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Artificial intelligence and synthetic biology: a tri-temporal contribution

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Abstract

Artificial intelligence can make numerous contributions to synthetic biology. I would like to suggest three that are related to the past, present and future of artificial intelligence. From the past, works in biology and artificial systems by Turing and von Neumann prove highly interesting to explore within the new framework of synthetic biology, especially with regard to the notions of self-modification and self-replication and their links to emergence and the bottom-up approach. The current epistemological inquiry into emergence and research on swarm intelligence, superorganisms and biologically inspired cognitive architecture may lead to new achievements on the possibilities of synthetic biology in explaining cognitive processes. Finally, the present-day discussion on the future of artificial intelligence and the rise of superintelligence may point to some research trends for the future of synthetic biology and help to better define the boundary of notions such as "life", "cognition", "artificial" and "natural", as well as their interconnections in theoretical synthetic biology.

Keywords: artificial intelligence; synthetic biology; cognitive systems; emergence; superorganism; superintelligence.

1. Introduction

I would like to suggest a triple contribution that Artificial Intelligence (AI) can make to Synthetic Biology (SB) within the framework of embodied cognition. This contribution is on three temporal dimensions: the past, present and future. My claims are: that AI can help SB through the study of some *past* issues that we can rethink in a present-day way, particularly issues that are related to the origins of AI; that AI can offer something to SB as regards some particular *current* research on complex adaptive systems and superorganisms, which involves an AI treatment of biological systems, and vice versa; that AI can provide some insight into SB through present-day theoretical and epistemological research on AI *future* development, especially that concerning the notions of general AI and superintelligence.

Contributions from these three specific segments of AI development can concur to create a general framework within which it is possible to steer the efforts of SB in the building of synthetic biological parts, cells or even more complex organisms, with the aim of exploring the basis of cognition and cognitive processes. This is in the spirit of the origins of AI because the initial impulse of AI has not disappeared today and it has been totally recovered following renewed interest in past elements that come together in the current embodied approach to cognition. In section 2, I outline what AI and SB are in general and what their aims are, trying to establish a common ground of interaction. In sections 3 and 4, I deal with issues of early AI that may prove useful to current SB. In sections 5 and 6, I address present issues of complex adaptive systems and biological systems that can help to create a fruitful interaction between AI and SB. In section 7, I raise some issues regarding the future of AI that may be relevant to discussions on future research

on SB. In section 8, I draw conclusions and point out that AI can, by contributing to SB, also can gain something from SB.

2. AI and SB: an overview

Since its origins, AI has been aimed at simulating any feature of intelligence by a machine (the starting conjecture of Dartmouth's proposal on AI in 1955). Two very different approaches have been used to achieve this aim: top-down, centralized, control-driven, logical-based systems that model one or several specific intelligent features or cognitive process; bottom-up strategies that involve systems, in which low level agents interact with each other, or micro-entities simulate the behavior of parallel processing, giving rise to emergent cognitive phenomena. While the former is the traditional approach, the latter is more typical in the new AI of recent decades, which is strictly connected to embodied and enactive cognition. While the former is considered to be too engineering-driven and oriented to explain (human-level) cognition, the latter appears to be more suited to explaining cognitive features of entities provided with a body and a brain, and acting in an environment.

Both approaches are still alive (Russell, Norwig, 2010), have a long history and have interacted with each other, leading among other things to the development of in-between positions and outcomes (hybrid models and systems), as well as specific and autonomous sub-fields of research. These include artificial life (A-Life), which is one of the most important because it is rooted in cybernetics, and deals with simulation and creation of artificial living entities. A-Life is also closely connected with new trends in AI, including complex adaptive systems. New AI, however, is a more general approach and is involved not only with life, but with cognition and cognitive processes. Most likely, AI is not a science, in the traditional meaning of the word, that is provided with a specific object, language and method (Matteuzzi, 2005). AI is a set of closely-related disciplines with different objects, languages and methods, but with a general aim and at least an abstract overall methodological feature: computational simulation and modeling. The history of its changes and trends is rich and justifies an attempt to find suggestions and ideas in AI that may enrich SB.

SB is somewhat different. Even if the idea and the expression are old[1], it is only with biological and genetic engineering and DNA sequencing – starting in the 1980s – that true synthetic biology has become possible. SB has two general main trends of research: i) designing and constructing new biological parts and systems; ii) re-designing natural and already existing biological systems, or parts of these systems, for useful purposes. Both trends involve biology but their targets are quite different and imply different methodologies. While the latter uses a top-down approach to build new biological systems by integrating biological parts into an existing system by exploiting mathematical models, the former makes use of a bottom-up approach to design and construct synthetic protocells starting from biochemical building blocks (Freemont, Kitney, 2012). In the last fifteen years the field of SB has split into specific subfields: bio-inspired and bio-mimetic SB; recombinant DNA applied to metabolic engineering; genome engineering; evolution; biological building using bio-bricks (Church, Regis, 2012).

Therefore, SB is a set of related disciplines – just as AI is – whose general aim is to obtain something living or that occurs substantially in living systems by manipulating biological matter. Both AI and SB exploit top-down and bottom-up approaches and both share a mathematical (SB) and/or logical (AI) conceptual framework and modeling in top-down approaches. Bottom-up approaches appear to be the common ground upon which AI and SB may influence each other. If SB wishes to deal with cognitive problems and develop proto-cognitive systems and systems with real cognitive processes, some AI bottom-up approaches, which I shall address in the next sections, are useful and fruitful. Bottom-up and bio-inspired AI approaches opened AI to the embodied and enactive approach. This is the new AI, which can influence SB approaches, insofar as its aims are

[1] The phrase has been used for the first time by Stépane Leduc in "La biologie synthétique, étude de biophysique", in 1912.

shared by and benefit from SB technologies, methods and conceptual framework, to refine its biological inspiration and commitment.

3. Biology and early AI

Interest in biology has been part of AI ever since this field of research originated, even before the birth of the label "Artificial Intelligence". Turing, one of the acknowledged fathers of AI, especially of the traditional, symbolical and logical AI, was interested in biological structure in the very years in which he dealt with the epistemological and philosophical problems of AI by addressing them starting from the question "can a machine think?" (Turing, 1948, 1950). In an article from 1952, Turing outlines a theory of morphogenesis based on chemical substances that "react together and diffuse through a tissue", producing a structure (Turing, 1952). The main idea of Turing's theory is that chemical reactions in an embryo generate spatial patterns or forms. He was interested in the abstract idealized chemical model underlying morphogenesis, which he called "reaction-diffusion" model. It is a mathematical model that, according to Turing, can be simulated, tested and improved by computer. Turing was far ahead of his time and unsurprisingly his work has been considered as a forerunner of A-Life[2].

A-Life is obviously not the same as SB. However, it is something that lies in the middle between AI and SB, because its methodology is strongly based on the synthesis of life-like behaviors and entities through computer and other artificial supports. Therefore, in some ways it is not just simulation: it is also realization of life (Langton, 1986). The question is quite simply whether life can be made artificially (Boden, 2006: 1322). But the general principle of extracting the logical form of living systems closely corresponds to Turing's ideas on morphogenesis and a mathematical theory of pattern formation from chemical abstract bases. According to Turing, pattern formation and differentiation are due to a breaking of symmetry[3] and uniformity that leads to new, different stable forms. Thus, providing a theory of morphogens and morphogenesis is basically providing a theory of what chemical reaction constraints, expressed with a non-linear differential equation, produce a new stable system.

The mathematical theory of embryology sketched by Turing is very interesting, especially in the light of his remarks on unorganized and self-organized machines of a work from 1948[4]. This paper introduces the idea of connectionism in a very similar way to the artificial neuron of McCulloch and Pitts (1943), and its main aim is to connect intelligence and learning. Turing speaks about models of artificial neural networks in terms of unorganized machines. These machines are formed by units (the abstract neurons) connected to each other and capable of having two definite states. The initial structure of neurons is random, which means the machine is unorganized, though the neurons can be trained through interference from outside. Two kinds of interference are possible: "there is the extreme form in which parts of the machine are removed and replaced by others. This may be described as 'screwdriver interference'. At the other end of the scale there is 'paper interference', consisting in the mere communication of information to the machine, which alters its behavior" (Turing, 1948: 419). The two kinds of interference can be seen as hardware replacement and software change, respectively. But this is too narrow a view. The two kinds of interference are not so different and the notion of interference closely overlaps, in present-day terms, the one of interaction (with an unspecified environment), though it may also result from a self-change process. Indeed, interference changes the machine. When interference is due to "internal operations of the

[2] On the birth of present-day A-Life see Langton (1986, 1989). On Turing and A-Life see Copeland (2004: 507-513) and Boden (2006: 1261-1267).

[3] Simmetry-breaking systems in the sense of Turing (1952) are studied in current research on multicellularity (Lu *et al.*, 2014).

[4] The two works (1948 and 1952) are different but connected, as Turing says in a letter to Young (8 February 1951); see Copeland (2004: 517).

machine" and affects the part of storage containing the instructions describing the machine itself, the machine is modifying itself.
Interference, in the sense of information communication and interaction, is a very interesting notion. It underlies the possibility to educate a machine, through interfering training. It is a very insightful and unprecedented anticipation by Turing of the idea of supervised training for improving the performance of a neural network, which is crucial for connectionism[5] and for machine learning and deep-structured learning, the present-day development of Turing's ideas on unorganized machines. The notion of educating a machine is fundamental, since it is equivalent to organizing an unorganized machine. The machine Turing is thinking of is the brain, in particular the brain of a newborn. So, interference and the possibility of self-modification are the crucial notions at the basis of self-organizing machines, from the point of view of biological systems. To Turing, interference by information communication is the most important of these notions because it is the origin of the self-modification capability. Thus, according to Turing, AI is the discipline that can help to create (virtual) machines capable of modifying themselves by exploiting the power of information self-communication, which is equivalent to the behavior of a machine that influences the machine itself.
These AI ideas are deeply rooted in biology and show how to connect biological inspiration to some biological fundamental features. The bottom-up approach to SB can make some progress by exploiting the link between self-modification and learning in the way Turing suggested, for example by trying to create collective systems of similar protocells that evolve into organized systems of specialized cells in response to external stimuli and environment.

4. From self-modifying to self-replicating machines

Von Neumann's approach to self-replicating systems is another theoretical contribution to our discussion. Von Neumann's interest in biology concerns replication, reproduction and evolution. In particular, his emphasis on connection between replication and reproduction is significant. On the one hand, reproduction is not merely replication. Biological organisms usually give rise to, or "produce", kittens. On the other hand, pure replication is not subject to evolution; for evolution to occur, we need 'errors' in the replication process. The aim of von Neumann was to define a theory of self-replication in general and to determine the conditions under which a replicator can be universal and reproduce any system, including itself. This kind of replicator is more a general than biological one, but it includes every sense in which replication and reproduction are part of the biological world. Moreover, von Neumann was interested in the logical, not physical, notion and explanation of replication. He was influenced by his mathematical and engineering attitude.
In the Hixon symposium of 1948, Von Neumann dealt with the problem of self-reproductive systems in general, and he addressed the problem of evolution through errors in reproduction (von Neumann, 1951). But in that talk he "described [just] an (imaginary) mechanical system capable of self-assembly from physical parts" (Boden, 2006: 1269). Although it was an interesting attempt, it was physical, not logical. In order to grasp the power of Turing Machines (Turing, 1936) and use it for biological purposes, and even for a general theory of self-replication, he needed a logical formulation of biological entities, which he found in cellular automata. A cellular automaton is a space in which cells change according to specific rules. Even though self-replication is not the only property of a cellular automaton (and not every cellular automaton can replicate itself), the logical simulation of self-replication both of single cells and of their "organic" clusters was von Neumann's first aim.
Cellular automata have been in practice, developed and realized by followers of von Neumann's work (he died in 1957). Many works by him were unpublished for several years and illustrate von Neumann's range of interests: cybernetics, symbolic emerging AI and simple computational models

[5] See Ruhmelhart, McClelland *et al.* (1986).

of the neuron[6]. A-Life is another outcome of his pioneering work, though it only started to be truly developed in the mid 1980s. Nevertheless, the contribution made by von Neumann cannot be limited to A-Life. By means of his theoretical computational systems (cellular automata), von Neumann encapsulated the two dimensions of self-replication: of a single entity, i.e. a cell, and of systems made by cells replicating themselves. The former is simple self-replication, the latter is replication and self-replication of complex systems, that reproduce themselves at some emergent level which is not necessarily the highest one. Self-replication and different grades of self-replication are made possible by the implementation of self-replication rules at a lower level. Therefore, even if it is in the form of mathematical and logical modeling, von Neumann provided a theoretical bridge between the collective behavior of micro-entities and emergence of phenomena in the realm of life, connecting AI with biology from a bottom-up point of view.

Traditional AI was not ready back in the 1950s for a general development of these ideas. A-Life reawakened interest in them because, even though mathematical modeling is crucial in von Neumann's view, it is closely aligned with biological evolution, which means he paved the way for collective evolutionary emergent phenomena in general. A-Life is the synthesis and simulation of living systems, but it is only partly interested in cognition and mind (Aguilar *et. al.*, 2014). Contributions from phenomenological views on cognition encourage the philosophy of A-Life to deal with the notion of emergence. In the same way, it can help to develop SB in the direction of a less logical and mathematical model. Enactive perspective claims that simulation is too poor to have cognitive systems and that we cannot avoid considering reality to achieve cognition. SB has an advantage over A-Life because most SB is on material things. SB can try to develop biological collective entities provided with proto-cognitive features by creating real cells that evolve into systems that behave collectively and are made up of specialized entities. Even in this case, the bottom-up approach, which is consistent with von Neumann's modeling, seems to be highly suited to producing emergent cognitive phenomena in synthesized biological entities, namely with a real body in a real (experimental) environment.

5. The present: emergence, superorganism and the foundations of cognition

How can current AI contribute to SB? My suggestion is that we can find the answer in studies on emergent biological phenomena, especially those on biologically inspired cognitive systems and complex adaptive systems. In particular, a good contribution can stem from swarm intelligence and its epistemological and theoretical grounding. An understanding of biological phenomena in terms of AI and computer science notions is equally important. The latter trend is the other side of the coin of the former.

In recent years, research on emergent phenomena and emergentism has become one of the most important topics in a range of fields (Bedau, Humphreys, 2008; Corradini, O'Connor, 2010). In cognitive science, emergence and emergentism have played an increasingly crucial role owing to the growing interconnection between cognition and biology, especially as regards two facts: i) cognitive phenomena have been progressively seen as part of biological ones; ii) cognitive modeling has developed far more deeply in the direction of embodied cognition and biologically inspired cognitive architectures. In order to support my suggestion and better understand emergent phenomena, I will discuss some aspects of *individuality* of entities involved in a specific kind of (complex) biological systems.

The shift in cognitive science research on such trends is not equivalent to an overall rejection of the standard, traditional problems and principles of AI and cognitive science, such as representationalism, functionalism and the identity of explanatory principles[7]. Cognitive models stemming from new trends in cognitive science have to deal with old problems and try to provide

[6] Von Neumann, as well as Turing, was interested in simulation of brain by means of the computer (von Neumann, 1958); see also Asaro (2011).

[7] See the five theses on the artificial in last chapter by Cordeschi (2002).

new solutions or solution methods. Moreover, the new trends in AI and cognitive science, especially the ones connected to biological heuristics, are deeply rooted in older traditions of research, such as cybernetics (Cordeschi, 2002) and complex adaptive systems, which have been studied and used in different fields since the 1970s (Holland, 1992). In particular, in recent decades a growing number of researchers have regarded such systems as the best way to solve computational problems of symbolic AI, to achieve new engineering feats, and to model cognitive phenomena in a bottom-up perspective that fills the gap between low-level and high-level cognitive capabilities – namely between learning, recognition, motion, etc., and abstract reasoning, planning, creativity, self-awareness, etc.

Swarm intelligence is one of the fields that has attracted a lot of attention over the last two decades. The swarm intelligence notion (Beni, 2007) is exploited in AI, especially on account of its connection with biological collective phenomena (the behavior of flocks, shoals and insect colonies) seen as a good inspiration for robotics and robot development (Bonabeu, Dorigo, Theraulaz, 1999), but also for multiagent-like software intelligent systems and for the study of cognitive features. Swarm intelligence is also connected with the notion of superorganism. Indeed, a superorganism, like an ant colony or a bacterial colony, is a form of swarm intelligence.

If we consider the most recent discoveries on superorganism behavior and structure, the case of insect colonies is particularly interesting for swarm (artificial) intelligence and for cognitive explanations and modeling. The notion of superorganism encompasses many different species: bacterial colonies such as Myxobacteria, Myxomycetes, colonial organisms such as Portuguese man o'war, bee colonies, termite colonies and ant colonies. Each of these shares the feature to be a group displaying more intelligent behavior than the behavior of each individual within the group. In the most evolved species of ants, group specialization has led to a high level of colony complexity, though this complexity does not correspond to a parallel complexification of the individuals that make up the colony.

The colony is a superorganism insofar as self-control, communication and adaptation to environment capabilities can be compared to those of an organism that shares the same complexity, such as some mammals or human beings. In the most recent approaches to cognition, especially the embodied approach, low-level and high-level cognitive capabilities are closely related to environment adaptation and interaction. Therefore, if we compare an organism and a superorganism, it is noteworthy that the latter seems to have a greater robustness and flexibility than the former thanks to the structure and the organization that serve different functions and purposes that we may refer to as cognitive (for example, communication and control, food research, defense from external threats). The organs and their functions in superorganisms are not compact entities like those in organisms, and the organ functions are processes that take place in a very distributed substrate, that can be replaced, to some extent and if required, more easily than in an organism. For example, in an ant colony, we have a nest in the place of a skeleton, stigmergy in the place of nervous systems, reproductive castes in the place of gonads, and so on. Thus, information and knowledge in superorganisms are distributed more widely than in organisms[8].

The comparison between complex organisms and superorganisms highlights the superiority, to some extent, of superorganisms, especially as regards flexibility and robustness of functions in their interaction with the environment. We may find a precedent of this comparison in the analogy between an ant colony and a brain within a framework of the philosophy of mind and AI (Hofstadter, 1979). It was used for several purposes: a) to define the relationship between reductionism and holism; b) to defend a multilevel perspective in mind/brain systems; c) to provide an explanation for mental phenomena from an epistemological standpoint; d) and to outline an explanation for emergent phenomena that preserves scientific plausibility and to explain downward causality. The aim of Hofstadter's analogy was thus to outline a new, dynamic and multi-level hierarchical way to consider the emergence of intelligence and mental phenomena in complex

[8] Consider, for instance, the case of bee colonies (Tautz, 2008).

systems. It is a view that combines both bottom-up and top-down aspects in the explanation of cognitive processes.
In keeping with this analogy, but from a reverse point of view, superorganisms have recently been described through a computer science terminology, a noteworthy inversion of traditional biological inspired computation methodology (Hölldobler, Wilson, 2009). In an ant colony, ants are agents that execute simple algorithms. They come to decision points where a change either in the *behavior* or in the *anatomy/physiology* of the ant can take place, depending on the group (caste) it belongs to. This is how higher processes or functions are transmitted to low levels. The resulting system is structured on different levels through which we have, on the one hand (the bottom-up "hand"), emergence, and on the other (the top-down "hand"), downward causality. It is only possible to speak of downward causality if we mean weak emergence, as weak emergence (Bedau, 1997) allows us to combine an autonomous explanation of the phenomenon with its causal dependence.
In the epistemological context of autonomy and dependence, we may see ants as *physical* and yet *functional* parts of the global systems, playing the role of linking different levels: the explanation of high levels is the outcome of complex interactions of micro-entities. If we consider an ant colony as being able to carry out cognitive tasks, in the same way as the ant-colony/brain analogy suggests, ants and the computational account of their functions within the global system can shed some light on cognitive aspects of similarly complex biological systems.
A superorganism as an organized level structure is an outcome of evolution. In particular, it is through multilevel selection that the complexity of the superorganism has increased, unlike the complexity of individuals that make it up. Indeed, the individuals are becoming increasingly specialized, with the number of tasks they can perform dropping increasingly over the evolutionary process. The first question is therefore: is there a suitable level (or range of levels) of *individuality* that single entities that make up a more complex biological entity need to have so as to be able to produce a single, complex, flexible and robust entity such as a superorganism? What are the requirements of this level of individuality, if any, in terms of autonomy from *and* dependence on the whole system? I suggest naming the hypothesis of this level of individuality the "principle of individuality". Being able to characterize it is relevant to the explanation of emergence of cognitive phenomena on biological bases, and to the creation of cognitive systems stemming from synthesizing biological entities with such properties.

6. The "principle of individuality"

Let's continue with our hypothesis and try to define the "principle of individuality" more accurately. We may assume that it is the optimal level to explain (and give rise to) emergent phenomena and that it should have a physical realization. For example, in a superorganism such as an ant colony, it may be the level of ants. What features do ants need in order to give rise to a superorganism, such as a global complex system? Ants can be characterized as both autonomous and dependent entities, i.e. individuals that not only have degrees of freedom and powers but also constraints.
Degrees of freedom or powers that seem to be relevant are:

1. autonomous movements;
2. simple and limited choice;
3. auto-supporting;
4. absence of reproduction;
5. minimal vital functions.

Constraints that seem to be important are:

1. connection with other similar individuals (by communication or specific behavior);
2. chemical "bonds";
3. physical proximity but not contiguity;

4. conditioned choice by environment (including superoganism "body" itself, i.e. the behavior of all ants as a whole);
5. the possibility of only being able to perform a simple action or a very limited number of simple actions;
6. high-level "programming" (the real-time needs of the colony).

These are only two hypothetical lists, but the point is that this way of considering things may prove useful in order to computationally or biologically create, from a bottom-up standpoint, global entities that exhibit typical features of a superorganism, like flexibility and robustness in environment interaction. An analysis of this kind may help to find the same features within other organizational entities. For example, we can make an analogy between superorganisms and human societies and cultures, and so (in our particular case) between ants and human beings. There are several differences between these two types of organization, the foremost being the higher degree of freedom and autonomy of human beings. Nevertheless, a comparison between colonies and societies, in accordance with the principle of individuality, might turn out to be interesting, especially in the perspective of agent-based models (Axelrod, 1997).

As a better analogy for our aims, I suggest the one concerning bacterial colonies and their ability to display and produce collective behavior (Ben Jacob *et al.*, 2011). If one takes the bacterial colonies as the first step leading to a superorganism – even though with some differences from ant and bee colonies – and if it is possible to find some preliminary conditions of cognition and cognitive capabilities in these colonies, it would be interesting to try to identify individuals that fall under the "principle of individuality". For instance, does a bacterium play the same role as an ant in a bacterial colony? Or should we consider the bacterial/cellular aggregate as the best candidate? Differences between ants and bacteria may be crucial: multicellular versus unicellular entities, stigmergy versus different chemical signaling, and so on. If we accept, however, that bacterial colonies display some foundations of cognition – like meaning-based intelligence as contextual interpretation of information from the outside (Ben Jacob, Shapira, 2005; Ben Jacob *et al.*, 2006) – there are interesting connections with the plausible assumption of cognitive features in superorganisms such as ant colonies. Moreover, by comparing different entities that are good candidates for the principle of individuality in hierarchical structures, we may attempt to clarify the relationship between emergent phenomena and the type of levels halfway between the lowest physical level and the highest organized level.

Why should such a view be relevant to SB? In recent decades, many cognitive researchers have drawn their inspiration from biological complex adaptive systems in order to reproduce knowledge and representational capabilities in systems provided with self-control and self-awareness, for both low-level and high-level cognitive capabilities: for instance, inspiration from the cellular metabolism or immune system (Hofstadter *et al.*, 1995; Mitchell, 2006), also for robotic building (Lawson, Lewis, 2004). A natural or artificial system requires some specific features to attain (self-) control, self-awareness and non-deterministic behavior: global information distributed in statistical and dynamic patterns, a random explorative capability, a strong but fluid interaction between low and high levels. Such a system is meant to be able to adapt to situations that it is "considering" and that it has to face while fulfilling its tasks. The building of a coupling relationship between the system and the situation involves (or rather, *is*) its representational capability and is closely connected to low-level and high-level interaction. For this reason, the system needs a micro-agent structure on different levels. This may also apply to relatively low-level capabilities, such as robotic navigation and mapping. We may consider this approach within the field of enactive cognition and the general thesis that patterns emerge inside an autonomous agent through a coupling relationship with its environment (Ziemke, 2003).

Self-awareness and self-control are not currently relevant targets in SB research, though they are relevant to the perspective of exploring foundations of cognition as they are closely related to system autonomous complex behavior. So, if these targets are not addressed for the time being

because they are beyond the scope of SB, the constraints I mentioned above may be an example of goals at a functional level that are relevant to SB in order to explore the foundations of cognition in biology, especially as regards the SB subfield of synthetic multicellularity. Multicellular systems have recently been investigated (Markson, Elowitz, 2014) because of their potential technological repercussions and by-products, such as tools and platform technologies for SB, as well as to gain an understanding of "the limits of developmental regulation, stability, and plasticity until we have recapitulated developmental processes on our synthetic platforms" (Maharbiz, 2012).

Other authors highlight further advantages of multicellularity, such as cross-feeding, shape selection or sex for exchanging genetic material and the creation of new genomic sections, thus accelerating the evolutionary steps, especially with methods like the conjugative assembly genome engineering (CAGE); however, they also point out the disadvantages, like the loss of cell immortality in multicellular organisms that leads to the loss of lifetime experience upon death (Church, Regis, 2012). Multicellularity is attained using self-assembly methods by genetically engineering desired behavior in cells, which once again constitutes a bottom-up approach (Galle, Hoffmann, Aust, 2009); or using constrained assembly for the formation of multicellularity (Maharbiz, 2012) under contextual pressures. In particular, the latter is close to the study of adaptive complex systems and swarm cognition systems because the interaction between body systems and environment brings about, or at least affects, the system capabilities. A major role is played by environmental constraints, but also by the functional constraints through which we describe the desired (hierarchical) system whose purpose is to provide cognitive behavior of the type described above. The fact that functional constraints are seen in AI as emergent may be an obstacle for SB, which uses assembly methods for controlling every step of multicellular system formation and does not willingly adopt emergent properties[9] for technological purposes or, for the same reason, uses bio-brick assembly. Nonetheless, an emergent interpretation and description of biological and cognitive phenomena seems to be unavoidable above a certain level of complexity and one of the most fruitful ways to study them is, at present, to consider the connection and interaction between systems and the environment.

The long-term contribution of SB to AI may therefore be based on trying to reproduce this particular intermediate level, by synthesizing organic individuals to create entities between a lower chemico-physical level and the level of the overall (super-)organic complex system. In other terms, entities need to be synthesized, starting from a chemico-physical substrate, in order to achieve collective behavior that is comparable to that of a (super-)organic system and that displays cognitive capabilities.

On the other hand, the contribution made by AI to SB is based on the notion that superorganisms can be described in computational terms. As for swarm intelligence techniques, we already have classes of optimization algorithms modeled on behavior of an ant colony[10]. A description of biological organisms in computational terms *inside biology* would, however, be far more interesting since it is different from a functional description of cognitive systems, even at the neuronal level, *within cognitive science and AI*. The stress lies on the explanation of biological events and not cognitive capabilities. In other terms, in this case *biology makes use of AI*, unlike the more common trend in which *AI makes use of biology*, such as in cybernetics, early AI and connectionism. We may cite just one example from the discussion on how interaction between levels takes place in superorganisms: "The steps of the program, in insect and machines, are envisioned as sequences of decision rules [...]. The programs unfold in a linear manner. As each successive binary decision point is reached, the individual colony member proceeds down one pathway or another until it comes either to the next *decision point* or to the end of the sequence. A particular *program* may guide the gradual anatomical and physiological development of individual colony members into one

[9] "I hate emergent properties. I like simplicity. I don't want the plane I take tomorrow to have some emergent property while it's flying" (Endy, 2005).

[10] Such as the Stochastic Diffusion Search algorithm of Nasuto and Bishop (1999). On this topic see also Dorigo and Stützle (2004). Similar attempts have also recently been carried out on bacterial colonies (Niu, Wong, 2012).

caste or another, or it may cause changes in a member's behavior within the ambit of its caste repertoire [...] A complete sequence of decision points that produces a caste, product or full behavioral response is called an *algorithm*" (Hölldobler, Wilson, 2009: 54).
This description allows us to examine a system and its properties from an abstract point of view, without considering whether it is a natural or artificial one, but addressing biological issues in an attempt to cast new light on biological emergent phenomena. Likewise, SB can make use of AI to tackle problems that originated in complex multicellular synthetic systems, in an attempt to hold together their emergent collective behavior and the *control* over single synthesized micro-entities (cells or bricks) that give rise to the organism. In addition, producing a synthesized superorganism as well as multicellular organisms can offer different views on the body-environment interaction, thereby clarifying the hierarchical levels of the biological entities involved.

7. The future: synthesizing superintelligence

The future is mostly unpredictable. Nevertheless, many predictions about future evolution of intelligence have been made in order to explore the possibility of superintelligence[11]. The main idea regarding this issue is that (sooner or, most likely, later) our technological achievements will place us in a position to build machines or biological entities that are more intelligent than human beings. This may come about in two ways: A) a superintelligence we can recognize on account if its power to do things we wish to do, but we are unable to do; B) a superintelligence that we cannot recognize because its powers, goals, motivations and methods are too far from our understanding. If A occurs, presumably we will be able to predict when we have it and control the artificial superintelligence achieved in this way. If B occurs, presumably we won't have control over the entity and the catastrophic forecast is, in the best-case scenario, that we will have to adapt our life to coexist with a different kind of intelligence system whose peculiarity is that it is more intelligent than ours; in the worst-case scenario, that the exact moment in which that happens will be the beginning of the end of mankind. There is a huge body of literature on this topic that is sometimes a cross between science and science fiction. However, setting aside science fiction and the ethical, social and cultural implications, I wish to mention a few points on superintelligence that deserve discussion and that may be relevant to the relationship between SB and AI.
Superintelligence is bound up with the development of computation power and processing technologies. In particular, the key point is to establish whether acceleration in technology at an exponential rate, as the one in recent years seems to show, could lead to a point of no return: the so-called technological singularity (Vinge, 1993), namely the achievement of a superhuman artificial intelligence. The accelerating process could, however, first lead to key enabling technologies that increase the potential of SB, also by drastically reducing the price of technologies involved in SB (Kurzweil, 2001). In a technologically-improved scenario, genetic manipulation, selection and engineering could lead to biological superintelligence through an understanding of the mating patterns behind intelligence. Implantation in embryos and embryo selection over many generations might significantly increase the intelligence quotient. Challenging problems have to be faced, however. For instance: a time delay and generation lag. Moreover, even if "DNA synthesis is already a routine and largely automated biotechnology, […] it is not feasible to synthesize an entire human genome that could be used in a reproductive context" (Bostrom, 2014: 30-41). Let's assume, however, that every genetic problem is solved; we will have biological enhancement "probably sufficient for the attainment of at least a weak form of superintelligence" (Bostrom, 2014: 43-44). Nevertheless, these hypothetical achievements would merely be forms of biological superintelligence that could at best produce smarter human beings by accelerating the evolutionary process. Such an outcome of SB is also known as transhumanism (Regis, 1991; Church, Regis, 2012: epilogue) and might result in a large number of increasingly intelligent people that produce

[11] For a general and up-to-date discussion of superintelligence see Bostrom (2014).

artificial superintelligence by playing the same role in future AI research as that played by Turing or von Neumann in the past. Moreover, SB techniques and methods can provide control over transhuman entities, according to "the rule 'Never hide information from the programmers'" (Church, Regis, 2012: 246). So, from this point of view, future SB could help future AI. And the other way around?

There are domains in which AI systems surpass human beings. Consider, for example, expert systems or some games, such as checkers, chess or Jeopardy! All these systems are dedicated to specific problems or tasks. There is no such thing as general AI and for the present it may seem too much to expect. It does not, however, appear to be impossible in principle. How can we achieve general AI and, shortly after that by using the same methodology, artificial superintelligence? Many answers are possible. Two pathways appear to be particularly promising: brain emulation[12], through neuron by neuron simulation[13], and artificial evolution, through evolutionary computation techniques (Chalmers, 2010).

Evolutionary computation, especially by using genetic algorithms, is a good candidate to achieve artificial superintelligence. After all, human intelligence is a product of evolution, and we may be able to identify and reproduce all features of evolution, not just some of them as happens nowadays, in order to produce intelligence (Moravec, 1988, 1998). The question of how evolutionary computation could achieve artificial superintelligence is a matter of discussion: will it be by feature simulation of the evolutionary process or just by increasing computation power in order to exploit the existing evolutionary computational technology in a fuller way? In both cases, the outcomes of evolutionary computation in attaining or not attaining (at least part of what we will recognize as) artificial superintelligence might help to achieve or avoid a similar development in SB. In other terms, recent analysis of possible future scenarios in AI and superintelligence can be exploited to gain some insight into current research on general and specific AI systems. This is a sort of regulative topic, used for orienting research in this set of disciplines. The same regulative and guiding role can be played by a similar kind of analysis in the SB field, both for social and ethical implications, and to decide what trends are most useful and promising according to different long-term targets.

Finally, another important contribution of this kind of research is to define the boundary between artificial entities and biological entities. If we achieve artificial superintelligence by means of an interaction of computationally evolved micro-agents, will this sort of superorganism be artificial or biological? What if this global entity is attained by transferring computationally evolved information into a synthetic unicellular or pluricellular organism? Will this kind of superorganism still be artificial? Collective superintelligence is another form of superintelligence (Bostrom, 2014: 54-56). The study of collective superintelligence, not within a social or cultural context but a biological one, as discussed in previous sections, may offer AI and SB reciprocal advantages.

8. Conclusion

In previous sections, I outlined the contributions that AI can make to SB, and in some cases SB to AI, by exploring a tri-temporal dimension scheme. Past research is relevant, especially for the biological aspects of early AI. I believe that Turing's and von Neumann's work was very open-minded and unconditioned by the subsequent development of the discipline. For the first time, they posed the question of whether life and intelligence can be exploited by exploiting biological notions in a bottom-up approach to cognition (intelligence features, evolutionary systems) and its functionalist characterization.

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[12] That is not brain uploading onto a machine, because brain emulation implies an evolution of the brain itself, while brain uploading requires a machine that is able to "receive" all the information in a brain and let it process autonomously. Nevertheless, both approaches might share the same technological substrate, even if it is not logically necessary. On uploading and its implications, see Strout (2006).

[13] This is the main objective, for instance, of Human Brain Project (https://www.humanbrainproject.eu/).

Current research on emergent phenomena, swarm intelligence and superorganism can help SB to outline interesting and more useful definitions of "life" and "cognition", and the relationship between them. This goal can be achieved by means of a computational, algorithmic description of biological events and collective phenomena within biology, which is the other side of the coin of the creation of biologically inspired cognitive architecture. Even in this case, a bottom-up approach to cognitive systems appears to be relevant to explaining emergent cognitive capabilities of embodied systems that interact with the environment. These ideas are likely to be relevant to SB research, especially that on multicellular systems.
Through an analysis of long-term targets, research on future prospects in superintelligence may help to pinpoint interconnections between AI and SB, and to sketch out a new general paradigm within which it will be possible to study AI and SB at an inclusive level of abstraction, thereby producing a new, more inclusive concept of life.
These three temporal dimensions are connected by the idea that intelligence is a biological and embodied phenomenon. The SB research area seems to afford new ways of testing AI assumptions by exploiting both earlier and more recent ideas to develop relevant biological material for a bottom-up exploration and creation of cognition.

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