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Self-organization, Autopoiesis, Free-energy Principle and Autonomy

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ABSTRACT: The aim of this paper is to extend the discussion on the free-energy principle (FEP), from the predictive coding theory, which is an explanatory theory of the brain, to the problem of autonomy of self-organizing living systems. From the point of view of self-organization of living systems, FEP implies that biological organisms, due to the systemic coupling with the world, are characterized by an ongoing flow of exchanging information and energy with the environment, which has to be controlled in order to maintain the integrity of the organism. In terms of dynamical system theory, this means that living systems have a dynamic state space, which can be configured by the way they control the free-energy. In the process of controlling their free-energy and modeling of the state space, an important role is played by the anticipatory structures of the organisms, which would reduce the external surprises and adjust the behavior of the organism by anticipating the changes in the environment. In this way, in the dynamic state space of a living system new behavioral patterns emerge enabling new degrees of freedom at the level of the whole. Thus, my aim in this article is to explain how FEP, as a principle of self-organization of living system, contributes to the configuring of the state space of an organism and the emergence of new degrees of freedom, both important in the process of gaining and maintaining the autonomy of a living organism.

KEYWORDS: free-energy principle – self-organisation – autonomy – autopoiesis.

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In the current literature, the free-energy principle (FEP) is approached in the context of predictive coding theory, which provides an explanatory framework about how the brain works, understood as "an inference machine that actively predicts and explains its information" (Friston 2010, 129). This means that the brain does not passively receive information about the world, but it develops a model of the surrounding world, which it permanently adjusts based on the information received from the environment. According to this theory, in order to minimize surprises, the brain makes predictions about what will happen – or indeed, is happening at the moment. An important role in this process is played by the perception-action dynamics, which actively contributes to predicting the changes in the reality: thus, perception optimizes predictions by inferring the hidden causes of the external changes whereas by action the error of the predictions is minimized.

Minimizing surprises involves limiting free-energy, which is a characteristic not only of the brain but of all self-organizing systems (Friston 2009; 2010). Free-energy is an important aspect of all biological systems, because, from the thermodynamic point of view, it is the working energy of the organism. However, free-energy can be understood from the information theory perspective, as a function of both sensory and internal states of organism. In this context, minimization of free-energy involves increasing the probabilistic information relating to the system's exchanges with its environment and the external causes of those exchanges. In other words, free-energy is considered as the upper bound of surprise (Friston 2009; 2010).

Starting from here, one can say that FEP is an important aspect of the functioning process of any self-organizing system, which, in order to maintain the internal equilibrium, it needs to control the entropy resulting from the flow of information and energy exchanges with the world. FEP is considered a consequence of the propensity of any self-organizing adaptive system to resist disorder and to maintain its identity and unity considering the external perturbations. The integrity of living systems is maintained (or is indeed defined) by placing an upper limit on the free energy of the system. This can be achieved in one of two ways; namely by changing sensory samples of the environment (i.e. sensory input) by action or by changing the internal states of the system that enabled sensory exchange to be predicted (Friston 2010). Limiting the free-energy of a living system is a prerequisite of the survival of an organism, involving the development of some mechanisms that would anticipate the changes in the environment and reduce the surprises from the external milieu.

In this context, the goal of my paper is to debate the relevance of the free-energy principle to the problem of biological autonomy, extending the discussion from the Bayesian approach of the brain to the process of self-organization of living systems. Considering this task, the paper is divided in four parts: the first part is an overview of the principles entailed by self-organisation in the case of living systems. In this way, a comprehensive approach of what a self-organizing living system means is achieved, taking into consideration different aspects of self-organization. In the second part of the article, the process of autopoiesis, considered in some enactivist theory as the origin of life, is approached from the point of view of the self-organisation principles, considering autopoiesis as a minimal case of self-organisation. Further, in the third part, the discussion about autopoiesis and self-organization is completed by discussing how FEP is involved both in the emergence of autopoietic systems and, in general, in the self-organization of any living system. Starting from here, in the last part, I discuss the role of FEP in gaining autonomy of a living system, considering two aspects. On one hand, I approach the way FEP contributes both to the internal self-organization of a living system, which in the autopoietic tradition is known as organizational closure, and to the emergence of its degrees of freedom, considering that any organism is also a dynamical system. On the other hand, the autonomy of a living system will be approached taking into account that any system has a boundary, which, in the case of a living dynamical system is a Markov blanket that provides a peculiar type of coupling of the organism with the world. Thus, my aim is to show that the issue of autonomy of the autopoietic theory can be completed by its approach from the perspective of FEP and dynamical system theory. In this way, a new account of autonomy of living systems is proposed, which takes into consideration not only the recent findings of autopoietic tradition, such as organizational theory, but also the research from dynamical system approach of living systems.

1. Self-organisation in living systems

At the origin of life lies self-organization of living matter, which entails the aggregation of molecules in a coherent structure, which would resist perturbations from the environment. According to the current research self-organization is a ubiquitous process, which can be found all over in nature both in inanimate forms, and in the realm of living system. For instance, self-organizing structures can be dissipative, such as hurricanes or dust devils that emerge in certain circumstances and last as long as certain conditions are met (Juarrero 2010b, 257). But self-organizing systems can also be flexible structures with the ability to evolve and self-maintain (Barandiaran & Moreno 2008, 327). In this case, the maintenance of the system is achieved by adapting the internal behavior to the changes in the environment and influencing the external conditions. These are the living systems, which, as self-organizing systems, involve a set of principles that are interdependent and operate spontaneously.[2] Together, these principles contribute to the emergence of an autonomous living system.

1.1. Principle of systemicity

The result of self-organization is the emergence of a system, meaning the configuration of some relatively stable structural assemblies, with a unitary behavior. Such a system is characterized by multistability (Camazine 2003, 34) or metastability (Nicolis & Prigogine 1977, 462), which entails the existence of several steady states the system can have, depending on the external conditions and parameters influencing the system. Thus, self-organizing living systems are not rigid structures but they involve a certain flexibility that allows for their fluctuation between certain states (Juarrero 1999, 111).

Consequently, a self-organizing system is a combination of stability and instability. This means that it is a structure, which, on one hand, obeys the deterministic laws of classical physics, exhibiting predictable behaviors,

[2] In other words, the difference between dissipative and biological systems is that in the former case, self-organization is maintained by the energy flow from outside, whereas in the latter, self-organization comes from inside the organism as a consequence of its internal organization (Ruiz-Mirazo & Moreno 2004, 238).

and, on the other hand, it is considered statistically unstable, enabling the emergence of new behaviors (Pattee 1988, 328).

Moreover, a self-organizing system involves the fact that certain elements are configured in a structure in which each part has a certain function it would exercise in order to maintain the whole.[3] This means that the elements of the system are selected, in order to be part of the new whole according to the powers they are assigned. Hence, exercising the powers of the parts depends on the functioning of the whole as well as on how they contribute to the integrity of the system. Just as, for instance, certain organs or functions of the living systems are enhanced, whereas other are diminished, according to the contribution to the survival of the organism.

Last but not least, systemicity involves the emergence of some forms of unity and identity of the system. The functioning of a whole involves the unity of processes and its actions. Unity is a consequence of the coherence of the system functions that converge towards the achievement of the same purpose, which is its survival. Identity is a consequence of the fact that processes and actions belong to the same whole. Both the unity and identity of the organism are operational, as they are the result of the internal processes of the system, which contribute to maintain its integrity.

1.2. Principle of spontaneity

Living matter has the property to self-assembly in organized structures, which would resist to the entropy of the surrounding world. An important characteristic of the self-organization of the living matter is the spontaneity of the elements coupling, which is carried out without the contribution of an external force or an internal generating principle. In other words:

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[3] The part-whole relation can also be approached from the perspective of their properties. Thus, the system can be seen as the total amount of the properties of its parts: "A system is a group of entities with some collective property (...) Maintaining the system is thus maintaining the collective property" (Newton 2000, 92). To put it differently, between the properties of the components and those of the system there is a relation of dependence. This means that "in a system, (...), the properties of the components depend on the systemic context within which the components are located" (Juarrero 1999, 109).

> Self-organizing systems, (…), have need for neither homunculus-like agents located inside a complex system nor any kind of cosmic instruction from the outside ordering the parts around, telling them what to do and when to do it. (Kelso & Engstrøm 2006, 93)

This means that self-organizing systems do not need the existence of a self (Kelso 1997, 8), a program (Thelen & Smith 1998, 281) or an external cause that would conduct the coupling of elements. In the self-organizing process, the coupling of elements is carried out spontaneously, without a control center conducting this process. And the laws under which coupling elements is carried out result from the very process of arranging the elements.

Moreover, in the case of living systems, spontaneity is a characteristic of the responses of the organism to the environmental challenges. Behavioral patterns emerge spontaneously without the mediation of a centralizing cognitive structure such as consciousness, which would generate a conscious mediated response to the environmental changes. In other words, living organisms have the ability to spontaneously self-organize under the pressure of environmental constraints, which determine the configuration of the state space of the organism and emergence of a behavioral response.

1.3. Principle of non-linearity

Self-organization enables the emergence, at the level of the whole, of some properties that the independent parts do not have. This means that the whole is not a mere addition of its parts. The aggregation of the elements determines the emergence of some new functions and powers, in the system, which do not represent the mere addition of the characteristics and powers of elements.[4] Aggregation of the elements in a coherent configuration enables the emergence of a higher-order organization of the whole, which exhibit a state space with a high-order dynamics than of the component states. This means that the whole has degrees of freedom greater than

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[4] In other words, "…dynamical processes provide empirical evidence that wholes can be more than just epiphenomenal aggregates reducible to the sum of their component parts. The newly organized arrangement shows emergent macroscopic characteristics that cannot be derived from the laws and theories pertaining to the microphysical level" (Juarrero 2010, 257).

those of its components. That is to say, it has alternatives of action and response to environmental challenges, more complex than the sum of alternatives of response of its parts considered independently.

The emergence of the new properties is a consequence of the non-linearity which is a characteristic of the biological world.[5] Non-linearity implies the unpredictability of the changes within the system, which means the emergence of new effects that cannot be deduced from the characteristics of the parts. This is possible because, in the self-organizing process, qualitative shifts emerge at the level of the whole that enable the enlargement of its state space and access to some new states by the system as a whole.

To put it differently, in the phase shifts of the self-organizing process "similar causes can have different effects and different causes similar effects; small changes of causes can have large effects, whereas large changes can also result in only small effects" (Fuchs 2007, 853). These shifts that determine new levels of self-organization to emerge are the consequence of the control parameters, which exceed some critical values under the action of the aggregate variables of the system. This determines the shift of the organizing patterns of the system and, implicitly, of the dynamics of its basic components meaning the emergence of new patterns of action.

1.4. Principle of circular causality

Self-organization consists not only in the aggregation of some components but it also involves modeling the dynamics of these components by the new emerging whole. Thus, the parts and the whole are in a mutually conditioning relation, which entails that the parts constitute the whole and in turn are constrained to adopt certain behavior by the whole. This circular causation relation determines the emergence of the micro-dynamics of components from the macro-dynamics of system, which in turn will determine the micro-level dynamics. In Kelso and Engstrøm's description (2006, 114-115), the circular causality relation involves the coordination of three levels: the "lower level" of the components interaction that results

[5] According to Thelen and Smith (1994, 58): „Self-organization is not magic; it occurs because of the inherent nonlinearities in nearly our physical and biological universe."

from macro-level (upward causation), the "upper level" that plays a boundary condition role, which constrains the dynamics of the coordinating elements (downward causation), and the "middle level" made of the coordinating patterns between the macro- and the micro level. Thus, circular causality is approached from the point of view of the dynamics between the upward and downward causation.

Approached from the perspective of the patterns created by the system, the circular causality relation entails modeling the dynamics of basic level by the patterns of action it creates at the higher level. In other words, from the coordination of the basic components a pattern of action results that integrates all parts of the system in a whole, which share a common dynamics. Thus, the coordination of the components of the system by its macro-patterns enslaves the behavior of the parts achieving the behavior of the whole. From this perspective, the circular causality is based on the slaving principle (Haken 1983), according to which the formation of the slowest microscopic patterns resulting from the fastest dynamics at the microscopic level involves decreasing the degrees of freedom of the system components and reducing the states of the system to only a few.

The reciprocal causation among the levels of a complex system can be understood in terms of the coupling or dynamics between microscopic (fast) and microscopic (slow) order parameters. This means that the microscopic fluctuations of the system that constitute its behaviour determine the emergence of macroscopic order parameters – that enslave the microscopic degrees of freedom (Bruineberg & Rietveld 2014, 5). This synergetic, enslaving principle rests upon circular causality and organises a system's degrees of freedom onto a low dimensional manifold that contains the macroscopic order parameters.

1.5. Principle of adaptivity

Self-organization entails the emergence of a living system that is fit to the condition of the environment within which it lives. Thus, in the self-organization process are involved both the internal parameters of the system, upon which the internal coherence of the system processes depend, and the external ones, a consequence of the environmental conditions. The external parameters determine the selection of those functions and powers that enable the whole to adapt to the changes and fluctuation to the environment. Depending on how it adjusts to the environment, the system is also characterized by certain robustness, which is "the system capacity to maintain its organization in the face of internal and external perturbations" (Barandiaran & Moreno 2008, 331). From this perspective, self-organization implies the emergence and selection of those patterns that would provide the robustness of the organism under the circumstances of environmental changes.

An important role in the process of adaptivity is the way the system is linked to its milieu. As living systems have emerged and developed for generations within a certain milieu, they are coupled initially and structurally with this milieu. Structural coupling involves that the organism, by means of its organs, perceives directly the changes in the environment and is prepared to provide optimal response to such changes. Thus, a living system is not an isolated structure within the environment it lives, but "the external structure or boundary conditions of complex systems are as much as part of the complex system as the internal structure" (Juarrero 2010a). This is what enables the living system to interact with the milieu, not only passively, by receiving information from the outside, but actively as well, by transforming the milieu where it lives. In other words, structural coupling involves symmetry between the system and the world, meaning their mutual influence (Di Paolo 2010, 50). By this mutual influence, the organism acquires the information necessary to preserve a state of dynamic equilibrium with the world. Consequently, adaptability involves regulation of an organism according to an interactive cycle between the living system and the world (Barandiaran & Moreno 2008, 335).

Structural coupling is facilitated by the emergence, in the process of self-organization, of a boundary between the living system and the world. This boundary (Ruiz-Mirazo & Moreno 2004, 244-245) is a demarcation between the system and the world, and it also enables exchanging information between the organism and the world. Boundary delimitates the internal space of the organism, its inner vital field whereby the system gains the autonomy of its internal processes. Moreover, boundary is endowed with receptors sensitive to the changes in the environment and with structures that enable exchanges with the external milieu, which would facilitate the adaptation of the organism.

1.6. Principle of optimality

Self-organization involves not only the emergence of simple responses of living systems to the environmental challenges. It also involves selecting those responses that are the most appropriate to the challenges in the milieu. In other words, the patterns of action emerging as a result of self-organization are the most efficient to answer to the changes in the environment (Bruineberg & Rietveld 2014, 5, note). This means that, on one hand, the behavioral patterns are generated according to the energetic possibilities of the system. That implies that the organism has the resources required to configure and complete the pattern of action. On the other hand, the patterns generated in the state space of the system should respond to as many parameters as possible of those, which influence the system. This means that state space of a system should also be made of optimal states to be occupied by the system in order to provide optimal responses. Thus, the survival of the organism means generating the optimal patterns, according to the energetic abilities of the organism, which would enable the coverage of as many variants as possible to respond.

1.7. Principle of thermodynamic non-equilibrium

The propensity of self-organizing systems is to maintain a state of stability, being from a thermodynamically point of view in a state of non-equilibrium due to the energy and information flows they are subjected to. Stability does not require the system to be in absolute rest, as this would mean the end of the system activity.[6] Stability is merely a transitory state, until the perturbation of the system variables and configuration of another stable state. This means that, "In self-organisation, the system *selects* or is *attracted* to one preferred configuration out of many possible states…" (Thelen & Smith 1994, 57). It results that, in case of living systems that evolve in time, self-organization involves reaching a dynamic (nonequilibrium) steady-state, considering the environmental conditions and the degree of development of the organism at that time.[7]

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[6] In Kauffman's terms, this means that "There is no agency at equilibrium" (Kauffman 2000, 66).

[7] In physics, the sort of stability associated with self-organisation and autopoiesis is referred to as 'non-equilibrium steady-state'. In other words, an ergodic or invariant

To put it differently, from the perspective of energetic and information exchanges, a living system is an open system which is in an ongoing flow of exchanges with the environment. This is due to the structural coupling that determines the ongoing interaction and permanent exchanges with the environment. As the system receives continuously energy from the exterior, it can maintain its current state, but, at the same time, its internal organization is in danger. This happens because, if a too large quantity of energy enters the system, the system entropy increases until the extinction of the system. Therefore, the problem a living system faces is how to maintain low entropy within the system and to control the energy and information flow to which it is subjected (Ruiz-Mirazo & Moreno 2000, 212-213).

The control of the flow exchanges with the exterior involves that the organism reaches a homeostasis state, whereby it gains dynamic equilibrium with the environment (Newton 2000, 93). In terms of dynamical systems, homeostasis means controlling the internal variables of the living system and maintaining them within some boundaries so that the system has a constant behavior oriented towards its preservation.

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To conclude, self-organization of living system implies spontaneous emergence of a systemic whole with operational unity and identity, which are given by the coherent functioning of its internal processes. The properties of this systemic whole are more complex than those of its parts and cannot be reduced to the properties of the components. The newly emerged whole is characterized by a state of dynamic stability. This is the consequence of the internal dynamics of the system, which is given by the reciprocal causation relation between the parts and the whole, and of the external dynamics, i.e. the state of thermodynamic non-equilibrium between the organism and the environment. Last but not least, a self-organizing living system is a system adapted to the environment, enabling multiple and complex behavioral patterns that are the most appropriate to responding to the

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property that is far from equilibrium and entails a succession of stable states. In what follows, we will also refer to this nonequilibrium steady-state as a 'dynamic equilibrium'.

external changes. Considering all this, one can say that self-organized living systems are characterized by a dynamic, non-linear and multidimensional state space, which is configured, taking into account the adaptive skills of the organism and the external parameters.

2. Self-organisation and autopoiesis

Taking into account that self-organization is an essential process in the emergence and maintenance of life, an important issue for understanding how living organisms function is the relation with the process of autopoiesis, considered to have a significant role in the emergence of life. According to Maturana (1987), the two concepts have nothing in common, that is he would "never use the notion of self-organization […]. Operationally it is impossible. That is, if the organization of a thing changes, the thing changes." This means that self-organization involves more than a re-organization within the system, but it involves a complete change of the system. In the terms of Collier (2004, 168), who analyzes the relation between the two concepts, autopoietic systems are able of self-governing and re-arranging their parts but cannot produce a new organization. In addition, Collier (2004, 151) shows that, according to Maturana and Varela (1980), the process of autopoiesis implies the existence of an organized self, whereas self-organization can be achieved in the absence of such a self. Notwithstanding, a closer analysis of Maturana and Varela's theory (1980), from the perspective of self-organization principles, shows the complementarity of the concepts of autopoiesis and self-organization.

According to the classical autopoietic theory developed by Maturana and Varela (1980, 79-80), a living system is an autopoietic machine, which has the capacity to maintain its internal variables constant. This means that living organisms are homeostatic systems that maintain their internal organization invariable. Thus, what differentiates autopoietic systems from other systems is the capacity to self-produce, which means the capacity to maintain their organization by themselves. This is possible because the internal organization of such system is a network of processes that generates and maintains the internal components, which contribute to the functioning of such processes. Hence, the internal processes of the system form an interconnected network that also generates the boundary of the system, which gives unity to the system.

Starting from here, autopoiesis is regarded as a "specific instance" (Varela 1992, 6) of self-organization, that is to say, a type of self-organization characterizing minimal living systems. As a self-organizing process, autopoiesis constitutes the identity of the system: thus, the identity of an autopoietic system is the result of invariant patterns emerging within the system due to its internal organization. These invariant patterns provide stability and continuity to the system, despite the energy flows that continually affect the living system.[8]

Moreover, as a self-organizing constitutive process, autopoiesis is characterized by the dynamics between the local component and global whole, meaning by reciprocal causation between "the local rules of interactions (…) and the global properties of the entity" (Varela 1992, 6).[9] Reciprocal causation is a circular causality where the components interaction determines the production of the whole, which, in turn, determines the maintenance of the components.

Furthermore, another basic characteristic of an autopoietic system is that as biological system it should have a certain relation with the environment. This relation is defined as a reciprocal coupling (Varela 1992, 7), whereby the system, on one hand, separates from the environment in order not to become one with it, and, on the other hand, maintains energy and information exchanges with its external milieu.

Last but not least, one can add that an autopoietic system is not the result of some external force that would create it, nor is it an internal homunculus, it does not lay at the basis of its organization. Even if any living system involves a self – which in its minimal form looks like a coherent pattern

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8 In terms of the dynamical systems theory, this means that attractors of a system are autopoietic or self-creating, the attractors being the consequence of the system propensity to minimize its entropy (Friston & Ao 2011, 7).

9 Starting from here, which is from the perspective of the process of autopoiesis, self-organization can mean "(a) local-to-global determination, such that the emergent process has its global identity constituted and constrained as result of local interactions, and (b) global-to-local determination, whereby the global identity and its ongoing contextual interaction constrain the local interaction" (Froese & Ziemke 2009, 497). In other words, the process of autopoiesis can be described, in dynamical systems terms, as the result of the dynamics between downward and upward causation.

emerging from the interaction of local components – this is the result of its internal organization (Varela 1992, 11). The internal organization of a living system emerges spontaneously taking into account only the coherence of the processes of the system and the circumstances in the environment.

Notwithstanding, in the later approaches of autopoietic theory, an important characteristic of a living system, which distinguishes it from other self-organizing systems, is self-determination (Moreno & Mossio 2015; Mossio & Bich 2017). According to this approach, biological organisms have the capacity to establish their own condition of existence, due to the circularity, which constitutes its internal organization. This means that "the organization produces effect (e.g., the rhythmic contractions of the heart) which, in turn, contribute to maintain the organization (e.g., the cardiac contractions enable blood circulation and, thereby, the maintenance of the organization)" (Mossio & Bich 2014, 1090).

Self-determination is a consequence of the closure of the organism, which has the capacity to self-constrain. In other words, the network of recursive and interactive processes that constitute the autopoiesis process is at the origin of what Varela (1979, 58) called organizational closure. Organizational closure implies that the system has the capacity to self-produce the constraints upon which its condition of existence depends (Bich 2016, 207). Approached from the perspective of the constraints generated by the internal organization of any biological system, organizational closure is understood as biological closure (Moreno & Mossio 2015, 5). Biological closure involves the fact that a biological system operates by means of the constraints it generates upon the thermodynamic flow it undergoes as open system that operates in far from equilibrium conditions (Moreno & Mossio 2015, 6). Due to biological closure, biological organisms have the capacity to self-constrain, namely to act upon their boundary conditions, which involves self-maintenance and self-determination.

To conclude, according to organizational view, self-determination is a characteristic of biological systems, which is not present in case of other self-organizing systems such as dissipative systems. This happens because: Dissipative structures posses a low internal complexity, which is precisely what enables them to *spontaneously* self-organise when adequate boundary conditions are met. In contrast to biological organisms, self-organizing systems are systems that are simple enough to appear spontaneously. (Mossio & Bich 2014, 1108)

The conclusion resulting from this is that the dissipative structures are guided by a single macroscopic constraint, being highly dependent on external conditions. Whereas biological organisms, as systems with a higher-order complexity, have the capacity to self-determine and self-maintain, due to the large number of constraints generated, which are in a close interdependence (that is they form a closure of constraints) (Moreno & Mossio 2015, 16).

From the point of view of dynamical systems, dissipative structures are considered structures dependent on external conditions (Juarrero 2015, 4). However, one may add, these are systems characterized by a limited state space, with finite and lower dimensionality. Due to this state space, they can configure only a limited number of simple patterns, as a response to the pressure of the environment. Unlike these systems, biological organisms, due to their complexity have a state space with a higher-order dimensionality, configured by the multitude of their variables. Such a state space enables the emergence of behavioral patterns with complex, and sometimes, unpredictable trajectories.

However, in both cases, the emergence of new properties of the systems, namely its nonlinearity, is due to the constraints acting onto the system. From this perspective, Juarrero (1999; 2010b) distinguishes between the context-free constraints, which are imposed from outside the system and does not generate novelty and complexity, and context-sensitive constraints, which operate as enabling constraints, determining the emergence of new properties. Context-sensitive constraints act based on the circularity relation between the part and the whole, acting bottom-up (as first-order contextual constraints), by correlating the parts of the system and enlarging its state space, and top-down (as second-order contextual constraints), by its new dynamics which the whole share with its parts. Hence, self-organization of complex systems is understood as the result of the dynamics between the context free and first-order contextual constraints, which by adding and correlating the parts determines the emergence of the new properties of the system, which provide a new dynamics to the system components (Juarrero 1999, 142).[10]

[10] In other words, self-organization involves, due to the constraints it is subjected to, the emergence of at least one bifurcation within the system, which would enable a more or less complex behavior (Hooker 2013, 764).

Consequently, enabling constraints determine qualitative changes in the whole system, enlarging the system's state space (Juarrero 1999, 143). Moreover, enabling constraints can determine the modification of the system state space, so that new trajectories can emerge and it can access new states (Hooker 2013, 761). In this context, self-determination, as a characteristic of the higher-order complexity self-organizing systems, is a consequence of enabling constraints. Self-determination refers to the possibility of a living system, due to enabling constraints on the system parameters, to generate new behavioral patterns and to configure a dynamic state space with new degrees of freedom. Organizational closure of a living system is the result of enabling constraints, which determine qualitative changes within the system.

To sum up, autopoiesis is a case of basic self-organization in the biological world, which involves all principles of self-organization. Notwithstanding, self-organization in the case of biological organisms involves mechanisms other than those in other self-organizing systems (i.e., dissipative systems). Biological organisms are self-organizing systems that are capable of self-determination due to enabling constraints. Thus, organizational closure of the living system, due to the enabling constraints of the system, exhibits a multidimensional state space, which allows the emergence of some complex behavioral patterns. Consequently, if self-organizing dissipative systems have an invariable state space, self-organizing living systems have a dynamic state space, which can be extended depending on the adaptive needs of the system.

3. The free-energy principle, self-organization and autopoiesis

One of the consequences of the self-organization of living matter in not only the emergence of a system with a coherent structure, but also with the capacity to resist ongoing perturbations from the environment. Starting from this, one can say that the FEP is an important aspect of any self-organising process (of a living system), which, as an open system, should control the energy and information exchanges with the exterior in order to not increase the system entropy. This means that without FEP living systems would not be able to exist because "the entropy of their sensory states would not be bound and would increase indefinitely” (Friston 2013a, 2), which would result in the extinction of organisms.

Minimizing free-energy has an important role in the organism adaptivity to the environment as well (Bruineberg, Kiverstein & Rietveld 2016, 2; Kirchhoff 2016, 4). In order to survive, any living organism aims at integrating in the environment where it lives. From the dynamical system point of view, this means that from the interaction between the organism and world results a whole as an organism-environment system (Menary 2007, 42). Thus, adaptivity involves the capacity of living organisms to create a system with the world. This means that in structural coupling of the organism with the world, which implies their mutual conditioning (Di Paolo 2005), an organism-world assembly results with a common dynamics. Thus, the organism does not act as an isolated entity, which receives passively information about the environment, but it becomes a part of the world coordinating its actions with the changes in the environment.

An important role in this process of adaptation is played by the internal structures of the living system, which detect and anticipate the changes in the world. Adaptivity involves attunement of the internal processes and actions of the organism with the changes in its econiche. This means that the organism does not develop a representational model of the world based on which it acts. But the organism is itself a model of the world where it lives, having a direct relation with it (Friston 2013b, 213). This involves, on one hand, that it is endowed with skills that complement its econiche, and on the other hand, that between the internal dynamics of the organism and the external one of the environment there is a state of equilibrium or optimal grip (Bruineberg, Kiverstein & Rietveld 2016; Bruineberg & Rietveld 2014). Thus, embodied skills of organisms, a consequence of their internal organization, achieve the integration of the organism in the environment and the creation of a system with a shared dynamics with external milieu.

The systemic coupling involving that every self-organizing living system to embody an optimal model of its niche (Friston 2011), makes the organism to exhibit the best patterns of response to the external challenges (according to a variational principle of optimality). Moreover, it results from the systemic coupling of the organism with the world that the skills of the organism are directed not only towards maintaining internal organization, but also towards anticipating the changes in the environment. Thus, the organism minimizes the external surprises that may affect the system, maintaining its activity within the boundaries of a low number of states that could ensure the survival of the system (Bruineberg, Kiverstein & Rietveld 2016, 2; Friston 2011). It results that the self-organizing living systems have the ability to change the configuration of their state space, controlling the states, which the organism can access by limiting its free-energy. This means that while functioning, the living systems aim at minimizing the surprises of entering in a certain state (Kirchhoff 2016, 4), reducing the degree of freedom of the system and its state space, by regulation of its free-energy.

It results from here that regulation, as a process that contributes to the organism adaptivity (Di Paolo 2005, 430), being a form of adaptive control (Mossio & Moreno 2010, 285), is one of the characteristics of a self-organized living system. According to the organizational theory (Moreno & Mossio 2015, 33), the mechanism underlying the regulation of living systems is explained by second-order constraints, which are different from constitutive constraints, which ensures maintenance of the organism under stable conditions. Second-order constraints emerge when the organization of the system is endangered, having the role to re-establish the internal closure of the organism. In this case, regulation involves modulation of the constitutive regime until the recovery of the closure of the organism. In this approach, regulation takes the form of a circular organization of organism: constitutive constraints are those that are at the basis of second-order constraints, and regulatory constraints by establishing a second-order closure contributes to maintaining the constitutive constraints. Thus, regulation involves decoupling from the constitutive level and increasing the complexity of organism, by means of the emergence of some new levels within the system, with new degrees of freedom.

The circular causality supported by the organism constraints is also at the basis of the mechanism of limiting its free-energy. Thus, at the level of constitutive regime, constraints that are at the basis of organizational closure harness the flow of energy of organism in order to maintain its organization, and, at the same time supports this flow (Bich, Mossio, Ruiz-Mirazo & Moreno 2015, 8). If the constitutive constraints cannot harness the free-energy of an open system, the result is the increase of its entropy. In this case, the regulatory constraints, which operate on the constitutive regime, emerge re-establishing the equilibrium within the living system.

Starting from these assumptions, one can say that FEP can be also understood as an important aspect of the functioning mechanism of the autopoietic living systems. According to Kirchhoff (2016, 3), the difference between autopoietic theory and FEP, is that the former refers to self-production and the latter refers to self-preservation. This means that from the autopoietic perspective, self-maintaining of a system is merely an internal issue, which consists in the self-production of its internal components, with no connection with its exterior. Whereas, from the point of view of FEP, self-maintaining of a living system should consider the environment within which it lives. In other words, from the perspective of autopoietic theory, self-organization of a system relates only to its internal organization, which involves maintaining internal processes and components. Furthermore, from the perspective of FEP, self-organization of a living system involves attunement of the system and world, in order to maintain the integrity of the organism, by developing a model of the world by the living system and anticipating the changes in the external milieu.

However, autopoietic theory and FEP are understood as being convergent to the extent that both have as a result maintaining a state of homeostasis of the organism (Kirchhoff 2016, 8). According to this point of view, the process of autopoiesis involves minimizing its free-energy by minimally self-produce the components of the organism so that it maintains a model of the world. Thus, organism, both by its internal processes and its actions tends to maintain structurally and functionally integrity of itself (Friston 2013a, 5).

Nonetheless, even if maintaining the internal equilibrium, despite the changes in the environment, represents a defining feature of the self-organizing biological systems (Friston 2010, 127), whereby they distinguish themselves from other self-organizing systems, introducing FEP involves that between organism and the world there is a state of dynamic equilibrium. To put it differently, homeostasis is the tendency of the organism to maintain the internal variables constant. But the steady state of an organism is not constant. It undergoes ongoing changes that imply maintaining equilibrium when moving from one state to another, depending on the quantity of free-energy from the system. Homeostasis is a state of equilibrium characteristic to simple systems that cannot access very many states and whose behavioral patterns aim at returning to the initial state. However, living organisms have a dynamic equilibrium that implies reaching of several states of stability along with the change of external and internal parameters as a result of the energetic changes with the exterior.

Thus, instead of homeostasis, one can speak of allostasis, which means “achieving stability through change of state” (Schulkin 2003, 21). This means that living systems are characterized by dynamic stability, which implies that the system is in equilibrium among several states and configures more trajectories to reach its states in the state space. From this perspective, the role of regulatory mechanisms is not to maintain constancy of their internal milieu, but to adjust continuously their milieu in order to survive (Sterling 2012, 5).

An important role in this dynamic of regulatory process is played by the anticipation of the changes in the environment. Thus, living organisms have developed special organs (such as the brain) that would monitor the internal and external parameters of the system so as to anticipate the changes and minimize error by adjusting their behavior according to the external changes (Sterling 2012, 7). In this process, the brain as an anticipatory organ plays the role of coordinating the internal organs and their functions in order to respond as best as possible to its predictions. Thus, living organisms achieve a predictive adaptation (Sterling 2012, 8), which involves regulating the organism by anticipating the changes in the environment.[11]

Explained from a dynamical point of view, regulation consists not only in mechanisms of constantly maintaining internal variables, but it also involves an external component. That means, minimizing free-energy of the organism, as a principle of its functioning, by anticipating the changes in the environment. Prediction of external changes has as an internal correlative the prediction by the brain of the future needs of the organism. In this way, the brain creates behavioral patterns that would adjust the internal

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[11] Notwithstanding, anticipation is not a characteristic of the organisms endowed with advanced cognitive skills, such as human beings. Research in biology have shown that we can also speak of predictive behaviors in the case of bacteria (Lyon 2015) or more developed animals that do not possess language, such as rats or monkeys (Pezzulo 2008). As Keijzer (2001) said, taking into account that anticipative behavior required a new macroscopic order that would control the organism, it results that all behavior is anticipative behavior. Thus, predictive adaptation is a characteristic of living organisms whereby the aim is to obtain a dynamic equilibrium with the world.

state space of the organism depending on the changes detected in the environment. Controlling free-energy involves modeling the state space of organism, its contraction or extension, so as not to occupy those surprising (i.e., high free energy) states that would endanger its function and, at the same time, to find the best responses to environmental challenges.

In conclusion, by introducing FEP as one of the principles of self-organization of a living system, it results that biological organisms, due to the system coupling with the world, are in a state of dynamic equilibrium with its milieu. This state of dynamic equilibrium involves adjusting the behavior of the organism by anticipating the changes in the environment that will affect the states of the organism. In terms of dynamical system theory, this means that state space of a living system is characterized not only by several stable states, which it occupies alternatively, depending on the external conditions. But state space of a living system is a dynamic space which can be extended or restrained depending on the organisms predictions and how it controls its free-energy. The consequence of attunement of the internal dynamics of the organism with the external one of the environment is the emergence of a dynamic state space that is configured depending on the anticipations of the organism, by adding or restraining certain states. Moreover, in this dynamic state space, depending on the abilities of the organism, several trajectories can configured in order to reach a certain state.

4. Free-energy principle and autonomy

One of the consequences of self-organization of living matter is to develop an autonomous biological system. Autonomy is the feature of the living systems to function independently of external conditioning, by creating its own conditions of existence to survive. In terms of organizational theory, autonomy of a living system can be approached from a double perspective: from the point of view of the internal functioning of the organism (this is the constitutive dimension by which identity of the organism is made up) and from the perspective of the relation the organism has with the exterior (this is the interactive dimension which refers to the system interaction with the exterior) (Moreno & Mossio 2015, xxviii). Thus, autonomy of a living system is a twofold issue, which needs to be examined both from the perspective of the internal dynamics of the organism and from the perspective of the external one.

According to organizational theory, constitutive autonomy is the consequence of the organizational closure, which results from generating within a living system of a new causation regime that produces and maintains the internal components of the living system (Moreno & Mossio 2015, xxvi-xxviii). Thus, between the components of a living system there is an interdependence relation whereby the constitutive elements of the system mutually condition by the emergence of a network of constraints that provides the internal functioning of the organism. Understood from this perspective, autonomy means self-determination (Moreno & Mossio 2015, 5) or self-maintenance (Moreno & Mossio 2015, 9) of the organism, which entails the capacity of a living system to replace its internal components, due to its internal organization, understood as a network of constraints that provides the regeneration of the system.

From the perspective of the internal dynamics of the system, the ability of an organism to self-maintain can be understood from the perspective of the circularity relation between the lower and higher-order level of its organization. This means that the level of the basic metabolic processes generates and supports the higher-order level of processing information, which, in turn, models the behavior of the lower level. The circularity relation between the levels of the systems also determines its dynamic organization, which involves ongoing self-organization of the components of the system according to an order pattern. From the perspective of FEP, the circularity relation contributes to reducing the system entropy, by introducing a macroscopic order to the system according to a self-organizing pattern, under the pressure of environmental conditions. Thus, the free-energy of the system is controlled by the emergence of a pattern of action that would respond to the immediate needs of the organism.

Hence, the main feature of the internal organization of a living system is not merely recursive production of its components, but also creating a more extended state space. In other words, increasing the repertoire of states encompassed in its attracting set or manifold. Autonomy of living systems does not consist only in preserving its internal organization, but it also refers to the states it can access as a result of the responses to environmental challenges that the organism provides as a whole. Thus, understanding autonomy of a living system should take into account that the state space of a living system is a dynamical one. This means, as we have already seen, that the state space of a living system can be extended or restrained due to the anticipatory structures of the organism that can mobilize its resources in order to configure some new patterns of action. Thus, living systems have the ability to access new states and control new trajectories that encompass such states thus gaining new degrees of freedom.

In other words, by limiting free-energy a new order is introduce in the system. This means that degrees of freedom of the components are restrained, according to the new order, whereas, at the level of the whole, degrees of freedom of the system as a whole emerge. FEP contributes thus to the emergence of the degrees of freedom of the system as a whole, by creating a multidimensional state space and patterns of action whereby the system entropy is reduced.

As mentioned before, in agreement with organizational theory, autonomy of a living system is not merely an issue of internal organization, but it also depends on how the organism couples with the world. Depending on the coupling with the external world, the organism receives information from it and has the possibility to respond to the environmental challenges. An important role in the coupling of organism with the world is played by the boundary of organism. This physical border which is the result of internal processes of organism traces the boundaries between the internal space of the organism and the surrounding world, and also facilitates the communication between them (Moreno & Mossio 2015, xxvii). The circularity relation between the internal processes of a living system, which constitute its physical boundary, contributes both to the preservation of internal processes and to the constitution of the system identity (Moreno & Mossio 2015, xxvii).

From the point of view of FEP, the physical boundary of the organism has a double role: an endogenous one of controlling the internal energies of organism. And from this perspective, one can say that FEP contributes to constituting the identity of organism by controlling its internal energy and redirecting it towards the patterns of action that would provide maximum efficiency of the system actions. However, from an exogenous point of view, the boundary of the organism plays the role to control the external flow of free-energy, filtering the quantity of energy that enters the organism. Thus, FEP contributes to the unity of the living system, protecting its internal integrity.

Depending on the complexity of the organism, this physical boundary can enable the coupling of the organism with the world on several levels. An example of such boundary is the cell membrane, which is a permissible selective structure (Ruiz-Mirazo & Moreno 2004, 245) that contributes not only to setting the boundaries between the organism and the world, but also to the adaptation of the organism by detecting the changes in the environment. Similarly, the nervous system not only enable the energetic and information interaction of the living system with the world, but also a direct coupling with it, which increases the possibilities of the organism to respond to environmental challenges.

In terms of dynamical systems, the boundary separating a self-organized complex system from its milieu is called Markov blanket. A Markov blanket is defined as a set of states delimiting the internal states of a living organism from its external ones (Friston 2013a, 2). According to this description, the states that form Markov blanket are linked with the internal ones of the system, forming thus a network made of parents, children and children's parents. The internal states are a probabilistic representation of the external ones being thus able to anticipate external changes (Friston 2013a, 7) and to put the system within a certain state, which would ensure its survival. Consequently, the role of Markov blanket is to stabilize the internal states of the system and to reduce the free-energy resulting from the dynamics between the internal and external states (Friston 2013a, 4). As boundary of the system, Markov blanket represent a dynamic demarcation between the organism and the world, which enables the systematic coupling with the environment and gaining a dynamic stability by anticipating the states of the system that are to be accessed.[12]

[12] The very existence of a Markov blanket – that underwrites a separation between the system and its eco-niche – means that the internal states can be interpreted as a probabilistic representation of the external states. This representational interpretation allows one to talk about the system anticipating or predicting external changes. Mathematically, this follows from the fact that the dynamics that maintain the integrity of the Markov blanket are gradient flows on something called Bayesian model evidence (i.e., negative free energy). This means the very existence of a Markov blanket – and implicitly the system – will look as though the Markov blanket is stabilising the internal states of the system.

At the level of organism, there can be several Markov blankets (Friston 2013a, 10): cell surface, neuronal systems, etc. This means that, depending on their complexity, organisms can exhibit multiple levels of limiting free-energy. Thus, membrane can be approached as a boundary, which separates intracellular states from the extracellular ones, hidden from the internal states (Friston 2013a, 2). Communication between the two is carried out by means of sensory states (corresponding to the states of receptors and ion channels), which receives the changes within the external states, conveying internal states to them, and active states (corresponding to various transporter and cell adhesion processes), whereby internal states act upon the external states (Friston & Po 2011, 2; Friston 2013a, 2). This circular relation allows for the regulation of the integral states of single cell organism in agreement with the external changes, by configuring some behavioral patterns, made up of sensory states and active states parameters. Moreover, active states are those that bound entropy of the system, providing thus the integrity of the Markov blanket (Friston 2013a, 5). This means that state space of a living system is made up of the active states of the system, meaning of the states, which the system can access as a response to the environmental challenges.

To conclude, autonomy of a living system entails taking into account both the internal dynamics of the organism the result of circular causation of the internal parts, and the external one, between the organism and its milieu (across the Markov blanket). Minimizing the system free-energy contributes actively to gaining the autonomy of living systems by configuring and preserving the state space of the system within certain boundaries. State space of living systems is a multidimensional one enhanced by the anticipatory structures of the organism, which enable the access to new states based on predictions of environmental changes. This multidimensional state space determines the emergence of some behavioral patterns with new degrees of freedom. Thus, FEP, as principle underlying the autonomy of living systems, determines modeling the state space of organism, depending on the responses that such organism can provide and the emergence of new degrees of freedom as a result of the complexity of emerging behavioral patterns.

5. Conclusion

To conclude, FEP has an important role not only in the functioning of self-organized living systems but also in underwriting the autonomy of living systems. Minimizing free-energy is a process that contributes both to the constitution of the internal organization of the system but also to the systemic coupling of the system with the world. From the perspective of the system constitutive dimension, enabling constraints characterizing the internal organization of the system determines the emergence of a multidimensional state space, with degrees of freedom higher than those of its components. From the perspective of the interactive dimension, FEP contributes to limiting the energy entering the system by anticipating the changes in its external milieu. The coordination of internal states with external states (across the Markov blanket) is performed by behavioral patterns, which also performs attunement of the internal regulating dynamics of free-energy with the external one. Thus, the autonomy of a living system depends on its multidimensional state space and the degrees of freedom of its behavioral patterns emerging from this state space.

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