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What can synthetic biology offer to the study of cognition?

Recent advancements in synthetic biology methods, both in vivo and in vitro approaches, make it possible to design, construct and manipulate simple chemical and/or genetic/metabolic circuitry used by cells to sense the environment and react to it. On this basis, synthetic biology is starting to contribute to the exploration of cognition through the construction of artificial models of minimal cognitive systems.

When will a synthetic minimal organism become "intelligent" in terms of minimal cognitive properties?

What is an inevitable biological property for developing minimal perception and cognition? Could it be conceived as a kind of homeo-dynamics, characterized in terms of a self-regulation mechanism generated by chaotic dynamics (i.e., a sort of extended form of autopoiesis)?

What kind of empirical analysis of artificial systems can be implemented to test for cognitive processes? In particular, is it possible to devise a Turing-like test for minimal organisms built by synthetic biology?

Could it be valid for all artificial systems, that is, systems implemented in software, hardware and wetware?

What are the limits, the possibilities and the implications of this approach to the scientific exploration of cognition?

AUTOPOIESIS, METABOLISM, COGNITION

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[**Abstract]** In this presentation I will show how the theory of Autopoiesis and Cognition, as thought by Maturana and Varela, can be experimentally disarticulated in multiple layers. Autopoiesis and Cognition were considered at the very beginning as two faces of the same phenomena. Now, thanks to the creation of simple chemical autopoietic systems is possible to consider the cognitive process as a more complex activity than autopoiesis and therefore cognition is not mechanically linked to the last. I'll call trascendental elements these fundamental criteria of life, because they reveal to be *a priori* and universals for every living system.

To answer this question I will refer to the theory of cognition by Maturana and Varela, as well as the subsequent elaborations developed by Pier Luigi Luisi and Michel Bitbol.

The authors identified autopoiesis as the blue print of minimal life and they were convinced that this was a unique property of living beings and therefore defined it as the necessary and sufficient condition to the realization of life. What is considered autopoietic, is necessary alive. Pier Luigi Luisi (Luisi et al. 1996) and other authors in the field, (e.g., Sheets-Johnstone, 2000; Fleischaker, 1988; Collier, 2004, 2008; Ruiz-Mirazo, Peretó, & Moreno, 2004; Hoffmeyer, 1998; Ruiz-Mirazo & Moreno, 2004; Di Paolo, 2005; Barandiaran & Moreno, 2006; Bourgine & Stewart, 2004; Christensen & Hooker, 2000) showed in different ways the flaw of such absolute deduction. There are chemical systems (Luisi et al. 1996) characterized by autopoietic activity that cannot be considered living – vesicles of surfactant capable of regenerating their lipid boundary by means of autocatalytic hydrolysis. Therefore, autopoiesis is a necessary but not sufficient condition in order to attribute the status of living being to an organism. Autopoiesis is a phenomenon that unites the world of inert matter to that of life and therefore is an expression of a constraint that would make the transition from one to another contiguous. The evident ubiquity of autopoietic phenomenology is what prompted me to formulate a relationship with the Kantian transcendental topic, in light of the definition offered by Kant himself in his *Critique of Pure Reason*: transcendental are those elements of the architecture of knowledge that present themselves as *a priori* and universals; they are not related to the contingent contents of subjective experience but they formally structure the subjective experience in general. By replacing the epistemological frame with the biological one, it can be said that: transcendental are those elements of life that present themselves as *a priori* and universal and are not subject to the material contingent constitution of an organism (i.e. its physical individuality); however, they formally structure the organizational phenomenology of any organism. Autopoiesis is the transcendental element of the architecture of life that defines the internal organizational of the living, or, more precisely, the transcendental phenomenology that qualifies the process of self-regeneration.

Bitbol and Luisi (2004) argued that in order to move from an inert autopoietic

phenomenology to a living autopoiesis, it is necessary for a chemical autopoietic system to operate a minimum level of "discernment" with the environment: the two authors believe that *metabolism* allows this step, therefore reaching the minimum level of cognition. Cognition in fact, argue Maturana and Varela, is that ability that beyond all doubts distinguishes the act of life. Life is a process of cognition, and cognition is a process that is realized in any form of life. Cognition for Varela and Maturana means "the domain of all the interactions in which an autopoietic system can enter without loss of identity", in agreement with the opportunity to retrace cyclically the internal states generated by these interactions, so as to allow *inferential and predictive* ability. In the structural coupling between the cognitive system and its environment, the essential energy exchange required by the thermodynamics of organisms – necessary to survival – is stable. So is preserved the cognitive identity of the unit: this is immediate as it is the result of a systemic configuration of the living, in which the vital element comes from a topological organization of the organism that does not allow intermediate and hybrid situations. An organism is either alive or is not, and to be alive means to be immediately configured as a system. Consequently, cognition is *a priori* and universally a property of life because it expresses the possibility for life to be without any mediation: in the exact moment of its occurrence, the unit is already cognitive, directly connected to the world that originated it and that pressed on it. In this sense, cognition becomes the third transcendental element of the architecture of life, where the metabolism outlined by Luisi and Bitbol is the second transcendental element as the medium that unifies the autopoietic phenomenology to cognitive ability: on one hand, the metabolic network refers to the autopoietic ability to regenerate components of the cell body through sequences of processes that take place within the lipidic boundary; on the other hand, the possibility to assimilate nutrients from outside is inherent to the metabolic function in itself, and with it, it comes the ability to operate a minimum level of discernment, which is the necessary condition to the implementation of a basic cognitive interactions. Metabolism is the network of processes (at a high level of abstraction) that changes its configuration for each system but remains identical in the material contingency of its functions. Therefore, it pushes the organism trough the environment and it ensures the mutual transformation entailed by the action. It should be added that a prerequisite for obtaining a biological cognitive process is a membrane capable to work as a *sensorium* and to be semipermeable. The semipermeability implies the possibility to connect the internal

environment of the organism with the external environment of the space-time region in which it is located, without altering the peculiar organization of the living system. It contains, protects, and limits, but at the same time allows the system to be crossed by a continuous exchange of energy and matter, as well as to feel the external stimuli. A necessary condition to trigger the homeodynamic processes of self-renewal is to feel something outside. Those processes are dialectically defined precisely by the recognition of something as foreign to the organization of the system. The criteria for assessing the "intelligence" underlying these series of processes could be:

1) independent mobility of the system observable on a macroscopic scale: The movement must be understood in a very wide sense, precisely to overcome problems of inclusion of plants and fungi, which with rare exceptions, they do not exhibit motility. However, it is possible to consider "movement" all that concerns dynasties and tropisms, as well as the flagellar push of *Euglena viridis*, based on the ejection of water; or the motor skills of some zoospores of certain fungi. The fact that we associate the behavior to the movement as a logic equation, and even before, the movement to the visible displacement in space, prevents us from grasping the dynamics of slowness reserved to the plant world, in which the behavior is better described in terms of change of state. The "change of state" must be understood as the ability of a cell body to dynamically respond to a certain range of input, a process that also includes the morphological arrangement of the living system during its ontogenetic cycle (the shape that it will assume, its co-emergence with the environment from which it will be changed and which in turn will change). For example we might bring the behavior of a plant such as Sagittaria saggittifolia. It is able to modify its structural order in function of specific changes in the niche in which it interacts, which can be both aquatic and terrestrial. When the water level rises to submerge it, in a few days the arrowhead turns its structure and assumes the configuration for the aquatic setting. The adaptation is therefore a fully reversible cyclic. Maturana and Varela consider this example a typical case of cognitive behavior, since it shows structural changes in the body of the organism, due to a response to external perturbations, and that these changes are meant to express a functional compensation for the self-maintenance of the unit. Obviously it remains suspended the issue of measurement of such an organismic activity (assuming to be

able to create a completely new living entity, how it will behave in this respect? We'll be able to recognize it as a living by abstracting from its chemical and structural composition?) The biggest experimental problem is the dramatic absence of fossils of the first hypothetical protocell. So it becomes impossible to identify which behavioral logic has adopted our ancestral kin.

2) discernment of physical-chemical substances accepted by the organization of the system and the acquisition of new ones. A new external component inside the system could lead to a global reorganization of the system itself in order to accept it (Bitbol, Luisi, 2004). The word "discernment" has meaning only in the context of evolutionary adaptation. As long as a living system is not forced to interact with a new nutrient (for example) there will be no trace, in a experimentally observable sense, of the activity of discernment. In fact, the discernment becomes manifest as "cognitive activity" – so in a wide meaning "intelligent" – if the "familiar/normal" structural coupling with the environment is interrupted. Always keeping us on the plane of single-celled living systems, only when the chemical information of a nutrient not yet considered this (so we enter into the phenomenology of adaptation) comes into contact with the sensory system and triggers an adaptive response, then we have a "visible" operation of chemical discernment that goes beyond the simple acknowledgment by "genetic program" – a sort of pure mechanical process.

   An hypothetical “Turing like” test – of course we are talking about a test for wet systems unable to release a code of symbolic output – must be able to simulate also the error in front of the new. This perfectly produce the evolutionary contingency and its dead ends, which are part of the behavior of the living - the failure of an evolutionary path.

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