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Emergence from biology to cognition: the case of superorganisms[1]

Over the last years the study of emergent phenomena and the problem of emergentism rose up to become one of the most important topic in different fields of research (Bedau, Humphreys, 2008; Corradini, O'Connor, 2010). Emergence commonly replaced the notion of holism in the traditional dichotomy between reductionism and holism, and it was considered in some cases as opposed to reductionism and in other ones as the complementary notion to it, in a sort of continuum of different positions. In cognitive science it played a more and more crucial role because of the tighter and tighter interlacement between cognition and biology, as regards especially two facts: that cognitive phenomena were progressively seen as part of biological ones; and that cognitive modeling developed far deeper in the direction of biologically inspired cognitive architectures. In this paper I try to make a hypothesis in order to better understand emergent phenomena through the definition of individuality of entities involved in some sorts of (complex) biological systems.
The shifting of cognitive science research on such trends was not equivalent to a whole rejection and elimination of standard and traditional problems and principles of artificial intelligence (AI) and cognitive science, as representationalism, functionalism and the identity of explanatory principles (see the five theses on the artificial proposed in the last chapter of Cordeschi, 2002). Cognitive models coming from new trends of cognitive science have to deal with old problems and try to give new solutions or methods of solution. Moreover, we could consider the new trends in AI and cognitive science, especially the ones tightly connected to biological heuristics, as deeply rooted into older or longer traditions of research, as cybernetics (Cordeschi, 2002) and complex adaptive systems, the latter being studied and used in different fields since 70s (Holland, 1992). In particular, over last decades a growing number of researchers regarded such systems as the best way to solve computational problems of traditional AI, to get new achievements from an engineering standpoint, to model cognitive phenomena in a bottom up perspective that is able to fill the gap between low-level and high-level cognitive capabilities, namely between learning, recognition, motion, etc., and abstract reasoning, planning, creativity, self-awareness, etc. On purpose, I do not mention representation, because, in a wide sense of the term involving the idea of some inner states or configurations of a system denoting external events, it seems to embrace all of such capabilities (and it is a topic that goes beyond the range and the aim of this paper).
Inside a large number of research lines we can find the one of swarm intelligence (Beni, 2007), in which researchers think to biological collective phenomena (the behavior of flocks, shoals and insect colonies) 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 in order to explain/reproduce intelligent phenomena. In part with the same purposes, perhaps we might add the study of bacterial colonies as well, and all of this within the framework of synthetic biology and the construction of biological systems.

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If we consider the most recent discoveries on superorganism behavior and structure, the case of insect colonies is particularly interesting inside swarm intelligence cognitive trend and for cognitive explanation and modeling. Superorganisms, indeed, are a particular and peculiar instance of a group showing an intelligent behavior, namely more intelligent than the one ascribable to single individuals of the group. In most evolved species of ants, the specialization of groups leaded to a high level of complexity of the colony, but what is interesting is the fact that such a complexity does not correspond to a parallel complexification of the individuals. The colony is a superorganism in the sense that self-control, communication, and adaptation to environment capabilities can be compared to the ones of an organism that shares the same complexity, like some mammals or human beings. Even better, if we compare organisms and superorganisms, the latter seems to have a higher robustness and flexibility in comparison with the former, because of the structure and the organization that realize different functions and capabilities (for example communication, food research, defense from external threats). As a matter of fact, the organs and their functions in superorganisms are not compact entities as in organisms, and the organ functions are processes that take place in a very distributed substrate, that, to some extent, can be replaced, if necessary, more easily than in an organism. Thus, information and knowledge of superorganisms have a higher degree of distribution than in organisms, and we could assert that the same is for representation too.

If the comparison between complex organisms and superorganisms shows the superiority, in a certain sense, of the superorganisms, especially as regards flexibility and robustness of functions, the analogy between an ant colony and a brain is not new in philosophy of mind and AI (Hofstadter, 1979). It was used with the aim to define the relation between reductionism and holism, to defend a multilevel perspective in mind/brain systems, to provide an explanation of mental phenomena from an epistemological standpoint, and to outline an explanation of emergent phenomena that was able to preserve scientific plausibility and, at the same time, to give effectiveness to downward causality inside such explanations and theories.

It is not possible to go too far with the brain/ant colony analogy, because of some differences between brains and ant colonies, but it is interesting to consider in a similar perspective the comparison between organisms and superorganisms and try to formulate some questions that can open new fruitful trends in cognitive modeling. As a matter of fact, superorganisms have been recently described through a computer science terminology, a sort of noteworthy inversion of traditional biological inspired computation methodology (Hölldobler, Wilson, 2009). In a superorganism like an ant colony, ants are agents that execute simple algorithms. They come to decision points where a change whether in their *behavior* or in their *anatomy/physiology* can take place, depending on the group (caste) it belongs. This is the way in which higher processes or functions are transmitted to low levels, and this sort of multilevel structure seems to be a good candidate for a real, effective phenomenon of emergence and maybe for an actual downward causality. Of course, speaking of a downward causality that is actual is possible if we consider the context of weak emergence as the one implied by the analysis of superorganism, as weak emergence (Bedau, 1997) allows to put together an autonomous explanation of the phenomenon with its causal dependence (and we could say also ontological dependence, but we leave aside the question). Because of its autonomy and dependence from the global system, an ant seems to be a good candidate for playing the role of link between different levels as regards the explanation of high levels as a result of complex interactions of micro-entities.

Superorganism as a multilevel organized structure is an outcome of evolution, in particular through multilevel selection that works by increasing the complexity of the superorganism, but not the complexity of the individuals composing it, that are instead more and more specialized. So the first question we can formulate is: is there a suitable level (or range of level) of individuality that single entities composing a bigger and more complex one need to have so that it is possible a single complex, flexible and robust entity as a superorganism? What are the requirements of such level of individuality in terms of autonomy from *and* dependence on the whole system? The existence of such a level is a hypothesis that I want to call “principle of individuality” and that could be a very fruitful constraint in cognitive modeling as well as in synthetic biology – especially for the foundations of cognitive phenomena – if it is possible to characterize it also as a required element in explanation of emergence.

In order to define more accurately the "principle of individuality", we could see it as the optimal level to explain (and give rise to) emergent phenomena and we could assume that it is the level of particular entities within a superorganism, like the one of ants. We could make some hypotheses concerning the features that these particular entities need to have in order to make up a superorganism (*i.e.* a global complex entity) and make it possible. Ants can be characterized as both autonomous and dependent entities – that is, entities that have both degrees of freedom or capabilities and constraints.

The degrees of freedom or capabilities that seem to be important for a definition of the principle of individuality are:

1. autonomous movements;
2. simple and limited choice;
3. auto-supporting;
4. no need of reproduction;
5. minimal vital functions.

On the other hands, the constraints that seem to be important for the same purpose are:

1. connection with other similar individuals (by communication and as to behavior);
2. chemical "bonds";
3. physical proximity but not contiguity;
4. impossibility of reproduction;
5. conditioned choice by environment and superoganism "body" (that is, the behavior of all ants as a whole);
6. doing a simple action or a very little number of simple actions;
7. high-level "programming" (the actual and real-time needs of colony).

These are just two hypothetical and modifiable lists, but could be useful in order to virtually (computationally) or biologically create global entities that are able to exhibit the very features of superorganism in terms of flexibility and robustness from a bottom up standpoint. And it could be interesting to see if it is possible to find the same features inside other organizational entities. Someone could think that the best analogy is the analogy between superoganisms and human societies and cultures, and so (in our particular case) between ants and human beings. But I think that there are several differences between such two types of organization, the first of them being the higher degree of freedom and autonomy of human beings. Nevertheless, a comparison between colonies and societies, in the light of principle of individuality might turn out as interesting, especially in the perspective of agent-based models (Axelrod, 1997).

As a better analogy, or a better line of investigation there could be the one concerning bacterial colonies and their capability to show and produce a collective behavior (Ben Jacob, Shapira, Tauber, 2011). In particular, if one takes the bacterial colonies as the first step on the way of superorganism, even though with some differences with ant and bee colonies, and if it is possible to find in them some preliminary conditions of cognition and cognitive capabilities, it is interesting trying to identify entities that fall under the principle of individuality, in spite of the differences between ants and bacteria that could be crucial: pluricellular vs unicellular entities, stigmergy vs different chemical signaling, and others too. But, if we accept that bacterial colonies have some foundations of cognition (meaning-based intelligence as contextual interpretation of information from the outside; see Ben Jacob, Shapira, 2005), there are interesting connections with the plausible assumption of the presence of some sort of cognitive features in superorganism like ant colonies as well. Moreover, a comparison between different entities into which we could identify some good candidates to be given with principle of individuality could make clear the relationship between emergence and emergent phenomena and the type of levels halfway between organism and superorganism. In summary, the lines of further research on “principle of individuality” are open in different directions.

Finally, since in the last decades many researchers have drawn their inspiration from biological complex adaptive systems in order to reproduce representational capabilities in systems provided of self-control and self-awareness (Hofstadter *et al.*, 1995; Lawson, Lewis, 2004; Mitchell, 2006) both for low level and for high level cognitive capabilities, we may wonder if the definition of the features of a supposed level of individuality could open new opportunities in order to better understand the issue of representation in cognition, an element that seems unavoidable in reproducing and explaining intelligent (adaptive, open-ended) behavior at many levels. Superorganisms, with their individual, physically autonomous but system-dependent entities, appear a very useful biological phenomenon to understand cognition.

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