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The Gaia hypothesis revisited: Introducing an Organic Theory of Gaia

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Abstract. The Gaia hypothesis, which proposed Earth as a planetary superorganism, was dismissed due to perceived conflicts with natural selection and unclear mechanisms for its emergence. Here, we address these issues by developing the *Organic Gaia Theory*. This theory holds that the emergence, sustainability and evolution of Gaia as superorganism can be explained by three observable and interrelated hypotheses: 1) the tendency of dissipative systems to follow *Thermodynamic Maximization Principles* by evolving toward structures of higher material and energy use until some local limit is reached; 2) the tendency of complex dissipative systems to organize in *Prigogine trinomials*, i.e. to become functional parts of a larger structure with the emerging capacities to coordinate its functional parts and to adapt its environment to its benefit; and 3) the tendency of expansive and reproductive systems to overcome local limits to their growth and complexity through the formation of trinomials of Prigogine trinomials through the process of symbiotic cooperation and *organic symbiogenesis*. The interplay of these processes make the emergence of a super-organism at planetary scale (Gaia) not only possible but probable. Aligning Gaia with thermodynamic and biological principles the theory implies a potential paradigm shift in biological and Earth system sciences.

1 Introduction

The first formulation of the *Gaia hypothesis* by James Lovelock and Lynn Margulis (Lovelock and Margulis, 1974) has proved to be highly influential for the interdisciplinary study of global environmental change by laying the foundation for the emergence of Earth System Science which has risen to central importance in the study of planetary environmental problems and the sustainability of the global civilization (Steffen et al., 2020). The hypothesis postulated that living beings (biota) collectively adapt their environment to their benefit in such a way that a planetary-scale macro-system, Gaia, emerges, with properties analogous to of a living being. The concept of homeostasis, central to Gaia, aligns with principles from cybernetics (e.g., thermostatic regulation unit) and biology (e.g., metabolic stability in mammals).

However, the strongest versions of Gaia, in which the organic analogy is elevated to a category, were criticized by evolutionary theorists (e.g. (Gould, 1988), (Maynard-Smit, 1988), (Kirchner, 1989), (Dawkins, 2016), (Doolittle, WF, 1981)). Ultimately, the hypothesis was reframed as Gaia theory, emphasizing co-evolutionary self-regulation more in line

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with cybernetics rather than organicity (Schneider, 2004). Subsequent theories varied, from conventional explanations of life's persistence as a product of chance (Watson, 2004) and adaptability (Volk, 2004), (Kirchner, 2002) to broader interpretations that somehow scale natural selection beyond the local interactions of organisms (Lenton et al., 2018), (Doolittle and Inkpen, 2018). Some authors will add that this biosphere-biota coevolution could be directed, or at least facilitated, by the principles of thermodynamics (Schneider and Sagan, 2005), (Kleidon, 2004). Nevertheless, in some works (Lovelock, 1989), (Lovelock, 1986), (Lovelock, 2000), (Lovelock, 1996), Lovelock assumed the idea of planetary physiology for Gaia, implying that Gaia was a living being or organism. However, he was unable to explain how a planetary super-organism could emerge within Darwinian frameworks and his exposition remained ambivalent (Lovelock, 2004, 2003). This problem has remained unresolved until today and constitutes the main purpose of this paper.

Building on (De Castro, 2020, 2019; De Castro and McShea, 2022; De Castro Carranza, 2013), this paper introduces the Organic Gaia Theory (OGT) which explains the processes by which Gaia, relatively early in terms of Earth's history, could have emerged as a living being that inhabits and builds the biosphere without trying to extend or complete Darwin's natural selection theory. OGT provides a novel interpretation of life's evolution and Earth's biosphere dynamics, challenging prevailing paradigms and offering new insights into addressing Earth system sciences and global environmental crises.

2 Core premises of the OGT

In the following, we expose three biophysical postulates that serve as the basis for the development of an organic theory of Gaia.

2.1. Application of Thermodynamic Maximization Principles (TMaxP) to biological systems

Postulate 1: In line with Thermodynamic Maximization Principles (TMaxP), thermodynamically open, dissipative systems tend to evolve towards stable and resilient structures of high complexity until they reach local limits. Consequently, the formation of these structures tends to increase energy and material use, and energy dissipation, at the system level.

In the field of thermodynamics, 'dissipative structures' are dynamic structures that feed on an energy/material gradient which keeps them 'alive'. They possess coherence and self-organization while remaining out of thermodynamic equilibrium, and can be of physical (e.g. a candle flame, a hurricane) or biological character (e.g. a moss or a termite mound).

Thermodynamic Maximization Principles (TMaxP) related with energy exchanges and entropy production have been proposed to govern many complex dissipative systems beyond the main laws or principles of thermodynamics (Dewar et al., 2014). Among the several TMaxP proposed, the maximization of the power (MaxP) (Kleidon, 2023) used by those dissipative structures and the maximization of the rate of entropy production of the total system (MaxEP) (Lorenz et al., 2001) are hypothesized to enable emergent patterns in very complex dissipative systems such as Earth systems and biological processes ((Kleidon, 2021; Kleidon and Renner, 2013, cf. Appendix A). These systems are not only stable and resilient to relatively small perturbations, provided that the gradient remains, but TMaxP would also facilitate the development of some structural complexity within dissipative systems: Structural complexity implies more available energy dissipation or dispersion routes, thus, allowing increasing energy flows through the structure (in line with MaxP) while accelerating the total entropy production of the structure and its environment (in line with MaxEP).

There are clear signs that TMaxP and TMaxP-induced complexity can be found in the biological realm. With regard to organisms, Zotin (Zotin et al., 2001) show that during the evolution of large animals oxygen consumption or respiratory intensity per unit of body mass has tended to grow in the last 600 million years in an accelerated manner (coherent with MaxP). This also implies a tendency to capture more free energy and disperse it faster, i.e. increase the entropy of the environment faster (coherent with MaxEP). Judson (Judson, 2017) attempts to generalize this observation to the long-term history of living beings. Equally, TMaxP seem help to drive the development of entire ecosystems until they reach maturity, and seem to lie at the heart of the evolution of the biosphere as a whole. For example, a coral reef will disperse more energy than a geologically ancient ecosystem like a stromatolite. At the same time, extant stromatolites will disperse more energy than the stromatolites in the Archean Eon because they incorporate more complex species from all kingdoms whereas in the Archean Eon stromatolites only incorporated prokaryotes (Bacteria and Archaea). Last, Schneider and Sagan (Schneider and Sagan, 2005) compile examples of different ecosystems where greater transpiration and greater dispersed energy in molecular motion occurs in mature and/or biodiverse natural ecosystems than in less mature, less diverse, or more degraded ones. This is because, statistically, it is more likely to find pathways of energy dispersion by increasing biodiversity and/or internal nestedness of an ecosystem.

At the macroscale, the biosphere can be considered a highly complex dissipative system and, consequently, contains many diverse pathways for the dispersion of solar photons. The higher the number of pathways, the higher becomes the probability of fast energy dispersion which, again, links biological complexity to MaxEP. Consequently, it is very likely that the rate of entropy production of solar photons per surface unit is higher for an Earth-like planet with a highly diverse biosphere than for an Earth-like planet without the presence of life or with a degraded biosphere. This theoretical hypothesis has been corroborated by comparing the Earth with Mars, Titan and Venus (Kleidon and Lorenz, 2006) and by comparing the biosphere in the pre-industrial period with the current biosphere, which is subject to degradation due to anthropogenic climate change and the loss of diversity and ecosystems (annex 1 in De Castro, 2020).

Therefore, TMaxP help to explain auto-organization towards stable and resilient complex structures, like the ones that biology science studies, until some local physical or environmental limit is reached. This means that thermodynamic principles, contrary to the historical vision of the entropy law as a tendency towards disorder, are an enabling force for the formation of 'organized', complex structures.

2.2. Prigogine postulate: trinomials in biological systems

Postulate 2: *There is a tendency in sufficiently complex dissipative systems to form Prigogine trinomials whose emergent properties exercise downward causation with a stabilizing effect on the system*.

According to Ilya Prigogine's thermodynamic vision, the stability and resilience of sufficiently complex dissipative systems is maintained through the formation of 'Prigogine trinomials' (De Castro and McShea, 2022) which in turn enhance entropy production. Prigogine (De Castro and McShea, 2022; Prigogine, 1977) assumes that some physical-chemical as well as biological, psychological and social systems tend to comply with a trinomial of relationships between *structure* (the system as a whole), *functions* (the system's parts) and *fluctuations* (energy/material exchanges) (Fig. 1).

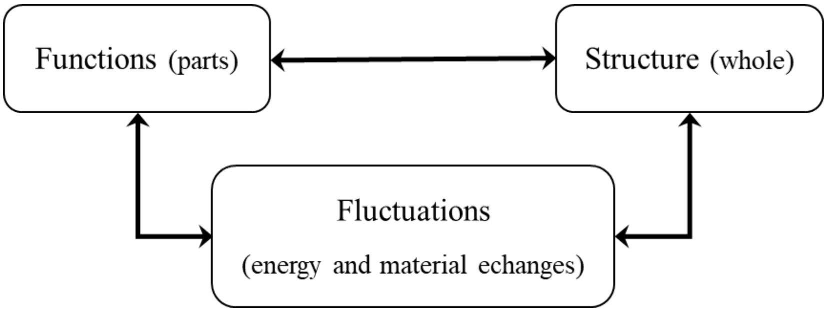

Figure 1: The trinomial according to Prigogine. Brackets denote alternative descriptions of the trinomial's components. Arrows depict causal relations and feedbacks. See text for explanations.

Importantly, Prigogine's trinomial comprises multidirectional causality (De Castro and McShea, 2022): On the one hand, it states that sufficiently complex dissipative structures emerge from, and are constituted by, their parts and the relationships between the parts, which are mediated by exchanges of energy and matter (bottom-up causal relationships). On the other hand, the trinomial also states that the emergent properties of the structure, resulting from the interacting parts, could give rise to relationships from the structure towards the functions (parts) and towards the energy and material exchanges with their environment (fluctuations) (top-down causal relationships). The importance of downward causation that is represented in the Prigogine trinomial as causal force from structure to functions is also acknowledged in (Noble, 2012; Noble et al., 2019) by the principle of '*biological relativity*' which they apply to the physiology of organisms. We call the downward causation from the whole to the parts 'orchestration' or 'coordination' of the functions *for and by* the structure, whereas, following the definition provided by Ortega y Gasset (Ortega y Gasset, 1933), the term 'technique' is used to describe the capacity to modulate or transform the fluctuations (i.e., the energy and material exchanges of structure and functions with the environment). We are aware that systematically considering downward causations introduces the 'teleology problem', a very controversial issue that constituted one of the criticisms directed to the first Gaia hypothesis by Lovelock & Margulis (Lovelock and Margulis, 1974). Postulate 2, which we expose here, constitutes a hypothesis that could be applied to many very complex systems, including the biological ones. Thus, we acknowledge that living beings behave at least as if they had intrinsic purposes, goal-directed behaviour and were capable to coordinate their parts to their benefit (see Appendix B).

Once the structure is formed, its stability and resilience would be facilitated by the mechanisms of postulate 1 (sect. 2.1). Equally, once emergent properties of the structure begin to exert downward causation through the application of 'coordination' and 'technique', further evolution of the system would be driven by bottom-up as well as top-down dynamics. The development of 'coordination' and 'technique' of a structure acquires particular significance when complex dissipative systems such as organisms reach local limits to their growth and evolution which will inevitably appear at some point. Williams (Williams, 1996), argues that organisms can extend the range of habitable environments, i.e. overcome local limits, in two ways: They can change the internal cellular machinery and/or they can change their own border so that the environment does not harm them. For example, faced with a hotter environment, an organism can generate a metabolism capable of functioning at high temperatures through new proteins that are more resistant to thermal degradation or it can generate a better organic insulator (e.g. a membrane, skin or bark). Lovelock (Lovelock, 1996), however, insists that there is a third way, namely, to modify the environment itself, for instance, by lowering the external temperature or by modifying the gradient between the interior of the organism and the outside. In other words, sufficiently complex dissipative systems characterized by Prigogine's trinomial relationships can adapt the environment to their needs by employing 'technique', i.e. by modulating energy and material exchanges with the environment. An example would be a bird (structure) employing 'coordination/ orchestration' of its muscle cells (functions) in order to modify energy and material flows (fluctuations) to its own needs ('technique'), resulting in a nest.

Hence, biological systems organized as Prigogine trinomials are able to overcome more local limits than isolated systems that are not integrated into a bigger structure. Likewise, by overcoming constraints to their growth and evolution they are able to increase energy flows and complexity, thus, also complying with TMaxP (cf. Postulate 1). As this links the presence of TMaxP to the development of Prigogine trinomials, we jointly refer to Postulate 1 and 2 as 'Prigogine dynamics' (cf. Appendix A).

2.3. Margulis Postulate: Nested Prigogine trinomials through symbiotic cooperation

Postulate 3: ***In the biological realm, local limits to the growth and evolution of life tend to be resolved through symbiotic cooperation and Margulis' generalized symbiogenesis, which give rise to a cascade of Prigogine trinomials.***

An organism, seen as a system/process, is stable as long as the flow of resources/energy is stable and the flow of waste does not affect it. The internal complexity of the organism increases the dispersion of the energy that reaches it with respect to a dead or simpler organism. In a finite world, if waste is not converted into a resource, a problem of material limits will

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inevitably appear. Given the exponential growth potential of living beings, combined with the limited availability of resources, interactions between offspring, the effects of waste generation and the laws of thermodynamics, the constraining pressure on living beings exercised by local limits is enormous. This problem was recognized and addressed by many authors after the 17th century (Vernadsky, 1926) and constitutes the driving force of Darwinian natural selection. Explicitly or implicitly recognized, it is the fundamental basis of some important 20th and 21st century theories regarding biological evolution (Lotka, 1922; Vernadsky, 1926; Volk, 2004) as well as sustainability problems of human economies (e.g. Georgescu-Roegen, 1986; Meadows et al., 1972).

Although, in theory, there are different ways of *temporarily* attenuating or overcoming local limits, including adaptation of the organism to the external environment and competition for scarce resources at the detriment of other organisms (cf. Appendix C), assuming the presence of Prigogine dynamics enables us to predict long-term tendencies with regard to overcoming limits.

First, we can expect the emergence and stability of cooperative 'strategies' in approaching limits, i.e. the coordinated 'sharing' or 'cycling' of material, because an increase in entropy production of one structure/organism might not imply a decrease in entropy production of another structure/organism as in zero-sum competitive strategies. Second, we can expect that these cooperative strategies will take the form of Prigogine trinomial relationships, due to the emergence of top-down causations in Prigogine trinomials. Last, we can expect that formerly independent trinomial structures merge into 'trinomials of trinomials' because of their superior capacity to address limits to growth and comply with TMaxP compared to isolated trinomials. For organisms, we note that the latter process is analogous to the concept of symbiogenesis.

Therefore, postulate 3 posits that in the long term there is a strong tendency to overcome local limits to the growth in the quantity and complexity of life through symbiotic cooperation and '*generalized symbiogenesis*' that tends to take the form of '*nested Prigogine trinomials*' (see next paragraph). The latter (also described as 'Matryoshka dolls' or 'wholes insides wholes') arise when a complex dissipative structure featuring its own functions in turn becomes the function of a larger structure, which in turn could become the function of an even larger structure. This dynamic has been shown to apply to the Major Transitions in Evolution (MTE) (De Castro and McShea, 2022) and explains the accelerated increase in the growth and complexification of life: In the process of the formation of a new structure/organism, which integrates formerly independent structures/organisms as functional parts, some local limitations the formerly independent organisms faced, might be removed, resulting in faster evolution and complexification.

The starting point in the formation of nested Prigogine trinomials is the concept of symbiosis, the common interdependent life of several living beings. Symbiosis allows the complexity of organisms to increase and facilitates the alleviation of limits to growth by the coordinated cycling of materials. At the same time, local limits could be seen as triggering symbiotic processes. Sometimes, the interaction between organisms can be very intimate and involve the exchange of genes and/or metabolites, as is the case of the lichen formed from a plant and a fungus, in which the plant provides sugars to the fungus and the fungus provides nitrogen to the plant. This close cooperation leads to the formation of a new macrostructure ('the lichen'). Once formed as an individual, the emergence of downwards causation begins to coordinate the symbiotic cooperation between the formerly independent parts (fungus, plant) for the sake of the new structure (lichen), and we could speak of a *symbiogenetic* process.

Commonly, symbiogenesis describes the formation of a new species (*genesis*) through the strong interdependence of several former species (*symbiosis*). However, here we will generalize the concept of Margulis symbiogenesis to refer to processes in which the symbiosis of several biological entities leads to the emergence of a biological macrostructure in which the cooperating entities are integrated as functional parts, reflecting trinomial relationships in Prigogine's sense. Consequently, biofilms, corals or lichens, for instance, could be seen as the symbiogenesis of a new living structure.

When several partners of the symbiotic cooperation have phylogenetic different origins and the reversibility of the symbiogenesis (the independent life of partners) is difficult or impaired, then we speak of *holobionts* (Margulis, 1991; Meyer-Abich, 1943). Once the structure becomes irreversible or very unlikely reversible, i.e. when former biological structures become integrated functional parts that cannot live independently from the new higher-level structure, we could speak of *organic symbiogenesis* resulting in a *symbiogenetic organism*. We acknowledge that the boundary between a holobiont and a symbiogenetic organism can be difficult to establish as the decisive variable is the degree of (ir)reversibility of the macro-structure. The former biological structures can be of the same (e.g. in the case of multicellulars) and of different (e.g. in the case of eukaryotic cells) phylogenetic origin. Combinations are also possible, which is illustrated for example by a Michaelensis termite colony formed by holobionts of prokaryotes inside pluricellulars (the termites) as well as by fungi in the termite mound. We will refer to these processes as *Margulis dynamics.*

In this framework, the outcome of each MTE could be regarded as symbiogenetic organism. The appearance of eukaryotic cells would be the classic example of symbiogenesis. Consequently, multicellular organisms as well as organic colonial structures (which both are, in turn, holobionts) constitute organic symbiogenesis caused by the symbiotic, cooperative relationships of genetically similar but differentiated cells or individuals and other partners of the symbiosis.

Symbiogenetic organisms, thus, can be seen as arising from a cascade of closed trinomials where each trinomial is completed and all the causal arrows are at work. A classical example would be colonial organisms whose parts (e.g. termites and fungi) are at the same time structures with functional parts (eukaryotic cells and bacteria), some of which constitute structures in themselves (the eukaryotic cells whose origin lies in the symbiogenesis of organic parts (bacteria). The increase of complexity not only resolves some local limits that lower-level structures (i.e. the less complex, formerly independent organisms) cannot surpass but the power used inside the system, and the total dispersion of energy, will likely be greater because of the complexity-induced increase in the number of dissipation pathways (see Postulate 1 and 2).

If there were no limits, the size and complexity of symbiogenetic organisms would make them relatively slow in reproduction, metabolism and potential growth compared to the participants of symbiogenesis living "independently". However, the evolution, growth and complexification of life in the face of limits requires symbiotic cooperation, which, coupled with Prigogine's dynamics acting as facilitating forces, leads to symbiogenetic organisms featuring stability, resilience and new emerging capacities. For instance, limits to the adaptation to external temperature variations impair the reproductive metabolism of prokaryotes. While some prokaryotes can reproduce once every 20 minutes at 25ºC, at temperatures lower than 0ºC their metabolism stops. Conversely, some birds and their symbiotic prokaryote partners (e.g. the emperor penguin (*Aptenodytes forsteri)* in Antarctica) can grow and reproduce once every year, and be metabolically active despite strong external temperature variations, because their high structural complexity gives them the homeostatic property of being homoeothermic and facilitates behavioural and, purposeful adaptations.

3. Towards an organic theory of Gaia

3.1. Nested Trinomial relationships in the ecological realm

The Prigogine trinomial can be applied to the ecological realm as ecosystems constitute complex dissipative systems and the relationships established among organisms belong functionally to the ecosystem that hosts them (De Castro and McShea, 2022) . Consequently, Postulates 1 – 3 (sect. 2), not only explain the increase and stability of hierarchical levels in MTEs but also suggest a tendency to form ecological macrostructures. This implies the formation of large ecosystems and the emergence of top-down causation that functionally integrates organisms, including their physical-chemical and biological processes. Over evolutionary time, the latter will tend to transfer their functions and purposes to the larger system. Therefore, although the first cells on Earth initially possessed high ‘interiority’ and ‘independence’, as their population increased, evolved and diversified, the pressure arising from biophysical limits to their growth soon led to the formation of ecological macrostructures (biofilms and ecosystems) and a transfer of ‘purpose’ to the macro-structure as formerly independent structures became functional parts of the new structure (see Figure 2). In line with Postulates 1-3, Guerrero and Berlanga (Guerrero and Berlanga, 2006) show that the formation of ecosystems was absolutely necessary 200 or 300 million years after the appearance of the first bacteria on the planet in order to regenerate biogenic material that would otherwise be exhausted much sooner. Thus, it was the recycling of matter through the activity of the first ecosystems that prevented global extinction and the drift towards a Venus-type planetary state.

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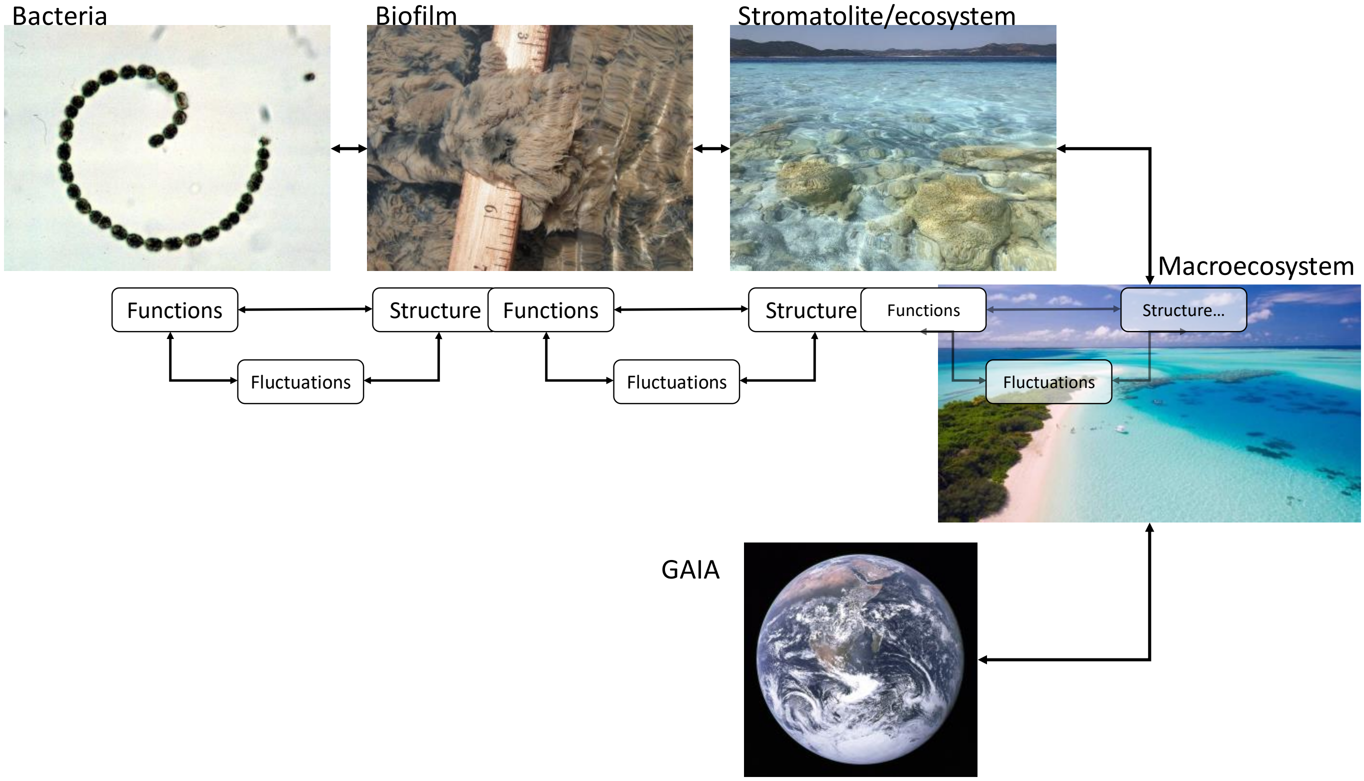

Figure 2: Succession of Prigogine trinomials nested within each other in the ecological realm. See text for explanations. Photographs are of public domain.

In our understanding, there is no obvious physical or biological law that inhibits the process of forming ever larger nested trinomials through generalized symbiogenetic processes as a reaction to the emergence of local limits until the planetary scale is reached by. This ecological super-structure is what we call Gaia. In fact, given the entropy-enhancing effect of complex nested Prigogine trinomials, in the presence of TMaxP, the emergence of Gaia is not only possible but probable (cf. Appendix A).

As Fig. 2 shows, bacteria populations aggregate in diverse communities and perform functions for the biofilms through cooperative symbiosis and the formation of holobionts, i.e. ecological units (‘structures’/‘wholes’) emerging from the symbiosis of a host organism, prokaryotes, virus and any other organisms or elements, which contribute positively to the structure. The biofilms in turn are one of several parts within a stromatolite ecosystem that is performing various functions for larger macroecosystems or biomes, which are in turn functional parts of Gaia. Although the first stromatolite ecosystems were involved in the formation of Gaia during geological times many diverse ecosystems evolved that could act as functional parts of Gaia, increasing her internal diversity. Like all lower-level structures (organisms, ecosystems etc.), Gaia, as the

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trinomial on the largest level, features all the dynamics and causal relationships constituting any Prigogine trinomial (sect. 2.2) which is illustrated in detail in (cf. Appendix C).

Assuming Gaia as planetary superstructure that closes the cascade of trinomials allows us to develop a new perspective on the evolution of life on Earth:

First, the MTE do not only result in greater complexity of organisms but also in greater internal complexity and diversity of Gaia which increases her resilience, her capacity to employ 'technique', and finally, her rate of entropy production and internal power use (cf. sect. 2.1 and 2.2). For example, due to MTE, in current ecosystems, thousands of species from all kingdoms are integrated with reef-forming stromatolites. At the same time, once formed, Gaia, begins to set the conditions for the further evolution of organisms on Earth's surface through ecosystems.

Second, most of the multicellular living beings are holobionts, which are constituted not only by genetic vertical inheritance, but also by ecological relationships with the possibility to give rise to horizontal genetic exchanges. The same holds true for the super-organism constituting the termite mound and other colonial organisms. In fact, evolutionary history is littered with horizontal genetic inheritance mainly mediated by virus and prokaryotes. This genetic 'promiscuity' and strong ecological relationships replaces the metaphor of the evolutionary 'tree of life' reflecting individual branches with vertical inheritance, with a 'coral of life', reflecting intermingled branches with horizontal inheritance. Adopting the latter metaphor, the evolution of life as a whole resembles the evolution of a single (super-)organism: Gaia.

Another parallel between Gaia and an organism is the coordinated cycling of essential materials. The cycling of elements has already been remarked by Williams (Williams, 1996) in the context of biogeochemical cycles in the total biosphere, and the extraordinarily elevated cycling ratios of the biosphere have been studied and quantified for instance by (Lenton et al., 2020; Volk, 2012; Williams, 1996). Based on Postulates 1-3, the cycling within multicellular organisms at the micro-level and Gaia at the macro-level can be explained by the genesis of a new, complex entity, originally emerging out of symbiotic cooperation in the face of resource limits, which is capable of coordinating its parts in such a way as to facilitate material cycling through the whole structure. In this way, material restraints are overcome and a new structure with high interiority can form. Thus, it is precisely the existence of high material cycling which points to the existence of a 'structure' (see Appendix C).

3.2. The emergence of Gaia as a super-organism

Applying the three postulates to the planetary scale we can describe the processes and the positive feedback cycle that leads to the emergence and evolution of the superstructure called organic Gaia (Figure 3):

1. Expansion of prokaryotes in number and diversity
2. Appearance of partial and local constraints and limits to their growth, diversity and complexity
3. Universal tendency to increase the entropy of the universe through increased internal complexity by cooperation-symbiosis and the formation of genetic and ecological nets
4. Breaking of partial and local limits and new expansion of the living beings

5. New partial limits
6. More cooperation-symbiosis leading to emerging macro-structures facilitated by Prigogine and Margulis Dynamics
7. Transfer of functions and processes to the emerging structure and causality from the emerging structure back to its parts that increasingly become functions of the structure, as well as to exchanges with the environment which are modified in benefit of the structure.
8. After repeated iterations from 1 to 7: Qualities of high organicity emerge via *organic symbiogenesis*; the structure becomes a superorganism that limits and selects the internal expansion of former 'cells', i.e. 'orchestrates' or 'coordinates' its functional parts.
9. Gaia accelerates 1-8 internally once that Gaia has emerged as an organic being
10. Gaia becomes an evolutionary organism with exponential growth potential, which also applies to her internal complexity (i.e. Gaia begets Gaia).

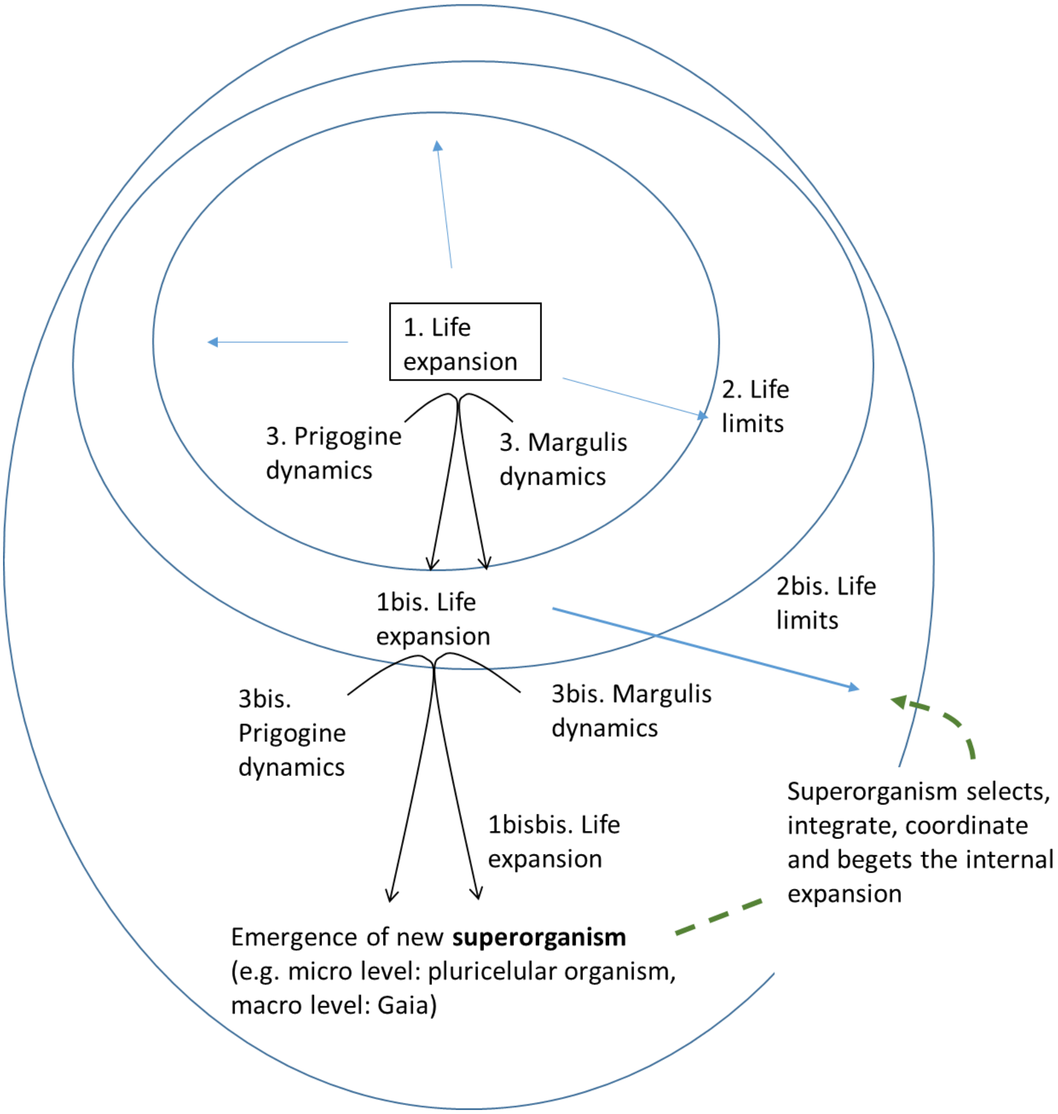

Figure 3: The general dynamic feedback process that gives rise to Gaia as an organic living being and superorganism.

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The potential of organisms for exponential growth tends to generate sufficient density to facilitate strong and intimate interactions between organisms as well as with the physical environment. These interactions are characterized by continuous exchanges of energy and matter, including genes and other information. Both physical factors and other organisms potentially act as limiting factors, influencing population growth. Evolutionary pressure to decrease and regulate limiting factors through the coordinated recycling of matter give rise to strongly symbiotic relationships, which allow to reduce the limiting factors. Due to higher cycling rates, the density of organisms thriving on Earth can continue to increase, their interactions increase and the coordination of the elements continues to increase auto-catalytically. This type of coordination is automatically selected. In this process, the presence of life increases, as does its relationship with the physical environment. The elements gradually lose their individual character due to the imposed needs for integration and coordination within the system. Part of the processes and functions of organisms are transferred to Gaia.

There is a positive feedback between potential growth, limiting factors and coordinated behaviour that raises the recycling rates and increases energy power used and total energy dispersion. Eventually, an adaptive structure or system with increasing complexity is formed. The increase in recycling and the associated functional integration of formerly independent entities into the structure ends up being so high that the physical environment is totally modified by the organisms and the adaptive structure itself. The structure begins to play a selecting role, a constraint factor for internal processes. The system ends up being an entity with very high organicity, with organic properties. Gaia emerges and her evolution then speeds up, resulting in accelerated material growth (her total biomass for instance) and accelerated growth of her internal complexity (both in the genetic and ecological realm), which evolves in non-linear ways. After repetitive cycles, Gaia ends up being the main factor that limits and orchestrate her cells' population (green dashed arrow in Fig. 3).

The increase in complexity observable in the evolution of life on Earth always follows the process illustrated by Fig. 3, both genetically and ecologically: expansion (in number and diversity), limits/constraints, coordination-integration-symbiogenesis, new expansion, new limits/constraints, more coordination-symbiosis, transfer of functions and processes, new superorganism that overcomes former local limits. It stands to reason that this process will continue exponentially until the appearance of absolute limits, such as the laws of thermodynamics or the speed of light, for example.

4. Discussion

4.1. Gaia's organic individuality

In contrast to cybernetic and Darwinian theories of Gaia, the dynamics described by the OGT suggest that Gaia can be qualified as a living being possessing organic individuality.

Ultimately, whether Gaia is considered a living organism or not depends on how the latter is defined. Lovelock's initial proposal for a property of living beings was the capacity for temperature homeostasis, which in the case of Gaia would be the regulation and long-term changes in the composition of the atmosphere. Later, several authors (Lenton et al., 2020; Volk, 2012; Williams, 1996) observed that the capacity for material cycling on the biosphere scale was also striking. In fact, the level of cycling on a Gaian level could be comparable to the cycling of materials within complex organisms.

Building on these prior works, we propose four properties (‘*RAMO* properties’) common to all living beings (‘organisms’) that would enable us to assess whether Gaia is a living organism:

i. **Recyclability**: the ability to cycle at high rates those elements that the organism uses most. This indirectly measures the interiority of the structure: The longer the elements cycle *within* the structure rather than outside of it, the higher its interiority.
ii. **Atomicity**: the ability to selectively use material elements required by the organism at an atomic-molecular scale and in low relative concentrations.
iii. **Multifunctionality**: the ability of the parts of the organism to perform several functions simultaneously and in a coupled way for and by the organism.
iv. **Organicity**: the ability of the organism to coordinate or organize the whole for itself in a coherent way in properties that we relate to metabolism and physiology, such the coordination of multiple material cycles (e.g. the H2O, CO2, CH4, PO4…) and the coordination of the multifunctionality of the parts.

It is beyond the scope of this article to conduct an assessment of RAMO properties for Gaia (see sect. 4.2). Instead, for now it suffices to note that sustaining and developing life on the planetary scale throughout the history of the Earth requires a degree of complex coordination only observed in living beings.

4.2. A preliminary research agenda building on the OGT

In this paper, we have presented the foundations of OGT. However, to fully develop the theory’s potential, an ambitious research agenda is required which would include several areas of future work:

First, to corroborate or falsify the OGT, researchers would need to gradually apply all RAMO properties to Gaia and examine to which extent Gaia exhibits these properties. The existing literature on biogeochemical cycles can provide a starting point for a detailed and comparative analysis of the cycling of different critical elements through Gaia. In the case that RAMO properties are seen as insufficient conditions to speak of a living organism, they still serve to guide future research in resolving the discussion about Gaia’s organic character: If Gaia was found to exhibit all RAMO properties the only way to deny Gaia a status as organism would be to find another complex *non-organic* dissipative system featuring RAMO properties because this would show that RAMO properties are not restricted to organisms. Also, If the RAMO properties of Gaia in the biosphere prove to be sufficiently high, in turn, not only the biosphere as physico-chemical system will be profoundly influenced and conditioned by Gaia, but also the interactions with other Earth systems. For instance, the deep lithosphere-mantle hydration feedback (e.g. (Höning and Spohn, 2016)) or the lithosphere-mantle energetic and dynamic interaction with the biosphere will be at least "complicated" by Gaia (e.g. (Dyke et al., 2011)). Rather than a coevolving ‘mechanism’, Gaia would be better qualified as a being able to modify her contour conditions in a beneficial way.

Second, the evolution of Gaia according to the OGT could be formalized through mathematical models able to depict the two opposing dynamics described in previous sections, namely (1) the exponential growth in the evolution of life, measurable by variables such as the diversity of species or families throughout geological time and throughout different kingdoms (prokaryotes, eukaryotes, animals, fungi, plants), proteonome or genome functional size or primary productivity in the biosphere and their living biomass; and (2) factors and events that counterbalance this exponential tendency such as local limits to growth and external perturbation, including high radiation for instance by the appearance of near supernova stars, comets and meteorites, large episodic volcanism and plate tectonics continental movements. Mathematical functions producing sigmoidal curves (for instance, the Verhulst equation) appear a suitable starting point for OGT inspired mathematical models. These models could verify or falsify predictions on evolutionary tendencies according to the OGT. For example, Prigogine dynamics could be applied to the debate on the origins of life, while Margulis dynamics could be used as explanatory factor once a reproductive-expansive cycle begins. Likewise, the OGT could lead to insights regarding the future evolutionary possibilities of Gaia.

Third, there is a need to develop falsifiable predictions based on the OGT that do not only include Gaia’s organic status and the past and future of life on Earth but also predictions arising from the study of the ‘physiology’ of Gaia. The latter would focus on how available data about the biosphere could be interpreted assuming an organic Gaian metabolism.

Last, interdisciplinary efforts including the social sciences could be undertaken to reflect on a ‘teleology’ of Gaia and implications of the OGT for the evolution of human society and the grave sustainability problems of the current global civilization.

5. Conclusion

In this article we presented the ‘Organic Gaia Theory’ (OGT) which explains how Gaia could emerge as an organic superstructure relatively early in Earth’s history and possibly began to act as conditioning force shaping the further evolution and complexification of organisms on a lower scale. The OGT builds on three postulates developed from the seminal works by Ilya Prigogine on non-equilibrium thermodynamics and trinomial relationships between structures, functions and fluctuations, and by Lynn Margulis on symbiogenesis. By applying Prigogine’s trinomial relationships to the biological realm, we arrive at the concept of nested or cascading trinomials, while, by extending the idea of symbiogenesis beyond the genetic realm, we develop the concept of generalized organic symbiogenesis. While thermodynamic maximization principles act as facilitating forces for the emergence of increasingly complex ‘living’ structures, only in combination with another

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thermodynamic related principle – the finiteness of matter and energy leading to limits to growth – living beings are pushed to undergo generalized symbiogenetic processes, which ultimately leads to the formation of the largest and most complex organic structure: Gaia. Once formed, Gaia herself, in analogous ways to complex organic structures on smaller levels (e.g. ecosystems and organisms), through geological time starts to evolve, coordinate and regulate her functional parts (through 'orchestration') as well as her environment (through 'technique') in line with thermodynamic maximization principles. In this way, Gaia becomes the main selecting evolutionary force for smaller-scale organic structures.

The OGT constitutes a paradigm shift in the study of biological systems as it goes beyond a categorical separation between the ecological and the genetic realm, acknowledging that strict frontiers do not exist. It offers a thermodynamically consistent interpretation of the evolution of life on Earth and is explicitly concerned with the role of downward causation and nested structures in the biological world. As such, it also transcends the Darwinian evolutionary paradigm in biology sciences. Considering Gaia an organic superstructure constitutes a novel framework for studying life, ecology, biology and evolution on Earth and opens up new perspectives on how to approach our civilization's sustainability problems.

Given this potential paradigmatic character of the OGT, it is of central importance to develop a set of falsifiable predictions that could act as validity tests for the theory. In the best case, the here exposed OGT would turn into a research project engaging a large group of scientists, which would hopefully allow the OGT to ultimately become a mainstream paradigm.

Appendices

Appendix A. TMaxP and Prigogine dynamics

A.1 Relationships between biological and physical laws

Cosmology describes the universe just after the Big Bang as an energy soup devoid of structure. Nevertheless, during the 13780 million years after the Big Bang, more and more complex structures have arisen locally. This extraordinary observation is not addressed by any scientific theory apart from thermodynamics.

The laws of thermodynamics have a special status in science because they are not based on theories but on direct observation of the material universe. They postulate absolute limits while opening up the space of possibilities through the concept of degrees of freedom. Equally, they are useful to explain transformative or evolutionary process in the biological realm, and some physicists have been trying to incorporate the importance of thermodynamics into processes of biological nature for more than a century (e.g. (Kleidon, 2024; Lotka, 1922; Prigogine and Nicolis, 1971; Schneider and Sagan, 2005; Schrödinger, 1992)).

One assumption behind the OGT is that there are laws specific to each scientific discipline that are not reducible to physics, be it thermodynamics or relativistic quantum mechanics. This is reflected in the incorporation of downward causation in the Prigogine postulate, and symbiogenesis in the Margulis postulate, the latter describing processes that are qualitatively

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different from the realm of physics. At the same time we assume that the first postulate, the TMaxP postulate, applies to every scientific discipline with dissipative systems of sufficient complexity. Thus, an implicit 'zero postulate' of the OGT is that a) biology must comply with the laws of thermodynamics, but that b) there are biological laws applying to structures beyond the atom-level that are not reducible to physical laws.

A.2. Thermodynamic laws and TMaxP principles

The first law of thermodynamics describes the conservation of the energy in the universe. The total energy is constant and indestructible and without transfer of energy or matter nothing happens. Any process, including the formation of structures, needs some energy gradient or local differences to take place.

The first law does not say anything about energy exchanges in particular which are addressed by the second law, i.e. the entropy law (entropy = S) which postulates that there is a tendency to favour energy exchanges that disperse the energy in the universe. There is a tendency to erase the gradients or local differences (Schneider and Sagan, 2005). The measure of the degree of the dispersion of the energy in a system is called entropy. Formulated in this way, it is a law of equality (and not of disorder, which is a subjective human concept (Lambert, 2002)). It is the most special physical law because it is the best established law that is mathematically expressed by an inequality: $\sigma = dS/dt >=0$ (being σ the temporal variation or flux of entropy).[1] If the system has local energy gradients or can degrade local gradients of its 'environment', and if there are enough degrees of freedom for energy exchanges to take place, then dS(system+environment)/dt > 0. The second law explains irreversible phenomena and history, i.e. local transformations. However, as the dispersion of energy tends to increase, there is a trend towards an erosion of the energy gradients. Therefore, at first sight, the second law cannot explain the observation of increasing structure in the universe as time goes by.

Evidently, physics has other more specific laws that help to explain each of the specific structure formation. For instance, the formation of the structure of a sodium chlorine crystalline solid has a lower entropy (electrostatic energy among the sodium and chlorine bonds) than when the ions were dissolved in the evaporating water. The formation of the crystalline solid is not against the second law because, although $\sigma_{\mathrm{NaCl}} = \sigma_{\mathrm{estructure}} < 0$ in the process of the crystalline structure formation, the evaporating water $\sigma_{\mathrm{water}} = \sigma_{\mathrm{environment}} > 0$, and $\sigma_{\mathrm{NaCl}} + \sigma_{\mathrm{water}} > 0$. If only the salt solid formation is considered, it seems that the entropy law has been violated; from a statistical formulation of the second law alone, the probability of the spontaneous salt formation is near 0. Nevertheless, if we consider the ionic forces and the global process then, under the right conditions, such as the possibility for the water to evaporate, the salt formation has a probability of 1.

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[1] There is another important inequality in physics - the Heisenberg uncertainty principle - which is related to the entropy law in a curious way. It has been shown that a violation of the uncertainty principle (**ħ**) would imply a violation of the entropy law (**S**), i.e. (***-ħ*** **=>** ***-S***) (Hänggi and Wehner, 2013).

The second law does not say anything about the change of the flux of entropy over time, i.e. about the velocity (σ (=dS/dt)) and acceleration (dσ/dt) of entropy S. Here is where Thermodynamic maximization principles (TMaxP) appear (Dewar et al., 2014):

If a system is in thermodynamic equilibrium with another system no energy or material interchanges between them happen. If two systems or subsystems have gradients between them but are near the equilibrium, it is observed and thermodynamically formulated by Prigogine that the rhythm of the increase of the entropy of the entire system is at a minimum, σ is minimal. This is the minimum principle and it is part of the TMaxP.[2]

If a system is far from the thermodynamic equilibrium, it can evolve towards states that dissipate or disperse the energy gradients at different rhythms. If the gradient remains, for example because it is external to the system, there is no static equilibrium in the system, thus, σ is always > 0. Nevertheless, we could still speak of a dynamic equilibrium (steady state) if the state of the system arrives to a σ = constant > 0. For instance, the planet Venus is mainly in thermodynamic equilibrium while the solar photons that arrive at Venus are dispersed, with the entropy of the solar photons increasing and σ being constant (if no other changes of the structure called Venus and the Sun happen).

In the last decades, various authors (Dewar et al., 2014; Kleidon, 2023) have stated that the most probable steady state in systems far from thermodynamic equilibrium, given local restrictions, is the steady state which forms a structure that disperses energy more quickly. In other words, among the possible steady states, there is a tendency to reach the one that maximizes the entropy production of an energy gradient. This is called the MaxEP (maximum entropy production) principle and although it has been demonstrated for some systems and energy gradients, there is still no universally accepted theoretical generalization, thus, it remains a hypothesis. In addition, the MaxEP principle does not speak of the process that leads to the different possible steady states or a priori what these are. In short, if there are two possible systems that disperse energy from their environment, and the systems are in a steady state which keeps their internal entropy constant, the entropy of the environment will be increasing. MaxEP means that the state that exhibits the fastest dispersion of the energy gradient feeding the system will be more probable. In addition, the system that has reached that steady state has generated some structure that allows MaxEP, and at the same time the structure processes part of that energy gradient to maintain itself.

MaxEP has been shown to be related to the fluctuation theorem which says that the probability of a system evolving towards an increase in entropy of value +Δs is exponentially greater than a decrease of it, -Δs. This in turn indicates that an increase is much more likely than a decrease in entropy in proportion to the size (number of possible configurations) and time that passes. If we compare the possible evolutions of a system towards the possible steady states, the parts of the system, which relatively to other parts, suffer a fluctuation or change that causes S to increase faster than others, will be self-selected, since their probability of reverting to "-Δs" is exponentially lower. This is related to Prigogine's idea of order (the formation of

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[2] Maximization principles refer to the differential mathematics of the minimum or maximum of a mathematical function. Extreme principles would, thus, be a more precise name.

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dissipative structures of a certain complexity) through small fluctuations. This evolution would then lead to a steady state that would tend to comply with the MaxEP.

TMaxP refer to the latter: depending on the degrees of freedom and the boundary conditions, the tendency is for the system to self-organize in such a way that the dispersion and processing of energy is as fast as locally possible.

A very knowledge example is the formation of the Bénard-Rayleigh cells. Before the formation of this structure the energy gradient is dispersed at a constant rate σ_1 but after the formation of the Bénard cells the rate $\sigma_2 > \sigma_1$. The Bénard cells are the result of the 'cooperation', 'coordination' or 'coherent movement' of billions of molecules. For Prigogine, they form quickly when a fluctuation of the movement is positively feedbacked and a sufficient energy gradient (related to the Raiyleigh number) is attained. Once formed, the structure tends to force the random Brownian movement (dissipated heat by conduction) to be reduced towards a cycling movement (dissipated heat by convection). Some molecules, colliding randomly before forming the cell structure, could cool down (slow down their speed) in short periods of time and space. However, when the structure is formed, it 'imposes' a coordinated movement that makes it more unlikely that some molecules 'cool down' in those short periods of time and space. In the system, after the cells are formed, the entropy increases faster and the power dissipated in the cells is greater than before the cells were formed. Although the molecules lose degrees of freedom with regard to their movement, the molecules have gained average energy dispersion, internal energy processing and energy dispersing into the environment. The cells are consistent with the TMaxP postulate of the OGT but also shows signs of compliance with the Prigogine postulate because the cell as a structure somewhat limits the possible movement of the molecules (it coordinates them). One way to measure the degree of closure of the Prigogine trinomial from this downward causation is to quantify this limitation of movement or coordination through the cycling ratios (CR) (see Appendix C).

A.3. Complexity, stability and evolution

Diversity and nestedness (or internal relationships) is a measure of complexity, and complex dynamical structures are relatively more capable to accelerate the energy dispersion constrained by local physical conditions because the probability to find new routes of dispersion increases and it is likely that one of them accelerates the total rate. The evolution of systems towards more complex, diverse and nested states, therefore, is line with TMaxP and Prigogine postulates.

Systems could have a tendency to grow exponentially until they approach some local physical limitation, i.e. the system is constrained by contour conditions. This means that we can expect a sigmoidal or logistic growth pattern in the system's evolution until a dynamic equilibrium is reached. Contour conditions (e.g. friction, gravity, viscosity or the form and characteristics of the liquid container for Bénard cells) prevent further evolution, although if these conditions and the gradient remain the structure is stable and resilient to soft perturbations. In other words, fluctuation theorem and MaxEP, along with their correlate MaxP (Maximum Power), stabilize dissipative systems outside thermodynamic equilibrium.

Thus, non-equilibrium thermodynamics under TMaxP lead us to two ideas applicable to living beings: 1) a probabilistic tendency in the universe for increasingly complex systems to form, and 2) a tendency for these systems to remain stable and evolve until they reach a limiting factor, provided that boundary conditions and energy gradients continue to exist without significant changes.[3]

However, when the structure complies with the Prigogine trinomial, in addition to directing its internal processes, it is capable of modifying and acting on the restrictions imposed on it (through 'technique'), modifying (or defining) the exchange boundary with the environment and, therefore, the environment itself and its exchange flows.

Appendix B. Remarks on the teleological problem

The scientific community, including Lovelock himself, used to confound the teleological phenomenon, the capacity to have goal-directed behaviour, objectives, purposes and anticipation, with the phenomenon of human self-awareness, foresight and planning capacity during many decades (Doolittle's critique to the Gaia hypothesis (Doolittle, WF, 1981)). However, recently some efforts have been made to reinitiate the debate on organisms' teleology such as in (Lenton et al., 2020; McShea, 2023; Noble and Noble, 2023; Weber and Varela, 2002). Lenton et al. state: "the teleological dimension of Gaia must be confronted directly, rather than being avoided to please biologists" (Lenton et al., 2020, p. 266).

Within the biological and ecological realm of experimental and observational biologists, it is common to study higher-level structures as autonomous from the quantum particles and atoms they are made of. This contrasts with a reductionist approach that rejects top-down causation and emergent properties, where everything would ultimately be reducible to physics. However, a standard reductionist framework struggles with explaining scientific observations beyond physics and chemistry (e.g., biology, neurology, etc.) because this paradigm refuses to acknowledge the emergent property of intrinsic teleology—namely, that organisms (or for the case of humans, the human mind) coordinate their parts for their benefit and purpose, even though organisms (and the human mind) emerge from these parts. The parts work for the whole that coordinates them. For example, we cannot describe the atomic processes that compel a stork to build its nest without invoking teleological emergent properties—i.e., the stork's *purpose*. Consciousness of the stork in a human sense is not required to speak of

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[3] It might be worth noting that TMaxP, given certain boundary conditions, tends to hold not only in systems as complex as the biosphere but also in dynamic atmospheres, such as those of Mars or Titan. Mars—or the planet Earth over time without the emergence of life—would always have been at the possible TMaxP within each boundary condition scenario. In the case of Earth, the development of life, by altering boundary conditions (e.g., through technique), could explain the following: 1.) The rate of entropy creation and power processing tends to increase over geological time as Gaia grows and becomes more complex. 2.) Although the physical part of the biosphere system complies with a TMaxP, the biological component increasingly contribute to the global total over geological time. That is, more dispersion comes from the biota, even if the overall total remained constant.

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purpose. The stork drives its parts and directs the creation and movement of its complex molecules to perform the actions required to fulfill that purpose. Arguably, to assume that only atomic-level physical processes exist is a hypothesis far more difficult to defend than assuming the existence of purpose, as the latter not only describes reality but also enables predictions that the purely reductionist approach cannot achieve (e.g., by observing the stork's beak, we can predict the type of context in which it operates).

While the 'purpose' of a machine is designed from the exterior of the machine (by the human engineer) the purposeful character of living beings is intrinsic and could be the emergent characteristic that defines organisms. From this perspective, a living being would be defined as a system with intrinsic teleology.

Appendix C. Contextualizing Darwin within the OGT

The mechanistic-reductionist paradigm caused Lovelock and Margulis' Gaia hypothesis to be 'darwinized' (Doolittle, 2017) and to be converted into a cybernetic theory of Gaia compatible with natural selection (e.g. (Doolittle and Inkpen, 2018; Lenton et al., 2018; Lovelock, 2003)). This led to a categorical rejection of 'strong' versions of Gaia, which approximated her characteristics to that of a living organism (Kirchner, 1989). Given the importance of downward causation in the processes leading to Gaia, the Darwinian paradigm is incompatible with the OGT; instead, at most one could try to "gaianize Darwin". This does not imply that Darwinian theories are obsolete or lose their validity. Rather, in the same way as classical Newtonian physics continues to be used and taught despite subsequent physical theories (quantum mechanics, relativity, chaos theory, and the thermodynamics of systems far from equilibrium) are neither compatible with nor extensions of it, the Darwinian view on biology can remain useful in a contextualized form. Newton's laws are useful for explaining observations in certain systems (those that are macroscopic and involve low energy and speed). While general relativity may ultimately approximate Newton's laws under such conditions, the paradigms, concepts, and hypotheses involved are distinct and, at times, incompatible or contradictory.[4] Analogously, the OGT will explain the reality of observable biological phenomena using different paradigms, concepts, and hypotheses. The OGT will make sense of some observations that Darwinism cannot explain and will offer falsifiable predictions distinct from those of Darwin and subsequent theoretical developments based on his ideas.

C.1. Different types of interactions to deal with local resource limits

The differences between a Darwinian paradigm and paradigm based on an Organic Gaia is illustrated by distinct approaches to solve the problem of local limitations (finite input and output flows of energy and materials) that confront growing, complex dissipative systems (Fig. C1).

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[4] For example, Einstein envisions space time distortions, while Newton sees forces and point particles; for Newton, the speed of light adds to that of a rocket, while for Einstein, it does not.

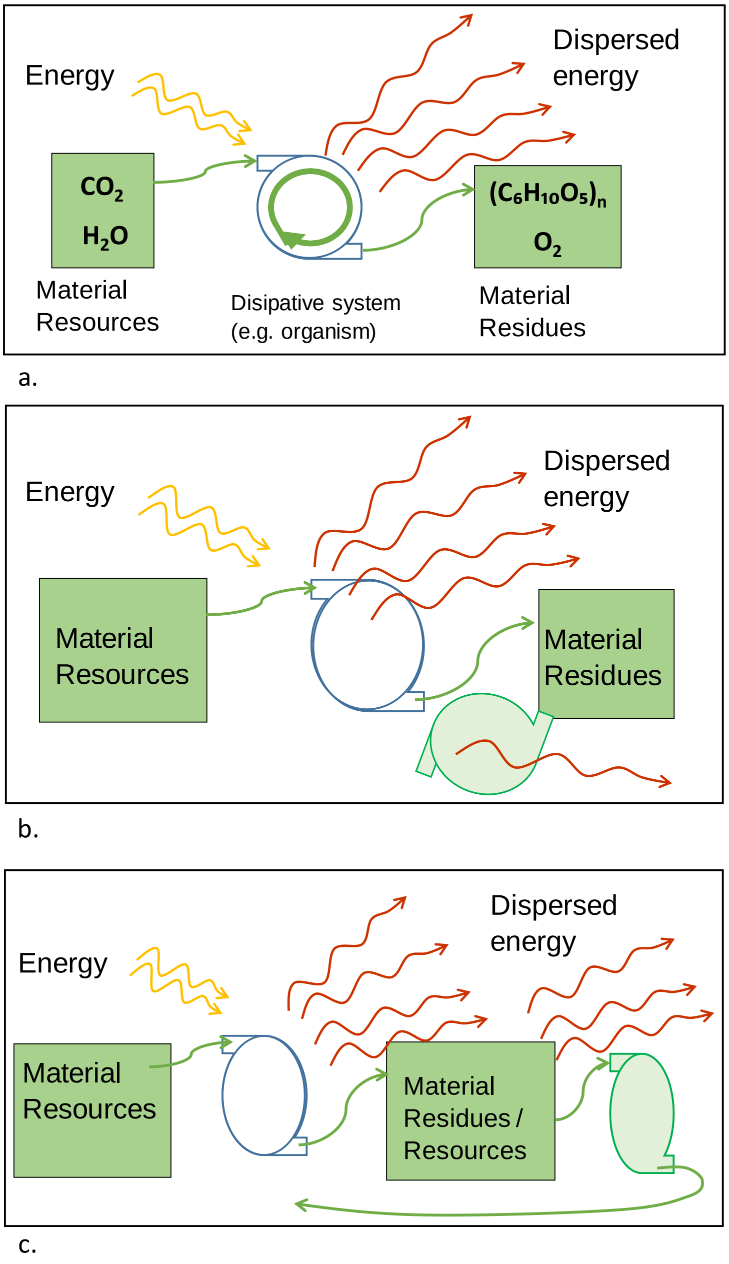

Figure C1. a) A very complex dissipative system, such as an autotrophic organism (e.g. a plant), is represented in a simplified way as system relying on the input of energy with high quality or high exergy (represented by yellow light photons), and material resources (in green rectangles) such as CO_2, H_2O and other compounds. The system transforms the input received into output consisting of that same energy, but more dispersed (maroon dark photons) and material residues or waste (such as oxygen and cellulose that may contain some exergy). b) Competitive view of Darwinism: two organisms (usually two animals) compete for a resource; the best adapted survives (blue light ellipse) and reproduces, the worst (green bold ellipse) dies, does not reproduce or

reproduces at a slower rate. c) Cooperative view of Darwinism: two organisms avoid resource competition (Kropotkin, 1902) since one organism uses the waste of another as a resource. After passing through several organisms, the initial resource can be recycled. For example, an animal breathes oxygen and generates carbon dioxide as waste; a plant uses carbon dioxide and regenerates oxygen.

Since Darwin, the interactions between organisms in the context of resource scarcity have been framed in terms of exclusive competition, i.e. involving losses for one party. This competitive vision of Darwinism is reflected in Fig. C1b. Exclusive competition tends to result in the elimination of the 'weaker' party. However, a dead organism produces less dispersed energy than when it was alive, and becomes 'waste' possessing some exergy (useful or high quality energy). The result of this type of interaction does not increase entropy production and complexity but rather constitutes a problem of material 'residues'.

From the perspective of the OGT interactions in the face of limits are not restricted to competition but rather are based on symbiotic cooperation or coordination. Fig. C1.c reflects this cooperative type of interactions where greater efficiency in the use of resources is attained due to increased material cycling. At the same time, an (eco)system begins to form that requires a greater energy flow. As the system becomes more complex, it tends to find more ways to dissipate energy, and Prigogine's dynamics render it more stable because entropy increases faster than in competitive interactions.

Fig.C1.c can also be seen as nascent ecosystem that cycles matter, resulting from the pressure generated by the growth of a diversity of living beings.

Fig. C2 shows an example of the ecosystem formation process due to the need to increase the recycling rate of the available matter, as well as the forces involved and the consequences that arise. It also links those processes to Prigogine's trinomial. By coordinating the reuse of resources (including genes) and by avoiding competition through cooperative symbiosis, organisms end up recycling matter, forming increasingly complex and capable ecosystems (symbiogenetic process).

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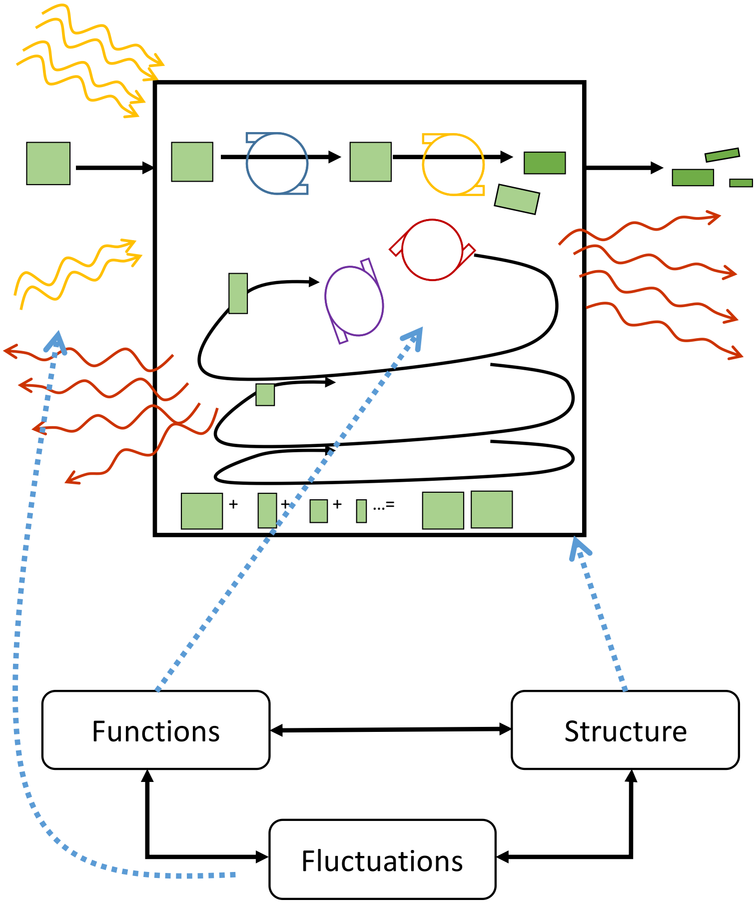

Figure C2. The OGT view on ecosystem formation and material cycling. See text for details.

In this example (Fig. C2), the recycling rate would be 50%: At first sight, one unit of material resource (green bold square) enters the 'structure' (the big rectangle) and ends up exiting the structure as waste. This will always be the case unless the structure is growing or degrowing. However, once the material has entered the structure, it cycles within it, being used by different parts of the structure (the green bold squares and rectangles in the lower part of the figure). Summing up the material use within the structure in our example results in twice the amount of the material that enters and eventually exits the structure. Thus, the system/structure requires fewer resources and generates less waste. However, to do so the system either needs more energy, or higher energy efficiency, and has to process more information based on collaboration (from the perspective of the functional parts) and coordination (from the perspective of the structure), which points to the formation of a Prigogine trinomial.

Adopting this perspective, we can define the recycling rate (RR) as the probability that a given atom or molecule comes from the internal processes of the system with respect to the total number of molecules used (i.e. internal processes plus flow external to the system under study). Thus, a RR = 0.5 means that 50% of the material used in a given time comes from former material use inside the system, and 50% has been generated outside the system. The cycling ratio (CR) is the number of times a molecule is more likely to come from an element of the system rather than from outside the system. CR=1/(1-RR), i.e. if RR is 50%, then CR=2 as reflected in Fig. C2. The interiority of an organism, which in turn distinguishes it from the environment, can be measured through these cycling ratios.

C.2. The Prigogine trinomial at the Gaian level

Applying the trinomial to the level of Gaia implies doing so at the scale of the Biosphere (Gaia's immediate environment) and shows how classical evolutionary theories and cybernetic theories about Gaia fall short. On the other hand, when the trinomial is completed, a more complete and coherent biological and ecological theory is generated that does not simply extend Darwinism. In Fig. C3 we apply the trinomial to the structure called Gaia.

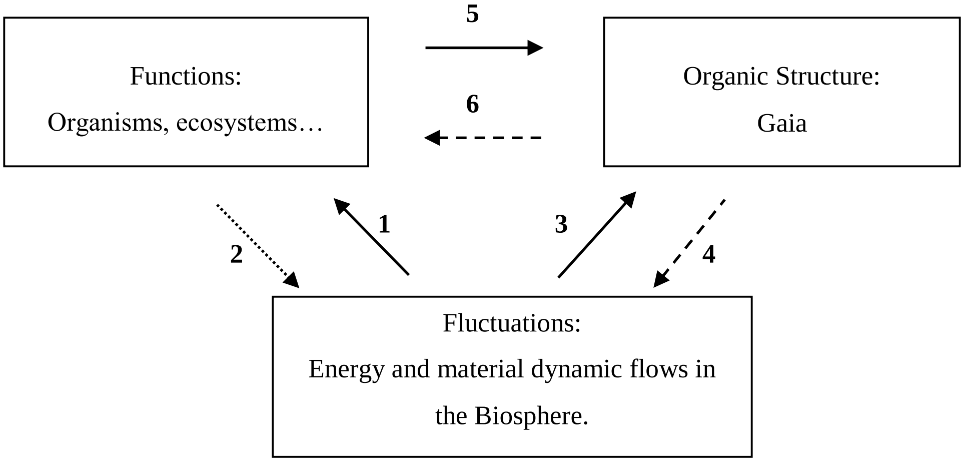

Figure C3: Prigogine's trinomial applied to Gaia. Arrows 1, 3 and 5 are "classic" influences in biology and ecology, although the structure is not seen as an agent. Arrow 2 is post-Darwinian, e.g. as the niche construction theory shows. Arrow 4 is the cybernetic Gaia proposition but without a structure possessing agency. Arrow 6 closes the Prigogine trinomial. More details are provided in the text.

The casual relations depicted in Fig. C3 act as follows:

1. Fluctuations toward Functions: This arrow reflects the strength of natural selection as studied in classical evolutionary biology. Fluctuations can be interpreted as the impact of changes in material or energy flows in the environment on the functions. In classical evolutionary biology the focus is normally on genes, organisms or their

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populations. These fluctuations can impair organisms' adaptation, stability or reproductive capacity. Consequently, the least or most effective organisms will be eliminated or promoted respectively. In the context of the trinomial, natural selection serves to erase detrimental fluctuations, e.g. a detrimental mutation that gives rise to a badly adapted organism (in a Gaian vision this means that the organism is not functional to itself, its environment and Gaia). Thus, in our scheme, error correction would be the most important function of Darwinian natural selection. Fluctuations can also be generated by interactions with other organisms, for example, when an organism gives or takes away energy from another organism.

2. Functions toward Fluctuations: This is what we call 'technique'; organisms (and ecosystems) regulate these fluctuations to their benefit by manipulating their local environment. This causal relationship is still underexplored because evolutionary biological theory tends to see organisms as reactive machines and not proactive beings possessing for example technical and anticipatory capacities. Thus, this causal relationship fits better with the works of Kropotkin (Kropotkin, 1902), Lovelock and Margulis' (Lovelock and Margulis, 1974) and with observational biologists and ecologists. Importantly, it is also compatible/consistent with concepts from post-Darwinian theoretical developments such as the "extended organism" (Turner, 2009), organisms as "ecosystem engineers" (Jones et al., 1994) and, especially, the concept of "niche construction" (Odling-Smee et al., 1996), incorporated in the so-called extended theory synthesis of evolution (Laland et al., 2015).

3. Fluctuations toward Structure: Exchanges of energy and matter at borders constrain, limit and modify the structure we call Gaia. Energy conservation and other physico-chemical principles, solar radiation, meteorites, climatic changes, material exchange by volcanism and plate tectonics, cosmic rays and other radiation etc. constitute material, energy and information sources but also act as limiting factors for the growth and expansion of Gaia. This causal relationship is valid for any dissipative system, living or dead, and applies to all scales (from organic substructures to that of Gaia that we reflect here).

4. Structure toward Fluctuations: Although this causal relationship has had little influence on classical biology, it was the basis for the initial Gaia hypothesis of Lovelock and Margulis: organisms cooperate to form the biosphere that hosts them for their benefit. Instead, for us, it is Gaia (and not organisms) who regulates the fluctuations just described through anticipation and technology. This includes regulation through the minimization of high radiation levels (e.g. ozone layer), the regulation of temperature and other parameters (Lovelock and Margulis, 1974), etc. Gaia also selects or modulates internal fluctuations (e.g. an observed increase in the level of oxygen to an optimum for complex organisms or the maintenance of water on the Earth surface). Seen as the technical capacity of Gaia, this causal relationship is similar to arrow number 2 in Figure but applies at the largest scale, i.e. the biosphere. Thus, we could view the biosphere as the extended phenotype (Turner, 2009) of the engineering or niche construction (Odling-Smee et al., 1996) of Gaia: The biosphere is "the home" of Gaia made by her.

5. Functions toward Structure: The organisms are part of the biosphere and conforming with their local physical environment jointly form the structure called Gaia. Sequential selection (Lenton et al., 2018), metacommunity (Leibold et al., 2004), whole system selection (Lansing et al., 1998), selection of processes and patterns (Doolittle and Inkpen, 2018), integrated rein control (Dyke and Weaver, 2013) or the holistic integration of processes (Kleidon, 2012) are all dynamic

approaches that through the arrows 1 and 2 try to give rise to arrow 4 (e.g. the homeostasis at planetary scale), but, not completing arrow 5, they also miss the top-down causation represented by arrow 6 and, thus, do not integrate the idea of Gaia as strong, complex and organic entity.

6. Structure toward Functions: Gaia chooses, directs and controls her functions such as organisms and ecosystems. Gaia integrates, coordinates or orchestrates her functional units for her own benefit. Importantly, this differs from the initial hypothesis of Lovelock and Margulis (Lovelock and Margulis, 1974) representing coordination as exclusively serving the organisms or functional parts, rather than the supra-organic structure. Gaia extends post-Darwinian theoretical developments at the organism level (e.g. (Jablonka and Lamb, 2014; Noble, 2012; Shapiro, 2011) to the biosphere level.

The symbiotic cooperation (arrow 5) gives rise to a Gaia that, according to Margulis (Margulis, 2008), becomes the selector of organisms. Gaia is mainly the result of the arrows 4, 5 and 6, although all the dynamics of the Prigogine trinomial are involved. A reductionist or bottom-up perspective stresses the fact that organisms form Gaia in a similar way than cells form a multicellular organism (arrow 5) while a holistic or top-down perspective focuses on how Gaia in turn integrates or coordinates the organisms (arrow 6) in a similar way that we speak of the physiology of an organism as a whole coordinating his cells.

It can be expected that a synergistic collaboration between post-Darwinian theoretical scholars, defenders of a cybernetic-like Gaia and the scientific community concerned with organisms-ecosystems-biosphere coevolution would add further details to the Prigogine trinomial, contributing to its closure and facilitating further advances in the development of the OGT.

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