

Organisational Closure in Biological Organisms

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ABSTRACT – The central aim of this paper consists in arguing that biological organisms realize a specific kind of causal regime that we call “organisational closure”; i.e., a distinct level of causation, operating in addition to physical laws, generated by the action of material structures acting as constraints. We argue that organisational closure constitutes a fundamental property of biological systems since even its minimal instances are likely to possess at least some of the typical features of biological organisation as exhibited by more complex organisms. Yet, while being a necessary condition for biological organization, organisational closure underdetermines, as such, the whole set of requirements that a system has to satisfy in order to be taken as a paradigmatic example of organism. As we suggest, additional properties, as modular templates and control mechanisms via dynamical decoupling between constraints, are required to get the complexity typical of full-fledged biological organisms.

KEYWORDS –

Introduction

In the contemporary debate in philosophy of biology and theoretical biology, a classical problem concerns the definition of what is a “biological individual” (Wilson 1999; Sober 2000; Gould 2002). At present, the mainstream trend favours evolutionary individuation, claiming that any entity on which natural selection acts is a biological individual (Hull 1992). In this view, organisms are simply one instance of the whole range of biological individuals as defined by the theory. Still, scientific studies in theoretical biology see increasingly to agree on the idea that organisms constitute a specific kind of biological individual that, beyond being the result of natural selection, express a specific form of organisational cohesion and that this organisation is characterised by a *distinctive* regime of causation, which make them irreducible to other physical and chemical natural systems. In particular, despite the variety and complexity of their

manifestations, all organisms would realize *self-maintenance* (Bickhard 2000; Barandiaran & Moreno 2008).

Self-maintenance refers to a causal regime, in which a system is able to exert a causal influence on (at least some of) the boundary conditions enabling its own existence and persistence. Taken in this general sense, self-maintenance is a widespread phenomenon in nature, not limited to biology, exhibiting different degrees of complexity. In all natural cases, it is realized by systems existing in far from equilibrium (FFE) conditions, which means that they maintain themselves by ensuring constant flow of energy and matter through them.

To the extent that biological organisms fit this general characterisation, they can be conceptualized as self-maintaining systems. However, whereas all organisms are a kind of FFE self-maintaining systems, not all FFE self-maintaining systems are organisms. The philosophical problem that we address in this paper concerns the conceptual *transition* from merely physical to properly biological self-maintenance.

Our central objective consists in arguing that organisms realize a particularly complex kind of self-maintenance, involving what we will call “organisational closure.” In section 2, we will first offer a characterisation of self-maintenance according to which it should be understood as a *distinct level of causation*, operating in addition to physicochemical laws, generated by the action of material structures acting as local constraints. In section 3, we will contrast self-maintenance realized through organisational closure (what we will call “organisational self-maintenance”), with the simpler kind of self-maintenance realized in the physical domain, and we will suggest that this distinction seems to adequately capture the distinction between biological and physicochemical systems.

Section 4 analyzes organisational closure in more detail, in order further to clarify its constitutive role in biological organisation. By focusing on the significant degree of complexity that is required for its actual realization we discuss two implications. On the one hand, we argue that organisational closure represents a crucial step towards biological organisation since, as recent scientific studies suggest, even its minimal instances are likely to possess at least some of the typical features of biological organisation, as exhibited by more complex organisms. On the other hand, organisational closure consists in a network of causal relations that, in adequate conditions, can undertake the increase of complexity leading to full-fledged organisms.

In the conclusion, we will argue that whereas organisational closure constitutes a pivotal concept to understand the specificity of biological organisation, it should not be taken as a definition of biological organisation and organisms. If our arguments are correct, then organisational

closure is likely to be a necessary condition for the transition from the physicochemical to the biological domain. Indeed, whatever system realizing organisational self-maintenance would possess at least some relevant biological features and, at the same time, would be able to undergo the evolution towards genuine biological systems. Still, organisational closure underdetermines, in itself, the whole set of requirements that a system has to satisfy in order to be taken as a paradigmatic example of organism.

Additional properties that we will mention include modular templates, required for reliable reproduction, and control mechanisms via dynamical decoupling between constraints, which enable the organism to react *adequately* and *adaptively* to external perturbation and changes. In a word, the gap between basic and full-fledged instances of organisational self-maintenance corresponds to the gap between mere organisational closure and biological autonomy.

Self-maintenance

The idea of self-maintenance refers to a distinctive regime of causation, which is seen as being emergent on the fundamental laws of physics and chemistry. In particular, *self-maintenance results from the action of local constraints*.

In a general sense, constraints are additional boundary conditions that, by reducing the degrees of freedom of the relevant system (i.e., an inclined plane which reduces to two spatial dimensions the motion of a ball on it), simplify its description and contribute to provide an adequate explanation of its behaviour, which would otherwise remain underdetermined. The characteristic feature of constraints is that they are causal effects produced by specific material configurations (such as surfaces, solid bodies, molecules, and membranes) that cannot be adequately described in terms of the dynamics of their surroundings and require an alternative and *irreducible* description (Pattee 1972; 1973). As a consequence, constraints are local and contingent causes, since their existence depends on the existence of the relevant material configuration. At the same time, because of the irreducibility of the configurations, they may be seen as a *distinct level of causation* that operates on top of physicochemical laws (Juarrero 1998; Moreno & Umerez 2000).

In describing physical systems, the material configurations, which generate the constraints, are most of the time introduced as external boundary conditions, whose existence is a prerequisite in the description of the behaviour of the system. In those cases, constraints are asym-

metrical causal relations. The constraint contributes to determine specific dynamics, while those dynamics play no role with regards to the material configuration that generates the constraint.¹ For instance, the inclined plane constrains the dynamics of the ball, but the constrained dynamics do not have any causal effect on the existence or maintenance of the plane.

Yet the constraint is not always asymmetrical. Indeed, there are cases in which a constraint by acting on some surrounding dynamics, contributes to determine its own boundary conditions. To introduce some labels, we could say that there are cases in which a constraint *C* constrains some surrounding dynamics *D* such that the constrained *D* (*D*_{*C*}) are the boundary conditions required for *C* to exist. Material configurations able to maintain their boundary conditions by exerting a constraining action on their surroundings can be described, we argue, as self-maintaining systems. As *C* itself would not (or it would cease to) exist if it did not act on *D*, *C* contributes to maintain some of the conditions required for its own existence. At first sight, however, the concept of self-maintenance seems problematic. Self-maintenance could be taken as an epistemic tool, useful only to make our explanations simpler, in which case it would be possible, at least in principle, to replace it by reductive accounts in terms of physical laws. Alternatively, self-maintenance could constitute a distinctive causal regime involving irreducible causal powers, in which case a naturalized account of its status is required.

A relevant contribution to naturalize the concept of constraint in relation to that of self-maintenance has been provided by theoretical biologist Stuart Kauffman, who has recently proposed the idea of the “Work-Constraint cycle” (Kauffman 2000; 2003). The Work-Constraint cycle is supposed to capture what Kauffman takes as a central feature of all biological organisms, namely the fact of acting “on their own behalf” (Kauffman 2003, 1089). Whereas this idea appears to be in accordance with common intuition, Kauffman’s scientific challenge consists in giving a naturalized and consistent account of it. The concept of Work-Constraint cycle plays precisely this role. The main idea is to link the idea of action to that of ‘work’, the latter being defined, following Atkins, as “constrained release of energy into relatively few degrees of freedom” (Kauffman 2003, 1094).

In this definition, the concepts of work and constraints are related: work is *constrained* release of energy. This connection gives a way to interpret the slogan acting “on their own behalf.” A system acts on its own

¹ In what follows, we will use the term constraint to refer to both the material configuration and its causal influence.

behalf if it is able to use its work to re-generate at least some of the constraints that make work possible. When this occurs, a Work-Constraint cycle is realized. In physical terms, it requires very specific conditions to occur. Actually, the cycle is inevitably a thermodynamic irreversible process, which dissipates energy and requires couplings between exergonic (spontaneous, which release energy) reactions and endergonic (non spontaneous, which require energy) ones, such that exergonic processes are constrained in a specific way to produce a work that may be used to generate endergonic processes, which in turn generate those constraints canalizing exergonic processes. In Kauffman's terms, "Work begets constraints beget work" (Kauffman 2000).

The Work-Constraint cycle describes in an elegant way how constraints can be realized in natural self-maintaining systems. As a matter of fact, self-maintenance is a common phenomenon in physical systems. The most classical example of self-maintaining physical systems is self-organizing dissipative structures (Glansdorff & Prigogine 1971; Nicolis & Prigogine 1977; Nicolis 1989). Dissipative structures are systems in which a huge number of microscopic elements spontaneously adopt a collective and macroscopic ordered pattern in the presence of a specific flow of energy and matter in far-from-thermodynamic equilibrium boundary conditions. In these systems, the macroscopic pattern exerts a constraining action on its boundary conditions that contributes to the maintenance of the FFE flow of energy and matter required to the persistence of the microscopic dynamics (Ruiz-Mirazo 2001, 59).

As a relatively simple example of a dissipative structure consider a flame. A flame is a (dynamic) configuration constituted by the coherent movement of billions of molecules and which possesses some emerging distinctive properties. Flames appear when, at given moment, some specific boundary conditions are realized (a specific temperature threshold). Once they have appeared, the maintenance of flames depends not only on a set of independent boundary conditions, but also on some constraining action exerted by the configuration itself on its surroundings.

The flame constrains its surroundings by turning them into appropriate boundary conditions through its energy flow which keeps temperature above combustion threshold, vaporizes wax, and induces convection (which pulls in oxygen and removes combustion by-products). It is through this action that flames contribute to maintain the FFE boundary conditions at which the flow of energy and matter traversing the system may continuously occur. Using our labels, the emerging configuration C (the flame) constrains the surroundings D (temperature, wax, oxygen), by turning them into appropriate boundary conditions D_c , required for its own maintenance. Given that they contribute to maintain some of

their boundary conditions by exerting a constraint that they contribute to regenerate, flames can be said to be a physical example of a self-maintaining system.

Elsewhere (Mossio et al. 2009), we have emphasized that self-maintenance provides a naturalized grounding for some of the properties usually considered as being proper to biological systems, namely their teleology and normativity. On the one side, since the constraining action of the structure maintains some of the boundary conditions required to their existence, self-maintenance allows explaining the existence of a system by appealing to the effects of its activity, in a scientifically acceptable way. To questions like, “why does this system exist?” it is legitimate to answer, “because it does X.” On the other side, self-maintenance naturalizes normativity. Since the existence of the system depends, at least in part, on the effects of its own activity, the system *must* act in a specific way; *otherwise* it would cease to exist. In this sense, the activity of the system becomes its own norm or, more precisely, the conditions of existence of its constitutive processes and organization are the norms of its own activity.

This means interpreting the *conditions of existence* of the system as the *norms* of its own activity: the system must behave in a specific way, *otherwise* it would cease to exist. In other words, the norms on the activity of the system are identified with its very conditions of existence (on which its activity has some causal influence). Hence, these norms are intrinsic, since not imposed by an external observer, according to some extrinsic criterion, and naturalized, since related to a factual feature of the system’s nature, and not deduced from some metaphysical or moral principle. In practice, however, we tend to use teleological terms only to characterize the role played by differentiated parts in a self-maintaining system (and not to the role played by the system as a totality). Now, since in physical or chemical self-maintaining systems one can hardly distinguish organizationally differentiated parts, the present claim is rather theoretical than operational.

Self-maintenance constitutes then a crucial step in the transition from the physicochemical domain to the biological one. Still, a wide range of physical systems, although self-maintaining, is certainly not biological. The main conclusion from this is that whereas all biological systems appear to be self-maintaining systems—and more precisely far-from-equilibrium self-maintaining systems, able to accomplish Work-Constraint cycles—not all self-maintaining systems are biological systems.

In the following section, we will argue that the kind of self-maintenance that is realized in biological systems requires a substantial increase of their internal complexity that dissipative structures do not possess.

Biological systems must realize self-maintenance through organisational closure.

Organisational Closure

In his *Critique of Judgment*, Immanuel Kant developed an account of biological organisms which is supposed to overcome the apparent conflict between the laws of nature, grounded in the synthetic a priori judgments produced by our understanding and the existence of *purposiveness*, which appears to go beyond natural causation. While putting forward a reductive account of teleology, according to which purposiveness and teleology are simply the language of reason in front of nature (regulative principles of reason), in the third *Critique* Kant gives a more ontological account of natural purposiveness, which is realized by organized entities, characterized as “natural purposes” (Kant 1987, §65).

In such a product of nature each part, at the same time as it exists throughout all the others, is thought as existing with respect to the other parts and the whole, namely as instrument (organ). That is nevertheless not enough (because it could be merely an instrument of art, and represented as possible only as a purpose in general); the part is thought of as an organ producing the other parts (and consequently each part as producing the others reciprocally). Namely, the part cannot be any instrument of art, but only an instrument of nature, which provides the matter to all instruments (and even to those of art). It is then – and for this sole reason – that such a product, as organized and organizing itself, can be called a natural purpose (Kant 1987, 253).

Kant grounds the idea of purposiveness and teleology in the idea of organization and, more precisely, in the fact that organisms are able to self-organize, so that the various parts do not and cannot exist by themselves, but only insofar as they contribute to constitute an organisation which, in turn, is a condition for their own existence and maintenance. Self-organization realizes then an “immanent purposiveness” (Huneman 2007), since the role and status of the parts can only be understood in relation to the idea of the whole that they constitute. In addition, Kant specifies that natural self-organization requires, in comparison to artefacts, the mutual dependence between parts, which would not exist separately from their relation with the other parts in the whole. Many examples show how in the cell the collective interaction among a rich variety of structures, including almost always enzymes, creates the loop between organization and function that Kant was looking for (Karsenti 2008). An example is the case of cytoskeletal molecules that self-organize into

patterns as a result of their collective behaviour. During mitosis, chromosomes induce the assembly of a spindle that acts on the chromosomes themselves. The chromosomes trigger the self-organization of a pattern (the spindle) that acquires the function of segregating them (Karsenti & Vernos 2001). In isolation, these patterns have no function because they have nothing on which to act. In the cell, however, this might be different.

The Kantian description of natural purposes lucidly points to the additional requirement that a self-maintaining system has to satisfy to become an organism--be organized. Whereas self-maintenance provides the grounding for the naturalization of some key biological properties even in the minimal form realized by dissipative structures, it constitutes only the first step of the transition from physics to biology. Indeed, dissipative structures realize a *minimal* form of self-maintenance, in the sense of depending on the work of a single constraint acting on its own boundary conditions (Mossio et al. 2009). As a consequence, minimal self-maintenance lacks a crucial property that is distinctive of the way in which biological systems maintain themselves; i.e., through a self-maintaining *organisation* of constraints.

What do we mean by an organisation of constraints? The main idea is that biological systems are able to maintain themselves by constituting a web of structures exerting mutual constraining actions on their boundary conditions, such that the whole web is *collectively* self-maintaining. The mutual dependence between a set of constraints is what we call an *organisational closure*. In biological systems, each constraint is not able per se to achieve self-maintenance, but it can exist insofar as it is subject to organisational closure; i.e., it contributes to the maintenance of a web of constraints which, in turn, maintains (at least some of) its boundary conditions. In particular, a set of structures subject to organisational closure is able to compensate their own decay, due to their far-from-equilibrium nature, by constraining their surroundings in such a way recursively to assure their own replacement. An example of a system subject to organisational closure is a reflexive autocatalytic system, namely, a system in which the construction of each constituent is catalyzed by another constituent in a global self-maintaining organization (Kauffman 2000).

The concept of organisational closure captures a distinctive property of the causal regime at work in biological systems, in which various different structures contribute by playing different mutually dependent causal roles to the global organisation, which *collectively* achieves self-maintenance. A crucial transition from the physicochemical to the biological domain is made by those systems in which various material struc-

tures are different and complex enough to exert reciprocal constraints that, collectively, realize organisational closure (Moreno 2004; Ruiz-Mirazo & Moreno 2004). The intimate association between complexity and integration accomplished by organizational closure is a mark, we argue, of biological self-maintenance.

Let us try a more formal definition. In section 2, we described a constraint C as the causal effect of an emerging structures on some surrounding dynamics D from which C is emergent. We claim that a system is *organisationally closed* if it constituted by a set of structures $C_1 \dots C_n$ acting as constraints such that, for each constraint C_i , (at least some of) the boundary conditions required for its maintenance are determined by the immediate action of another constraint C_j , whose maintenance depends in turn on C_i as an immediate constraint.

Three main features of this definition should be emphasized. First, organisational closure requires that at least *some*, but not all, the constraints under which the system can exist have a relation of mutual causal dependence. This can be expressed by saying that biological self-maintenance requires (at least) a *partial closure* between the whole set of constraints constituting it. Among other reasons, the condition of partial closure is at least the consequence of the fact that self-maintenance is a *context-dependent* determination. A system is self-maintaining only in a given context; i.e., only if a given set of independent boundary conditions is also fulfilled. As we mentioned in section 2, boundary conditions also are a kind of constraints exerted on the system. Hence, organisational closure cannot be but partial, involving only some of the constraints that generate the organisation.

Second, organisational closure must involve constraints and not only constrained processes. This second condition requires that each constraint C_i must act on the boundary conditions enabling the very existence of another constraint C_j and not simply exert a causal influence on the effects of C_j . Accordingly, a conceptual distinction between organisational closure and a causal cycle is to be drawn. A causal cycle consists in at least two processes that, given a set of constraints, have causal effects on each other in a circular way. In this case, one or more constraints harness the various processes in such a way that they enter in a cyclic trajectory, while—in contrast with the organisational closure—their existence does not depend on these processes. In the case of the causal cycle, the existence of the constraints is given and independent and only their causal effects are mutually influenced. An intuitive and simple example of a causal cycle is the motion of two balls on a billiard table. If a force is externally applied, a ball can start rolling and hit the other one. When this happens, the first ball may stop its motion and

transmit the force to the second ball, which may start rolling. Let us imagine that the table is configured in such a way that the second ball, after having hit all the table borders, comes back behind the first ball, hits it, and the transmission continues. This situation can be described as the mutual causal influence of two processes (the motions of the two balls) which, given a set of externally given constraints (the table, the borders, and the balls) and some initial conditions (the application of a force), generate – of course, in ideal frictionless conditions – what we call a causal cycle of constrained processes. The main point to note here is that, evidently, the processes involved in the cycle do not play any role in generating the various constraints, which contribute to determine the cycle. Or, which is the same, each constraint does not contribute to determine the boundary conditions at which other constraints exist, and vice versa. That is why the motion of the balls realizes a causal cycle, but not an organisational closure. In contrast, when organisational closure is realized, constraints – as in the case of enzymes in living cells – are generated and continuously re-generated *within* the system. For example, the chemical reactions of metabolism are organized into metabolic pathways, in which one chemical is transformed through a series of steps into another chemical, by a sequence of enzymes. Enzymes drive desirable reactions that require energy and will not occur by themselves, by coupling them to spontaneous reactions that release energy. But the production of enzymes, too, takes place within the metabolic organization of the cell. When enzymes are needed (because of their continuous decay) they are produced in metabolic pathways helped by other enzymes, which in turn are produced with the participation of other ones . . . in a recursive way. All of the enzymes have to come from somewhere, so there are enzymes that produce the cell's enzymes. In other words, cell metabolism is “enzymatically closed.”

Third, each structure subject to organisational closure must exert a *direct* constraint on the boundary conditions of other constraints, without the intervention of intermediate constraints. A constraining relation is indirect when a constraint C_1 acts on a pre-existing constraint C_2 and modifies its activity in such a way that C_2 contributes to the production of a third constraint C_3 . Imagine that C_3 , in turn, contributes to maintain the boundary conditions at which C_1 exists. In this case, C_1 and C_3 could be said to be “mutually dependent,” since the existence of the one depends on the activity of the other. Still, since C_1 acts on C_3 through the intermediate action of C_2 , whose existence is independent from C_1 , the causal regime realized here by C_1 , C_2 and C_3 cannot be taken as an example of organisational closure.

The characterisation of organisational closure above is to be taken as

a tentative one, and it is still quite general and abstract. More accurate definitions, able to capture additional properties of organisational closure as realized by biological systems, could certainly be formulated. In section 4, we will discuss this aspect in more details. Still, the “working definition” above can already be put to work in a useful way, since it allows ruling out most counterexamples.

Let us consider a couple of these counterexamples. Consider, first, the relation between a river and its bed. Apparently, their mutual relations seem to realize precisely a (minimal) organisational closure: the river generates the bed, and the bed, by canalizing water, generates the river. Yet, the example can be ruled out quite easily. Given an adequate initial input of water, a flow can be generated by a slope in the configuration of the ground. The flow, in turn, can progressively dig a bed which, once it is created, may further canalize the flow of water and accelerate its own digging. In this description, the only constraint at work is that exerted by the bed on the flow of water, whose subsequent behaviour (including the fact that they dig the bed) is perfectly determined by the causal effects of the constraint. Since there is no need to appeal to some emerging property of the river, beyond that generated by the constraint exerted by the bed, to explain its activity and its effects, there is no reason to claim that the river acts as a constraint on the bed. As a consequence, in the description of the causal relations between the river and the bed there is a single constraint and then, no organisational closure.

A second example, quite known by the philosophical literature, is that of the water cycle.² In the case of the water cycle, a set of structures (clouds, rain, spring, river, sea, clouds) seems to have mutual causal relations that fit the idea of organisational closure. For instance, the clouds generate the rain, which (contribute to) generates a spring, which generates a river, which (contribute to) generates a lake, which generates clouds, and so on. Again, after detailed scrutiny, the situation reveals to be very much the same than in the previous case. The causal effects produced by most of the structures involved in the cycle on the following structures are determined by the external constraints which act on the system (ground, sun...) and no distinctive causal effects are produced by some emergent properties of the water structures. We do not appeal to some distinctive (i.e. some configurational property of the river which would appear when the river is constituted) property of the river to explain its action on the lake and we do not need to appeal to some distinctive configurational property of the lake to explain why the clouds are produced. Since there is no reason for appealing to a distinctive con-

² See Ruse 2003, 263-264 for a discussion of this example in the debate about functional attributions.

straining action of the configuration, we do not interpret the whole cycle as an instance of organisational closure.

The characterisation of organisational closure given above is then able to discriminate between cases of mutually dependent constraining relations and most other physical loops and cycles. Still, the central issue is to understand what makes organisational closure a constitutive property of organisms. In the following section, we will discuss this issue in more details, by focusing on the requirements, in terms of internal complexity, that a system has to fulfil in order to realize organisational closure. Because of these requirements, organisationally closed systems, even in their minimal form, are likely to possess several properties typical of full-fledged biological systems.

4. Organisational Closure and Biological Complexity

The complexity of biological organisms, no matter how minimal they are, goes far beyond that of any physical self-maintaining system. Any characterization of biological organisms appealing to organisational closure should then show that this notion could be put to work to account for biological complexity and this at least in two ways. First, it should be clarified what is minimally required in terms of internal complexity for a physicochemical network to realize this form of closure and can consequently be taken as an (even minimal) relevant transition towards biological systems. Second, arguments should be provided to explain why systems subject to organisational closure possess the relevant properties to undertake the increase of complexity eventually leading to the emergence of “genuinely biological” complexity, as it is realized in organisms. In this section, we will discuss in some details both issues.

As in the case of dissipative structures, organisationally closed systems realize self-maintenance in far from equilibrium conditions, which means that the whole system exists only insofar as a continuous flow of energy is maintained. Organisationally closed self-maintaining systems are able to canalize this flow to produce work, which in turn maintains the flow. Accordingly, they act on their own behalf, to use again Kauffman's words. Yet, the distinctive character of organisationally closed systems is that its maintenance is the result of the collective activity of a set of constraints that, as we have argued, make specific contributions to the global self-maintenance of the system. Therefore, as we have explained in a previous work, they have *functions* (Mossio et al. 2009, Moreno & Ruiz Mirazo 2009). The conceptual relation between closure and functions suggests that organisational self-maintenance occurs only if various

localizable structures make a *specific* and *distinguishable* contribution to the maintenance of the whole organization. The complexity underlying biological organization requires the interplay between structures being themselves sufficiently complex and differentiated to generate effects to which different functions can be ascribed.

In this sense, the conditions that a set of material structures has to satisfy in order to realize organisational closure, even in a minimal form, suppose considerable internal complexity. Recent studies in the so-called “proto-cellular” systems (Szostak et al. 2001; Luisi et al. 2006; Solé et al. 2007; Rasmussen et al. 2008) show that catalysts, membranes, and templates are key elements in the evolution towards life (although the presence of all of them at the same time seems difficult). Accordingly, primitive systems realizing a minimal form of organizational closure could have been constituted by the integration of relatively simple constraints, but of different type: on the one hand, global constraints (like membranes) and on the other hand, specific constraints (like catalysts). As recently pointed out by E. Szathmary, the key idea is as follows:

We know that lipids (more generally, amphiphilic compounds with a hydrophobic tail and a hydrophilic head) tend to form supra-molecular structures, such as bilayers, micelles and vesicles. They can grow autocatalytically. Now imagine that we have a mixture of molecules in any one vesicle. Some of them may act as catalysts of certain reactions. It is theoretically possible that some will catalyze their own incorporation (direct autocatalysis), or there will be a gang of molecules each exerting some catalytic function; thus as a net result, the incorporation of all members of the gang is ensured by the gang (reflexive autocatalysis) (Szathmary 2006, 1764).

In this view, a minimal form of organizational closure and functional differentiation would emerge as the result of the integration of a set of structures of different nature that, by exerting constraining actions on each other in a sort of mutually reinforcing network, would give rise to collective self-maintaining dynamics (Moreno & Ruiz Mirazo 2009). In these systems the organizational closure involves on the one hand far from equilibrium self-organizing (spontaneous) processes and global dissipative patterns and, on the other hand, processes of self-assembly that produce molecular structures whose states are closer to equilibrium conditions (or at the edge between equilibrium and non-equilibrium conditions).

The crucial step at which the integration of these various structures and processes may be said actually to produce an organizational closure is that these diverse constraints have mutually to enable their continuous maintenance. By synthesizing its own constraints, the system becomes

capable to perform a diversified modulation of its own self-maintaining dynamics. On this property of functional differentiation of constraints relies, as we will discuss below, the possibility of increasing its own internal complexity.

A well-known example of this type of “proto-cellular” systems showing organizational closure is Tibor Ganti’s “chemoton” (Ganti 1975; 2003). The chemoton (which was introduced by Gánti as a model of a minimal living system) consists in three functionally dependent autocatalytic subsystems: the metabolic chemical network, the template polymerization, and the membrane subsystem enclosing them all. The correct functioning of the chemoton lies in the precise stoichiometric coupling of the three subunits. It ensures that both the surface and the inner components evolve into doubling their initial value, leading to the subsequent division into two identical chemotons. Although this is a holistic system in the sense that its parts (i.e., each of the three coupled autocatalytic cycles) cannot be changed without changing the whole system (Maynard Smith & Szathmary 1999), the parts make functionally specifiable contributions to the global self-maintenance. For example, the template cycle’s contribution is specific and not identical to, say, that of the membrane production cycle.

A more recent model of minimal organizational closure with functionally specifiable parts is the minimal lipid-peptide protocell system of Ruiz-Mirazo and Mavelli (2007; 2008). The model describes a self-reproducing vesicle whose membrane consists of both fatty acids and small peptides, taken as precursors of current biomembrane main components (phospholipids and protein channels).³ The aim of the study is to simulate realistically membrane processes coupled to chemical autocatalytic reactions. In the experiments performed *in silico* by these authors, the mechanical dynamics of the membrane is operationally coupled to the chemical dynamics of an autocatalytic network in such a way that when the osmotic pressure reaches a certain threshold, peptides in the membrane open channels. In fact, because of the elastic tension (a mechanical process), polypeptides inserted in the membrane adopt the suitable conformation to become waste-transport channels, making possible a faster release of the waste molecules and, thus, a decrease in osmotic pressure differences. The model describes a system realizing a minimal closure, in which the various structures have specifiable and

³Further work by these and other authors (Piedrafita et al. 2009) suggests that this type of systems had its origin in formerly independent systems (self-maintaining chemical networks, self-assembling vesicles), each with its own recognizable dynamics and requirements for stability; when they coupled together they were transformed, becoming strongly inter-dependent.

distinguishable functions. Peptides in the membrane have the function of keeping the amount of internal compounds below a certain threshold, so that the system avoids a possible osmotic burst. In turn, the autocatalytic network has the function of synthesizing fatty acids and aminoacids, so that the lipidic/hydrophobic boundary can be formed. Collectively, these structures constrain in different ways the flow of energy and matter so that the system can work, in turn, to maintain those very structures in far from equilibrium conditions.

While being very simple (and virtual), these models illustrate that a considerable complexity is required to realize even a minimal form of organizational self-maintenance. It is for this reason, we argue, that organizational closure is a crucial step in the transition from the physicochemical to the biological realm.⁴ In fact, a system actually subject to closure, even if very simple, is likely to possess some of relevant features and functions typical of the organization of organisms as, to take the example above, catalysis and compartmentalization through a membrane.

In addition to constituting a crucial step in the transition from the physicochemical to the biological domain, organizational closure plays a central role in making possible the evolution and increase of biological complexity. Let us discuss this second point in more detail. The central idea concerns the effects of variations on structures subject to organisational closure. Suppose that, in a system realizing organisational closure, a variation or a structural modification occurs in a given constraint, such that its causal effects are modified. Given the mutual dependence between the different constraints constituting the system, a variation of one constraint would likely affect other constraints, their properties, and their dynamics, which in turn could affect other constraints, and so on. When this happens, the variation is then *transmitted* across the various functional components and two outcomes are possible. Either the resulting modified organization cannot realize closure and self-maintenance anymore, in which case the system disintegrates. Or, the new organization is still able to self-maintain, in which case a new regime of self-maintenance can appear. The transmission of variation may in some circumstances make possible the synthesis of increasingly complex structures, which could in turn act as new constraints, generating more sophisticated and accurate functions, provided that the whole set of con-

⁴ As noted in the introduction, although we think that organizational closure makes the crucial transition between the physicochemical and the biological domain, and that all organisms are organizationally closed systems, we do not conclude that any organizationally closed system is a (full-fledged) organism. See the conclusion for additional comments on this point.

straints subject to closure guarantees the self-maintenance of the global system⁵.

To see why organizational closure is a crucial requirement for the increase of complexity through the transmission of variation, compare the case above with that of a minimal dissipative structure, such as the flame. In this case, a variation of some component (the various material structures involved in the flow) does not affect the behavior of the other, because it does not exert any specific causal contribution to the maintenance of the whole. Because of this, the flame will keep behaving in the same way in spite of various possible modifications of its components.

If the components of the self-maintaining structures are not complex enough to exert distinguishable functions and then realize functions, there seems to be no reason to suppose that variation could result in an increase of internal complexity. Only an organizational closure of chemical structures can, at least potentially, promote this type of cyclic, self-modifiable reactive systems (Kampis 1991), *potentially* able to evolve towards unlimited degrees of organizational complexity and versatility.

In principle, the synthesis of structural and organizational diversity can be unlimited. In this sense, the system can indefinitely explore what Kauffman (2000) calls “the adjacent possible” not only in the space of catalytic processes, but in a more general space of functional constraints.

Conclusions

The central claim of this paper is that organisational closure constitutes a fundamental property of the distinctive causal regime at work in biological organisms and a pivotal step in the transition from the physicochemical to the biological domain. Admittedly, the characterisation of organisational closure (and the regime of organisational self-maintenance that it generates) developed in the previous sections is not meant to provide a *definition* of biological organisation and organisms. Claude Bernard, in his *Leçons sur les phénomènes de la vie communs aux animaux et aux végétaux* (1885), explicitly advocates the view according to which the attempt to provide a definition of life would never be successful, because of the intrinsically a posteriori

⁵In this paper, we will not develop the issue concerning the relation between the “transmission of variation” in the organizational sense and in the sense of “inheritance”. Here we restrict our analysis to the organizational conditions for the increase of complexity of a system, which requires that random perturbations can affect in a viable way the global organization, and generate differentiable ways of organization. This seems to be a necessary condition for the inheritance of variations among individuals.

knowledge that we have of it. Instead, a better service to science, he claims, consists in characterising biological phenomena by contrasting their properties with those of non-living ones.

Yet, organisational closure provides the framework for – at least in principle – an open expansion of functional variety. In this sense, organisational closure would be able to support the evolution towards genuine biological systems by way of the increase of functional complexity. In this sense, organizational closure can be taken as an essential *mark* of living organisms.

Indeed, although in principle organizational closure may open the way to an indefinite increase of complexity and functional differentiation, organisational closure underdetermines the whole set of requirements that a system has to satisfy in order to be taken as a paradigmatic example of organism. For instance, in minimal prebiotic systems, which formally realized minimal organizational closure, the capacity to increase their complexity was severely limited, because of the limitations of their mechanisms for hereditary transmission. Such a bottleneck in the evolution of complexity, due to the holistic means of reproduction, could not be overcome until the appearance of modular templates (Maynard Smith & Szathmari 1999).

Another example is adaptive control. Any full-fledged organism possesses at least a minimal capacity to modulate (internally and interactively) the trajectories of the essential variables of its own constitutive organization, which in turn requires controlling the metabolic paths so as *appropriately* to compensate external perturbations before the system reaches critical situations. For example, bacteria are able to monitor and control their internal processes, to anticipate internal tendencies, to evaluate graded differences in the outcomes of otherwise equally viable states, and to produce the appropriated behavioral responses.

Again, adaptive control was presumably absent in early prebiotic organizationally closed self-maintaining systems, whose stability against perturbations in time would rather rely on internal redundancies and feedback loops. Yet, this kind of mechanism faced another strong bottleneck, since control relationships can be established only between modules whose characteristic time scales are sufficiently different, which means that some sort of *dynamic decoupling* have to exist between the controlled and controller subsystems.⁶ Overcoming the bottleneck re-

⁶ As Bechtel (2007) has pointed out, if control is to involve more than strict linkage between components, a property that varies independently of the basic operations is required. The manipulation of this property by one component can then be coordinated with a response to it by another component, so that one component can exert control over the operation of the other. Therefore, what is required for an effective control system is a property that is sufficiently independent of the processes of mate-

quires making a significant jump in the degree of complexity, by incorporating into proto-metabolic systems heritable modular components, which would be able to behave in a “stoichiometrically free” manner with respect to the basic constitutive organization of the system (Grieseimer & Szathmary 2008). As a consequence, these components can explore new dynamically decoupled chemical paths, and perform regulatory and control tasks.

Because of these bottlenecks, then, organisational closure and self-maintenance cannot be taken as definitions of living organisation of organisms. Nevertheless, the concept of organisational self-maintenance lies at the heart of a research program aimed at scientifically justifying the hypothesis according to which it constitutes the characteristic causal regime at work in biological organisms. Beyond the pioneering work of classical authors (Rosen 1991; Varela 1979; Pattee 1973), a number of conceptual, formal, and experimental models spelling out specific properties of biological systems, interpreted as organisationally closed self-maintaining systems, are currently being developed (Kauffman 2000; Luisi 2006; Olasagasti et al. 2007; Hofmeyr 2007).

One of the main challenges of this research program consists precisely in providing a comprehensive account of the mechanisms through which biological systems bridge the gap between simple organisational self-maintenance and full-fledged biological autonomy, endowed with the whole set properties constituting living organisms.

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References

- Barandiaran X., Moreno A., 2008, “Adaptivity: from Metabolism to Behavior”, *Adaptive Behavior*, 16(5): 325-344.
- Bernard C., 1885, *Leçons sur les phénomènes de la vie communs aux animaux et aux végétaux*, Paris: Librairie Baillière.
- Bechtel W., 2007, “Biological Mechanisms: Organized to Maintain Autonomy”. In: Boogerd F., Bruggeman F.J., Hofmeyr J.H.S., and Westerhoff H.S.V. (eds),

rial and energy flow that it can be varied without disrupting these basic processes, but still able to be linked to parts of the mechanism so as to be able to modulate their operations.

- Systems Biology: Philosophical Foundations*, Amsterdam: Elsevier, 269-302.
- Bickhard M., "Autonomy, Function, and Representation", *Communication and Cognition – Artificial Intelligence*, 17(3-4): 111-131.
- Gánti T., 1975, "Organisation of Chemical Reactions Into Dividing and Metabolizing Units: The Chemotons", *BioSystems*, 7: 15-21.
- Gánti, T., 2003, *The Principles of Life*. With a commentary by J. Griesemer and E. Szathmáry. Oxford: Oxford University Press.
- Glansdorff P., Prigogine I H., 2000., 1971, *Thermodynamics of Structure, Stability and Fluctuations*, London: Wiley.
- Gould, S.J., 2002, *The Structure of Evolutionary Theory*, Cambridge, Mass.: Harvard University Press.
- Griesemer J., Szathmáry E., 2008, "Gánti's Chemoton Model and Life Criteria". In: Rasmussen S., et al. (eds), *Protocells: Bridging Nonliving and Living Matter*, Cambridge, Mass.: MIT Press, 481-512.
- Hofmeyr H.J.S., 2007, "The Biochemical Factory That Autonomously Fabricates Itself: A Systems Biological View of the Living Cell". In: Boogerdt F., Bruggerman F.J., Hofmeyr J.H.S., and Westerhoff H.V. (eds), *Systems Biology: Philosophical Foundations*, Amsterdam: Elsevier, 217-42.
- Hull D., 1992, "Individual". In Keller E.F. and Lloyd E. (eds), *Keywords in Evolutionary Biology*, Cambridge, Mass.: Harvard University Press, 180-187.
- Huneman P. (ed.), 2007, *Understanding Purpose? Kant and the Philosophy of Biology*. Rochester, NY: University of Rochester Press.
- Juarrero A., 1998, "Causality As Constraint". In: Vijver G., Salthe S.N., Delpo M. (eds), *Evolutionary Systems: Biological and Epistemological Perspectives on Selection and Self-organization*, Dordrecht: Kluwer, 233-242.
- Kampis G., 1991, *Self-Modifying Systems in Biology and Cognitive Science*, Oxford, Pergamon Press.
- Kant I., 1987 (1790), *Critique of Judgment*, Indianapolis, Hackett Publishing.
- Karsenti E., Vernos I., 2001, "The Mitotic Spindle: A Self-made Machine", *Science*, 294: 543-547.
- Karsenti E., 2008, "Self-organization in Cell Biology: A Brief History", *Nature Reviews*, 9 March: 255-262.
- Kauffman S., 2000, *Investigations*, Oxford: Oxford University Press.
- Kauffman S., 2003, "Molecular Autonomous Agents", *Philosophical Transactions of the Royal Society A*, 361: 1089-1099.
- Luisi P.L., 2006, *The Emergence of Life: From Chemical Origins to Synthetic Biology*, Cambridge: Cambridge University Press.
- Luisi P.L., Ferri, F., Stano, P., 2006, "Approaches To Semi-synthetic Minimal Cells: a Review", *Naturwissenschaften*, 93(1): 1-13.
- Maynard Smith J., Szathmáry E., 1999, *The Origins of Life: From the Birth of Life to the Origin of Language*, Oxford: Oxford University Press.
- Moreno A., 2004, "Auto-organisation, autonomie et identité", *Revue Internationale de Philosophie*, 2(59): 135-150.
- Moreno A., Umerez J., 2000, "Downward Causation at the Core of Living Organization". In: Bogh Anderson P. et al. (eds), *Downward Causation*, Oakville, CT: Aarhus University Press, 99-117.

- Moreno A., Ruiz-Mirazo K., 2009, "The Problem of the Emergence of Functional Diversity in Prebiotic Evolution". *Biology & Philosophy*, 24(5): 585-605.
- Mossio M., Saborido C., Moreno A., 2009, "An Organizational Account of Biological Functions", *The British Journal for the Philosophy of Science*, 60(4): 813-841.
- Nicolis G., 1989, "Physics of Far-from-Equilibrium Systems and Self-organisation". In: Davies P. (ed.), *The New Physics*, Cambridge: Cambridge University Press, 316-347.
- Nicolis G., Prigogine I., 1977, *Self-organization in Nonequilibrium Systems: From Dissipative Structures to Order Through Fluctuations*, New York: Wiley & Sons.
- Olasagasti F., Moreno A., Pereto J., Moran F., 2007, "Energetically Plausible Model of a Self-maintaining Protocellular System", *Bulletin of Mathematical Biology*, 69 (4): 1423-1445.
- Pattee H.H., 1972, "Laws and Constraints, Symbols and Languages", In: Waddington C.H. (ed.), *Towards a Theoretical Biology 4, Essays*. Edinburgh: Edinburgh University Press, 248-258.
- Pattee H.H., 1973 (ed.), *Hierarchy Theory. The Challenge of Complex Systems*, New York: Georges Braziller.
- Piedrafitra G., Mavelli F., Morán F., Ruiz-Mirazo K., 2009, "On the Transition from Prebiotic To Proto-biological Membranes: from 'Self-assembly' To 'Self-production'", *Proceedings of ECAL'09*, Springer, LNCS Series.
- Rasmussen S. et al., 2008, *Protocells: Bridging Nonliving and Living Matter*, Cambridge: MIT Press.
- Rosen R., 1991, *Life Itself: A Comprehensive Inquiry Into the Nature, Origin, and Fabrication of Life*, New York: Columbia University Press.
- Ruiz-Mirazo K., 2001, *Physical Conditions for the Appearance of Autonomous Systems with Open-ended Evolutionary Capacities*, PhD dissertation, University of the Basque Country.
- Ruiz-Mirazo K., Moreno A., 2004, "Basic Autonomy As A Fundamental Step in the Synthesis of Life". *Artificial Life*, 10(3): 235-259.
- Ruiz-Mirazo K., Mavelli F., 2008, "On the Way Towards Basic Autonomous Agents: Stochastic Simulations of Lipid-peptide Cells". *Biosystems*, 91: 374-87.
- Ruiz Mirazo K., Mavelli F., 2007, "Simulation Model for Functionalized Vesicles: Lipid-Peptide Integration in Minimal Protocells". In: Almeida e Costa F., Rocha L.M., Harvey, I., Coutinho, A. (eds), *Proceedings of ECAL 2007. Lecture Notes in Computer Science*, 4648, Heidelberg: Springer, 32-41.
- Ruse M., 2003, *Darwin and Design: Does Evolution Have A Purpose?* Cambridge, Mass.: Harvard University Press.
- Sober E., 2000, *Philosophy of Biology*, 2nd ed. Boulder: Westview Press.
- Solé R.V., Munteanu A., Rodriguez-Caso C., Macía J., 2007, "Synthetic Protocell Biology: from Reproduction To Computation", *Philosophical Transactions of the Royal Society B*, 362: 1727-1739.
- Szathmary E., 2006, "The Origin of Replicators and Reproducers", *Philosophical Transactions of the Royal Society B*, 361: 1761-1776.
- Szostak J.W., Bartel D.P., Luisi P.L., 2001, "Synthesizing Life", *Nature*, 409: 387-390.
- Varela F.J., 1979, *Principles of Biological Autonomy*, New York: North Holland.
- Wilson J., 1999, *Biological Individuality. The Identity and Persistence of Living Entities*, Cambridge: Cambridge University Press.