Towards Autopoietic SB-AI

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Abstract

This programmatic paper continues a series of works that we are dedicating to introduce a novel research program in AI, which we call Autopoietic SB-AI to indicate two basic elements of its procedural architecture. (1) The *first element* is the innovative *methodological option* of synthetically studying the cognitive domain based on the construction and experimental exploration of *wetware* –i.e., chemical – models of cognitive processes, using techniques defined in the field of Synthetic Biology (SB). (2) The *second element* is the *theoretical option* of developing SB models of cognitive processes based on the theory of autopoiesis. In our previous works we focused on the epistemological and theoretical groundings of Autopoietic SB-AI. In this contribution, after a general presentation of this research program, we introduce the SB technical framework that we are developing to orient Autopoietic SB-AI towards a twofold goal: building organizationally relevant wetware models of minimal biological-like systems (i.e., synthetic cells), and, on this basis, contributing to the scientific exploration of minimal cognition.

Towards SB-AI: the possibility of cross-fertilizing Synthetic Biology (SB) and Artificial Intelligence (AI)

The idea of applying biochemistry to the artificial modeling and recreation of natural intelligence – prefigured in the 1920 science-fiction masterpiece *R.U.R.* (Čapek, 2004 transl.), in which the term "robot" was originally introduced – is now becoming frontier scientific research (Damiano and Stano, 2018). At the basis of this advancement there are two main recent developments in contemporary science.

The first is the emergence, in the 1990s, of a *body-centered*, and biologically grounded, approach to AI, usually called Embodied AI (EAI). The proponents of this approach – pioneers such as Rodney Brooks, Rolf Pfeifer and Luc Steels – converged in the idea that, in order to successfully explore natural cognitive processes through the construction of artifacts, specialists in AI have to build and experimentally study the adaptive behaviors of "complete" or "embodied agents," that is, functioning interactive machines incorporating biologically informed theses on adaptation and cognition. In other words, not programs for computers, as in classical or computational AI, but biological-like robots: biologically inspired artificial systems endowed with bodies that dynamically embed them in environments (e.g., Pfeifer and Scheier, 1999). This development, as such, reoriented AI back towards its cybernetic origins and, more precisely, toward the original cybernetic project: structuring a unified study of biological systems and machines, and this way attempting to overcome the divide between the inorganic and the organic world (Damiano and Stano, 2018).

If until now EAI focused on the implementation of embodied agents as *hardware robots*, new possibilities have been recently prepared by the second of the scientific advancements we mentioned. This is the constitution, at the beginning of the 2000s, of SB, a sci-tech research domain, at the crossroad between biology and engineering, originally dedicated to design and build biological parts or systems not existing in nature, and to use them for practical purposes. Within SB this bioengineering vein has been newly combined with frontier experimental approaches oriented towards basic science – i.e., origins of life and theoretical biology. This explorative vein shares with AI the "understanding-by-building method" (Pfeifer and Scheier, 1999), through which it engages in the (bio)chemical fabrication of living-like systems of minimal complexity. Research in this area spans from generation and evolution of phenotypic diversity (Parrilla-Gutierrez *et al.*, 2017) to cell models, targeting not only on structural, but also organizational aspects of living systems (Luisi and Varela, 1989) through the "synthetic cells" (SCs) approach (Stano *et al*., 2011). This frontier approach, aiming at putting living systems together starting from biochemical molecules, is particularly relevant for the potential integration of SB and AI, since it provides methodological and experimental preconditions to their cross-fertilization.

Why SB-AI? The interest of a cross-fertilization between (Embodied)AI and SB

In the late 90s, while EAI was already producing effective adaptive robots, it became evident that its ambition – schematically: modeling in embodied agents the whole range of natural cognitive processes, humans' included – was out of reach. Pioneers such as Brooks announced that a "fundamental change" was needed, as EAI's robots lacked "some organizing principles of biological systems" and could not aspire to their cognitive performances (Brooks, 1997). Converging analyses accused EAI to concentrate on bodily superficial aspects, such as anatomical structures, and neglect the body's organization, i.e., the network of functional relations generating its most specific feature – metabolic self-production. According to this view, EAI produces merely imitative models of biological and cognitive processes, and cannot create robots with the performances of living systems. To overcome mere imitation, EAI needs to shift from "organismoid" to "organismal" robots: build artificial agents sharing not (only) superficial features of biological systems, but (also) their form of organization (Ziemke, 2003; Damiano and Stano, 2018).

The SB-AI cross-fertilization represents a fresh possibility of realizing this shift. In our view, the most interesting attempts of founding an organizational approach to EAI (e.g., Di Paolo, 2003; Froese and Ziemke, 2009) converge in a difficulty: recognizing the chemical nature of the biological body's organization, but focusing on hardware and software models to recreate it synthetically. What is missing in these attempts, and needed, is the introduction of *wetware* – i.e., chemical – models, particularly suitable for the artificial implementation of the biological organization. In this perspective, the main interest of a cross-fertilization SB-AI relies in the possibility of filling this gap.

The theoretical framework: towards an Autopoietic SB-AI

Drawing on these ideas, the research program we are introducing in this paper targets the development of an organizational EAI based on techniques developed by SB. From the theoretical point of view, our SB-AI project adopts the autopoietic cognitive biology (e.g., Maturana and Varela, 1980) as its main theoretical framework. As we explained in detail in (Damiano and Stano, 2018), this is due to three main reasons. (a) The theory of autopoiesis proposes a well-defined theoretical model of the biological organization. (b) This model concerns the basic living (i.e., cellular) organization, and, by characterizing this organization as a self-producing network of chemical processes, is susceptible of concrete implementations through SB (in particular, SCs) techniques (Luisi and Varela, 1989). (c) Within the autopoietic theory, the model of the basic living organization is associated to an embodied view of cognitive processes. More specifically: A radically embodied view, which identifies these processes as biological processes, and describes them in terms of dynamics of self-regulation through which living or autopoietic systems maintain their organization in structural coupling with their environment.

The main implication of this option is that it positions the synthetic study of embodied cognitive processes at its fundamental, but neglected, level of inquiry: the level of the emergence of (minimal) life, currently explored by SB.

The technical framework: towards a SB cybernetics of networks

Current advancements in SC technology are based on bottom-up approaches that promise a (partial and progressive) chemical modelling of cellular processes of self-regulation. Indeed, they allow the construction of cell-like systems of unprecedented complexity. For example, we have devised SCs capable of self-regulatory activities based on the expression of just six genes (Damiano and Stano, 2018). SCs are initially in a homeostatic state, in terms of balanced synthesis and degradation of their membrane lipids – recalling the very primitive system designed by (Zepik et al., 2001). The environment can perturb this state by presenting a chemical X that triggers the production of a self-inhibitory mechanism. The latter induces the homeostasis failure (in favor of SC growth), as well as the production of an otherwise absent receptor for a chemical Y. In a sense, this is an anticipatory mechanism. If the environment presents Y molecules, these will tune the intra-SC network by counteracting the action of X (i.e., degrading X) and so restoring the lipid homeostatic state. Accordingly, the whole system (SC plus environment) appears integrated/coupled, at least with respect to lipid homeostasis. For future efforts in the direction here described, it is necessary to frame SCs and chemical networks together, for example by means of macromolecular networks (signaling, phosphorylation, transcription factors; e.g., see Hellingwerf et al., 1995). The goal is achieving, in a somehow minimal form, artificial neural-like chemical networks that couple the environment fluctuations and the SC. In this manner our approach contributes to the development of a chemical AI rooted in the autopoietic theory (even if actual SCs are still far for being fully autopoietic). Moreover, the environment capacity to perturb the SC chemical network is "selective", in the double sense that (i) only some perturbations are 'perceived' by the system, (ii) given a perturbation, the system would respond by selecting one possible route among the whole set of possible responses. This approach would constitute an experimental case for the MacKay theory of semantic information (MacKay, 1969). In particular, it would allow us to identify the 'meaning' of a certain perturbation as the selective operation it applies to the network, evaluated by considering whether the triggered change is useful or not to the system's goal – which, in our context, corresponds to maintaining the system autopoiesis.

On these technical bases, the goals we consider achievable are three. (1) The construction of organizationally relevant autopoietic wetware models of minimal cells. (2) The experimental exploration of the (currently controversial) autopoietic "life=cognition" thesis (i.e., the synthetic exploration of the threshold of life, the threshold of cognition and their relations); (3) the study of the basic bio-chemical mechanisms of signaling and regulation (e.g., those involved in metabolism, immune responses, etc.) whose mutual influence with human high level cognitive performances (e.g., driving in conditions of stress) is currently at the attention of the embodied cognitive science.

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