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Self-organization and autonomy: Emergence of degrees of freedom in dynamical systems

Auto-organização e autonomia: emergência de graus de liberdade em sistemas dinâmicos

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ABSTRACT

Approached from the point of view of the basic processes that constitute the self-organization of living systems, autonomy means the generation of identity and the minimal unity of a system, as a consequence of the self-production of internal components and processes of an organism, self-regulation of its internal variables, and self-sustaining of its internal resources. However, a living system is also a dynamical system, which means that the emergence of identity and the unity of the system is inseparable from the generation of its degrees of freedom. These degrees of freedom have different levels of complexity, given by the multidimensional patterns instantiating them, offering various alternatives to respond to environmental perturbation. From the point of view of the multidimensionality of degrees of freedom of a living system, which depends on the degree of self-organization and complexity of the organism, one can distinguish three types of autonomy: minimal or basic autonomy, sensorimotor autonomy, and strong autonomy. Put in these terms, autonomy depends on the abilities of the organism to access some degrees of freedom of higher complexity, to enhance its degrees of freedom by its coupling with the environment, as a result of its bodily skills, and to consciously control and monitorize its degrees of freedom, as a result of its higher-order cognitive abilities.

Keywords: self-organization, autonomy, degrees of freedom, dynamical system, autopoietic system.

RESUMO

Abordada do ponto de vista dos processos básicos que constituem a auto-organização dos sistemas vivos, autonomia significa geração de identidade e unidade mínima de um sistema, como consequência da autoprodução de componentes internos e processos de um organismo, auto-regulação de suas variáveis internas e auto-sustentação de seus recursos internos. No entanto, um sistema vivo é também um sistema dinâmico, o que significa que o surgimento da identidade e a unidade do sistema é inseparável da geração de seus graus de liberdade. Estes graus de liberdade têm diferentes níveis de complexidade, dados pelos padrões multidimensionais que os instanciam, oferecendo várias alternativas para responder à perturbação ambiental. Do ponto de vista da multidimensionalidade dos graus de liberdade de um sistema vivo, que depende do grau de auto-organização e complexidade do organismo, pode-se distinguir três tipos de autonomia: autonomia mínima ou básica, autonomia sensório-motora e autonomia forte. Dito isto, a autonomia depende das capacidades

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do organismo de aceder a alguns graus de liberdade de maior complexidade, de aumentar os seus graus de liberdade através do seu acoplamento com o ambiente, como resultado das suas capacidades corporais, e de controlar e monitorizar conscientemente seus graus de liberdade, como resultado de suas habilidades cognitivas de ordem superior.

Palavras-chave: auto-organização, autonomia, graus de liberdade, sistema dinâmico, sistema autopoiético.

Introduction

In terms of autopoietic theory, both in the classical version and in the later developments, autonomy designates a feature of living organisms, i.e., of biological systems with adaptive mechanisms, which have the capacity to self-sustain and survive under the conditions of environmental perturbations. Autonomy is an emergent property of the self-organisation of a living system as a principle that lies at the origin of the emergence of forms of life. Thus, autonomy is approached only from the perspective of constitutive processes of self-organisation, which contribute to creating basic organisms (cell- or unicellular-type organisms). However, the approach of incipient forms of life, regarded as simple dynamical systems, does not solve the issue of understanding the autonomy of organisms with a much more complex organic architecture.

Consequently, in this article this I intend to identify types of autonomy of living systems, taking into account the results of autopoietic theory, with further developments, as well as the living systems approach in terms of the dynamical system theory. Thus, in the first section, "Self-Organization and Autonomy", I will show how the basic processes of autopoiesis, have contributed to creating what we may call operational autonomy. In the second section, "Self-organization and Degrees of Freedom in Dynamical Systems", I will discuss the topic of self-organisation from the perspective of dynamical systems, showing that the self-organisation process is inseparable from the process of producing the system's degrees of freedom. From here, I will define the autonomy of a living dynamical system in terms of the degrees of freedom it may access.

Finally, in the last sections, assuming the definition of autonomy in terms of degrees of freedom, and, considering the degrees of structural complexity of living systems, I will draw a distinction among three types of autonomy: minimal autonomy, which has been approached in different versions of autopoietic theory, sensorimotor autonomy, which belongs to organisms with minimal cognitive resources, and strong autonomy, which can be met in the case of organisms with higher-order cognitive skills.

Self-organization and autonomy

The starting point of dynamical system theory in approaching living system is the theory of biological organisation, according to which biological organisms are the consequence of the spontaneous self-organisation of living matter, which is not governed by strict laws, nor is the consequence of an internal agent, such as a self (Thelen and Smith, 1998) or some external forces. Self-organization is the result of a propensity to order exhibited by living matter, whereby elementary particles are coupled in an on-going interaction, which determines the occurrence of some complex structures with emergent properties that can self-sustain considering external conditions.[2] From this perspective, a self-organizing system is not only a mere assemblage of previously separate components, but entails their dynamic interaction in order to configure a new higher-order steady structure, with properties that cannot be reduced to individual properties of parts, and which would resist environmental perturbations. Thus, the propensity of living organisms to self-organization determines the emergence of forms of life with different organic complexity, able to exhibit higher patterns of behaviour as a response to environmental challenges that are decoupled from the basic mechanisms of their biological life. Consequently, one can say that living systems are self-organizing systems, which have the ability to self-maintain and adapt spontaneously to environmental circumstances, exhibiting various degrees of organic complexity and autonomy.

The emergence of autonomy of a living system should be understood starting from the constituent processes that are at the origin of its self-organization, such as the process of autopoiesis. In Maturana and Varela's terms (1980), living systems as autopoietic machines are characterized by their constantly maintaining an internal organization, which entails the continuity of the organism's internal processes without any other external goal. The process of autopoiesis consists of a network of recursive processes that regenerate and preserve internal components of the organism and thus, sustain the network of process that produces them. This means that what characterizes autopoietic systems is operational unity or opera-

[2] In Thelen and Smith's terms, "[s]elf-organization is not magic; it occurs because of the inherent nonlinearities in nearly all of our physical and biological universe" (Thelen and Smith, 1994, p. 58). In other words, self-organization is the consequence of the nonlinear relationship existing among the components of a system, which makes the interaction among the parts determine the emergence of some properties at the level of the whole that differ in quality. Unlike the classical, linear causality, which generates some "aggregative" systems, whose characteristics result from the simple addition of the properties of the components (Thompson, 2007, p. 419), nonlinear causality allows the coupling and mixture of some processes or heterogeneous elements, which would lead to effects that differ structurally from their determining causes. Thus, nonlinearity means more than the simple reorganization of the elements as it allows for reaching levels of higher complexity that cannot be obtained by simply adding parts.

tional closure, whereby the organism gains identity and unity. According to later enactivist approaches, the identity of an autonomous system is constituted by the recursiveness of the set of interdependent processes, which are self-sustaining and self-generating (Di Paolo and Iizuka, 2008, p. 411), becoming an invariant that persists through time and resists changes caused by environmental perturbations on the organism.[3] Thus, the process of autopoiesis constitutes a unitary whole that self-creates the condition of its existence.

By constituting its identity and unity a living system gains an operational autonomy given by the dynamics of its internal operations. This autonomy should be understood from the fact that an autopoietic system is always embedded within a certain context, trying to sustain and preserve its identity and unity under the conditions of environmental fluctuations and perturbations. This means that an autopoietic system is an open and homeostatic system, which operates under precarious conditions.[4] As an open system, an autopoietic system is characterized by an exchange of energy with the environment. Thus, it is a dissipative structure that, through its interaction with the environment, gets the energy required for its preservation; but it also consumes energy in order to sustain its internal organization, which is subjected to an on-going flow of energy exchange with the environment.[5] Depending on the quantity of energy received from exterior, the system may have moments of instability, reaching certain thresholds and overcoming them through the emergence of new levels of organization.

From the point of view of the energy exchange with the environment, the system is considered to be far from a thermodynamic equilibrium, meaning that it never reaches equilibrium with the environment except by losing its identity, which occurs only by ceasing its activity. As an organism characterized by non-equilibrium, the living system has only a tendency toward equilibrium, undergoing states with a transient stability, which it reaches through on-going regulation of its internal processes.

An important role in this process is played by homeostasis, which, as a feature of living systems, entails the regularization of their internal variables with a view to constantly preserving both the relationships among them and the response patterns determined by the relationship of the organism with the environment. Thus, homeostasis represents the propensity of the organism to maintain some recursive patterns, which are to preserve the autonomy of the system.

Moreover, according to later approaches to autopoietic theory, the autonomy of a living system would imply a boundary that is a result of the on-going interaction among the components, whereby the organism demarcates itself from the exterior and controls the energy flows coming from the environment (Ruiz-Mirazo and Moreno, 2004, p. 238). Boundaries facilitate the structural coupling between the system and the environment whereby the external structure of the system comes to be "as much as part of the complex system as the internal structure" (Juarrero, 2010a, p. 2). In this way, the boundary internalizes the feedback, by sending to the organism signals about external perturbations, which determines the adjustment of its internal reactions in compliance with the environmental modifications. It follows that this boundary, which is a result of self-organization, being generated endogenously, is a structure whose sensibility is adapted to external changes, making the organism an open system with different possibilities for interacting with the environment.

Starting from this, one can conclude that an autonomous autopoietic system is an open system, embedded within a certain context, which is in a dynamical non-equilibrium with it, whose internal mechanism aims at generating its own components and internal relations with a view to preserving them and, at the same time, generating its own identity and unity by creating a boundary that demarcates the organism from the external environment. Such a system is characterized by an operational autonomy, which represents a weak form of self-governance, to the extent that even if it is produced by the system and makes self-preservation its goal (Collier, 2002, p. 1), it does not involve a conscious regulation of the organic processes or achieving an external goal.[6] Operational autonomy is a consequence of the self-organization of living system, and, therefore, should be understood through its constituent processes. From this perspective, operational autonomy consists in generating identity and the minimal unity of a system, as a consequence of the self-production of the internal components and processes of the organism, self-regulation of its internal variables, and self-sustaining of its internal resources.

[3] Autonomy entails the existence of an operational identity of the organism irrespective of its level of activity. "Autonomy as operational closure is intended to describe self-generated identities at many possible levels" (Di Paolo and Iizuka, 2008, p. 411).

[4] Di Paolo and Iizuka state that "[b]y *precarious* we mean the fact that in the absence of the organization of the system as a network of processes, under otherwise equal physical conditions, isolated component processes would tend to run down or extinguish" (Di Paolo and Iizuka, 2008, p. 411).

[5] However, in some dissipative structures, boundary conditions are either imposed from the outside (as Bénard cells) (Juarrero, 2009, p. 91), or insufficiently controlled (Collier, 2004, p. 153). This means that these dissipative structures are characterised by an exogenous autonomy, which requires an external control of boundary conditions, and not by an endogenous autonomy, which is the exclusive result of their internal processes.

[6] One can speak of a more advanced form of self-governance in the case of an adaptive autopoietic system, which actively monitors its own states and acts towards improving the circumstances of the autopoietic process (Di Paolo *et al.*, 2010, p. 50). A system with properties such as self-monitoring, control of internal regulation, and control of external exchanges (Di Paolo, 2005, p. 430) has the possibility of a better adaptation to the environment by means of complex behaviour, which aims at achieving its own goals and not just a direct adjustment to the exterior perturbation.

Self-organization and degrees of freedom in dynamical systems

The idea behind the theory of self-organization in the dynamical system approach is that the interaction of elementary particles has as a consequence a cohesion between parts owing to the generation of an orderly pattern of behaviour, which takes over control of the system at a certain moment, constraining the degrees of freedom of the components to join them in a functional whole, giving up some of their possibilities to act. The emergent organization of the system is a result of its multi-causal character (Thelen and Smith, 1998, p. 281), according to which the mutual influence of the parts, endowed with causal powers, determines the expansion of the internal processes, cancelling the pre-existing order through the emergence of a higher-order structure, which endows the organism with the ability to respond to environmental perturbations—which the components, separately, did not have. Structurally speaking, self-organization is the consequence of the circular causality relationship of the system (Lewis, 2002, p. 41), which means that the cohesion of the basic elements generates a higher-order pattern, which in turn determines the cohesion of its parts. Circular causality shows that self-organization is an on-going process, where the higher and bottom levels of the system generate and influence one another, determining the stability of the system as a whole as a result of the internal dynamics of the components. This circular dynamics is at the origin of the constitution of organism identity and maintenance of equilibrium, under the influence of energy perturbations coming from the environment.

This means that as dynamical systems, self-organizing systems are not invariable but evolve in time, alternating moments of instability with stability. In terms of the dynamical system theory, one can say that the factors influencing the system, called parameters, operate on its variables, which are in an interdependent relation, determining their simultaneous modification and the change of the system state (Van Gelder, 1998, p. 617). The variables of the system have an on-going dynamic and, due to their coupling with various external parameters, their evolution can be explained by a set of mathematical equations.[7] It results in the system being characterized by several states, which correspond to the alternatives to modify its variables, which, together, form the state space of the system. State space is a representation, in a system of coordinates, of all the acting and responding possibilities that the system could have in its history.

Due to the influence of parameters on the internal variables, the system exhibits moments of instability, depending on the external fluctuations that threaten its internal organization. In phase transition, which is the transition from one steady state to another, the system is oriented towards the discovery of some new self-organizing patterns (Kelso and Engstrøm, 2006, p. 116) by means of a control parameter, which is a transitive pattern that opens the possibility of the system to self-organize in new possible configurations. Control parameter merely facilitates the transition from the old organization to the new one, ensuring the adaptation of the system to the new conditions, without imposing any order pattern. The configuration of the system in a steady state is the result of the emergence of a self-organizing pattern as an order parameter or collective variable, which takes over control and coordinates the variables of the system at a certain moment, determining the reduction of the degrees of freedom of its components (Kelso and Engstrøm, 2006, p. 115-116) to only few alternatives to act. Thus, order parameters define the degrees of freedom of the whole system, which are gained by condensing the degrees of freedom of its components, as a result of the adaptation to the perturbations caused by the external parameters.

An order parameter determines the system to settle into one or a few patterns of behaviour (Thelen and Smith, 1994, p. 58), which means that, from a topological approach, it configures a certain pattern in the system's state space, made up of points in this space corresponding to the states of the system that could be occupied at a given moment. This means that the system comes to be guided by an attractor, which corresponds to the trajectory a pattern of behaviour describes in the state space, which determines the position of the system as a response to the external perturbations. The system state space contains a number of finite attractors—the less they are, the more organized and steady the system is considered (Newton, 2000, p. 94)—of which only some are active at a certain moment, meaning that they influence the behaviour of the system. Depending on the external perturbations and on how strong these patterns are, as a result of giving appropriate responses to the challenges of the system, the system oscillates between these attractors, which are "the total number of alternative long-term behaviours of the system" (Kauffman, 1993, p. 177), representing the degrees of freedom of the system.

Some attractors have a regular configuration, describing a determined orderly pattern with a uniform trajectory. Such examples are point attractors, which determine the stability of the system by its convergence toward a steady point in its state space. Periodic attractors belong to the same category, having a cyclic trajectory and taking the shape of a periodic loop (Juarrero, 1999, p. 154), which always reverts to its initial state by occupying repeatedly the same positions.

Other attractors, such as chaotic (or strange) attractors, have an irregular trajectory, but not non-coherent, which does not pass through the same points in the state space but occupies convergent positions against the previ-

[7] Equations represent rules of evolution (Van Gelder and Port, 1995, p. 6) of the variables. Consequently, a dynamical system operates according to certain deterministic sequences where each state of the system is a consequence of a previous state.

ously covered trajectories.[8] The trajectory of strange attractors is not random, but it has a higher degree of complexity as it corresponds to a higher order. Unlike point or periodic attractors, which are zero- or uni-dimensional (Kauffman, 1993, p. 178), strange attractors are multidimensional, as they are able to have many coordinates represented by the variables of the system.[9]

Thus, beyond the overall degrees of freedom resulting from the configuration of the operational space of the system, represented by state space, attractors, depending on their dimensionality, instantiate these degrees of freedom, which depend on the number of variables that are affected by the particular situation in which the system is embedded. Point and periodic attractors instantiate simple degrees of freedom, which include a limited number of alternatives for responding to environmental perturbations. Strange attractors characterizing higher-complex systems have higher-order degrees of freedom, which offer multiple alternatives to respond and adapt.

To conclude, the self-organization of a dynamical system involves reaching the stability of the system by means of an emergence from the interaction of the components of some self-sustaining operational patterns that can maintain the identity of the system in spite of external perturbations. These operational patterns define the degrees of freedom of the system from whose association the autonomy of the system results.

From the point of view of the part–whole relationship, the circularity that is at the origin of the system's self-organization determines the degrees of freedom of the system. The cohesion of the parts and their coordination with a view to adopting a unitary behaviour is due to the constraints within the system, which, by means of a double dynamics, i.e., endogenous and exogenous, determines the generation of a systemic whole, whose causal powers are exercised on the parts. From the point of view of dynamical system theory, the role of constraints within a system is explained by Juarrero's theory (1999, 2010b), which draws a distinction between constraints that limit the response options of the system, namely context-free constraints, and constraints that enable one to find new ways to act, namely context-sensitive constraints. Constraints imposed on the system from the exterior, which belong to the first category, determine the system to change from a state of equiprobability and independence, where anything can happen, to a determined state that reduces the degrees of freedom of the system to one alternative from the previous ones, whereas it cancels the others. If there are no new options for response, context-free constraints are limitative as they cannot be at the origin of the emergence of complexity, which offers a higher-order self-organization to the system.

Different to constraints that only push the system toward a certain state that is to be abandoned as soon as the external pressure disappears, Juarrero (1999, 2010b) stresses the importance of context-sensitive constraints, which are the result of relations set up between the parts of the system as a consequence of adding them. In this case, the consequence of cohesion is the interdependence of elementary particles, whose behaviour undergoes qualitative modifications within the newly created ensemble. Thus, context-sensitive constraints determine the emergence of new properties and generation of some higher-complex levels, which "enlarge the variety of states the system as a whole can access" (Juarrero, 1999, p. 138).

This is possible because context-sensitive constraints operate both bottom-up, by generating the conditions for the emergence of a higher organization, and top-down, by generating the boundary conditions that operate on the lower level. First, one can speak of first-order contextual constraints, which operate toward synchronising and correlating the particles that are at the same level of complexity. By coupling the components, first-order contextual constraints determine the emergence of a new operational space of the system, with more degrees of freedom than its components, which opens new response alternatives to the whole. Second, one can speak of second-order contextual constraints that are the result of the influence exercised by the new emergent level on its components so that they can behave in certain way. Thus, second-order contextual constraints represent the closing loop of the circularity relation among the levels of the system, whereby the higher-order pattern controls top-down the bottom level generating it.[10] In other words, the second-order contextual constraints restrain the degrees of freedom of the parts by diminishing the state space of the components (Juarrero, 2010b, p. 262) and increasing the probability of occurrence of certain events (Juarrero, 1999, p. 146), by configuring the bottom level according to the new higher organization of the system. Thus, new and higher-order degrees of freedom emerge in the system.

The result is that, according to Juarrero (1999), self-organization, due to first-order contextual constraints that operate locally at the level of the elementary particles, determining their cohesion, generates a new structure endowed with higher-order causal powers. The new structure operates globally on the ensemble of particles, conveying on them a differ-

[8] Attractors have a basin of attraction, which includes the sum of the possible states to be occupied that are determined by that order pattern. In the case of strange attractors, due to their unpredictable character it is difficult to know, even in probabilistic terms, what position in the basin of attraction is to be occupied by the system.

[9] Strange attractors can also occupy intermediate positions between two dimensions. This means that their multidimensionality is fractal in the sense that it can be expressed by fractions and not as an integer (Kauffman, 1993, p. 179; Ward, 2002, p. 213).

[10] The part-whole relationship is described in terms of top-down causation (Juarrero, 2009, p. 89) or downward causation (Thompson, 2007, p. 426) whereby one can understand the causal efficacy of the higher level, which operates by structuring the lower level, in the sense of modelling and limiting the state space of the components according to the requirements of the higher emergent organization.

ent dynamics and having as a consequence the generation of a unitary and systemic whole. In other words, self-organization involves the dynamics of circularity between first-order contextual constraints that generate new degrees of freedom, enlarging the system state space (Juarrero, 1999, p. 145), and second-order contextual constraints that reduce the degrees of freedom of the components by reuniting and configuring them in more complex structures, which offer the system greater alternatives for responding do its parts.[11]

Put in these terms, one can say that first-order constraints generate first-order degrees of freedom, which entail the sum of all states that could be occupied by the new emergent whole. Whereas second-order constraints determine second-order degrees of freedom, which are a consequence of the complexity of the patterns that are configured in the multidimensional state space of the system. Thus, second-order contextual constraints correspond to the order parameters that, as organizing patterns, compress or enslave (Thelen, 1995, p. 57) the degrees of freedom of the components with a view to the emergence of certain behavioural patterns, with basins of attraction deeper than the components of the system have separately. The depth of these basins of attraction, which give dimensionality to attractors, is given by the number of system coordinates, which represent the variables that contribute to the generation of this pattern. Thus, the degrees of freedom of the system are not determined by the positions that could be occupied in the new operational space of the system, resulting from the addition of the degrees of freedom of the components, but rather by the dimensionality and complexity of the patterns that bring together the states included in this operational space.[12]

As a result, self-organization involves the generation of a new hierarchy of levels where transition to a higher level of organization creates the possibility of accessing some increasingly complex degrees of freedom by adding new coordinates in the state space, which are represented by the system variables. This means that self-organization involves generating and re-generating constraints that modulate the flow of energy and contribute to the recursive maintenance of the organism (Ruiz-Mirazo and Moreno, 2004, p. 241). In the process of generating constraints whereby the organism self-creates the rules for its organization, the living system self-regulates the degrees of freedom of its components. By regulating and modulating the degrees of freedom of its parts, the system creates its degrees of freedom as a whole. In this way, one can define the degrees of freedom of the system as representing the number of possible positions or states the system can occupy, considering its independent variables, without breaking the exogenous or endogenous constraints it undergoes.

To conclude, it results from the convergent approaches of the dynamical system theory in topological terms and from the part–whole relationship perspective, whereby through self-organization the degrees of freedom of the system are produced, which together give its degree of autonomy. This means that the processes underlying self-organization and autonomy should be understood from the perspective of the production of degrees of freedom of the system. Thus, in terms of dynamical systems theory the autonomy of a living system means the self-production (autopoiesis) of its degrees of freedom, the self-regulation of the degrees of freedom of its components, and the self-sustaining of internal processes in order to maintain and to enlarge the degree of freedom of the system. Consequently, the emergence of identity and unity of the system is inseparable from generating its degrees of freedom, whose level of complexity, given by the multidimensional patterns instancing them, offer varied alternatives for responding to environmental perturbations.

Types of autonomy in self-organizing systems

Approaching the autonomy of living organisms in general, it can be inferred that this is a gradual matter given by the self-organization level of the organism and by the complexity of the degrees of freedom the organism has gained.[13] From the point of view of the process of autopoiesis, which means the generation of the system's organization, the degree of autonomy of a living system is a consequence of the way it regulates and modulates its internal processes in order to adapt to environmental conditions. For highly organized organisms, the question of degrees of autonomy is raised in terms of the ability to control their degrees of freedom due to their mechanisms for adaptation to environment. As a result the degree of autonomy of a living system is given by the degree

[11] This means that self-organization operates according to the principle "the whole is more than the sum of its parts" (Baumeister and Vonasch, 2011), which means that the degrees of freedom of the system as a whole are not only a mere addition of degrees of freedom of its components, as the former are of an higher level. The system, owing to the emergent properties, has degrees of freedom that provide a higher degree of autonomy than that of its parts. From this perspective, self-organization as a consequence faces not just the limitation of the degrees of freedom of the system components, but also the increasing complexity of the degrees of freedom of the system and in this way its autonomy.

[12] The possibility of accessing the states contained in this operational space is also the consequence of the complex abilities of the system that can determine the emergence of some strange attractors with higher-order degrees of freedom.

[13] Self-organization involves creating new hierarchic levels where each level has a certain degree of complexity. These levels, which are interconnected, provide increasingly developed degrees of autonomy so that the lower levels (e.g., material) are less autonomous, whereas the higher levels, which are supported by the lower ones (e.g., cognitive level), could have a greater level of autonomy (Collier, 2004, p. 166-167).

of complexity of the organism's mechanisms, whose role is to maintain its identity and equilibrium with the environment.

Starting from these premises, it is difficult to quantify the degrees of autonomy characterizing the living systems, their diversity being a consequence of the heterogeneity of living kingdoms, where each organism exhibits its own kind of autonomy. However, referring to the multidimensionality of the degrees of freedom of a living system, which depends on the degree of self-organization and complexity of the organism, one can distinguish three types of autonomy: minimal or basic autonomy, sensorimotor autonomy, and strong autonomy.

Minimal autonomy

Constitutive autonomy of the system (Froese *et al.*, 2007; Froese and Ziemke, 2009), or minimal autonomy (Barandiaran and Moreno, 2008), is the result of the metabolic activity of the organism that generates a minimal identity constituted by the biological processes that sustain the existence of the living system. This minimal identity does not involve complex biological structures that would offer self-awareness to the organism, rather it is a consequence of the (internal) recursive patterns forming at the level of the organism as a result of the constitutive processes.[14] Constitutive autonomy involves generating an identity as a consequence of the operational closure of the organism, whereby it experiences an on-going self-constituting process in order to prevent its disintegration (Froese and Di Paolo, 2011, p. 6).

Preserving the minimal identity of the organism also involves a physical boundary, which separates the organism from the environment, thus becoming a prerequisite for the emergence of its constitutive or basic autonomy (Ruiz-Mirazo and Moreno, 2004, p. 241-247). The basic type of biological boundary is the membrane, whose purpose is, on one hand, to protect the internal processes of the system against environmental perturbations, and, on the other hand, to control the energy flows necessary to its functioning. Membrane demarcates the space necessary to the system so that its basic processes, which regulate its internal responses and through which it communicates with the external world—i.e., catalysis and energy currencies—, are able to function, as the membrane is a boundary with selective permeability and with channels of interaction with the environment, as the result of local and global constraints (Ruiz-Mirazo and Moreno, 2004, p. 245; Moreno and Etxeberria, 2005, p. 163). This means, on one hand, that membrane is the consequence of internal constraints resulting from the cohesion of the elementary particles and from reactions that connect these particles, and, on the other, that it has causal powers exercising top-down constraints on the basic level by aggregating the elementary particles into a functional whole that contributes to carrying out the same tasks (i.e., the survival of the system within its environment). Thus, membrane is the consequence of endogenous and exogenous constraints that are at the origin of the system's self-organization, playing an important role in its adaptation. Owing to its sensitivity to changes in the system environment, it provides a basic form of coupling and interaction between organism and the environment in which it is embedded, so that the living system can preserve its identity and unity.

Consequently, constitutive or minimal autonomy is the level of autonomy that characterizes living systems with minimal forms of life, which offer responses to the environmental perturbations only by changing their internal organization. Such organisms respond to external changes only at a metabolic level, determining the activation of some adapting processes with a view to preserving the biological integrity of the system (Moreno *et al.*, 1997, p. 115). This means that systems with minimal autonomy have the ability to give automatic responses to the external perturbations, which are the consequence of the mechanisms that would ensure the survival of the organism. In this case, one can speak of a metabolic agency (Moreno and Etxeberria, 2005, p. 163) as a form of agency characterizing a biological organism, which, even if not endowed with self-reflective abilities, has basic intentionality, given by the orientation of the living system toward its environment in order to find the resources required to work properly and preserve its basic functions.[15]

Consequently, minimal autonomy—as a basic form of autonomy of living systems—is not a gradual property of an organism (Froese *et al.*, 2007, p. 459) but comes from the internal biological processes of a living system with a basic structure that generates minimal forms of identity and unity. Minimal autonomy is a property of the biological domain, i.e., of living forms that do not possess cognitive abilities, not even incipient ones. In terms of the dynamical system theory, minimal autonomy is constituted by simple recursive patterns, existing at the level of the system, which generate an order parameter with lower complexity instantiating simple degrees of freedom.

[14] From this perspective, Thompson (2007, p. 260) also speaks of a kind of biologic self, "because the dynamics of the system is characterized by an invariant topological pattern that is recursively produced by the system and that defines an outside to which the system is actively and normatively related".

[15] Such an agent, understood in the minimal sense, would be defined as "an autonomous organization that adaptatively regulates its coupling with its environment and contributes to sustaining itself as a consequence" (Barandiaran *et al.*, 2009, p. 367). In other words, a minimal or biological agent is not only the passive receiver of changes in the world but also has the possibility of regulating the flow of information coming from the world, which means that it uses the information received from the environment for its own adaptation (Di Paolo, 2005, p. 443). Therefore, it is also called an adaptive agent, its aims being to adapt to the environment, which entails maintaining some recursive interactions with the environment (Froese and Di Paolo, 2011, p. 10).

Sensorimotor autonomy

Unlike organisms with simple organization, which have a basic coupling with the world based on the regulation of the organism's internal responses, organisms with a nervous system achieve adaptation through the world's being enacted in a dynamic feedback loop, by connecting sensory processes to motor ones, which opens the organism to the possibility of a nonlinear interaction with the world. From the biological point of view, there is a great difference between organisms characterized by minimal autonomy and those with a nervous system. This means that the degree of complexity of the latter determines the emergence of a level different from the metabolic one, with different dynamics (Moreno and Etxeberria, 2005, p. 167) that offers the system the possibility of accessing other degrees of freedom. This new level, which is dependent on the metabolic one, exercises constraints on the latter, determining new behaviours to appear through the emergence of some new degrees of freedom that would expand the system's alternatives to respond.

In other words, the nervous system, by coupling the sense organs with effectors, integrates the agent into a mobile unity (Thompson, 2007, p. 244), beyond the biological one, which generates some new patterns of action. The organism's coupling with the world is no longer achieved by means of a physical boundary, which, as an interface, facilitates exchanging of energy with the surrounding world. But owing to the nervous system, the organism is integrated into the world through some sensorimotor loops that reunite the internal processes, the body, and the world in a dynamical pattern. Thus, perception is detached from the metabolic responses of the organism, being connected with its movement ability,[16] the two mutually conditioning one another: perception is influenced by the position and movements of the body, and the movements of the body are determined by the need for orientation within the environment, which results from the organism's needs to adapt and survive.

In other words, the organism's perceptual space is structured according to the opportunities to act that are identified in the environment. This means that organisms do not perceive the world in a neutral way, but objects around us are perceived according to their utility in accomplishing our actions. The consequence of the organism's sensorimotor coupling with the environment is the perception of the world according to the affordances (Gibson, 1977) which help the organism to achieve its goals. In terms of the dynamical system theory, affordances facilitate the attractors of the dynamical cycle perception–action by integrating the organism-environment system in a dynamic pattern of action. Affordances do not involve higher-order cognitive abilities, but they are a non-inferential and non-representational way of perceiving the world from the perspective of the sensorimotor abilities of the organism. These abilities demarcate the space of action of the organism within the environment, called its niche, which consists of all the affordances perceived (Silberstein and Chemero, 2011, p. 7).[17]

Consequently, sensorimotor abilities determine the emergence of a different type of agency, which does not merely involve the regulation of the internal processes but also a new way of relating the organism to the world, whereby the former does not based only on internal adaptive reactions alone, but also by gaining information that would improve its abilities to act. Owing to the sensorimotor loop, organisms exercise a feedback control (or closed-loop control) on their variables, where "the inputs provided to the system depend on its current outputs, which are often affected by the current circumstances" (Eliasmith, 2009, p. 137), which means that the world of the organism is continuously constituted anew, by revealing new ways of acting in the world. Thus, the relation of a sensorimotor agent with the world is characterized by what Merleau-Ponty (2005) calls an intentional arc, which corresponds to the set of bodily skills, whereby an organism responds to changes in the world, directly, without the need for cognitive representations. In other words, the world is perceived at the pre-reflective level in terms of the motor abilities of the organism, which involves only direct responses and spontaneous adjustment to changes in the world, without the need for cognitive reflective abilities.

Even if sensorimotor coupling does not involve higher-order cognitive abilities, and sometimes not even a nervous system (Van Duijn *et al.*, 2006), one can speak in this case of a basic or minimal cognition. This is a basic embodied cognition, which entails that information from the environment is processed by the sensorimotor structures and transformed into motor impulses that lead to the performance and success of an action. This means that, through the sensorimotor coupling with the world, the organism receives information necessary for its adaptation since it has access to a new epistemic level, beyond the one generated by the metabolic processes (Etxeberria *et al.*, 1994). Moreover, motility, together with the emergence of the nervous system, leads to a higher organization of the organism and to the generation of some cognitive phenomena, such as emotions and awareness (Moreno and Etxeberria, 2005, p. 170).

Consequently, sensorimotor autonomy entails that organisms are endowed with basic cognitive resources. They are

[16] One can also speak about incipient forms of motility in the case of simple organisms, which lack a nervous system; but in this case, motility is merely a result of metabolic processes, i.e. "an extension of the set of mechanisms that are required for self-maintenance" (Moreno and Etxeberria, 2005, p. 167).

[17] From this perspective, sensorimotor abilities depend on the autonomy of the organism, which involves "the maintenance appropriate relations among the nervous system, the body and the environment, i.e., the maintenance of affordances and the cognitive-phenomenological niche" (Silberstein and Chemero, 2011, p. 10).

capable of behaviour, which means that they not only simply offer a response as a result of constitutive coupling with the environment, they actually control their interactions with the environment and can pursue the achievement of some goals external to themselves (Di Paolo, 2005). Such an organism, with a multicellular architecture, whose adaptation relies on motility and whose body is controlled by a nervous system, is characterized by behavioural agency (Barandiaran and Moreno, 2008, p. 336). This type of agency entails a type of autonomy, which even if it involves detachment from the metabolic level, entails the coupling of the organism with the world with simple patterns such as cycle attractors, which have degrees of freedom with lower dimensionality. As a result, although sensorimotor autonomy enhances the degrees of freedom of the organism by detecting new possibilities to act within the environment, it remains dependent on the responses to external perturbations without instantiating any higher-order behavioural pattern.

Strong autonomy

In case of the beings with higher-order cognitive skills, one can speak of strong autonomy, which characterizes an agent that has the ability to control its alternatives to respond and to be consciously aware of its degrees of freedom. This means that beings with higher-order cognitive skills have the possibility to choose their own goals, independently of environmental conditions or immediate organic needs, can imagine plans with regard to future actions, and can conduct counterfactual reasoning, imagining situations where things could have happened differently (Wilson, 2002, p. 626). This is possible as such organisms have the advantage of operating with offline cognition, owing to the existence of a higher-order level, besides the biological and sensorimotor ones, which has the ability to process information and create responses to environmental perturbations, detached from the energetic current flow to which the organism is exposed. In other words, organisms with higher-order cognitive abilities are capable of ideomotor action, which does not represent a mere response to external events (i.e., stimulus-based actions), but involves behaving according to some internal aims and thoughts (Waszak *et al.*, 2010, p. 185).

Higher-order cognitive skills are the consequence of the complexity of the brain, which has the possibility to create patterns of action in a nonlinear way (Kelso, 1997, p. 257). The brain of such an advanced organism is itself a dynamical system, which it self-organizes through the large-scale integration of neurons situated in various areas of the brain, in patterns that determine responses by causing a certain behaviour in the organism. This property of the brain whereby autonomous parts can interact and influence one another, creating a pattern of action without losing its independence or part thereof, is called metastability (Kelso and Tognoli, 2009, p. 107). In the metastable regime, the brain creates a dynamic state space whose coordinates are given by the nonlinear interaction of its regions with various functions, which determines the emergence of patterns with higher-order degrees of freedom.

In the same way as a dynamical system, the brain alternates between states of instability and stability, by the emergence of some attractors, which, owing to the nervous system, participates in the sensorimotor cycle of coupling to the world, determining the emergence of some multidimensional behavioural patterns. Such a brain is capable of strange attractors, with an unpredictable trajectory, which determine stochastic chaotic behaviour (Freeman, 1999, p. 153), with many and complex degrees of freedom. Moreover, the internal relation of circularity, which characterizes dynamical systems, acquires a semantic content (Juarrero, 1999), owing to the emergence, by means of the aggregation of neurons, of a new metacognitive level that is consciousness. This appears to be a globally coherent activity operating as an order parameter (Freeman, 1999), which exercises top-down control, voluntarily and not automatically on the bottom level (Frith, 2009, p. 203). Thus, consciousness facilitates awareness and coupling of the cognitive contents of our thoughts, which are the emergent properties of the patterns of action created at the level of neuronal ensembles.

Consciousness, as a biological phenomenon representing the highest level of cognitive complexity, is at the origin of another type of intentionality, different from the one based on bodily skills, which involves patterns of action with conscious content resulting from the coupling of the organism with the world. These patterns of action, generated by the higher cognitive level to determine the neuronal level to trigger a certain behavioural response, are intentions. Intentions are not the direct causes of our actions but they play the role of context-sensitive constraints, being higher-dimensional, neurologically embodied attractors, which underlie several types of neurons, including the motor ones (Juarrero, 2010b, p. 267); they play the role of structural causes, which guide our actions, programming our behaviour to act in a certain way within certain circumstances (Slors, 2013, p. 107). One can say that such intentions define the vector field of the system, associating to each point in the system's state space a direction of movement, which will be followed in case such a pattern of action is activated.

Consequently, higher-order cognitive agents have the ability not only to monitor and regulate the responses of the organism that appear as bodily or cognitive patterns, but also to control behaviour through the possibility of including intentions within medium and long-term action plans, which are beyond the immediate priorities of the organism. This is possible through regulating the living system's own activity by voluntarily assuming certain norms, with no relation to the basic processes of the organism, but acquired from other forms of life (Barandiaran *et al.*, 2009, p. 372). This means that, in the case of higher-order cognitive agents, not only is interaction with the environment important, so is interaction with similar beings, where new possibilities to extend the autonomy of the living system emerge. Beings with higher-order cognitive skills are capable of participatory sense-making (De Jaegher and Di Paolo, 2007), whereby they coordinate their actions, producing, together with other similar living systems, new significances and values that are not the consequence of the organism's adaptability, but lay at the basis of the social and cultural world. In this new world of meanings, the agents, by choosing the values and norms to follow, have the possibility of reaching a new level of autonomy that cannot be achieved by any other biological organism.

Consequently, strong autonomy represents the highest level of autonomy that a biological being can reach, which involves not only a new identity, but also a personal autonomy.[18] This is possible owing to the complexity of cognitive structures with which such organisms are endowed, which provide them with the ability of a higher-order control of their own actions and degrees of freedom as a result of the emergence of consciousness. Strong autonomy involves the conscious control of the multidimensional degrees of the freedom of the organism, which provides the organism with an unlimited and varied array of open-ended responses to environmental challenges.

Conclusion

To conclude, one of the consequences of the capacity of living matter to pursue self-organization is the emergence of autonomy of the living system. Consequently, any living system has some autonomy, given by the level of its evolution as a biological organism and the complexity of its internal organization, which is given by the way it is coupled with the external world and controls its responses to environment perturbation. Taking into account that any living system is also a dynamical system, the result is that autonomy depends on the degree of freedom of the whole system, whereby the organism enhances its possibilities for adaptation to environment perturbations.

Therefore, the autonomy of an organism is a gradual problem that involves, in its minimal forms, the emergence and preservation of the organism's identity and unity. This is minimal autonomy that is the result of constituting processes of self-organisation, which involves simple degrees of freedom. In organisms with a nervous system and minimal cognitive resources, autonomy is defined in terms of second-order degrees of freedom, but with lower dimensionality. It is generated by sensorimotor skills, which open new possibilities for the organism to act in an environment, but remain dependent on the external conditioning. However, situation is different in the case of organisms with higher-order cognitive skills, which involve the conscious control of actions, which means the possibility to access some multidimensional degrees of freedom. Put in these terms autonomy depends on the ability of the organism to access some degrees of freedom of higher complexity, to enhance its degree of freedom through its coupling with the environment, as a result of its bodily skills, and to consciously control and monitorize its degree of freedom, as a result of its higher-order cognitive skills.

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[18] Generally speaking, a person is a being endowed with higher-order cognitive skills who behaves according to her own set of values and norms. From this perspective, one can say that "autonomy is a second-order capacity to reflect critically upon one's first-order preferences and desires, and the ability either to identify with these or to change them in light of higher-order preferences and values" (Dworkin, 1988, p. 108).

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