Synthetic Biology and Artificial Intelligence: Toward Cross-Fertilization

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The workshop "What Can Synthetic Biology Offer to Artificial Intelligence?," hosted by the 14th European Conference on Artificial Life (Lyon, France, 4–8 September 2017), brought together specialists from different disciplines to discuss the possibility of generating synergies between synthetic biology (SB) and artificial intelligence (AI). The specific goal was the exploration of cognition through "understanding-by-building" strategies. The workshop participants were asked to define potentially effective roles that SB could play in the development of the "embodied approach" that characterizes contemporary cognitive science and AI, with a focus on frontier research on minimal artificial life and cognition.

Keywords: embodied AI; embodiment; minimal cognition; minimal life; synthetic biology; synthetic cells; synthetic method

The Fourth Edition of the SB-AI Workshop Series

In the early 1990s, embodied cognitive science (CS) emerged from the so-called "crisis" of classical, or computationalist, CS as the attempt to properly take into account the role(s) played by the biological body in cognitive processes. Since then, the progressive establishment of the new embodied approach has engaged contemporary CS in a multiple process of self-transformation, which has involved changes in its

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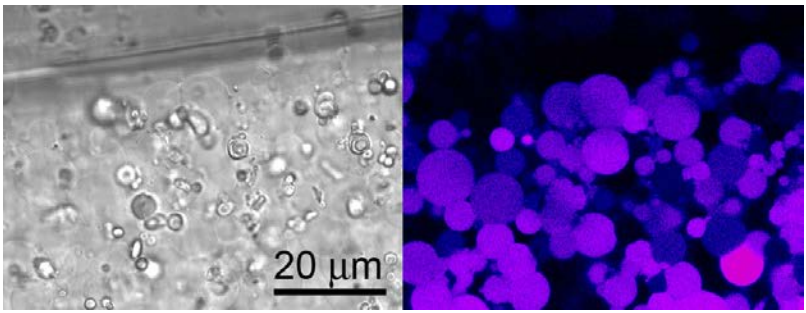
objects of investigation, leading questions and descriptive models, as well as research directions, approaches and methods. However, after almost three decades, specialists in CS and in the philosophy of science and of mind have started to seriously question the depth of this metamorphosis. In particular, they question the capability of embodied artificial intelligence (AI) to bring into its experimental scenarios artifacts that can be considered as actual models of the biological body (e.g., [1]).

The SB-AI workshop series was planned in 2012 to stimulate the involvement, in embodied AI research, of an emerging direction of inquiry called synthetic biology (SB). This is one of the avant-garde strands of contemporary biology. It is devoted to the chemical synthesis and assembly of biological parts, systems and/or processes to modify extant biological cells or, in the most ambitious cases, to the construction of synthetic cells (Figure 1) [2, 3].



(a) (b)

Figure 1. Bottom-up approaches to synthetic biology allow the construction of cell-like systems, based on the encapsulation of solutes inside liposomes [3]. In particular, these kinds of "synthetic cells" (to date, not alive) can perform a series of nontrivial biochemical operations such as protein synthesis, enzymatic catalysis, pore formation, generation of chemical energy upon irradiation, chemical communication with bacteria, DNA replication, and so on. (a) "Giant" liposomes in bright field; (b) the same sample imaged by fluorescence. The size bar measures 20 μm.

As we recognized in 2012 during a workshop on the "understanding by building" method [4], current SB theoretical and technical developments allow us to prospect its cross-fertilization with embodied AI (Table 1). In other words, the state of advancement of SB allows us to plan the assignment of a challenging but highly rewarding programmatic task: building chemical models of minimal living systems and experimentally exploring their minimal cognitive functions.

SB	AI	SB-AI
As engineering science		
Engineering biological functions	Engineering cognitive functions	Engineering cognitive functions through engineered biological functions and vice versa
As explorative science		
To synthetically explore *life* by constructing/studying scientifically informed artificial models of biological processes	To synthetically explore *cognition* by constructing/studying scientifically informed artificial models of cognitive processes	To synthetically explore *biological cognitive* functions, as *cognitive biological* functions, by constructing/studying scientifically informed artificial models of them

Table 1. From SB and AI to SB-AI.

Although this ambitious goal is certainly difficult to reach, the research path itself is worth of implementation, as it can elicit important theoretical and methodological insights and intriguing considerations, even at the initial or intermediate stages.

The workshop "What Can Synthetic Biology Offer to Artificial Intelligence?," hosted by the 14th European Conference on Artificial Life (Lyon, France, 4–8 September 2017), was the fourth edition of the SB-AI series. It was directed toward the creation of a highly interdisciplinary community able to critically discuss, fruitfully correlate and programmatically improve the emergent research programs involving cooperation between SB and AI in the exploration of cognitive processes.

The main idea was that of promoting the interaction between experimental research and theoretical and/or epistemological reflection, leading to the emergence of a strongly interdisciplinary front line in SB, AI, philosophy of science and related fields. We asked the participants to cooperatively tackle such issues as the following:

- Can SB constructively explore embodied cognition and intelligence through the construction of biological systems and phenomena? If yes, how? In which conditions and in what ways could this exploration positively contribute to AI research? That is: what can SB offer to AI?
- What are the groundings, the procedures, the expected results and the impacts of current research programs involving SB in AI research?
- Can SB support the structuring process of an effective embodied approach to the cognitive sciences and AI? Why and how?
- Can we at the present time plan concrete collaborations among computer science, robotics and SB in the scientific study of natural forms of intelligence? How?

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- Can SB contribute to the development of new forms of cognition alternative to the ones we know?

Organized with the financial help of the Earth-Life Science Institute of Tokyo, the workshop could count on the participation of a number of scholars with different backgrounds. The opening talk was from the organizers, who presented the main theme by critically surveying the evolution of embodied AI and discussing the roles that SB can play in addressing the challenges involved in the evolution of embodied CS and AI in novel directions. In his talk, Pier Luigi Luisi (University of Roma Tre and ETH Zürich) summarized the main results of the pioneer SB experimental approaches carried out by his group in the past 30 years (chemical autopoiesis [5]) and discussed the very notion of cognition. Darren Nesbeth (University College London) provided a technical introduction to current SB top-down approaches and artificial genetic networks. Leonardo Bich (University of Bordeaux) deepened the focus on SB experimental explorations of minimal cognition, developing an epistemological analysis of experiments involving interaction between minimal (artificial or artificial and natural) cognitive systems. The talk by Alvaro Moreno (University of the Basque Country) addressed a central issue in current CS—that is, agency. In particular, he focused on a description that is valid both for natural and synthetic systems displaying minimal living features. Francesco Bianchini (University of Bologna) discussed the problem of conciliating emergent properties and "predictions," especially in the unexplored field of construction of artificial systems, such those falling in the realm of SB. Finally, Andrea Roli (University of Bologna) presented an innovative proposal based on well-known genetic regulatory networks and applied it to bio-robotics, foreseeing an interesting blend among the dynamic network theory, attractors and autonomy. Prominent scientists in AI, like Takashi Ikegami (University of Tokyo), participated as discussants. A more detailed comment on the workshop can be found elsewhere [6].

Here, we present a collection of selected papers in which the workshop speakers have presented *in extenso* and re-elaborated the central ideas discussed during the meeting.

With this editorial project, we continue here the tradition of publishing SB-AI post-workshop papers, as we did with regard to the first and second edition of the SB-AI workshop series (ECAL 2013, Taormina, Italy; ALIFE 2014, New York, USA) [7].

This special issue, hosted by *Complex Systems*, continues our dissemination efforts, aiming at attracting the interest of more and more colleagues toward what we consider a necessary paradigm shift in embodied CS and AI.

As guest editors for this special issue, we include five papers. The authors of the papers in this volume engage in a number of overlapping issues concerning the SB-AI interface, including—from the technical side—the connection among genetic regulatory network and synthetic cells, attractors and autopoietic states, and so on, as well as—from the theoretical side—concepts like autonomy, agency, minimal cognition and emergent properties in design, prediction and synthetic modeling.

This volume starts with "Synthetic Biology and Artificial Intelligence: Grounding a Cross-Disciplinary Approach to the Synthetic Exploration of (Embodied) Cognition," in which we (Luisa Damiano and Pasquale Stano) discuss the central workshop theme in the context of contemporary CS, robotics, SB and AI. We draw on frontier developments in synthetic cells SB to introduce a pioneering research program in SB-AI that we define as *Chemical Autopoietic AI*. The promise of this approach is two-fold: (1) building organizationally relevant wetware models of minimal biological-like systems that contribute to the exploration of (embodied) cognition; and (2) supporting the full realization of the "embodiment turn" in contemporary AI.

Insights from the contemporary science of complexity are central also in Andrea Roli and Michele Braccini's paper "Attractor Landscape: A Bridge between Robotics and Synthetic Biology." The authors focus on genetic regulatory networks (GRNs), owing to their capability of producing complex behaviors, notwithstanding the compactness of their description. For example, cell differentiation can be modeled using GRNs and attractors. The innovative approach, according to the discussion by Roli and Braccini, consists of the design-specific cell dynamics that can match the attractor landscape required for attaining a target behavior in a (bio)robotic system.

Francesco Bianchini explores convergences between SB and AI in the contribution "The Problem of Prediction in AI and SB." He deals with this from the perspective of the philosophy of science of prediction. He focuses his philosophical exploration on synthetic modeling scenarios in which prediction concerns the behavior of artificial or biological systems, for example, when the production of an autonomous system is considered in an open-ended and uncertain context.

Minimal cognitive interactions are the focus of Leonardo Bich and Ramiro Frick's paper, "Synthetic Modeling of Biological Communication: A Theoretical and Operational Framework for the Investigation of Minimal Life and Cognition." Here the authors analyze conceptual and experimental work in SB related to different types of interactions considered as examples or models of communication. Then, they discuss and critically analyze their pertinence and relevance for the wider understanding of this biological phenomenon and its minimal instances.

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The concept of agency is at the center of Alvaro Moreno's paper, entitled "On Minimal Autonomous Agency: Natural and Artificial." Here the author presents research on the simplest material building blocks and their organization that, either naturally or artificially, could achieve the simplest form of organization necessary to display agency. Following Moreno's perspective, the study of how the biological domain has generated agents is ultimately necessary to understand paradoxical cases of minimal agents and, at the same time, to develop insights critical for their artificial fabrication.

Complex Systems has a long tradition of studies on systems displaying emerging properties. Taken together, the papers in this volume indicate some of the ways in which contemporary scientists and philosophers are forging new, multidisciplinary perspectives on the synthetic method in the exploration of cognition, via the contribution of SB to AI. We attempted to crystallize, in written form, the spirit and the discussions of the workshop, hoping that it can be of inspiration to colleagues, from prominent academics to young followers. We are indebted to Hector Zenil, managing editor of *Complex Systems*, for asking us to act as guest editors for this post-workshop collection (and especially for his friendly and productive collaboration). We thank also all colleagues who participated as speakers or as attendees at the workshop and contributed to its success.

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