Life Beyond Biology: Perspectives on the Earth as an Organism

A. Salazar *

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Abstract

The idea that planet Earth can be considered as an organism is discussed in perspective. To this end, we provide a historical context for the concept of life, as well as a summary of important advances in planetary science. We show that autonomy, which has been described as the fundamental property of living organisms (H. R. Maturana, 1975), is consistent with the operation of the whole planet coupling (WPC), which in turn describes the organization of the Earth (Foley & Driscoll, 2016). This leads us to explore the network of processes involved in the regulation of our planet from an innovative perspective, suggesting further interactions between its subsystems and new functions for the Earth's magnetic field (EMF). The realization that the definition of life is applicable to a system such as a planet then leads us to question the situation of life in the universe and the boundary between physics and physiology. Finding it blurred, we discuss the thermodynamic implications of a physiological universe.

Key words:
autonomy, whole planet coupling, organism, physis

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*angelsh-@outlook.es
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Introduction

The idea that the Earth is a living organism has ancient roots, but its popularization in Western culture can be traced back to the publication of *Gaia: A New Look at Life on Earth,* by James Lovelock (J. Lovelock, 2000). However, a careful reading reveals that Gaia theory only tentatively suggests that the entire set of living beings on Earth - also called the biosphere - could be viewed as a single organism controlling its environment for its own benefit. Therefore, Lovelock's Gaia does not exactly encompass the whole Earth, and it leaves the definition of *living organism*, which should be an essential part of such a theory, rather unclear. As a result, the remaining association between the Earth and a living organism is quite ambiguous in its concepts, and thus its applicability is limited.

> "The entire range of living matter on Earth [...] could be regarded as constituting a single living entity, capable of manipulating the Earth's atmosphere to suit its overall needs and endowed with faculties and powers far beyond those of its constituent parts".
> - James Lovelock, 1973.

There is another approach worth considering, though older and less thoroughly examined. Here we need to reconsider the work of James Hutton, a scientist who has been called the father of geology because his most famous publication, *Theory of the Earth* (1798), is usually considered as the catalyst for the discipline. Less well known is the fact that the fundamental ideas in Hutton's work were significantly influenced by an intuitive comparison he made between the network of processes operating in the solid Earth and the characteristic dynamism present in every biological process (Tomkeieff, 1948). The latter implies that the fundamental paradigms of geology may have been profoundly influenced by an idea derived from the observation of the living world. Note that what is associated with a living organism in this approach is not just the biosphere, but the entire solid phase of the planet. This is illustrated in the following quotation.

> "The pattern manifest in the organism was transfered by Hutton to the Earth as a whole. In this consists the *secret of Hutton*".
> - Sergei Tomkeieff, 1948.

Because of historical contingencies, this connection between concepts has generally been misinterpreted, limiting the realization of its full explanatory potential. As a good starting point, note that the *Theory of the Earth* was published some 50 years before Charles Darwin's *On the Origin of Species*, and was indeed a source of inspiration for the latter. It should be understood that, during Hutton's lifetime, theoretical biology was so underdeveloped that even creationism was a conceivable possibility. Fortunately, scientific endeavors to study both living organisms and the planet have advanced considerably in the intervening centuries, and continue to do so. At this point, the seemingly close relationship between these scientific fields warrants an overview that focuses on the genesis and interrelatedness of scientific ideas in both. The following introduction is intended to be such an overview, basing the claims presented on the recognized works of eminent specialists in the fields concerned, and innovating by putting these claims into perspective. As our perspective gains coherence, we will discuss its implications across fields.

Life Sciences

Throughout the development of Western culture, living organisms have been characterized through various frames of reference. Early on, the paradigm known as *vitalism* assumed the existence of an immaterial principle, typically called the soul, that animates living matter and thereby justifies its dynamism. After the rise of the Darwinian paradigm, living organisms were seen as the result of an evolutionary process mediated by adaptation to the environment, competition, and reproduction. This theoretical development promoted a new and practical way of understanding living organisms and served as a catalyst for the emergence of ideas in modern biology. However, the key element of theoretical biology, contained in the question: *What is a living organism?*, remained unresolved at that time. It is worth clarifying that the automatic answer "something that adapts to the environment, reproduces, and evolves" is only an enumeration of processes which, although present in living organisms today, all lose their meaning when applied to limit cases. For example, leaving aside the paradox of virus - alive or not? - it is possible that the first living organisms, although alive, were not yet able to reproduce, were not yet adapted to the environment, and had not yet evolved. Nevertheless, what appeared at that time still had to exhibit the main property of living organization, from which all the processes mentioned should be deduced without resorting to vitalistic notions. As the following quotation shows, this aspect had not yet been addressed by the end of the first half of the last century:

> "Organisms are, by definition, organized things. But although we have an enormous amount of data on biological organization [...], we do not have a theory of biological organization, i.e., a conceptual model which permits explanation of the empirical facts".
> - Ludwig von Bertalanffy, 1968.

Deeply influenced by Whitehead's cosmological vision (Whitehead, 2010), Bertalanffy began a search for new conceptual tools that led him to the foundations of General Systems Theory (GST). The GST groups together a set of conceptual tools based on the notion of *system*, which is simply defined as a *"set of elements standing in interaction"* (Bertalanffy, 1968). Because of the abstract nature of its foundations, the GST can be seen both as a way of describing properties inherent in a particular system and as a means of transferring such properties between different systems. This framework has provided important tools for exploring the properties that distinguish living organisms from other systems, and therefore for answering the question of *what a living organism is*. The resulting theoretical model, discussed in detail below, would allow us to test whether, as Hutton intuited centuries ago, the Earth and living organisms share a common pattern of organization. In GST, such a convergence would be called a *homology*, referring to the phenomenon that occurs when, although the constituent elements within the systems under study are different, the principles arising from their collective operation are formally identical. A perfect example is the comparison between *heat* flow and *fluid* flow. When a homology is established, it allows the transfer of information in a way that was perfectly summarized by Bertalanffy as *"it will be no longer necessary to duplicate or triplicate the discovery of the same principles in different fields isolated from each other"* (Bertalanffy, 1968). This paper relies heavily on this statement.

What follows is a brief explanation of the basic principles behind the organization of living systems according to the theoretical model developed from GST by H. Maturana and Fco. Varela (H. Maturana & Varela, 2006). Starting from the concept of *homeostasis*, where a system maintains certain parameters within a constant range of values (Cannon, 1929), the authors realized that self-regulation in living organisms reaches such a level of complexity that it maintains not only isolated factors constant, but rather the integral organization of the system. This new dimension of order was called *autonomy* and was defined as the ability of a system to maintain its organization stable, which occurs through a coupling of self-sustaining feedback loops linking the operation of its processes. The very etymology of the term *autonomy*, i.e., self-referring, perfectly reflects how the functions performed by the various subsystems of a living organism refer to the maintenance of that system *itself*, as opposed to the the operations of a machine that produces something *different from itself* and whose operations are therefore not *self*-referring. This distinction will be quite important in our discussion below, but for now, we need to consider how the constituents of a system influence the way in which its autonomy is realized.

In the case of biological organisms, autonomy is achieved through the cyclical production of their own molecular components, a dynamic so characteristic that a nelogism has been coined to describe it: *autopoiesis*, i.e., self-producing (H. Maturana & Varela, 2006). In order to identify which pattern of organization is truly transposable, it is fundamental to understand the subtle difference between autonomy and autopoiesis. Both terms refer to a cyclical dynamic of self-regulation, but while autonomy leaves the underlying mechanism open, implying only that a coupling between all the *processes* of the system results in its activity becoming continuous and recursive, autopoiesis refers to the specific way in which a cell becomes autonomous: through the continuous and recursive production of its molecular components. In this sense, autopoiesis over-reflects the particular dynamics of dissolved organic compounds in liquid water and is not easily applicable beyond it, but autonomy is a much broader concept and thus transposable. This line of reasoning leads to the idea that a system with a constitution other than a colloid of biomolecules and water could become autonomous in a way other than by producing its own components, for although the autopoiesis of living organisms is conditioned by the specific properties of organic compounds and water - size, chemistry, etc. - the result of their collective operation: the pattern of organization that emerges - autonomy - does not necessarily depend on this particular mode of operation.

An important consequence is that the organization of any autonomous natural system will necessarily be homologous to that of living organisms, which achieve the same autonomy through their autopoiesis. Therefore, an analysis of the Earth as a living organism can be approached by asking whether it is an autonomous system, which would be the case if its organization is based on the coupling of self-sustaining feedback loops between its constituent operations. The next section outlines the major processes in the Earth and their interactions in order to explore this possibility.

> "The fundamental feature that characterizes living systems is autonomy"
> - Humberto Maturana, 1975.

Planetary sciences

During the last few centuries, the scientific study of planets has been focused on specific aspects of particular bodies, and this has not been conducive to the development of a general theory of planets and stars (Tozer, 1985). The latter is equivalent, in the language of the last section, to saying that the question: *What are planets and stars?*, has not yet been properly answered. The case of Hutton's *Theory of the Earth* may be particularly illustrative: although prolific, this pioneering work focused only on certain aspects of the solid Earth related to the cycle of rocks, and therefore, the relatively limited set of ideas it embodied did not encompass the entire network of processes inherent in the functioning of our planet. Since then, the study of planets has seen the progressive development of new specific disciplines, and what is considered to be the Earth has changed dramatically. Consequently, Hutton's transfer of the pattern manifested in the organism to the Earth *as a whole* is inaccurate according to our current knowledge: the Earth is much more than thought.

The first significant improvement relates to the scientific study of the EMF. This phenomenon had been known for centuries before Hutton's time through the use of the compass, but with the advent of more accurate instruments, it began to attract more scientific interest. In the 18th century, changes in declination over the course of a day were recorded, and consequently called *daily variation* (Graham, 1724). Further research linked similar perturbations to the presence of auroras and changes in solar activity

(Stern, 2002). A century later, when C. F. Gauss developed the spherical harmonic analysis to describe the EMF, it became possible to distinguish between a component in the interior of the planet - the main field - and another in the upper atmosphere - the outer field - the latter being the cause of periodic variations under solar influence (Gauss et al., 1839). Gauss himself suggested that the outer field could be the consequence of a layer of conductive gas - *plasma* - suspended on the main field, and later, B. Stewart hypothesized that electric currents constantly flowing in this conductive layer could act similarly to an induction engine (Stewart, 1886). This layer was demonstrated in 1901 and named the *ionosphere* (Green, 1974), and its inductive mechanism was called the *atmospheric dynamo* (Baker & Martyn, 1953). The latter consists of solar-driven currents in atmospheric plasma, and remarkably, its product could increase the power of the main field that contains it.

As for the main field, it was already thought to be generated inside the planet, but its underlying mechanism remained unresolved at that time. Since the temperature of the Earth's interior is above the Curie point of any metallic material, Gilbert's original idea of the Earth as a magnet was out of question. Then, in 1919, Joseph Larmor proposed the *dynamo theory*, which sees the main field as the result of convective currents in the liquid and conductive metallic core of the planet (Stern, 2002). The general consensus is that these currents are driven primarily by the removal of heat from the core to the mantle. This model imposes two major constraints. First, the mantle acts as a valve, controlling the energy available to the geodynamo. Second, the geodynamo has a limited amount of fuel, so the proposal of additional sources of energy have been required to explain its continuous operation for more than 3 Ga (Roberts & Glatzmaier, 2000). The most prominent one is that additional energy could come from differential precipitation of material in the solid inner core (Roberts & Glatzmaier, 2000), and an alternative theory hypothesizes a natural nuclear reactor inside the core (Hollenbach & Herndon, 2001). From this apparent lack of energy it can be concluded that the mechanism generating the main field is not yet fully understood. To summarize, with regard to the main phenomena influencing the EMF, it is necessary to consider two different induction mechanisms: an *atmospheric dynamo*, ultimately driven by solar energy and amplified by the amount of plasma held in the main field, and the *core dynamo*, which certainly generates the main field but whose source of power remains controversial.

The second major line of research concerns the movement of the Earth's crust and mantle. In the first era of geology, only the existence of vertical ground motion was accepted: igneous and compressive processes were then thought to cause uplift of the Earth's crust, while weathering and erosion were solely responsible for its downlift. Major changes occurred in the 20th century: The process began with Alfred Wegener's idea of continental drift (Hallam, 1975), and after a series of significant discoveries, such as oceanic ridges and trenches, and other evidence, including global seismological studies and hot spot tracking, arrived at modern tectonics. This process also took into account the polarization of magnetized rocks in the seafloor, which not only supported the idea of seafloor spreading, but also showed that the EMF undergoes aperiodic reversals whose causes are not yet fully understood (Cox et al., 1963). Once the theory of physical convection was developed (Benard, 1900), it proved applicable to the mantle (Turcotte & Oxburgh, 1967), broadening the context of tectonic phenomena and opening the way to our current understanding of the global mantle circulation. One problem that arises here is that the motion of a convecting system driven by highly viscous flows, such as the mantle, would require nonlinear rheological behavior at some critical points (Bercovici, 1998). This question is conveniently approached by considering that our planet has two different types of litosphere that play very different roles in mantle convection. Just by examining the relief of the Earth, it is clear that its height, in terms of accumulated area, has two distinct maxima: a feature called *bimodal hypsometry*. These maxima correspond to the continental and oceanic litospheres, the latter covered by an average layer of water of 3897m (Weatherall et al., 2015). From a dynamic point of view, the continental litosphere floats above the astenosphere due to its lower density, while the oceanic litosphere is actually the upper boundary layer of mantle convection (Turcotte & Oxburgh, 1967). The process of this convective layer begins when oceanic ridges generate new litosphere, which then moves laterally into trenches and eventually sinks through the mantle. The trench fraction at plate boundaries, together with their surface fraction of oceanic litosphere, seem to be the two main features influencing their velocity (Forsyth & Uyeda, 1975). The latter points to an element that favors a nonlinear rheological behavior in these structures. This element is water, which influences the rheological properties of the oceanic litosphere on its way to the trenches (Naliboff et al., 2013), where it becomes dense and weak enough to sink into the mantle (Dymkova & Gerya, 2013; Regenauer-Lieb et al., 2001). Water also acts as a lubricant at the margins of plates, allowing them to slide (Lenardic & Kaula, 1994), and when ingested by subduction, it reduces the viscosity of the mantle in a way that is critical for convection (Hirth & Kohlstedt, 1996; Rychert et al., 2020) and possibly for the formation of continents (Campbell & Taylor, 1983). Finally, on the deep side of tectonic processes, the relatively cold litospheric remnants reach the core-mantle boundary (CMB), where they gain positive buoyancy from the heat emanating from the core and rise again, transporting hot material available for surface tectonic processes such as seafloor spreading (Maruyama et al., 2007). In this way, the ocean-litosphere interaction results in the transport of cold litospheric material to the CMB. Since, as we mentioned above, the operation of the geodynamo is constrained by the rate of heat removal from the core to the mantle, this interaction can be thought of as controlling the geodynamo and, by extension, the magnetic field (Olson, 2016). Roughly speaking, the entire tectonic cycle can be viewed as an efficient and *rather complex* way of releasing the Earth's thermal energy, which depends on the presence of water on one hand, and is essential for maintaining the geodynamo on the other.

As the last and decisive line of progress in planetary sciences, the 20th century brought the first scientific surveys in space. The new technological developments led to the organization of the International Geophysical Year in 1957, the same year that the first satellite was launched (Korsmo, 2007). Since then, several equipped spacecraft have studied the Earth and other planets from a satellite perspective. We have discovered that planets are immersed in a stream of high-energy plasma, called the *solar wind* (Schunk & Nagy, 2009). Because of its electric charge, the plasma has strong interactions with planetary magnetic fields. As a result, the EMF acts both as a barrier to the solar wind and as a container, trapping multiple layers of plasma around the Earth. This is exemplified by the alignment of the *plasmapause* - the outer boundary of the *plasmasphere* - with geomagnetic field lines around $4R_E$ (Carpenter, 1966). The dynamic of these structures results in a transfer of energy from the solar wind to the EMF, where several dynamo mechanisms - discussed in detail below - are responsible for damping its excess. Since these mechanisms isolate the atmosphere from the solar wind, they can be considered as an example of the magnetic field regulating the atmospheric volatile inventory. Furthermore, the fact that the plasmasphere shares the atomic components of water: H^+ and O^+ (Schunk & Nagy, 2009), suggests that this regulatory interaction is directly related to the ocean.

These considerations are strongly supported by the contrast between Venus, Mars, and Earth, with only the latter having an intrinsic magnetic field or a massive hydrosphere. Not surprisingly, some authors have proposed that an intrinsic magnetic field protects a planet's lighter volatile elements, hence the hydrosphere, from being eroded by the solar wind (Egan et al., 2019; Lundin et al., 2007), and it has even been suggested that the magnetic field could also return already detached plasma back to the ionosphere (Seki et al., 2001). Note that this type of interaction would close a feedback loop in the network of processes of the planet, connecting the geodinamo in the core, mantle tectonics, the volatile inventory, and the outer magnetic field. In fact, going back to our last comparison among planets, the Earth is unique not only in having an intrinsic magnetic field and a massive hydrosphere, but also in having plate tectonics and the associated mantle dynamics, and in the emergence of organic life, which here is coupled with the idea of a massive hydrosphere and called *habitability*. These facts raise the question of why *all* of these processes - magnetic field, plate tectonics, and habitability - occur on Earth and *none* of them on Venus or Mars.

This question leads us to introduce the concept of *whole planet coupling* (WPC) (Foley & Driscoll, 2016). The WPC proposes that a regulatory feedback loop between a habitable climate, tectonics, and the magnetic field explains the maintenance of all these processes on Earth, while their complete absence on Venus and Mars is explained by an imbalance in the network - in the WPC - that could have led to their complete cessation. For example, a critical decrease in tectonic activity could reduce the rate of core cooling to the point of shutting down the geodynamo, further altering the dynamics of the atmospheric plasma and leading to the dessication of the planet. As this chain reaction goes on, the dynamic equilibrium that governs the organization of the planet is disrupted, as are all the processes involved. In contrast to more specific frameworks, the WPC embraces the Earth system in terms of its overall organization, and thus can be considered as a remarkable step forward in the formulation of a general theory of planets (see Figure 2 for context). What is missing, however, is the perspective of this concept within a broader theoretical framework, especially in the light of its remarkable parallelism with the autonomy of living organisms.

Discussion

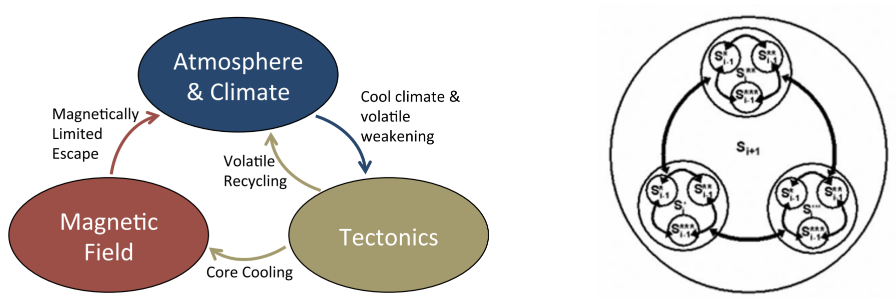
It is worth noting that there is an important element of philosophy in this problem. The basic idea is that the natural world can only be understood by comparison with elements of the human experience that are symbolized through a linguistic network. This approach emphasizes the search for practical ways to conceptualize natural systems so that they can be studied with increasing precision. Once a comparison is found to be useful, scientists begin to extend its applicability, giving rise to a *paradigm*: a conceptual model, analogous in some ways to a scientifically based belief (Kuhn, 1997), that allows us to project our linguistic networks onto the universe in order to understand it.

We can then say that our current knowledge of the Earth is based on a certain set of paradigms, which in turn are influenced by comparisons with elements of the human experience. For example, the dynamic nature of the magnetic field and the mantle is usually understood in terms of induction and heat machines. From these comparisons, the Earth is viewed as a heat machine whose products, in terms of physical work, are mantle convection and, through a coupled induction mechanism, the magnetic field (Olson, 2016; Roberts & Glatzmaier, 2000). The corresponding paradigms are plate tectonics and the self-excited dynamo. These allow scientists to constrain certain aspects of planetary functioning by comparison, but leave intact those dynamics that do not occur in the objects with which we are comparing - in this case, in heat and induction engines. Consequently, the dynamics associated with complex interactions between terrestrial subsystems, and more generally the integral organization of the planet, are beyond the reach of these models. At the same time, the WPC has been proposed to address the organization of the planet by pointing out that its processes constitute a self-regulating loop, but since the operation of machines, which is the usual comparison in science, depends on external regulation - by us - the WPC seems to lack an appropriate comparison in terms of the human experience. As a result, we cannot develop a paradigm from the WPC, nor can we use it to constrain the organization of the planet. However, some other regulated system may be appropriate for this comparison instead of the usual mechanical analogy.

It follows that the concept of autonomy, derived from the study of living organisms, is perfectly suited to these requirements, for although a heat machine, i.e. a system that converts heat into physical work, and an induction machine, i.e. a system that converts physical work into magnetic energy, may address certain aspects of planetary dynamics, an autonomous machine, i.e. a system that regulates its own organization, encompasses such dynamics much more accurately.

The usual controversy over this kind of framework shows that the choice of comparisons in the natural sciences tends to be biased. On one hand, the comparison of natural phenomena with mechanical artifacts - machines, engines, and as we shall see, even software - is a commonly accepted resource, but on the other, scientists become overly skeptical when this has to be done with concepts derived from the living world. Note, for example, the remarkable delicacy with which the author here treats this issue (J. Lovelock, 2000). This bias is the result of a rejection that stems from a historically rooted metaphysical misunderstanding of living organisms and their properties. Any comparison requires a clear understanding of what is being compared, and in the case of living organisms this implies distinguishing between the practical explanatory resources derived from their study, and esoteric notions inherited from old paradigms such as vitalism, which, far from being practical, have encapsulated life on earth as a unique and anomalous aspect of nature. But if we strip biological concepts of their vitalistic inheritance, all that remains is a pattern of organization: a natural and transposable pattern. The consideration that the Earth follows this pattern is in GST equivalent to the recognition of a homology, and it is therefore equivalent to considering the whole Earth as *living* like a biological entity, just as heat can be considered as *flowing* like a fluid (Bertalanffy, 1968). Specified in this way, the view of the Earth as a living system should not stand as a mere poetic suggestion, as seems to have happened with the actual Gaia theory (J. Lovelock, 2000). In fact, the recognition that both systems share a homologous organization allows the transfer of descriptive resources that may be useful to understand those planetary processes that would otherwise be inaccessible to us, which is justified because, although neither the organization of planets nor that of living organisms is currently fully understood, the latter is much more accessible. This is also the reason why our theory of living organisms is more advanced than that of planets, and fully justifies the search for homologies - see above in Introduction.

We can then use the organization of living organisms, which is also based on autonomy, to constrain the interactions and processes that make up the organization of our planet, similar to other constraints used in physics. It would then be possible to infer further relationships between processes within the Earth, or to emphasize the importance of relationships that have already been proposed but whose importance has been underestimated. This idea will be explored in more detail in the next section. For now, note that the ultimate reason for the comparison stems from the fact that some systems in nature cannot be understood solely as the sum of their components, but rather in terms of regulated feedback loops between their processes (Bertalanffy, 1968). When observed in living organisms, this has led to the notion of *autopoiesis* (H. Maturana & Varela, 2006), while in planetary science the concept of *whole planet coupling* refers to a very similar property (Foley & Driscoll, 2016). It is indeed a perfect homology, which in this case is referred to with the idea of *autonomy* (H. R. Maturana, 1975), indicating that both, the Earth and living organisms, are **natural autonomous systems**.



(a) Whole planet coupling (b) Autonomous system

Figure 1: Comparison between the Earth and an organism (Foley & Driscoll, 2016; Rudrauf et al., 2003).

The ease with which the notion of whole planet coupling fits into that of autonomy is well illustrated in 1. It is possible that a similar association was made by James Hutton more than two centuries ago, and more explicitly - but not in exactly the same way - by James Lovelock in recent years. Now, the current state of scientific knowledge has led to our approach, and so we can see how, more than two centuries after an intuitive transfer of the pattern manifested in the organism to the Earth laid the foundation for the scientific study of the planet (Tomkeieff, 1948), the collective efforts to study both the Earth and living organisms are still converging in their theoretical underpinnings. It has taken several advances in different subfields to fill in the theoretical gaps needed to formulate this problem accurately, the most important of which are illustrated in Figure 2. Progress has also tended to focus on concrete and isolated aspects, the overall theoretical process being slowed down by the over-specialization and lack of generalists in the scientific community, a problem already noted by Bertalanffy (Bertalanffy, 1968), for while this particular aspect of modern science increases the precision of each field, it also hinders communication among scientists and thus the flow of information necessary to solve general problems such as this one. The latter, together with the deep metaphysical misunderstanding of living organisms brought about by vitalism (H. Maturana & Varela, 2006), justifies the slow acceptance of these ideas in the modern scientific community.

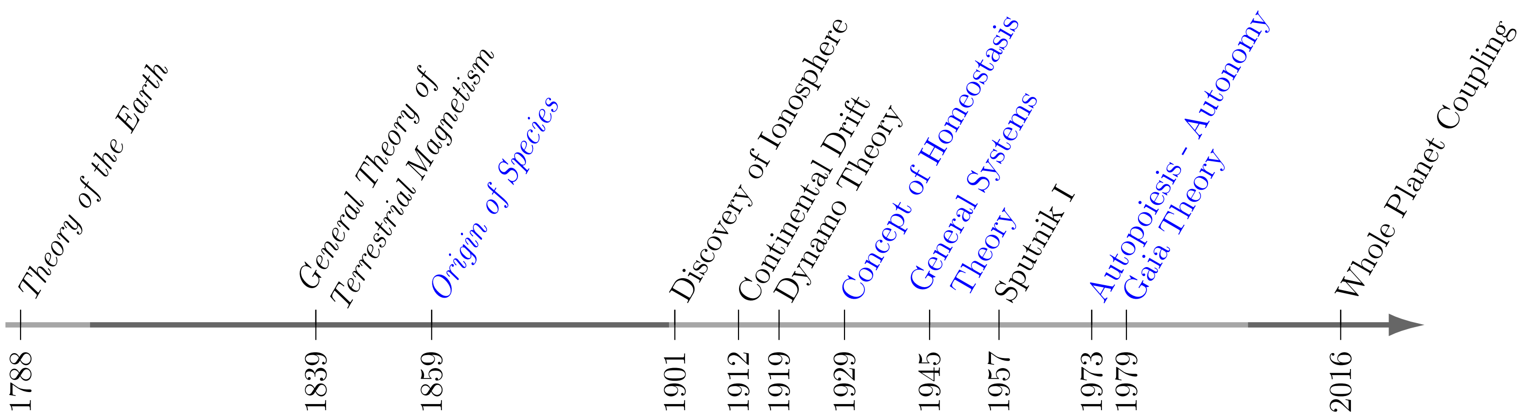


Figure 2: Time arrow showing parallel developments in Earth sciences (black) and theoretical biology (blue) (Bertalanffy, 1968; Cannon, 1929; Darwin, 1859; Foley & Driscoll, 2016; Gauss et al., 1839; Gerstner, 1968; Green, 1974; Hallam, 1975; Korsmo, 2007; J. Lovelock, 2000; H. Maturana & Varela, 2006; Roberts & Glatzmaier, 2000).

Processes in the Earth System

This section outlines the applicability of autonomy when it is superimposed on the WPC. In other words, we will discuss how autonomy constrains the organization of the planet. Returning to Figure 1, this idea can be illustrated by examining the relationships on the original WPC (1a) that are missing when it is compared to a generic autonomous system (1b). The major differences fall into in two categories: those that arise from the relationships between the three major subsystems, and those that arise from the internal regulation of each subsystem. Let us examine the first category. Figure 1a shows the loop that simply defines the WPC, hereafter referred to as the *main loop*, which consists of three interactions: 1: The main field is generated in the core, and this operation requires a sufficient rate of heat loss to the mantle. 2: The global mantle circulation (tectonics) absorbs heat from the core, but requires a cool climate and a massive hydrosphere (habitability). 3: The planet's volatile inventory, and thus the hydrosphere, is protected from solar activity by the EMF, produced in the core in step 1. As we can see, the main loop is clearly unidirectional. However, as shown in Figure 1b, control in an autonomous system should be multidirectional: its operation is based on its stability, so connectivity must be maximized. Considering the long-term operation of the WPC in the Earth - more than 3Ga (Roberts & Glatzmaier, 2000; Schopf, 1993; Shirey & Richardson, 2011) - the latter seems very likely, especially with respect to the geodynamo, whose longevity still defies science.

In any case, it is interesting to note that Foley and Driscoll have already pointed to a regulatory process in the opposite direction (Foley & Driscoll, 2016). Figure 1a shows a second arrow between *"Tectonics"* and *"Atmosphere & Climate"*, suggesting that tectonic activity could regulate Earth's atmospheric composition by recycling subducted volatiles from the mantle into the atmosphere. This can be seen as the first indication that Earth's regulatory processes are multidirectional. It is then easy to see a second bidirectional regulatory relationship between the subsystems *"Magnetic Field"* and *"Tectonics"*. When heat is transferred from the core to the mantle in a way that is strictly necessary for the geodynamo to operate (Roberts & Glatzmaier, 2000; Stevenson, 2009), thermal energy also becomes available for the global mantle circulation, of which tectonic activity is a part. As a reference, in (Maruyama et al., 2007), it is said that cold slab remnants accumulated at the CMB gain positive buoyancy as a consequence of heating from the core and aided by post-perovskite phase transformation - which here can be considered as an additional regulatory mechanism - giving rise to mantle plumes and releasing heat to the upper mantle. These multidirectional regulatory processes strongly reinforce the idea of an autonomous Earth, and lead us to consider the third interaction from this perspective: that between *"Atmosphere & Climate"* and *"Magnetic Field"*. Starting from the direction of the main loop, it has been proposed that magnetically limited escape prevents the erosion of the atmosphere by the solar wind (Lundin et al., 2007), but actual in situ measurements do not clearly confirm this, and some authors have even argued that it may not be the case (Gunell et al., 2018). Moreover, regulation in the opposite direction is hardly intuitive in this case. We may then see an application of autonomy here: If the Earth is constrained according to this theoretical framework, it is likely not only that the magnetic field protects the volatile inventory, but also that the volatiles are able to reciprocate the magnetic field. In this scenario, we could reconsider the operation of the atmospheric dynamo, emphasizing the role of volatiles in the absorption of solar radiation and its conversion into magnetic energy. In a first step, solar radiation is absorbed by atmospheric gases in the ionosphere. This structure is then driven, among other factors, by atmospheric tides originating in the ozone layer (Yamazaki & Maute, 2017), which is of biogenic origin (J. Lovelock, 2000). The result is the convective pattern that is responsible for the daily variation of the magnetic field. In this way, which is not the only one, the habitability of the Earth contributes to the regulation of the magnetic field. These interactions will be discussed in more detail below.

The second issue that arises from the comparison between an autonomous system and the WPC is the internal regulation between the elements of each of the three major subsystems (minor compartments in Figure 1b). We can begin by noting that the subsystem referred to in the WPC as *"Atmosphere & Climate"* - a stable climate that allows for a massive hydrosphere - together with Lovelock's description of Gaia - the biosphere as a self-regulating entity capable of manipulating the atmosphere to ensure its persistence and development - actually form a single emergent process - here referred to as *habitability* - that corresponds perfectly to what might be expected of a subsystem of an autonomous system. Among the three major subsystems, however, this one has a peculiarity with some implications worth commenting on. When we think about the interrelationship of its elements, it is fundamental to consider that *we are one of those elements*. Out of the entire universe, the human system has evolved in this sector of this relatively small planet, and because we must have perceived and reacted to the climate and other living organisms in order to survive, we experience them with much more vivid precision than the rest of the universe. These phenomena can then be identified and conceptualized with a greater clarity than the material components of those structures of the planet - or the universe in general - with which we have not interacted with during our evolution. Consider, for example, the differences in the degree of precision with which we name phenomena that occur on the surface of the Earth or on the surface of the Sun. It is even possible for us to observe the self-regulating functioning of the Earth's surface from within, such as the regulating effects of water on climate, or the precise recycling of matter and energy carried out by living organisms in ecosystem networks. As a result, both the complexity of the elements and the self-regulation of the Earth's surface have been overestimated, while the same features in other natural systems have been neglected. This has biased Gaia hypothesis to point to regulation only in this subsystem of the planet, leaving the activity of its inorganic phase out of the theory. The bias has been reinforced by the way of understanding life that we have inherited from vitalism, which presupposes an element that distinguishes living organisms from the rest of the universe. Consequently, only living matter can be compared to living organisms, and thus Lovelock's Gaia consists only of *"the entire range of living matter on Earth"* (J. Lovelock, 2000). But a definition of life in terms of organization and autonomy can fully encompass the inorganic Earth. Indeed, if the planet is an autonomous system, its subsystems would reflect its overall functioning, and similar to what happens in fractal geometry, the regulation we see on the surface would be but a reflection of the overall functioning of the Earth System. In this sense, the habitability fulfills what would be expected of an autonomous planet, but in such a case, we should be able to observe the same self-regulating functioning in the other subsystems as well.

The next Earth subsystem to be considered is referred to in the WPC as *"Tectonics"*, and can be summarized as encompassing the dynamic activity of the planet's silicic phase. It extends from the solid surface to the CMB, and is involved in the ongoing functioning of the global mantle circulation, which gives rise to plate tectonics in the upper boundary layer and to core cooling in the lower. Mountain ranges and ocean basins are some of its most visible surface products. The tectonic operation is well suited to illustrate that the tendency to view the Earth's subsystems as self-sustaining is not limited to habitability. In (Lenardic et al., 2019), it is proposed that the overall operation of the mantle is linked through a self-regulating feedback loop. In this framework, the various properties of the mantle, in terms of composition, physical parameters, and dynamic activity, are related in such a way that each operation requires, and at the same time is responsible for maintaining, the dynamic activity of the entire network. Consequently, if each operation does not occur within the appropriate range of values, the functioning of the entire system - i.e., plate tectonics - may shut down and the mantle would enter in a stagnant lid modality, like Venus or Mars. The operation of the mantle is curiously compared here to the boot-up process of computer software, in which certain critical factors co-arise in such a way that *"one factor does not cause another, but they emerge collectively with the links between them"* (Lenardic et al., 2019). Note that an organic tissue also meets this requirement, but the fact that living organisms were considered from a vitalistic perspective forced one to compare the other natural systems only to mechanical artifacts - remember that only organic matter could be compared to living organisms. However, since the dynamics implicit in a comparison do not depend on the particular choice of representation, one could simply conclude that the mantle is a self-regulating system. The conclusion is then similar to that of the Gaia hypotheses, differing only in the choice of comparison because, as noted in the previous paragraph, the fact that Lovelock's Gaia consists of organic matter helps to ignore the limitations of the vitalistic framework. This underlying parallelism indicates that two of the three major terrestrial subsystems are already considered to be self-regulating by experts in the their respective fields, strongly reinforcing the idea that our planet is an autonomous system and leading us to approach the third subsystem in the WPC from this perspective.

We have arrived at the *"Magnetic Field"*, which is the least constrained of the three major terrestrial subsystems by current models, and also the least studied due to the inaccessibility of its key elements: the core and atmospheric plasma. Nevertheless, its self-regulation is already implied in the models describing the operation of the planetary dynamo, the very name of the model: the *self-excited dynamo*, suggesting this type of activity. The model is named for the fact that, as explained in (Roberts & Glatzmaier, 2000): *"the magnetic field facilitates convection [in the core]"*, which implies that it feeds back into its own generation mechanism. However, the evidence for self-regulation provided by this model does not consider the external magnetic field, which is understandable since it is based on a comparison with an induction machine, whose physical work, once converted into magnetic energy, is lost. Moreover, when the underlying reason for this self-regulating dynamic is addressed, only an unknown "thermodynamic reason" can be aduced, then suggesting that the system could maximize or minimize some thermodynamic parameter, such as entropy. Even if this were true, it would not necessarily suffice to address the organization of the system, for as rightly pointed out in (Bertalanffy, 1968), *"organization does not seem to be adequately expressed in terms of energetics"*. The thermodynamic framework is therefore useful for constraining how the magnetic field may be generated, but at the same time it is inadequate for dealing with some aspects intrinsic to the organization of the terrestrial subsystem in which it is assembled, as well as its further interactions with other elements of the Earth System. This is where the autonomous planet paradigm can fill in the gaps of the mechanistic description. The resulting model would treat the magnetic field in terms of its overall organization, emphasizing that its activity is neither isolated nor confined to the core, and leading to the conceptualization of a self-regulating terrestrial subsystem whose organization, like that of the other two, is characterized by a self-sustaining pattern of multidirectional regulation among its components. This leads to a curious speculative hypothesis about the interactions between the magnetic field, the core, their connection to the outer atmosphere, and the extraplanetary environment.

If the whole Earth were to be conceptualized as an autonomous system, then it would be important to consider that living organisms - our reference in this case - do not only disperse energy, but are also capable of concentrating it, this being a basic requirement for their very existence. Interestingly, the absence of a similar process in the functioning of mechanical devices and engines - because their energy supply depends on us - justifies ignoring this possibility in a mechanistic approach. But here, our current approach gives us four clues that, taken together, do support this idea. The first was presented above: the convective currents that generate the magnetic field in the core are driven by heat dissipation into the mantle, but there seems to be a lack of the thermal energy required to explain the long-term operation of the geodynamo, and this deficiency is currently explained ad hoc (Hollenbach & Herndon, 2001; Roberts & Glatzmaier, 2000). Second, the Earth is completely embedded in an enormous flow of solar energy, which, if not effectively dissipated, could disrupt its organization. In particular, an excess of energy reaching the surface would render the planet uninhabitable by drying out the hydrosphere. Moreover, a large part of the planetary structures responsible for absorbing the excess in solar energy operate through dynamo mechanisms that convert it into electrical currents, and are thus coupled to the magnetic field. As we can see, the EMF consists of two dynamo regimes, one of which - the core - seems to have an energy deficiency, and the other - the magnetosphere-ionosphere system - operates to dissipate an excess. Third, one of the fundamental features of the dynamo mechanism is the contactless transfer of energy involving conducting and rotating systems, and in this case both systems are conducting and in constant rotation. Fourth, the perspective that the magnetic field, like the other two major terrestrial subsystems, is self-sustaining, implies that each of its processes requires and at the same time is responsible for the maintenance of the entire network that it constitutes, leading us to question whether the magnetosphere-ionosphere system exerts some effect on the core. This leads to the possibility that, through a coupling of magnetic induction mechanisms, the external magnetic field could act as an antenna, drawing *useful energy* from the Sun and making it available for the geodynamo and the internal processes of the Earth System.

To illustrate this scenario, let us summarize the main dynamo mechanisms generated in the interaction between the Sun and the EMF. To simplify our explanation, we can consider that the solar energy reaching the Earth consists of two contributions: radiation and plasma. The effect of solar radiation is particularly important in the ionosphere at mid-low latitudes, where it creates two hemispheric convective cells that increase the strength of the magnetic field on the day side of the planet and also converge in the *equatorial electrojet*, a belt-like electric current that increases the amplitude of the magnetic anomaly by a factor of 2-3 (Yamazaki & Maute, 2017). These cells are the cause of the daily variation reported in the 18th century, and their inductive effect has also been detected in other planetary structures, such as the ocean (Koch & Kuvshinov, 2013) and the mantle (Schmucker, 1970), so it would not be surprising that some of the energy supplied could reach the metallic core, which is considerably more conductive.

The other major energy input to the planet is solar plasma: a constant flow of high-energy ionized particles that carry the solar magnetic field in a "frozen" state. It collides with the outer boundary layer of the EMF, compressing it into a *bow shock* located at a distance of about $12R_E$ on the sunward side of the Earth, while in the opposite direction the EMF extends freely to $150R_E$ (Schunk & Nagy, 2009). This compression and the resulting asymmetric configuration of the EMF can be seen as the first damping mechanism for solar plasma. To follow, the insulation here is not perfect, and solar plasma can enter the magnetosphere through open field lines in the polar caps, either to access the polar ionosphere directly or to accumulate in the tail of the magnetosphere, where the *magnetospheric dynamo* generates strong earthward electric currents. The mid-low latitudes are protected from this effect by the radiation belts: concentric structures composed of terrestrial and solar plasma - mainly protons, electrons, and atomic oxygen - trapped in the closed field lines of the EMF and bouncing between hemispheres. It is believed that a ring current formed on the outside of the radiation belts absorbs the excess of energy from events such as magnetic storms and substorms, thereby protecting the upper atmosphere from erosion by high-energy magnetospheric currents (Akasofu, 2021). However, some of the energy accumulated in the magnetosphere is effectively conducted to both poles through the longest closed field lines - the outer ones. This energy is then injected into the polar ionosphere, and damped by the creation of two additional dynamo-like convective cells at each pole (Yamazaki & Maute, 2017) with their respective *auroral electrojets* (Akasofu, 2021). In summary, we have considered four structures responsible for the absorption of solar energy: the hemispheric dynamos on the sun-side of the planet, the bow shock, the ring current, and the polar dynamo circuit (see Figure 3). It is generally assumed that the energy resulting from these processes is completely dissipated as heat and lost (Lyon, 2000), but in the context of an autonomous Earth it could be that some of it is transferred to the core by a mechanism of coupled induction, then linking the operation of the *magnetospheric* and *ionospheric dynamos* with the *core dynamo* and as noted above, the EMF with the volatile inventory of the planet.

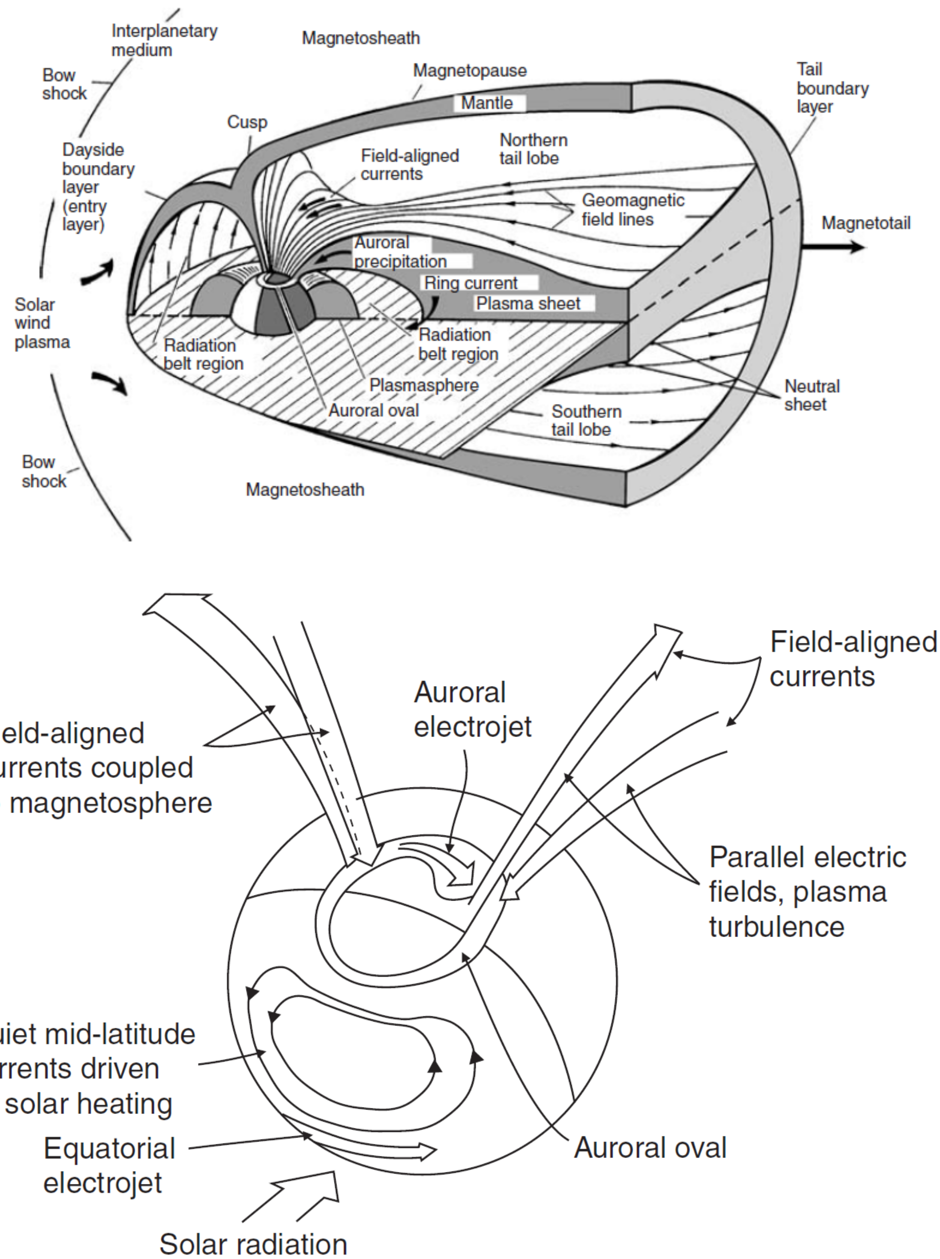


Figure 3: Sketches of the magnetosphere (top) and the major current systems in the terrestrial ionosphere (bottom) (Schunk & Nagy, 2009).

Before closing this question, one final clarification is necessary. It may seem that our last suggestion was rather cumbersome, but it is actually quite simple. The main problem is that our actual knowledge of the interactions between EMF and the Sun is far from complete. Both our data collections and the paradigms we use to frame them have a long way to go. Nevertheless, our proposal is not based on magnetic field data, but simply derives from viewing the EMF as a self-regulating system. A highly organized planet would not waste the massive amount of solar energy surrounding it. Moreover, considering that the magnetosphere-ionosphere system converts this energy into electric currents and magnetic fields, the idea that this energy eventually reaches the core is not far removed from the distant action of the core deflecting the solar wind in the bow shock. In both cases, magnetic energy generated by an induction mechanism affects the dynamics of a conductive material in another planetary structure: in the first, heat-driven currents in the metallic and conductive liquid core generate a magnetic field that affects the plasma in the outer layers of the planet, and in the second, plasma currents in the outer layers of the planet could similarly affect the liquid core. Then, the key point from our perspective is the possibility that the core is trapping some of this energy. In this scenario, the solar energy would provide an additional power source for the planetary dynamo, and since the heat emanating from the core would then be available to the mantle, it would also fuel its dynamics and thus the motion of the entire solid Earth. It is important to note that it is precisely the assumption of autonomy that allows us to predict the degree of coordination necessary for the core to harvest solar energy, but that in spite of this, the current state of knowledge about the Earth does not reveal the underlying mechanism of this process, nor its efficiency. Consequently, predicting the exact amount of energy captured would be imprecise. All we can do is infer the energy that could potentially be available to the core by observing the dynamics of the planet's outer structures. In this respect, the above list of processes should be considered only as possible sources of magnetic energy, not all of which would necessarily reach the core or be effectively captured. The point is simply to illustrate that, under the assumption of an autonomous Earth, some dynamic of the outer magnetic field could compensate for at least part of the energy lost from the core, and thus help explain the long-term operation of the geodynamo and the Earth system in general. This type of conclusion will be justified in the following section, as well as its theoretical implications.

Life Beyond Biology

The idea that the Earth is an organism is even reflected in the basic nomenclature of scientific disciplines. This point was already noted by Lovelock, who coined the term *"geophysiology"* in an attempt to address the active interactions and regulation within the biosphere and with the inorganic phase of the planet (J. E. Lovelock, 1989). From this concept arises a curious paradox that will guide the development of the work that follows. Let us begin by considering the contrast between *physics* and *physiology*, two disciplines which, as can be seen when they are presented together, share a common ethymological root: *physis*, which in Greek means *nature*. But although both disciplines could be equally defined as *"the study of nature"*, they differ considerably in their approach to nature, and in the case of the Earth this difference is particularly interesting. It is clear that the Earth is part of nature, but while geophysics is a well-established discipline concerned with the material composition of the planet and its physical fields, geophysiology is only a fringe concept proposed by an independent scientist who attempted to establish a comparison between the Earth - or part of it - and a living organism. The fact that the concept of life is at the heart of the matter leads us to recapitulate the above debate, this time focusing on its implications for the way we understand life. As a starting point, it is important to make a clear distinction regarding the relationship between the human experience, language, and reality. There are objects in our experience that are not intrinsically alive, and others that indeed are. For example, unlike a dog, a stone is clearly not alive. The concept of life was probably raised to outline this obvious distinction when common linguistic networks began to develop in human societies. However, the resulting view was framed by a now obsolete approach that, instead of describing the actual functioning of living organisms, theorized an immaterial guiding principle exclusive to them. This narrow vision could have pointlessly isolated a set of ideas in *physiology*, limiting the transfer of information to *physics*, and thus hindering the simple *study of nature*. On the other hand, the size of our linguistic networks has increased dramatically over the past few centuries, and the earlier qualitative distinction between objects in our experience has not been updated to accommodate this expansion. In other words, the scope of natural systems in contemporary science ranges from subatomic particles to galaxies (see Figure 4) and probably requires a much broader range of distinctions than the archaic alive/inert scheme used to categorize dogs and stones. Within this scheme, physiology deals with that part of nature that is considered to be alive, while physics deals with nature in general, whether it is alive or not. The concept of life is the gateway that allows us to switch from one framework to the other. Living systems, on one side of the gate, are ultimately understood in terms of comparisons to our own processes and inner meanings, while non-living systems, on the other side, are described only in terms of empty machinery. In this framework, the fact that natural non-living systems are always described as lacking any kind of *agency* is justified simply because the processes that define the motion of machines - the common choice of comparison in modern science - are either stochastic or determined by us. The natural world has been described according to these comparisons to the point that the only way to reconcile the two views - the *somehow* organized living world and the non-living mechanical reality - and thus to explain how directionality and organization arose in this universe, was to conceptualize living organisms in the same mechanistic terms as non-living reality - see the title of (H. Maturana & Varela, 2006): *of Machines and Living Beings*. This process, already accomplished, led to a non-esoteric definition of life in which concepts such as autonomy and autopoiesis were found to be the guiding non-supernatural principle describing the dynamic operation of living organisms and giving rise to the rest of their characteristic properties. But then, this non-vitalistic description of life has the necessary side effect that the resulting concepts must be transferable, which is understandable since its basic postulates are simply to describe the phenomenon of life without appealing to non-physical notions. In a sense, the present work can be seen as a test of the applicability of such concepts to natural systems other than biological organisms. Hereafter we outline some important consequences of this interdisciplinary transfer.

A physiological planet

The first consequence of the notion of autonomy being suitable for the Earth is the possibility of transferring to it conceptual tools proper to physiology. As a possible starting point, it will be useful to transfer the basic notion of *physiological function*. This important tool allows one to describe the components of living organisms as arranged to perform specific operations required by the overall system they comprise. For example, the human eye is a complex structure that has evolved according to how it has historically been used to perceive our surroundings. It is easier to understand the structure of the eye in terms of its functions because it is not accidental; it is the way it is because its operation is useful *to the human system* and thus can be selected. Here we should note that the complexity of the *function proposition* lies in the fact that it requires a reference subject: that to which the function refers - the entity. For example, the proposition “a function of the eye is to see” requires the subject *that* sees. In this sense, the exaggerated qualitative distinction imposed on the notion of living being was justified by the fact that, in a vitalist framework, these were the only possible subjects to which functions could be refer. This created a dichotomy in which the non-living majority of the universe was seen as composed of random processes governed by universal physical laws, and the living world, although subject to the same laws, was somehow endowed with physiological functionality and meaning. Framed in this way, it should be clear why the notion of autonomy has emerged as the fundamental common property of living beings. Autonomy literally means self-referring, and thus the concept fully justifies the possibility of describing the components of an autonomous system in terms of functions. In particular, the operation of any component of an autonomous system can be referred to its contribution to the maintenance of the autonomy of *that* system. Consequently, in this framework we can refer functions to the components of the planet, with the Earth itself being the reference subject of such functions. This can be illustrated with the example of the Earth’s magnetism. In this case, a traditional physical approach would measure and decompose the forces involved in the operation of the core in order to constrain its components and processes. The subsequent perspective leads to an understanding of how the magnetic field can be generated in the core. A physiological approach would rather consider the role of the core in terms of how its various requirements and products affect the organization and autonomy of the Earth System. This approach is based on integration and leads to characterize the operations of the core in terms of their contribution to the continuous and recursive operation of the WPC, the generation of the magnetic field being one such operation. The latter leads to the proposition “a function of the core is to generate the magnetic field”. Once this is stated, we are actually applying a physiological concept to a planet, and thus we have found a practical application of considering it as a living creature.

The discovery of a self-referring entity also opens the way to the transfer of more specific functions. For example, in the last section, by comparing the Earth to living organisms, we discussed how it could harvest energy from its environment. Now we can properly say that what we have actually done is to apply descriptive resources from the *nutrition* function of living organisms. But this is not the only function that can be transferred to an autonomous Earth. In particular, the function of *centralization*, which is fundamental to describe some physiological systems, carries with it an important set of theoretical tools that can be quite accurate in this case. In practice, centralization consists in the presence of *leading parts* within the system, or in other words, of certain structures whose dynamics dominate its behavior. The main idea is that small changes within these leading parts cause large changes in the whole system through *amplification mechanisms* (Bertalanffy, 1968). A system needs centralization to perform functions such as *integration, coordination*, and *information processing*. For example, the human system is centralized by its nervous system. As a precedent in relation to the Earth, we refer again to Lovelock's theory, where, since living organisms are the only active element, they exert control over the entire inorganic phase of the planet, which is considered only as a passive and thus controlled element (J. Lovelock, 2000). This is no longer an option when considering an autonomous Earth. The reason is that, while the scope of a centralization mechanism should cover the entire system - from the core to the magnetopause - living organisms only reach a thin layer on the surface. A much more ubiquitous mechanism would be required to centralize the Earth. It naturally follows that the most appropriate mechanism to cover this function is the magnetic field; apart from the fact that the entire planet is embedded in it, there are some features of its operation that fit into this framework with remarkable accuracy. First of all, we cannot deny that the natural centralization mechanism that we know better, the nervous system, is driven by directed electric currents that occur at the most protected point of the system in question. This is exactly what happens in the Earth, with the magnetic field being generated in its core. But in addition, the magnetic field has a close relationship with each element that is critical for the maintenance of the WPC. Leaving aside the feedback currents that are induced in the core - from which the main field originates - we could start by considering that the oceanic litosphere, which is a fundamental element for plate tectonics, mantle dynamics, and core cooling, shows a regular pattern that is directly related to the activity of the magnetic field (Cox et al., 1963).

Transferring the idea of centralization, it would then be possible to speculate that the polarity pattern in the oceanic crust could be *prehended* by the centralization mechanism to regulate, as an example of how this logic works, the rate of production of new oceanic litosphere. The latter could be important in explaining the long-term operation of the planetary dynamo, as the Earth itself could have been controlling its core cooling rate through tectonics. The situation may be similar for the ocean, understood as a fundamental element for climate regulation. The ocean is the largest water reservoir above the surface, and contains a massive amount of dissolved salt, whose concentration may have been relatively constant throughout the Earth's history, although the underlying processes of regulation are still not clear (J. Lovelock, 2000). It is interesting to note that salt increases the electrical conductivity of the ocean, and thus its interactions with the magnetic field. In fact, the presence of a salty ocean is sufficient to maintain a weak induced magnetic field on bodies like Europa (Stevenson, 2009). In the case of the Earth, this massive uptake of salt can be seen as favoring the connection of the main body of surface water with its centralization mechanism, a connection that could be important for the self-regulation of habitability, and in turn to explain the fact that the salinity of the ocean is stable. Finally, the effects of centralization can be considered in the context of the EMF and plasma. The plasma is a remarkably reactive and dynamic environment in which various signals, ranging from internal ones such as whistlers to those caused by the intensity and direction of the solar wind, are readily transmitted as electromagnetic waves. The magnetic field, as a mechanism of physiological centralization for the planet, would connect this environment to the core, where these signals would trigger inductive responses. An analogy can be made to the induction coil of an electric guitar picking up the signal from a vibrating metal string. Here the plasma serves the same signaling function as the metal string, but in this case the activity of the magnetic field could in turn affect the particular disposition of the plasma around the planet. Such a dynamic sheath could endow the Earth with a kind of *sensitivity* and *responsiveness* that could be fundamental for the accomplishment of some of its physiological functions. For example, a sensitive and responsive magnetic field could serve as a means of protecting the planet, or even capturing energy, from events of increased solar activity such as flares and coronal mass ejections (Walsh et al., 2014). This type of activity suggests that a natural system traditionally thought to be inert could exhibit some kind of *agency*. The cosmological implications of this proposal are discussed below.

Molecules and organisms

The application of physiological concepts to the Earth implies an effective extension of the boundary imposed by the concept of life to systems traditionally thought of as inert. This reinforces the idea that the inert/living dichotomy yields a simplistic description that does not accurately reflect the reality of nature. Turning this idea back to the problems of theoretical biology, it is now possible to reformulate our view of life. To do so, it is worth considering for a moment the contrast between our description of the origin of life and that of the origin of multicellular organisms. There is a broad consensus in the scientific community about the factors that lead to multicellular life. Since cells are considered to be alive, they have a physiological reason to aggregate: a colony increases the stability of the environment for *each individual cell*, so it is functional *for them* as referenceable subjects, and therefore understandable to us. Note that functionality here refers to the meaning that the aggregation process has for the cells, in terms of its consequences on the network of processes that constitute the autonomous operation of each cell. Because of their agency, cells can then arrange themselves to perform specific functions within an aggregate, leading to increasing levels of organization until the aggregate also becomes autonomous and is said to be a multicellular organism whose functions are subordinated to the needs of its cellular components. The origin of life, on the other hand, seems to have created a dramatic anomaly in the universe. This is because biomolecules, the basic components of living organisms, are qualitatively considered to be non-living systems, and thus are assumed to have no agency. Consequently, the fact that molecules randomly "bouncing around" suddenly assemble in the exquisite order we observe in the simplest organism seems to be a monumental paradox. Note, however, that models describing the behavior of molecules are strictly mechanical-statistical only because this is the easiest way to study systems that are quite numerous and inaccessible to our direct experience. Consequently, while it is possible to predict the overall behavior of large masses of molecules using statistical methods, these models do not describe the individual behavior of concrete molecules (Weaver, 1948), and so the real properties of molecules are still not fully accounted for. In this sense, it may well be that the origin of life paradox, like so many scientific problems before it, exists only in the paradigms we use to frame it, in this case as qualitative inaccuracies in our description of molecules and atoms.

This again underscores the importance of the contrast that planets, as organized natural systems, offer to the concept of life, for unlike molecules and atoms, planets can be studied individually rather than by statistical methods. The parallelisms found in this contrast blur the previously sharp distinction between living and non-living organized natural systems, and in turn lead to new conclusions about the origin of life. According to the resulting *soft definition of life*, some of the components of living organisms may have had internal physiological functions, so that they did not just "bounce around" randomly, but operated according to certain sequences of intrinsically - i.e., within themselves - directed processes that led them to aggregate, just as cells aggregate, or as we do when we form societies. This mode of operation is perfectly captured in Whitehead's concept of *creativity*, the ultimate principle whereby the *disjunctive diversity* of the universe tends to coalesce into actual entities (Whitehead, 2010). The particular concrescence that gave rise to cellular life occurred when the conditions provided by the internal states of planet Earth were suitable for prebiotic compounds to organize into organisms. At a primitive stage, several biomolecular organizations should have emerged before one of them eventually acquired an autonomous organization. This process of generation could have been continuous until some primitive organisms developed further mechanisms to stabilize their autonomy, such as reproduction, as well as more stable components, such as DNA, rapidly displacing those that did not and thereby setting up the modality of life we are familiar with (H. Maturana & Varela, 2006).

The idea that there were physiological reasons both in the functioning of the planet and in the behavior of molecules that led to the emergence of living organisms also raises the possibility that different molecules in other layers of the Earth may have coalesced into similar modes of organization. This leads us to consider the popular scientific claim that, because of chemical similarities, another form of life could be based on silicon instead of carbon (Sagan, 2000). The latter is usually countered by saying that the properties of carbon are unique in that the the strength of the chemical bonds is sufficient to allow stability, but not enough to impose prohibitive energy costs on interactions (Killops & Killops, 2013). One might reply that this is only true under the conditions found at the Earth's surface. For example, the CMB is unlikely to allow the same stability for the strength of carbon chemical bonds that we observe here. In this case, it may be that silicon-based molecules, because of their greater weight, are actually able to form organized systems under different temperature and pressure conditions in other layers of the planet. In fact, this is exactly what happens on Earth. Starting from the fact that the planet itself can be considered as a silicon-based organized system - for silicon is probably its most basic structural element - each mineral species can also be considered as a modality of organization which, although not as complex as that of biological organisms, resembles their genesis, where, as described above, several types of molecular organizations should have emerged before the operation of some of them closed in on itself and became autonomous. At first glance, this leads to the idea that minerals reflect intermediate steps in a chain reaction similar to that which eventually led to the genesis of what we call living organisms. As an aside, we might note that similar complexly organized but not yet autonomous molecular dynamics exist in other planetary structures. A good example is the intricate reaction chains between neutral atoms and ions responsible for the absorption of high-intensity radiation in the terrestrial ionosphere (Schunk & Nagy, 2009). But returning to silicic systems, given that many of the minerals found on the surface were actually formed deep underground - where conditions are more conducive to the movement of heavy molecules and their subatomic constituents - and were further displaced to the surface - where their constituents became static - it may be that the operation of these minerals in the mantle is either approaching or has achieved autonomy. If this were the case, some of the minerals displaced to the surface would be somewhat reminiscent of fossils, which are simply the now static remnants of systems that were autonomous in another time and space, and some regions of the mantle would be populated by assemblages of siliceous organisms. As for the core, since this structure is mainly liquid and metallic, we can assume that both molecules and their constituents can move freely there. In addition, the high pressures allow these molecules to eventually crystallize, and the abundance of thermal and electromagnetic energy provides plenty of potential fuel, so nothing rules out the possibility that the core hosts complexly organized systems.

It remains to consider the consequences of the interaction between the development of autonomous units in a planetary structure and the autonomy of the planet. First of all, we should remember the curious reciprocity between the increasing complexity of the biological systems on the surface and the progressive development of the atmosphere - see (J. Lovelock, 2000). The climatic stability - supported by the functioning of the WPC - provided the necessary conditions for the slow evolution of complex biological organisms, but then the biosphere also modified these conditions through such processes as the biogenic oxygenation of the atmosphere. Generalizing this scenario, we can conclude, first, that the particular conditions provided by the Earth's integral autonomy are an important supporting element for the closure and subsequent development of complex molecular systems, and second, that the operation of these systems in turn involves molecular reactions whose products can radically alter the chemical composition of the planet. Let us now consider the mantle in the same terms. Movement in the silicic phase of a tectonically active planet is responsible not only for transporting minerals to the surface, but also for driving important fluxes of matter into the interior, such as the continuous ingestion of oceanic lithosphere. This process favors important contrasts in the temperature, density, and molecular composition of the mantle, which may ultimately be fundamental to maintaining the dynamic equilibrium and providing the energy sources necessary for whatever complex molecular organisms may have evolved in its depths. But then we should also consider the potential products of these systems. It is interesting to note that, similar to the atmosphere, the mantle is thought to have undergone a massive oxygenation in its early stages of development, the cause of which is usually attributed to the transfer of oxidized compounds from either the surface or the core (McCammon, 2005). In addition to the above alternatives, our perspective leads us to consider that the product of chemical reactions derived from some kind of autotrophy in the mantle could have altered its redox state from within, thereby favoring a molecular equilibrium that would in turn feed back into its continued operation and the autonomy of the entire planet. It should be clarified that the last point is not intended to concretize a solid hypothesis about the evolution of the mantle, but simply to illustrate how this perspective introduces another variable into the study of the planet, which can be summarized in the view that the products of physiological reactions are neither simple nor easy to predict, and that these reactions are not necessarily limited to the surface. Given the unfolding of forces resulting from the operation of a self-organizing system as massive as the Earth, it may be that some unforeseen and precise reactions occurring in its interior - both in the mantle and in the core - are fundamental to understanding its evolution. Consequently, the possibility that the bulk molecular composition of the Earth is regulated by multiple control points - and not just by the biosphere - must be considered in order to avoid the construction of linear, oversimplified geochemical models.

The Solar System

Having discussed the implications of this *soft definition of life* for the major subsystems of the Earth, the next question is whether there are other autonomous planets. This possibility resonates with the development of a general theory of planets and stars, and will be translated here into a brief examination of the major bodies in our solar system. Since the original purpose of the WPC was to explain the differences between Venus and the Earth (Foley & Driscoll, 2016), a good starting point is to note that Venus is unlikely to be autonomous. The same can be said for Mercury, for although it has a weak magnetic field (Stevenson, 2009), it seems to lack the other subsystems involved in the WPC. As for Mars, there are a few peculiarities to consider. First, while relating its topography to the geometric center yields a unimodal hypsometric distribution, like that of Venus, when it is related to the center of mass, this distribution becomes bimodal, like that of Earth (Aharonson et al., 2001). Therefore, although different, the topography of Mars is more similar to that of Earth than that of Venus. Second, analysis of the Martian crust reveals a regular pattern of magnetic anomalies, which has been discussed as indicating a simultaneous stage of early tectonics and geodynamo on Mars (Breuer & Spohn, 2003). Third, the presence of water in the Martian crust has been discussed several times (Carr, 1996). All of this suggests that Mars may have been autonomous for a period of time in the past, which, by implying a second case of autonomy in the Solar System, suggests that planets may have a slight tendency to develop an autonomous organization. This idea may be an important starting point for considering the case of gas giants. To begin with, these planets are characterized by large accumulated masses, rapid rotation rates, and multiple satellites (Williams, 2024). Although their massive volatile inventories do not allow us to clearly determine whether there is any kind of crust or tectonic phenomena in their interiors, they all exhibit large magnetic fields (Stevenson, 2009), abundant water (Sanchez-Lavega et al., 2019), and atmospheric electricity, ranging from lightning to electromagnetic waves conducted by atmospheric plasma, such as whistlers. Except on gas giants, this group of phenomena has been observed only on Earth (Yair et al., 2008). In addition, Jupiter has been reported to be a source of synchrotron radiation (Santos-Costa et al., 2017), an emergent phenomenon, perhaps shared with the other gas giants (Kavanagh Jr, 1975; Santos-Costa et al., 2003), whose presence suggests that the complexity of their magnetic fields exceeds that of the terrestrial one. The occurrence of these complex phenomena leads to the conclusion that the gas giants are self-organizing systems. This tendency to self-organization is already present in the Earth and Mars, but since the latter is now static, and the Earth, which is autonomous, is less dynamic in some of its emergent processes - i.e., the magnetic field - the gas giants are likely to exhibit a considerable degree of autonomy, perhaps greater than that of the Earth.

At this point, the discussion can be broadened by noting that, if the organization of the planets is considered in terms of the activity of their processes, then stars appear as a much more active version of what planets are. The Sun contains 99% of the mass of the Solar System (Whipple, 1964), and its magnetic field reverses polarity just every eleven years, much more frequently than any other known planet (Hathaway, 2015). It also produces the energy necessary for life, and energizes the ionospheres of all the planets in its orbit - note the curious similarity between these last two processes. Moreover, since each planet in the Solar System orbits the Sun and is coupled to its magnetic field, which extends beyond the orbit of Neptune (Masters, 2015), the operational environment of the Sun as a system includes, for redundancy, the entire Solar System, including all of its planets. With this in mind, it is then possible to make an observation regarding the organization and disposition of the planets in the Solar System. Mercury and Venus are closer to the Sun than the Earth. Neither is truly autonomous, but both exhibit related features, the presence of which cannot be adequately explained by current models of planets. In the case of Mercury, it is its weak magnetic field, and in the case of Venus, the apparently recent renovation of its crust 0.5 Ga ago (Solomatov & Moresi, 1996). They are followed by the Earth, which is autonomous, and Mars, which could have been autonomous in the past but failed. Finally, the gas giants could all be autonomous systems with an intensity greater than that of the Earth. Thus, we can point out - but not yet explain - a *progression* in the development of the planets in the Solar System, which in a certain way resembles the different stages that living organisms pass through during their ontogenesis. Although the information is still insufficient to address the actual organization of the Solar System, nor the directionality of its processes, it is worth suggesting a slight similarity in the relationship between the Sun and its planets and physiological functions related to *gregarity*. In the light of the electromagnetic interaction in the ionospheres, we could see a kind of *comensalism*, and in the above-mentioned outward progression in the degree of autonomy in the planets, even a kind of *reproduction*. In no case should these suggestions be taken literally, as facts. The purpose here is simply to illustrate how the physiological framework can be used to broaden the range of interactions considered in systems traditionally thought of as inert because of a narrow view of life. The most likely possibility is that the functions performed by planets are quite different from those of organic systems, albeit organized and with some *direccionality of processes*. Perhaps the most important aspect of this view is that all planets depend on stellar activity, so just as the self-regulation of habitability reflects the autonomy of the planet, the functioning of each planet could reflect the dynamic activity of the Solar System, leading us to conceive of it as autonomous. Through a simple logical chain of dependencies, these considerations can be further extended to galaxies - as self-organizing sets of stars. We are finally approaching cosmological scales, and our discussion must be extended accordingly.

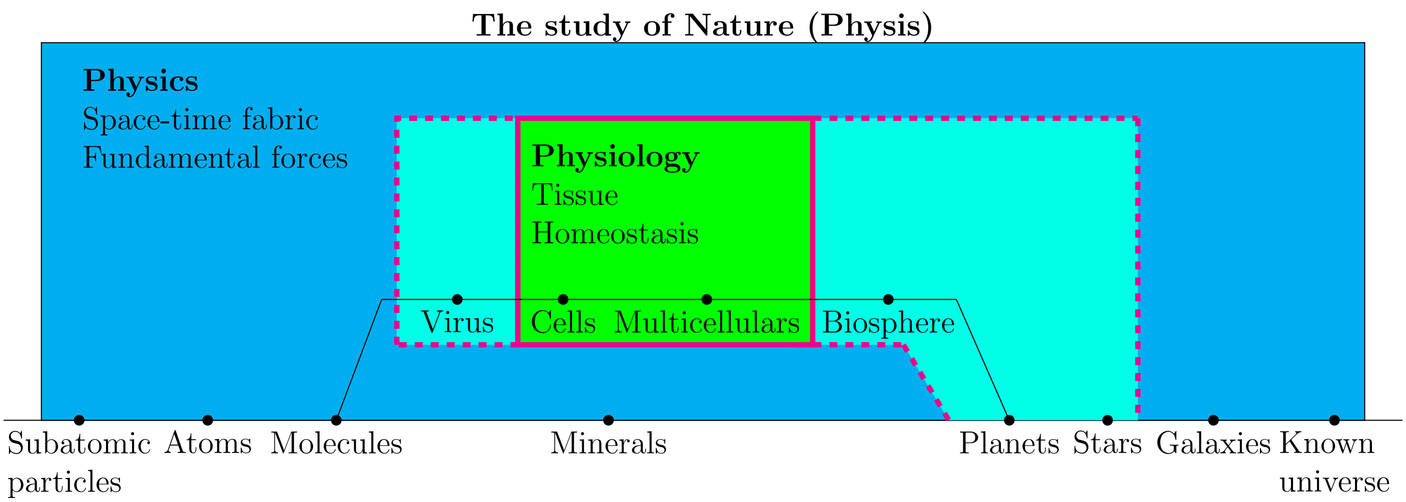


Figure 4: Schematic of the language used to study of nature (physis). A dimensionless scaling of self-organizing natural systems is represented by black dots, ranging from subatomic particles to the entire universe. The red solid line represents the current concept of life. Its interior, in green, groups the realm of nature which is covered by physiology. Dashed red lines represent a more flexible approach to life. Light blue areas indicate systems that are not considered to be alive per se, but have already been explored using related concepts. Dark blue indicates systems that are generally considered to be non-living and are studied only through the lens of physics.

Thermodynamics and cosmology

The logical coherence of any description of the universe requires an explanation of its remarkable dynamism. The early development of Western cosmology was based on a geocentric model that relied on divine intervention to explain motion. With the advent of modern science, the geocentric scheme was replaced by the heliocentric model of the Solar System, which removed our planet from its central position and established mechanistic laws to explain motion (Kuhn, 1992). The idea that the Earth was just another planet, instead of the divine scenario it appeared to be, then led to the rejection of explanations based on divine intervention. At the same time, the human experience was flooded with new concepts resulting from the increasing presence of mechanical devices. These concepts filled the gaps left by the removal of earlier teological explanations, and as a result, our current cosmology is based on comparisons to machines. Since every machine requires useful energy to function, the logical coherence of this description shifted its reliance on divine intervention to the availability of useful energy to drive motion in the universe. From this perspective, the evolution of the cosmos is seen as a thermodynamic process that began in a state of maximum specificity, serving as the primordial source of useful energy, and will end in a state of maximum homogeneity, in which no further work could be done (Penrose, 2006). Seen in this light, living organisms appear to be a remarkable local exception to the process of the universe (Schrödinger, 1992). These systems exist by constantly producing their own organization, and as such they can be thought of as creating specialty out of homogeneity. In a tree, for example, there is a *dynamic* network of processes that is specifically arranged to collect simple components from its environment and assemble them into the precise pattern of organization that constitutes the tree. This movement is based not only on the dissipation of energy, but also on the increase in organization required for the tree to function. The apparent thermodynamic contradiction implied by this mode of operation probably lies in the peculiarities of the paradigm shift that gave rise to our current cosmology. The confusion stems from the fact that the primitive Western paradigms mentioned above depended on divine intervention to address not only motion, but also life - think creationism. But there is a significant difference between motion and life with respect to machines, and thus to the transition to mechanicism: machines move, but they are not alive. Consequently, the paradigm shift from creationism to mechanicism affected our descriptions of life and motion in very different ways: the explanation of motion then fit into a much more accurate scheme, but that of life did not, and so the latter came to be considered an anomaly and was somewhat left out of the scientific description of the universe. This has led to a subtle and usually ignored cosmological dilemma: if the emergence of life cannot be adequately explained, but life implies and causes some kind of motion, then our cosmology will not account for that motion. At first it did not seem to matter: life was seen as an anomaly occurring only on the surface of this planet, so it could simply be thought of as a highly unlikely probabilistic state that otherwise had nothing to do with the general thermodynamic tendency of the universe. In this sense, the recognition of autonomy in a system such as a planet opens up a new area of discussion, for it suggests that the motion inherent in the functioning of living organisms may encompass a greater proportion of the dynamic activity of the universe.

Unlike a static planet, which "runs out of fuel" as it approaches the thermodynamic equilibrium that implies the cessation of its activity, an autonomous Earth is driven toward self-sustainability. This mode of operation implies a tendency to collect energy from its environment, to concentrate it, and to use it to create the pattern of organization that allows its functioning to be continuous and recursive. We have discussed that these considerations can be extended to organized systems of larger size, such as solar systems or galaxies, and that only by attributing physiological properties to the components of a system is it possible to address its ability to self-organize, so that the same properties must also be attributed in the other direction: to systems of smaller scales, such as atoms. This leads us to extend the physiological framework to any kind of self-organizing natural autonomous systems - *organisms* - in existence (see Figure 3). In terms of energetics, this view implies that the wastes of some systems are recovered by the active processes of others, just as plants use the wastes of our respiration to produce new organic matter. It is obvious that molecular waste is not comparable to heat dissipation, but then it can be argued that the scale of natural systems far exceeds that of biological organisms, both in size and in the range of their processes. In this scenario, the broad antennae of some stellar magnetic fields would capture and organize energy from their environment, and all scales of nature would be similarly regulated by the organisms operating there. According to this view, the emergence of new levels of organization is explained by a pervasive tendency of organisms to coalesce into larger and more stable organisms. This tendency is called *creativity*. A final contrast with the current scientific cosmology illustrates why the mechanistic paradigm yields a description in which the behavior of molecules is stochastic and in which stars are assumed to have a finite amount of fuel that is consumed until their operation ceases: these models are based on comparisons to human-made machines, such as cars. The activity of the resulting universe necessarily ends when each star "runs out of fuel," as would happen to gasoline-powered cars in a hypothetical end of oil. In contrast, a cosmology based on comparisons with organisms shows that some stellar processes could be directed to replenish the energy consumed in their functioning. The resulting universe could be similar to an ecosystem, but with a greater degree of autonomy derived from being all-encompassing. As our last quotation shows, this idea is far from innovative:

> "In this way then we ought to affirm according to the probable account that this universe is a living creature."
> - Plato, 360BC aprox. (Plato, 2019).

Concluding remarks

On the premise that any description of the universe is based on comparison with elements of the human experience, we have intended to exemplify how comparison with living organisms allows us to accurately capture the true complexity of some natural systems. Our conclusion is that the physiological framework may be a necessary counterbalance to avoid an oversimplified description of reality. However, a closer look reveals the underlying reason for this: since the human system, as the most basic element of the human experience, is indeed a living organism, the conception of a non-living universe would involve the *unnecessary* sacrifice of vast descriptive resources from our experience. From this perspective, the human system should be the most important element to be *taken as natural* in our description of the universe, and consequently, the fact that it is to be treated as a mere thermodynamic anomaly shows that the logical coherence of the description has been violated at its very root, for it proves ineffective to address how it is that the descriptors exist. On this basis, Plato's choice of comparison is still the most sound, for once this universe is seen as a living organism, we emerge as a natural manifestation of its functioning. Just another system in a universe of systems: like a geometric detail within a fractal pattern. In this way, our functions and meanings would simply be reflections of the functions and meanings inherent in every organism in existence, and we can therefore use them to explain, in our terms, the processes we observe in nature.

As a guide for the application of this view, we should consider, first, that nature - *physis* - does not exhibit such inhomogeneity as the vitalistic concept of life assumes, but is composed of organisms operating at all of its scales, and second, that the subsequent cosmology would require, whenever appropriate, the application of those scientifically based concepts previously isolated in *physiology* to address the dynamics of regulation, creativity, and potential autonomy of this universe and the organisms within it.

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