still represent life occurring in the same world over two different time periods. Thus, we may be able to place some restrictions on the probabilities of chemical evolution for the origin of life.

Another point is the interest in life elsewhere in the universe, life that could potentially be so different that it will provide an advancement in our understanding of life. As life beyond the Earth has not yet been found, a solution could again be to seek it here at home. Can 'life as we do not know it', so to speak, hide among 'life as we know it'? Can anything be said about such life, even partially on the basis of 'life as we know it'?

Strictly speaking, Figure 1 represents the whole story of life from its origin to its end. It contains the whole set of life on Earth. Even 'life as we do not know it' must exist within a system, a system with interdependent variables, although this system will include variables interacting in a way that is unfamiliar to us. There is in fact such a system, well known to us, but whose variables interact in such a way that it is not generally considered as life, but which in the light of the framework presented, can be interpreted as such - viruses.

Viruses possess a peculiar position in comparison with what is perceived as life. They have probably existed as long as terrestrial life. They closely follow the organisms on the axes of the graph, but do not follow the life cycle of these organisms. Whether viruses can be considered as life is debated. However, the fact is that viruses occur within the figure: they are a subset within the graph.

We do not perceive viruses as life because, in an abstract sense, we are inside the graph itself. We do not see life from the outside in its entirety. We only see some values, some trends.

Thus, when we see a single value for life, we see a single autonomous organism. When we see a trend for life, we see a single internally reproducing species.

In contrast, when we see a single value for viruses, we see a piece of genetic information in a protein coat. When we see a trend for viruses, we see an integrating and/or replicating piece of genetic information.

Thus, when we only look at values and trends for viruses, we do not see life. However, when we consider evolutionary variation for the subset of viruses, we see 'life as we know it.' This asymmetry confuses us. Because when we look at a single value for 'life as we know it,' we see a dynamic autonomous lifeform, and when we look at the whole evolutionary variation, we see 'life as we know it.' We have become accustomed to automatically perceiving this as the symmetry of life.

The issue here is that our view of viruses focuses only on a single value or trend rather than the full spectrum of variation in the entire system over time and space. Evolution is not given by individuals and species. Such a notion is analogous to considering only a single neuron in a human brain. There is no consciousness to be found in a single neuron, and a single neuron does not give us much understanding of consciousness. However, by considering the whole network of neurons, i.e., the connectome, that produces consciousness, we can obtain an understanding.

Thus, viewed from within the graph, a familiar system of viruses is seen, but with its variables interacting in such an unfamiliar way that it is not considered life. Yet, if the graph is viewed from the outside, this consideration changes. Here, we find the same overall system for 'life as we know it.'

The set of 'life as we know it' exhibits evolutionary variation over time, an overall continuation of genetic information, mutations, and natural selection in the graph. These same conditions are met by the subset of viruses. This vast subset exhibits the same overall continuation of genetic information, mutations, and natural selection; moreover, this subset can migrate back and forth on the x-axis and can increase or decrease in number on the y-axis. Thus, the perceived asymmetry does not apply to the graph as a whole. The two sets show the same pattern, with both appearing very much like life.

Some objections can be made to this interpretation. It could be said that life moves toward greater complexity, while this is not the case for viruses. However, although we have become accustomed to thinking that life evolves to be more complex, the bulk of life has remained prokaryotic throughout the history of life.

Of course, it is now known that giant viruses or girus exist, which are larger than some species of bacteria [La Scola et al., 2003; Brandes and Linial 2019]. These giant viruses have large genomes in comparison to the average virus and contain a number of genes not present in other life forms. However, the majority of viruses have remained simple, i.e., are distributed on a figure in the same way as 'life as we know it,' with the majority in a mode to the right of a left wall. Thus, just as a modest tail of multicellular life is seen moving to the right, where the fence of adaptation causes such life to remain in existence, a similar modest movement of large viruses is seen in a right-skewed tail. In both cases, they fill only a dwindling part of the set and subset. In either case, this behavior cannot be interpreted as a trend.

It could also be argued that all 'life as we know it' originated from a single common ancestor, which does not seem to apply to viruses.

The first viruses may have arisen from macromolecules such as protein, RNA, or DNA at the same time that cellular life appeared, according to the so-called virus-first hypothesis [Mahy and Regenmortel, 2009]. In fact, viruses may have originated deeper inside the left wall and may have emerged several independent times, as their emergence seems to require less of chemical evolution than that of an autonomous cell. Other viruses may be younger, having arisen from pieces of RNA or DNA from cellular life, according to the so-called escape hypothesis [Mahy and Regenmortel, 2009]. Thus, viruses may have arisen several times in the past by these mechanisms, and consequently, the subset of viruses on Earth does not have a single common origin. This aspect could truly separate the two sets.

However, while we have become accustomed to life in a world originating from a common ancestor, one may ask whether this is a necessary feature of all life forms in a set of life or whether it simply applies to this particular set of 'life as we know it' because it is a characteristic of terrestrial life, which happened to proceed in this manner. Thus, this view is valid for one set of life, but not necessarily for another set.

As stated before, evolution is not given by individual values and trends, but by the full spectrum of variation in the entire system. For example, if prokaryotic life occurred several times independently on Earth, as I suggested for bacteria and archaea, and if these life forms could engage in genetic transfer with each other, then a common origin would not be a necessary feature. The prokaryotic set of life would proceed in the same way. The conclusion is the same for viruses. Viruses can emerge over several periods, but the evolutionary variation for the entire subset would proceed in the same manner, regardless of whether they arise from one or more origins.

Thus, it is possible that an entire subset of life exists among the other domains of life, which we do not see because we are, in an abstract sense, inside the graph itself. Yet, if we step outside the graph and see it in its entirety, then we see that viruses appear very much as a vast supra-domain subsumed in the graph for the totality of life on a world. Such life belongs to a supra-domain, in that it does not exist beside the other domains nor is it limited to affecting only one of them. Rather, this life affects all of the domains.

Although Section 3.1 stated that it is not easy to see how life could arise at the left wall and be simpler than the most rudimentary functional bacterium, there is potentially a non-trivial example here. After all, viruses are not cellular life. In a way, for such a simple rudimentary bacterium, the focus is on a single value. However, viruses have bypassed this focus by skipping the cellular step and instead proceeded directly to evolutionary variation.

While ancient viruses originated at the left wall, similar to cellular life, viruses require of cource 'life as we know it' in order to continue or re-emerge later. They are carried forward by the other domains. Thus, in principle, ancient viruses in this supra-domain, which evolved at the same time as cellular life appeared, can exist for a time, but cannot reproduce without the other life forms.

On the other hand, prokaryotes also cannot drive evolutionary variation in the graph without external resources. Thus, a bacterium is no more autonomous than it depends on external material and a flow of energy to reproduce. Prokaryotes do not exist in a vacuum, but are integrated into the environment, deeply dependent on available planetary or solar resources. Thus, for viruses, cellular life merely represents a layer of refinement between this external material and energy flow, a difference in degree rather than a fundamental difference.

5. Conclusion

Can a different kind of life exist than what has been discussed? When asking such a question, one must keep in mind that we are thus not simply considering another kind of biology; but also considering another kind of chemistry and another kind of physics. Figure 1 represents a coherent interdependent whole. Thus, the term 'kind' is crucial here.

There has been much discussion on kinds, more precisely on natural kinds, which are outside the focus of this article. Here, the following definition will be used [Bird and Tobin, 2018]: 'To say that a kind is natural is to say that it corresponds to a grouping that reflects the structure of the natural world.'

One can no longer say that a species is a natural kind because lineages usually evolve gradually over time, leading to the emergence of new species, meaning that a single value characteristic of a particular species can change over time. Thus, assuming that natural kinds participate in the laws of nature, could the whole system in the figure possibly itself be considered a natural kind? From this viewpoint, a completely different system of life might be imagined. Once again, we are asking not only for another kind of biology, but also implicit asking for another kind of chemistry and physics.

However, can it be ruled out in advance that another kind of biology exists? In principle, it cannot. There may well be a kind of chemistry and physics that has not yet been discovered that can change the state of affairs. Yet, this may be a very strong demand to make. If we do not find evidence of a different kind of chemistry and physics in another solar system and, indeed, do not expect a different kind of chemistry and physics in another solar system, then why expect a different kind of biology in that solar system? Indeed, why would one make demands on its existence?

Due to the importance of an issue of this magnitude, one must adhere to high standards of not only evidence but also of theoretical rigor. At present, there is no empirical pressure, and in fact, no theoretical pressure to support such a claim. Thus, why should we commit belief in the absence of empirical and theoretical pressure?

That is not to say that potential life elsewhere cannot be mind-boggling. While the range of possibilities is ultimately restricted by the first principles reviewed above, we also see that there is room for a vast diversity of life within these restrictions. Thus, a great deal can be inferred about how life in the universe must arise and behave, while evolutionary variation makes room for the marvelous diversity of life that exists here on Earth.

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