Chapter 21

Systems and Organizations: Theoretical Tools, Conceptual Distinctions and Epistemological Implications

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1 Introduction

What is a system, and how can we characterize and identify it with respect to its background? Which are the relations and components that are crucial for its description? Every domain of investigation makes different distinctions when identifying a system, and it is not just a question of scale: different kinds of relations are considered as pertinent in order to describe the phenomena or object of study, and different operations of partition are performed in order to extract the relevant components. Let us think for example of how many system domains can be found in a human body: from molecular and cellular ones, to systems including complexes of organs up to ecosystems populated by our bacterial symbionts. As a consequence, the same material entity can in principle be described in terms of different kinds of systems, each with specific components and organization.

Indeed, the word "system" is almost never used alone, but it is usually paired with an adjective that specifies its domain of application: physical, chemical, biological and so on. One of the challenges is to develop as much as possible the understanding of the relational dimension that characterizes "systemhood" independently of realizations in specific domains [20, 241].

In this respect, of course, the main focus is on the notion of organization. Defined generally as the topology of relations that characterizes a certain system, it can mean very different things, and its specification could be somehow arbitrary or, however, extrinsic to the system, to the extent that it would depend on the purposes of an external observer or designer. Although such specification might be useful in the

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domain of artifacts, it might be of little help in the case of natural and human systems. What I suggest is to find ways to characterize organization endogenously, in terms of the degree of functional integration[1] achieved by a system, that is in terms of an effective role played by a specific topology of relations in specifying the internal and external dynamics of the system. This can allow us to identify a system according to what is relevant to its own dynamics, and not just as the result of an arbitrary, or theoretically weak partition of a certain *medium*.

One way of doing this is to focus on those systems—such as living ones, but not only them, let us think also of ecological and social ones—that are capable of forms of self-maintenance, that is, of specifying to a certain degree their own dynamics and maintain themselves with respect to their environments. In this context a thriving work has been recently done based on the concept of constraint, which implications I will present and analyze in the following sections.

2 The Notion of Constraint and Its Organizational Implications

A crucial role in characterizing natural systems, especially self-maintaining ones, was ascribed to constraints by pioneering researchers in System Theory, such as Howard Pattee [17]. Yet, it is especially in the last two decades that this notion has raised a renovated interest and has undergone a profound development [8, 9, 13].[2]

Usually the term constraint stands for an asymmetrical relationship such as that holding between boundary conditions and dynamics. When the behavior of the system is underspecified, constraints constitute an alternative description which provides the missing specifications (normally by decreasing degrees of freedom). The pivotal role played by this notion in Systems Theory depends on the fact that it allows us to focus not only on the internal dynamics of a system, but also to take into consideration the conditions of existence of these dynamics, and how in some cases they can be affected by the activity of the system itself: general examples are the river modifying its bed, or a living system modifying the boundaries conditions of its internal environment (Ph, osmotic pressure, concentrations of enzymes, etc.).

Speaking of properties of the internal environment, a foundational role in this tradition had been played by Claude Bernard's pioneering work already in the middle of the nineteenth century. He distinguished between natural laws, common to all phenomena, and *mileux*, those boundary conditions that specify the specific properties of distinct phenomena [1]: different *mileux* realize distinct phenomena, not because they follow different natural laws, but because they are characterized by different sets of constraints acting in addition to laws.

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[1] By functional integration I mean here the degree of mutual dependence between those subsystems and processes—what I would call functional as opposed to structural components [2]—that are necessary for the functioning of a system and are identified and characterized in terms of such contribution.

[2] See Umerez and Mossio [22] for a brief but detailed review on the notion of constraint.

Bernard applied this very powerful tool to the case of organisms. Living processes exhibit distinctive properties with respect to other natural systems due to the specificity of their internal *milieu*. Their internal *milieu*, in fact, is self-produced, self-specified, and self-maintained, since all components contribute to the realization of the conditions in which all other components are immersed.

The underlying idea is that in some way living systems are capable of generating as well as maintaining some of their distinctive constraints. And this idea is at the basis of a notion of organisms as full-fledged systems: unities distinguishable from their environment in terms of their own activity, and whose organization plays an effective role in specifying their underlying dynamics.

Yet, the notion of constraints has always escaped precise definition, besides the general acknowledgement of its role in providing additional specifications to dynamics that otherwise would be insufficiently (or incorrectly) described. With the goal of providing a naturalized notion of constraint capable of expressing operationally its role within a system—not only as an independent external condition—a definition has been recently proposed:
Given a particular process *P*, a configuration *C* acts as a constraint if

1. at a time scale characteristic of *P*, *C* is locally unaffected by *P*;
2. at this time scale *C* exerts a causal role on *P*, i.e. there is some observable difference between free *P*, and *P* under the influence of *C* [14, 164].[3]

Typical examples are the activity of an enzyme, which catalyses a reaction without being directly affected by it; a pipe harnessing a flux of water, etc.

The relevance of this definition lies in the fact that (1) it specifies and allows us to describe two orders of “causes” in natural systems: processes and constraints; (2) it entails a notion of organization that is more complex than a flat network of relations, by introducing a basic functional hierarchy; and (3) it allows us to characterize constraints both in terms of their composition and realization (as material structures), and in terms of their action upon lower level material processes (as functional components of a system). In the following two sections I will present some implications of this idea, and I will propose some conceptual distinctions based on it.

3 Two Kinds of Organizational Closure

The notion of constraint has been recently used to describe a fundamental feature of (biological) self-maintaining systems, that is, their circular organization through which the activity and existence of the system come to coincide.[4] This idea has been

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[3] A more detailed analysis can be found in [12].

[4] The idea that in those far from equilibrium systems which are capable of self-maintenance and self-production, the very existence and activity of their constituents depend on the network of processes of transformation that they realize, and they collectively promote the conditions of their own existence through their interaction with the environment.

expressed in the literature through the notion of (organizational) *closure* (by Piaget [18], Rosen [19, 21], Maturana and Varela [10]). Yet, by means of the concept of constraint closure can be expressed more rigorously in such a way as to embrace not only self-production and self-maintenance, but also the contribution of the system to its own conditions of existence. The basis of this reformulation of closure derives from Bernard's notion of internal milieu, and it is implicitly alluded in the autopoietic theory when it emphasizes the role of the membrane of a living cell in contributing to the specification of its self-determined internal phase space. The idea consists in taking specifically into account the capability of the organization of a system subject to closure to specify part of the internal and external boundary conditions that enable and control its dynamics. The result is the possibiity to characterize system that is capable of a minimal form of self-determination, rather than being driven by external conditions.

Starting from a conceptual reformulation of Kauffman's [9] idea of work-constraint cycles and Rosen's [21] model of closure to efficient causation, it is possible to characterize organizational closure along this line as a closure of constraints [15]. In this view a system realizing closure is capable of generating some of the constraints that control and enable its dynamics, in such a way that the existence and activity of each of these constraints in turn depends on the action of other constraints in the system. Therefore closure consists in a mutual (generative) dependence between self-produced constraints acting on basic processes.[5] An example is represented by Kauffman's abstract auto-catalytic sets, where all the catalysts (i.e. constraints) are produced within the system through the contribution of other catalysts in the system, acting as constraints on the underlying biochemical processes. By expressing closure in terms of constraints, this approach is able to provide a precise characterization of what is considered as functional closure (at the level of constraints) as opposed to physical closedness (e.g. the consequence of a boundary), or to structural openness (at the level of processes, the flux of environmental matter and energy on which the system acts to maintain itself).

This idea is also very useful in order to distinguish between two different uses of the word closure, *operational* and *organizational*, often confused with each other. As stated in [4], a fundamental difference between them lies in the fact that the former implies a form of recursivity of operations, while the latter has a deeper self-referential character (which can be expressed globally by a self-referential function $f(f) = f$ rather than a recursive one). Organizational closure, unlike operational one, involves not just a circular recursion or a closed network of operations, but rather a mutual generative dependence between components realized through a closed topology of transformation processes.

What is crucial besides the activity of the components is the status of their conditions of existence. This distinctive feature of organizational closure becomes clearer, and distinctions can be made more precisely, if we express it in terms of constraints:

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[5] 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 depend in turn on C_i as an immediate constraint. The system is self-maintaining because its constraints, through closure, are able to act on some dynamics in such a way that, in turn, the same dynamics contribute to maintain some of the boundary conditions that allow their existence [12, 14, 15].

we have operational closure when there is a circularity of processes (e.g. exchanges of signals in a network of computers), but all the constraints that enable it are independent from it and externally specified. There is organizational closure, on the other hand, when some of the constraints are produced from within, i.e. when at least part of the conditions of existence of the organization are specified by the very dynamics of the systems (through mutually dependent functional components acting as constraints).

Therefore, introducing the notion of constraint in the characterization of systems provides a powerful theoretical tool, which makes it possible to make distinctions between hetero-specified and self-specified organizations.

4 Levels of Integration

How can distinct constraints be integrated in a system organization? And in what sense and to which degree can we say that they are mutually dependent? Let us consider here two simple cases of model systems that achieve self-maintenance by realizing closure: the Chemoton [7], and M/R-systems or auto-catalytic sets [9, 19, 21]. Both are characterized by hierarchical networks involving two orders of causes (processes and constraints), but they realize two different forms of systemic integration, that we can define respectively “confederative” and “unitary” [2].

Let us think first of Ganti’s Chemoton, a model of pre-biotic system organized as a biochemical clockwork, in which three autocatalytic subsystems—respectively a metabolic cycle, a template subsystem and a compartment—are directly coupled like chemical cogwheels. The autocatalytic subsystems act as constraints on the underlying biochemical fluxes, and interact with each other in terms of supply and demand of metabolic substrates.

These subsystems are mutually dependent—and therefore realize closure—only in a very simple form, to the extent that they provide one another the material substrates necessary for their own maintenance. But in principle they could exist in isolation, provided the environment contains the appropriate nutrients in the right amount.

Let us consider, in comparison, Rosen’s and Kauffman’s models. Both are metabolic networks characterized by organizational closure in presence of cross-catalysis: that is, each catalyst is generated through the action of at least another catalyst, which constraints the process of production of the former, in such a way that they are collectively capable to realize self-production and self-maintenance. In this case different constraints are not just simply coupled through supply and demand of metabolites, but each depends on the direct action of another constraint for its production and maintenance.

By considering the relation between constraints, therefore, it is possible to identify different forms of functional integration even in very basic systems realizing organizational closure. The Chemoton represents the most basic degree of integration, that we can call integration of level 1, between coupled constraints; in the second case a generative dependence establishes a level of integration 2 between mutually enabling constraints.

A new degree of integration (of level 3), in turn, emerges in presence of mechanisms of coordination of basic functions (such as regulatory ones), that is, in presence of new orders of constraints that independently modulate the underlying ones, by selecting between different basic functional regimes available [5]. The hierarchy can grow further by adding new functional orders.

5 Epistemological Remarks: Constraints and Degrees of Logical Openness

An analysis in terms of constraints (and forms of self-constraint) conveys a strong notion of system, that is, a self-specifying unity with a highly integrated organization. A first epistemic implication of it concerns the status of components. The idea that they depend on the system for the specification of their behavior and, even more, that they also exist only as far as they are part of the organization, implies that they have to be identified (as constraints), with respect to the role they play in this very organization, that is: *top-down* as functional constraints, rather than bottom up on the basis of their material composition [3].

Another and more general implication is related to the fact that the constraints considered in the previous sections are *non-holonomic* [17], that is, they are themselves dynamical, time-dependent and therefore nonintegrable, and they realize a (indirect) loop with the dynamics they affect. On this basis I suggest that a correspondence can be established between orders of constraints and degrees of logical openness [11],[6] as each new order of constraints poses further limitations to the possibility of providing a dynamical description (see for example Hooker [8]).

Basic closure, i.e. one order of self-constraint, would exhibit a logical openness of degree 1, since there are already limitations to the possibility of its dynamical description, and alternative strategies of description are required. For example simulations [6], though providing only partial descriptions, are better suited for catching its distinctive features, and synthetic realizations would be even more informative.

Regulatory mechanisms, as higher-order constraints, add further degrees of logical openness (2 or more), and we know that natural complex systems, unlike basic simplified models such as those analyzed here, are characterized by many more interacting orders of constraints acting at different levels of organization. In such a scenario, each phenomenon would require different modeling strategies as well as specific criteria for selecting which are, functionally speaking, the most pertinent levels of organization involved and the relative constraints: describing ecosystems would imply considering, for example, the set of constraints directly involved in the relation between organisms and niches, rather than those at the level of the cells that compose these organisms [16]. Therefore when multiple orders of constraints are involved, the application of specific selective criteria and the combination of

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[6] The possibility or not to formulate models of the behavior of the system that converge to an optimal (or complete) description of it.

qualitatively different, though partial, models—chosen heuristically, according to the goals of the explanation—seems the most fruitful alternative strategy to that, impracticable, of building increasingly comprehensive dynamical models.

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