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CONFERENCE REPORT

Life, Autonomy and Cognition: An Organizational Approach to the Definition of the Universal Properties of Life

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Abstract This article addresses the issue of defining the universal properties of living systems through an organizational approach, according to which the distinctive properties of life lie in the functional organization which correlates its physicochemical components in living systems, and not in these components taken separately. Drawing on arguments grounded in this approach, this article identifies autonomy, with a set of related organizational properties, as universal properties of life, and includes cognition within this set.

Keywords Universal biology · Organization vs. Structure · Biological autonomy · Cognition

Introduction

In this article we address one of the most debated open questions about life and its origins —"What are the universal properties of life?"—on the basis of an emerging theoretical approach. We propose to call it "the *organizational* approach", since it arises from a multiplicity of research trends in contemporary theoretical and experimental biology which, as described in detail elsewhere (Bich and Damiano 2008; Letelier et al. 2001), focus their inquiries about life on the *organization* of living systems. Indeed, these 20th century research trends, among which we include for example the traditions of Self-organization, Relational Biology, Systems Biology, Synthetic Biology, Autopoiesis and Artificial Life, converge in a general basic research hypothesis. Synthetically: the specific properties of life lie not in its physicochemical components, which can be found also in non living systems,

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but in the specific way in which these components are functionally correlated—organized—within living systems.

This perspective on the specificities of life constitutes the starting point of this article. On the basis of this postulate, we operate theoretically on notions and arguments provided by different proponents of the organizational approach in order to structure and develop an organizational inquiry on the universal properties of life, and to provide an answer to the open question about them, coherent with this approach. The article is developed in three steps: (a) a preliminary discussion about the universal properties of life based on the organizational approach, and the definition of the general setting of our organizational inquiry about these properties; (b) the development of this inquiry, leading to the definition of autonomy, and some related properties, as universal properties of life; (c) the inclusion of cognition within this set of properties.

Universality in Biology: An Organizational Approach

One of the most rigorous—and yet neglected—formulations of the organizational approach to the study of life can be ascribed to Jean Piaget, whose theoretical production in the domain of biology inspired some influential pioneering research lines such as the traditions of self-organization and of autopoiesis. The basis of the Piagetian organizational view of life can be found in a simple yet powerful theoretical remark, which grounds a strong theoretical connection between biological universality and organization. Schematically: living systems can be described as dynamical systems in which all the constituents are constantly under transformation, while the systems themselves, as relational unities of components, remain the same, despite the changes in the external environment as well as in their constituents. It is easy to find an exemplification of this theoretical acknowledgment if we consider the simplest living system, i.e. the cell: a dynamical system which, as a global unity of components, keeps its identity (remains the same), while its components are constantly involved in the metabolic turnover (continuously change). Piaget (1967) elaborated this remark in a conceptual distinction which has been playing a crucial role for the development of the new organizational biology, since it proposes an explicit notion of biological organization able to ground a scientifically rigorous description of living systems. We refer to the Piagetian distinction between "structure" and "organization" of living beings, according to which (a) their *structure* is their transient materialization, that is, the concrete and continuously changing aggregate of physicochemical components of which a living system is constituted in each instant, while (b) their *organization* is the permanent relational frame which connects the components into systems, that is, the unchanging network of functional relations which defines a living system as a global unity of components. This is a conceptual distinction which, as formulated by Piaget, offers a theoretical key to a dynamical description of living systems, since it corresponds to the distinction between the *variant* and the *invariant* aspects of the biological dynamics—not only at the ontogenetic level, but also at the phylogenetic level. In fact, the relational unity is what remains unchanged not simply through the permanent flux of physicochemical components typical of biological organisms, nor only during the ontogenetic transformations which can make a living system unrecognizable from one observation to the next. The relational unity is also transmitted through reproduction, and remains unchanged in the flux of generations. In this sense, the relational unity is the invariant of the biological dynamics, and thus the lowest common denominator of living systems. Distinguishing this invariant relational frame from the changeable materializations of living systems and determining its configuration, amount to isolate an element which defines the class of dynamical systems belonging to the biological domain. In other words: it amounts to define a universal aspect of life.

Here lies the relevance of the Piagetian distinction between organization and structure for the development of the organizational approach—a relevance which is at least triple. *Firstly*, this distinction opens the possibility of producing an operational explanation of life, that is, the opportunity of defining a mechanism able to generate the living dynamics. This is the chance exploited by the Autopoietic Biology (Maturana and Varela 1980), according to which defining life corresponds to defining the organization, and not the structure, of life. The latter, in fact, is always changing, and in principle can be manifold. *Secondly*, the distinction between organization and structure generates significant implications for the role that the sciences of the artificial can play in the study of life. In fact, it implies that an artificial system displaying a structure different from that of known living systems can be considered to belong to the class of living systems if it shares their organization. Therefore the exploration of such a "made-by-men" system can offer pertinent insights for the study of life. This is the epistemological option adopted by contemporary research lines such as Langtonian Artificial Life (Langton 1989), and Chemical Synthetic Biology (Luisi 2007). Thirdly, and consequently, the Piagetian distinction grounds the idea of a "universal biology", an idea shared by the research trends just mentioned, as well as by other lines of investigation belonging to the organizational approach. We refer to the notion of a science that, since it focuses on the organization and not on the structure of living systems, is able to study the fundamental principles of life "as it is" and "it could be", and to provide mechanistic—i.e., "operational", "synthetic" or "constructive" (Pfeifer et al. 2008; Damiano et al. 2011)—explanations: hypotheses on the organizational mechanisms which generate the fundamental living phenomenology, that is, the dynamics from which all the biological phenomenology arises.

Our organizational inquiry on the universal properties of life intends to develop this orientation of biological research through the adoption of a thesis which allows us to well-define the field of exploration. To put it schematically: the fundamental living phenomenology is the phenomenology of the individual, and not that of the species, since, from a logical and phenomenological point of view, an organism has to be alive for reproduction and evolution to arise (Bich and Damiano 2007). On the basis of this thesis, our research on the universal properties of life focuses on the organizational properties of the biological individual and, in particular, of the minimal biological individual, which, in principle, can be considered able to generate all living phenomenology.

Autonomy and Four Related Organizational Properties as Universal Properties of Life

The adoption of this setting of inquiry requires us to focus the search for the universal properties of life on an organizational property common to all biological individuals. At a general level, it can be described as a relative independence from the environment consisting in the capability of a system to express activities of self-determination. Usually it is called "autonomy", and considered to be manifest, in different forms, in a wide variety of systems, belonging to a range extending from prebiotic to meta-biological systems (Dumouchel and Dupuy 1983). Within the biological domain this property is acknowledged to assume very specific features, which characterize it as "biological autonomy": the distinctive capability of living systems of realizing a permanent activity of self-production and self-maintenance through exchanges of matter and energy with the environment. In other words: the capability, specific to biological systems, to materially produce and maintain themselves as global and processual unities by functioning as systems of production (synthesis and destruction) of their own components. As such, biological autonomy designates not only a property shared by all biological individuals, beginning with the cell. It expresses also, and primarily, an organizational property belonging to these systems. In fact, it cannot be referred to any specific component of living systems (its structure), as it rests on the peculiar and distinctive way these same components—or, better, the processes they are involved in—are related.

This is why biological autonomy has been a topic at the centre of the researches of the organizational approach since its beginning in the 30s. The elaboration of this idea had been particularly intense until the 70's and we are assisting now in a new phase of development.

In the remainder of this section, we will try to draw progressively a schematic outline of this very articulated notion. We will do so by listing and describing four organizational properties of living systems that are intrinsically related to, or coextensive with, biological autonomy, and thus can be considered as universal properties of living systems. We will ground their description in some of the models of biological systems elaborated by organizational biology, and will focus in particular on models proposed by Piaget and his sources. This choice is intended to emphasize the relevance of his work within organizational biology, which, unfortunately, is still largely ignored, even by outstanding reviews dedicated to this area of the biological research (Letelier et al. 2001).

The *first* of these four organizational properties of living systems related to autonomy can be found in the *reticular* or *circular character of their organization*, commonly acknowledged as supporting their dynamics of self-production. This aspect of the biological organization, which expresses the networked character of biological metabolism, was pointed out by many proponents of the organizational approach, and is the object of many interesting models in this tradition, for example the models of M/R systems proposed by Rosen (1972), of closure by Piaget (1967), of the hierarchically organized system by Weiss (1968), of autopoietic organization by Maturana and Varela (1980), and of the chemoton by Ganti (2003). Among them, the Piagetian model—a general model of biological metabolism—has the merit not only of being very simple and intuitive, but also of having introduced one of the most diffused notions currently used to describe the circular character of the biological organization: the notion of organizational closure, which very rarely is acknowledged as introduced by Piaget.

This notion is proposed in Piaget (1967) as complementary to von Bertalanffy's idea of the "thermodynamical openness" of living systems. It describes the organization of living systems as a concatenation of transformative operations that produce their components by synthesis and destruction. Piaget conceived this as a dynamical chain in which each operation triggers and integrates at least another, and thus realizes a global self-determined dynamics. The notion of closure pictures this process as a cyclical dynamics which, as long as it receives matter and energy exogenously, is able to regenerate itself.

One implication of the idea of closure is the thesis according to which the chain of operations, while continuously transforming the components of living systems, regenerates the functional relations of production between them, and, in doing so, also regenerates the chain itself. In this sense, the notion of closure points to the complementarity between structure and organization of living systems, consisting in their mutual and indissociable entailment. The invariant relational frame (the organization) cannot exist without its concrete and transient realization into specific elements and their specific operational relations (a structure) and, conversely, there cannot be a concrete unit of elements in flux (a structure) without a relational frame able to integrate them in a permanent global unit (the organization).

The *second* organizational property of biological individuals related to autonomy can be found in the *hierarchical character of their organization*. The term “hierarchical”, referred to the circular organization of living systems, does not imply centres or isolable mechanisms which would determine the autonomous dynamics of living systems. It refers to the capability of the whole system, as a relational unity of components, to contextually constrain the dynamics and the properties of the components, and to characterize biological autonomy as a form of self-production which includes self-regulation.

This idea is made remarkably clear by the theoretical model elaborated by Weiss—derived from collaborations and mutual influences with Piaget—which describes living systems as “hierarchically organized” systems (Weiss 1968). According to this model: (1) The circular scheme of organization, by connecting the components in a network of functional co-dependencies, stratifies biological systems in (at least) two qualitatively different levels: (i) the level of the parts, which are intrinsically unstable and can in principle exhibit highly variable behaviors; (ii) the level of the organizational correlation of the parts, i.e., the whole, which, unlike its antecedent level, is strongly invariant and capable of conservative behaviors. (2) This qualitative difference between two levels relies on the fact that belonging to a whole reduces the degrees of freedom of the parts, in such a way to re-determine the expression of their individual properties and, in this way, their behaviors. (3) In particular, the fact of belonging to a whole imposes the parts a collective dynamics, i.e. its global dynamics of self-production, and a collective activity of regulation of their behaviors when they deviate from this dynamics due to internal or external perturbations. (4) The activity of regulation is due to a circular causal interaction involving the two levels previously specified. It implies that a deviation of one or several parts or processes from the range of their standard dynamics in the systems triggers a conservative reaction through the whole as a relational unity connecting the parts. This reaction compensates the deviation through interrelated variations in the lower level processes involving the parts, in such a way that, as long as the destabilization is lower than the stability threshold of the whole system, they eliminate its destabilizing effects. (5) The conservation of the organization as an invariant is realized through structural variations, that is, through the activation and realization of different patterns of self-production that compensate for the destabilizations.

The *third* organizational property of living systems related to autonomy can be defined as *adaptive interaction,* and refers to their capability of interacting through processes of self-regulation. As the Weissian model shows, the circular organization of living systems functions as a feedback mechanism. Therefore, ascribing to these systems such a circular organization amounts to imposing a specific condition on the conceptualization of their relationship with the environment. This cannot be considered as a passive exposure of living systems to environmental pressures. On the contrary, it has to be conceived as a reciprocal dynamics, in which both the environment and the living systems play an active role. The idea is that the environmental variations, when producing a local alteration in the dynamics of a living system, inevitably activate its dynamics of self-regulation. This process leads to a change in the dynamical configuration of the system, and to the instantiation of a different one among its possible patterns of self-production: a dynamical pattern which is able to eliminate the destabilizing effects of the perturbation. An example of this kind of internal change can be found even in the very basic cases, like in the modification of the metabolic dynamics triggered in *Escherichia Coli* by the environmental variation consisting in a molecule of sugar (β-galactose) reaching its membrane, one of the classical paradigmatic examples of genetic self-regulation in unicellular systems (Jacob and Monod 1961). The presence of the sugar produces a chemical disequilibrium within the living system, and thus activates a dynamics of self-regulation which, through a complex process of gene derepression, leads to the instantiation of another metabolic pattern. The latter produces a variation in the membrane which allows the passage of the molecule of sugar in the internal environment, and then its metabolization, in such a way that it eliminates the chemical disequilibrium. As this example shows, the exogenous pressure triggers the adoption of a different pattern of self-production, consisting in an active response of the system. Moreover, the specificities of the instantiated self-regulative pattern cannot be ascribed to the environmental action in itself. They have to be ascribed to the specificities of the system: its self-regulative capabilities, based on its organization, its structure and its history of interaction with the environment. Also, it has to be noted that the regulatory activity of the system acts on the maintenance of its conditions of existence. These are not only the internal ones, characteristic of the internal *milieu* of the organism and dependent on its self-production. They comprise, in fact, also the external conditions, to whose viability the system contributes through its transformative interactions with the environment.

Within the context of organizational biology, the interactive dynamics between living systems and their environment is conceptualized through notions such as the autopoietic concept of "structural coupling", or the self-organizational concept of "co-evolution". They portray the living system and its environment as two systems endowed with an endogenously determined dynamics, which, by exchanging energy and matter, influence their respective internal processes through mutual perturbations. Each of them triggers, although it does not determine, changes in the dynamics of the other. Each, as long as it maintains its organization, develops an evolutionary trajectory compatible with that of the other. The idea is that of a coupled evolution, realized through interferences and correlated instantiations of endogenous compatible patterns both in the living system and in the environmental one. The two systems are tied in a relationship of radical interdependence resulting not from a direct action of one system on the other, but from the coordination, through self-regulation, of their respective self-determined dynamics.

Within this perspective, adaptive interaction opens the possibility of the evolution of living systems as a complex interplay between endogenous and exogenous factors, in which the environment influences, but not univocally determines, the transformation in the systems. This theoretical view replaces the traditional notion of "natural selection" with that of "natural drift" (Maturana and Varela 1980). The latter does not describe the evolutionary transformation of living systems as a movement of progressive and passive *adequation* of the structure of the systems *to* that of the environment. On the contrary, according to the notion of natural drift living systems have evolutionary pathways which are compatible with both their structure *and* the environmental structure.

Adaptive interaction has the same basic features when it involves other living systems. The resulting co-evolution can be described as a dynamics in which each system triggers and influences, but does not determine, changes in the dynamics of the other system. Also in this case, the interaction consists in a coupled evolution, realized through perturbations and correlated instantiations of endogenous self-regulative patterns in the living systems involved. Their dynamics, during the interaction, are strongly interdependent, due not to direct actions of one on the other, but to their coordination through self-regulation. Adaptive interaction with other living systems opens to organisms the possibility of population interaction, and of participation to communities and inter-individual systems.

The *fourth* organizational property of living systems related to autonomy can be described as their capability of *self-distinction*. There is a general agreement in organizational biology about conceiving biological autonomy as a form of self-production which includes not only self-regulation, but also self-individuation. However, there is no agreement about the form of self-distinction characterizing life as it is and it could be. The debate on this issue proposes a wide range of solutions, from a purely functional to a topological distinction, and, concerning the latter, from self-consistence typical of gels to self-separation through the production of a barrier. The latter solution, though the most widely accepted, is also being questioned today, as even the existence of the cellular continuous membrane—i.e. the classical paradigmatic exemplification of the concept of a topological barrier built by living systems to identify themselves—is currently under debate (Pollack 2001). Here we use the notion of *self-distinction* not only to express the shared thesis that all living systems, in one way or another, define the space of their realization (as biological bodies). Through this notion we would like also to support the theoretical trend, typical of the organizational approach, which characterizes the limits of living systems as relative, and stresses the thick interconnection of these systems with both their environment and other systems. According to this view, living systems, by defining the space of their realization, do not separate themselves from their environment and the other living systems populating it. On the contrary, they establish with them relations of radical dynamical interdependence (co-evolution), and constitute a global system-(systems)-environment dynamic unity, like the niche, as the very unit(y) of evolution (Bateson 1972)—and of cognition.

Biological Autonomy and Cognition

The relationship between autonomy and cognition is a topic that stirs up strong interest among the proponents of the organizational approach. Since the 40s many of them—especially the proponents of the self-organizational and the autopoietic approach to cognitive biology—have been elaborating a view of cognition based on the concept of biological autonomy, as an alternative to the traditional computationalist perspective. The main idea developed by this trend can be summarized as follow. Computationalism eliminates from the inquiry on cognition the property that distinguishes living systems from artifacts: the capability of the former of producing and maintaining themselves by themselves, without the intervention by engineers. Natural cognition cannot be referred to a heteronomous input-output calculating device, conceived on the basis of the computer. It has to be grounded in the organization supporting the autonomy of living systems: the mechanism of their self-production and self-maintenance, i.e. their closure.

Today the "autonomy" trend in the study of cognition is an integral part of the growing "embodied cognitive science"—a promising candidate for the substitution of the still dominant computationalist cognitive science (Clark 1999). To the emerging "embodied approach" it proposes a significant series of theoretical shifts away from the "orthodoxy of the PC". Basically, it proposes to conceive: (a) the contact with the environment not as *reception of exogenously defined information*, but as *perturbation*; (b) the cognitive process not as *computation on physical symbols,* but as *self-regulation* whose significance (or role) is not specified externally as a "rule" or a"purpose" as in artifacts, but grounded in the closure of the metabolism and, as such, referred internally to the system that harbors it; (c) the product of the cognitive process not as the *representation of an independent and external reality,* but as the *association of internally generated operational meanings* (meanings expressed in dynamical patterns of self-regulation) for environmental variations perceived as perturbations.

Despite a general convergence on this reconceptualization of natural cognition, the proponents of the autonomy approach to cognitive science tend to diverge on the universality of cognition as a property of living systems. Some radical lines of research in autonomous cognitive biology recognize cognition as an organizational and, thus, universal property of living system, co-extensive with biological autonomy. Their argument is based on the idea that, when there is biological closure, than there are cycles of perception-action through self-regulation, i.e. embodied cognition. This position has been developed by Piaget by relating the notions of “assimilation” and “accommodation” to the concept of closure—notions borrowed from the embryologist Conrad Waddington in order to invert the traditional “stimulus-answer” paradigm according to an autonomous perspective: “At the beginning there was answer” (Piaget 1967). His theoretical proposal has been developed by proponents of the self-organizational and the autopoietic approach to cognition (Maturana and Varela 1980; Bitbol and Luisi 2004) and radicalized by some of them. Authors such as Atlan (1983) and Varela (1979) generalized the Piagetian concept of closure, and attributed cognition, as the capability of creating operational meaning for perceived perturbative events, to all autonomous systems, conceived as systems characterized by (biological or not biological) closure. But there are also different positions, according to which we found cognition in the proper sense only when self-regulation is realized through the nervous system.

Our proposal is to maintain the identification between cognition and self-regulation characteristic of the autonomy approach, and to well-define the latter through the already proposed distinction between stability and regulation (Bich and Damiano, this issue). In other words, we propose to consider as cognitive only the proper processes of adaptive interaction, wherever they take place in the biological evolutionary tree. We mean by them those interactive dynamics with the environment or other systems in which living systems, as organized unities of components, actively respond to external perturbations by instantiating endogenous patterns of self-regulation that express internal operational meanings generated for external events. Conceived in this way, cognition is a universal property of life, which corresponds not only to the capability of creating a meaningful world as a background for the interactions with a perturbative environment (Maturana and Varela 1980; Varela 1979). It has to be conceived also as the capability of creating unity. We refer to the complex unity system-(other systems)-environment: a relation of radical interdependence between systems engaged in their self-construction that, with Bateson, we think of as “the unity of the mind” (Bateson 1972). This is one of the main contributions of the notion of biological autonomy to the study of cognition. The mind, when conceived as the space where the cognitive processes take place, cannot be relegated to the head, or in the intra-individual space. It is the relational unity permanently (re-)generated by the dynamics of self-regulation which, connecting living systems to their environment and other systems, makes possible the multiple process of co-evolution in which life consists.

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