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CHARACTERIZING EMERGENT PHENOMENA (1): A CRITICAL REVIEW

Eric BONABEAU [1], Jean-Louis DESSALLES [2], Alain GRUMBACH [2]

Abstract
Emergence seems to be a central concept in Artificial Life, Cognitive Science, and many other related domains, but the meaning of which is not really agreed upon. In this paper, we critically review some major conceptions of emergence and give some examples of phenomena that are usually considered emergent.

Résumé
La notion d'émergence se situe au centre des Sciences Cognitives, de la Vie Artificielle, et de nombreux autres domaines connexes. Il s'agit pourtant là d'un concept sur lequel les avis ne s'accordent pas réellement. Nous nous proposons ici d'établir un état des lieux, en décrivant les courants majeurs qui se dessinent autour de l'émergence, et en dressant une liste, courte mais représentative, de phénomènes qui sont généralement considérés comme émergents.

I. WHAT IS IT PEOPLE CALL EMERGENCE?

The aim of this paper is to review some contemporary concepts on emergence. Emergence seems to be a central idea in Cognitive Science and a "key concept" of Artificial Life (Bedau, 1992), but there is no real agreement on what is should imply for a phenomenon to be emergent. Consequently, it is even more difficult to find the right tools to achieve emergence and

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1. CNET Lannion B-RIO/TNT, 22307 Lannion Cedex & Laboratoire de Physique des Solides, Université Paris-Sud, 91405 Orsay Cedex.
2. Département Informatique, Télécom Paris, 46, rue Barrault, 75013 Paris.

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to control emergent phenomena: besides the usual question of the nature of emergence, there are some more practical questions regarding the way of achieving the ambitious task of making properties appear "spontaneously".

The paper is organized into five parts: we first give some examples of phenomena usually considered emergent (section 2); in the following three sections (sections 3, 4, 5), we review the main features that allow for a distinction between different conceptions of emergence: levels, observers and models; we finally briefly discuss the implications of and the issues raised by emergence in Cognitive Science and Artificial Life. In a companion paper (Bonabeau *et al.*, 1995), we propose a unifying conceptual framework allowing for the description and the characterization of emergence and emergent phenomena: this framework, based upon levels of organization, levels of detection, and information theory, is shown to contain most examples described in the present review.

II. EXAMPLES OF EMERGENT PHENOMENA

This section is dedicated to the presentation of a broad spectrum of examples which illustrate (different notions of) emergence. Our companion paper (Bonabeau *et al.*, 1995) is aimed at giving a formal framework to understand what these examples have in common.

II.1. A picture of...

The first example is illustrated by a picture from R.C. James, which shows a set of black and white patches (figure 1)...

... and after a few seconds, one can see a dalmatian dog "emerge". Our perception has been attracted towards this particular pattern, which is highly improbable in the space of all images composed of black and white patches. In that sense, this example can certainly be related to Atlan's idea (see section 3) that emergence corresponds to a highly constrained trajectory in a huge space of possible outcomes, i.e. (microscopic) entropy decreases during the process of emergence, with the associated feeling that some kind of ordering is taking place.

Figure 1. An image of...
(from a picture by R.C. James in [Lindsay et Norman, 1980]).

II.2. Ants, termites, and other social insects

This second example deals with ants, or more generally with swarms of insects (Hofstadter, 1979).

Figure 2 shows an ant bridge between two tree branches. The example of termites building arches which join at length scales much bigger than the size of one insect, also given in (Hofstadter, 1979), is very much of the same nature. Many more examples could be drawn from the field of animal societies, which have "emergent" problem-solving abilities. For instance, an ant colony is able to find the food source closest to the nest thanks to simple trail laying (consisting in depositing a large quantity of a specific

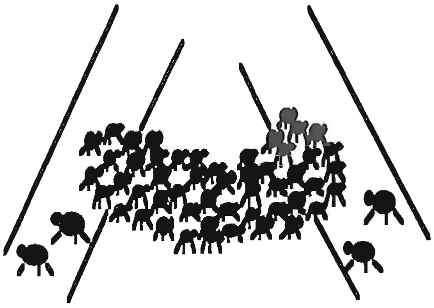


Figure 2. Ant bridge.

chemical called pheromone when coming back to the nest from the food source) and trail following behaviors (ants follow gradients of pheromone). Such examples clearly have several levels of description, of behavior, of organization, of detection: a collective biological entity possesses abilities at the level of the whole that individuals do not. Hence the idea that these systems exhibit emergent properties, such as emergent information processing and collective decision making, whereby stimuli from the environment are efficiently and collectively processed without any central controller.

II.3. The economy

This example involves economic agents who act at a micro-level (purchase, sale), and trigger macro-level phenomena. Each agent follows personal, local goals, and participates in the global economic evolution such as global decrease, global increase or crash. But he cannot foresee or control such evolutions. Aggregate economic quantities in general, such as prices, are often considered emergent.

II.4. Traffic jams

In the case of a traffic jam (figure 3), what appears is an entity whose properties need not have anything in common with the properties of its constituent units (cars). In particular, one may have a stationary or even moving back traffic jam while all cars are moving forward. This higher level structure, whose equations of motion are not easily derivable from those of cars, emerges from the interactions between the cars.

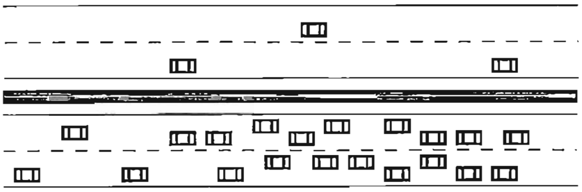


Figure 3. A traffic jam emerges from the behavior of all vehicles. New cars arrive as others leave, but the traffic jam remains. It can even move back while all cars are moving forward.

II.5. Von Foerster magnets

The well-known example of Von Foerster magnets introduced as an intellectual exercise (Von Foerster magnets do not exist) illustrates what one expects when one thinks of emergence (Atlan, 1983). More precisely, it shows how noise can lead to organization. Starting with a (seemingly) disordered set of magnets, one ends with a (seemingly) highly structured network of magnets: order has emerged out of disorder, thanks to the presence of noise. Here again, the trajectory of the system in the space of all possible magnets' configurations has been attracted towards a very specific region – not only specific in statistical terms, but also in terms of what it represents for the observer: a highly ordered region.

II.6. The emerging spiral

In the example described by Lawler (Lawler, 1980), a spiral apparently appears when a child drawing with a logo turtle specifies 89° instead of 90° (figure 4). The new spiral is not composed of straight lines: two neighboring points on this spiral do not belong to the same segment. What is emergent is the property of being smoothly curved while constituent units (segments) are not. In other words, this property of the macroscopic pattern cannot be easily derived from the nature of the microscopic elements.

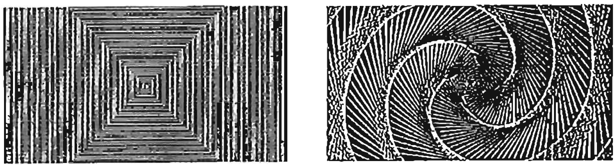


Figure 4. The almost square spiral (89° angle) drawn by the Logo turtle reveals an emergent four armed spiral (after [Lawler, 1980])..

II.7. H_2S

This is a simple example to illustrate how difficult it may be to derive the properties of a molecule given the properties of its atoms. The smell of H_2S does not exist at the atomic level, while it does exist at the molecular level. Other examples of the same type include the intricate shape of a snowflake, the geometrical structure of hemoglobina, etc. Due to the difficulty of inferring the macroproperties from the microcharacteristics of the system (in many cases because of the huge number of components and/or the complexity of their interactions), such examples are often considered emergent.

II.8. Cellular automata

In cellular automata (CA), very simple local rules can give rise to very complicated, or highly structured global patterns (see e.g. [Langton, 1986]). It can even be shown that some CA are capable of universal computation. Let us recall that a CA is a regular, discrete array of discrete state cells (the simplest CAs have cells with just two states: 0 and 1): at each time step, a given cell takes a state depending only on the states of its neighbors at the preceding time step. CAs are perhaps the simplest examples of systems exhibiting emergent properties. These properties are of two kinds:

(1) Particular structures may appear (see e.g. figure 5, where the temporal evolution of a 1D-2state-CA is shown – time and space correspond to the vertical and horizontal coordinate, respectively –, with a complex but regular nested set of inverted triangles of all sizes), and in this respect, emergence in CAs is similar to other examples involving some kind of ordering.

(2) There may also be for some CAs a formal impossibility to predict the behavior of the CA from its rule and initial conditions, for those CAs equivalent to a universal Turing machine, due to the halting problem. It is difficult in general, except for very simple rules or initial conditions, to predict the evolution of a CA. Because of this underivability of the global evolution of a CA from the microscopic rule, it may seem natural to speak of emergence.

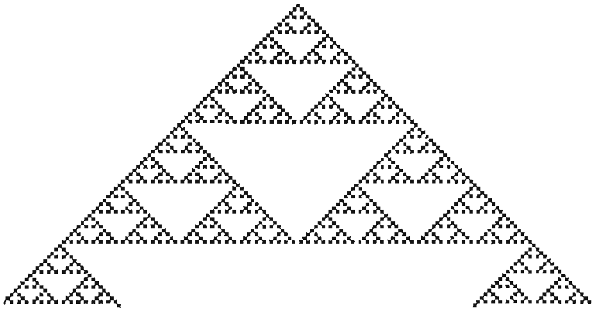


Figure 5.

II.9. Benard convection

Benard convection rolls constitute an example of a dissipative structure (Nicolis & Prigogine, 1991). These rolls appear when the temperature gradient applied to a liquid (with given boundary conditions) reaches a critical value.

Therefore, as the level of noise is increased (the temperature gradient), an ordered structure emerges at a macroscopic level when the critical value is crossed. It is of course very hard to predict the particular structure that appears from a microscopic knowledge of the underlying mechanisms. Dissipative structures are an important example of emergent phenomena, of which we give two other instances (II.10 and II.11).

II.10. Autocatalytic networks and hypercycles

Non-linear feedbacks in a set of chemical products which can react with each other or mutually catalyze their generation can dramatically reduce the space of possible products, so that a specific, restricted ensemble of molecules eventually becomes self-sustained, while the others disappear. One can consider this process as the emergence of a metabolism (provided it is stable enough), whereby the self-sustained set of chemicals in the stirred reactor integrates the inflow of new chemicals by transforming them into members of the ensemble.

II.11. Dyctostelium discoïdeum

These slime mold amoebae have a life cycle which consists of: – isolated cells – cell agregate – plasmodium – multi-cell organism (see figure 6). The isolated cells may aggregate to set up an entity which has a topological and functional organization (Nicolis & Prigogine, 1989). This emergent higher-level entity, is a multicellular organism, whose contituents undergo a differentiation: the initially identical elements split into two different sub-populations of cells, one composing the body of the multicellular organism, while the other one composes its germinal part. Emergence here takes place in two distinct manners:

(1) When the amoebae aggregate, they do so by forming a spiralling pattern, which emerges from a "trail-laying/trail-following" behavior (i.e. they emit a chemical substance whose gradient they in turn follow).

(2) A multicellular organism, with differentiated cells, emerges out of the aggregation of individual cells.

II.12. Osmotic growth

In osmotic growth, Na_3PO_4 and $CaCl_2$ mixed in an aqueous solution give rise to arborescent structures (figure 7). Thus, due to osmotic pressure, tree-

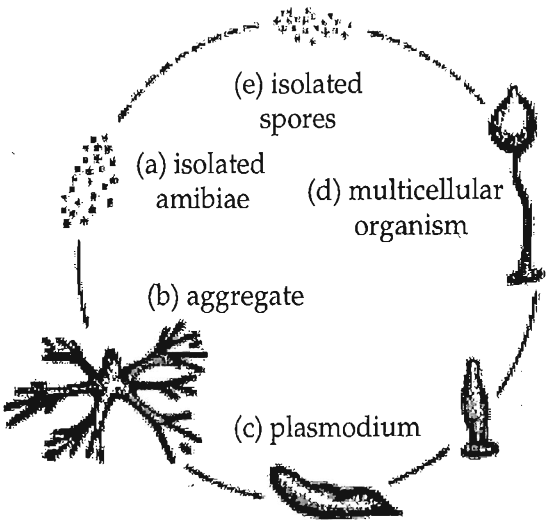
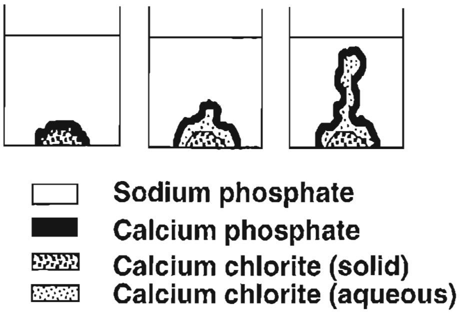


Figure 6. Dyctostelium discoïdeum. (After [Nicolis & Prigogine, 1989]).

like patterns have emerged out of this chemical-physical reaction (see e.g. in [Langton, 1989]).

II.13. Pask electro chemical device

Pask's device has been reintroduced by Cariani who describes it as an adaptive coherer consisting of a "*set of electrodes inserted into an aqueous solution of ferrous sulfate and sulfuric acid. A pattern of current would be passed between the electrodes and ferrous dendritic threads would precipitate out of the solution, thereby changing the resistances between the electrode nodes. Training was accomplished by testing the resistance among the nodes of the network for perceptible (above a treshold) changes in resistance when given some stimulus, and rewarding by applying more current to those nodes. The device could be trained to become sensitive to sound and magnetic fields. In about half a day, the device could be trained to discriminate between two frequencies of sound*" (Cariani, 1989). This is, according to him the clearest operational example of emergence relative to a model (see section 5).



Reactions :

$$CaCl_2 \text{->} Ca^{+2} + 2\,Cl^-$$

$$3\,Ca^{+2} + 2\,PO_4^{-3} \text{->} Ca_3(PO_4)_2$$

Figure 7. Osmotic growth. (After [Zeleny et al., in Langton, 1989]).

III. LEVELS

It has become obvious from the previous examples, that the notion of emergence involves the existence of **levels** (of description, of organization, of behavior,...) for a large number of people. In the following definition proposed by Lewes in 1874: "*Emergence: Theory according to which the combination of entities of a given level gives rise to a higher level entity whose properties are entirely new*" (Lewes, 1874), the most commonly accepted features of emergence appear. We find the notion of a level composed of elements that realize higher-level structures when (appropriately) combined, and the properties of the new structures cannot be derived (in some sense to be defined) from the properties of the lower-level elements Lewes gives the example of a molecule of water, whose characteristics cannot be inferred from those of its constituent atoms. In order to convey the fact that higher-level properties are not intelligible in terms of the lower-level properties, the term "*unspeakability*" has been used (Kampis, 1991). How to define this unspeakability is yet another issue, addressed in our companion paper (Bonabeau *et al.*, 1995) by formally introducing levels of organization and levels of detectors. There is another important idea behind Lewes' point of view: properties applying to the level of the whole are qualitatively different from those that allow to describe the level of the parts.

Along the same lines, emergence is, according to Hillis (Hillis, 1988), a process through which a system comprising many components produces a global behavior that looks much more organized than the behavior of the parts. He suggests the example of a snowflake, which is a highly organized structure (regular, self-similar, etc.) emerging from interactions between water molecules: the connection between the properties of water molecules and the final shape of the snowflake is far from obvious.

For Varela, Thompson and Rosch (Varela *et al.*, 1991), emergence is a modern word for what was called self-organization during the cybernetics years, the heart of which being the passage "*from local rules to global coherence*". Emergent properties, though they have no clear definition, have been found in many places "*across all domains – vortices and lasers, chemical oscillations, genetic networks, developmental patterns, population genetics, immune networks, ecology and geophysics*": in each case, "*a network gives rise to new properties*". The example of cellular automata, where complex global patterns can "emerge" from a network of simple interconnected elements, is paradigmatic. The main idea is that of attractors or configurations in a phase space, towards which the system converges without any central controller: for instance, in the case of a "neural network", "*because of the system's network constitution, there is a global cooperation that spontaneously emerges when the states of all participating 'neurons' reach a mutually satisfactory state*". But for the study and the simulation of cognitive systems, one needs to go further than emergence, because the behavioral richness of biological systems lies not only in their architectures, but also in their coupling with the world at large, and structures then emerge along with a meaning grounded in the world (enaction being the process through which the system brings forth a world).

Piaget's conception of emergence in the context of social sciences (and not developmental psychology, where emergence is a controversial topic), introduces an additional notion of feedback. For Piaget, there are three types of processes describing the behavior of populations (Piaget, 1980):

(1) Composition (additive or atomistic), which defines the properties of the society as a whole, i.e. global behavior.

(2) Emergence: process through which the society as a whole generates new properties with respect to the individuals, and these novel properties are imposed to components.

(3) Relational processes (relational totality): set or system of interactions modifying individuals from the start, and therefore explaining the variations

in the properties of the whole.

Some related ideas (Amy, 1992) state that emergence can apply to both microscopic and macroscopic levels. There is macro-emergence (the global property) and there is micro-emergence (the consequences of the global property on the local parts). Thus the whole is more than the sum of its parts ("*Collections of units at a lower level of organization, through their interaction, often give rise to properties that are not the mere superposition of their individual contributions, but gives the ensemble substantially new, emergent properties*" [Taylor, 1991]), but also a part embedded in the whole is more than an isolated part. For instance a node in a connectionist network acquires some sort of meaning linked to the relationships of the whole network with the world (since the node belongs to the distributed representation of several objects). On the other hand, there are constraints between the parts that prevent the whole from taking certain states, and thus the whole is less diversified than in the absence of interactions. Therefore, all the relationships between the whole and its parts can be summarized as follows (with qualitative +, > and < signs):

(i) $S>(S_1)+\ldots+(S_n)$

(ii) $(S_i)_s>S_i$

(iii) $S<(S_1+\ldots+S_n)$

The situation of the parts within the whole is related to what Klee calls "nomic-emergence", characterized by the fact that "*micro-properties or micro-constituents are brought into a novel relational structure in virtue of their integration on the higher-level organization. This new relational structure is responsible for new law-like regularities to the behavior of the system at that higher level of organization*" (Klee, 1984). Campbell (Campbell, 1974) and Popper (Popper, 1987) use the word "*downward causation*" to describe the notion of macrodetermination, i.e. the effect of the whole on the parts. For organismic biology, this phenomenon of macrodetermination whereby the whole subjects the parts to certain ordering constraints is essential for explaining the living, living systems "*being dominated by the interactions of numerous variables, all of which can at once be both cause and effect*" (Popper, 1987). According to Weiss, "*it is solely the ordered interactions of the molecules – their behavior – that makes them participants in the process of life*", which in turn influences the molecules (Weiss, 1970).

Atkan (Atlan, 1983, 1985, 1987) is also interested in microscopic and macroscopic levels. Self-organization is, according to him, the emergence of macroscopic spatio-temporal patterns out of an homogeneous, indistinguishable set of microscopic states. Emergence thus leads to a reduction of the system's space of possible states: in the case of boolean networks, Kauffman (Kauffman, 1990) and Atlan noticed a restricted space of attractors – namely a few very short attractors. This type of emergence is related to the level of observation at which one is located: a "microscopic" observer can distinguish between all the microstates, hence there is no emergence for him, while an observer at the macroscopic level initially notes a highly degenerate macrostate – the microscopic realizations of that particular macrostate not being accessible to the observer. For this macroscopic observer, emergence corresponds to an improvement of his ability to distinguish between macrostates: emergence produces an increase of "macroscopic entropy", and a decrease of "microscopic entropy".

We now turn to more "functional" definitions of emergence, since the definitions we have seen so far were related to "structural" emergence, without any reference to possible functions that emergent structures may implement.

Steels (Steels, 1991) defines the concept of emergent functionality (within the context of distributed AI) by saying that a function is emergent if it is achieved "*indirectly by the interaction of more primitive components among themselves and with the world*", and if each component is not reducible to a subfunction of the function the whole implements: this is in contrast with hierarchical systems "*where the functionality of such a system can be tested and is readily recognizable as a subfunction of the global function*".

Hofstadter (Hofstadter, 1979, 1985) describes collective phenomena, where information that is present at a given level (that of global activities) may not be present at another level (that of local elements): "*It is critical to focus on collective phenomena, particularly on the idea that some information or knowledge or ideas can exist at the level of collective activities, while being totally absent at the lowest level. In fact, one can even go so far as to say that no information exists at the lowest level (... no ideas are flowing in neurotransmitters...)*". He gives the example of swarms of insects: "*What you see at the top level need not have anything to do with the underlying swarm of activities bringing it into existence. In particular, something can be computational at one level, but not at another level*". This example refers to the emergence of a computational or information processing ability. The notion of feedback is also of importance, particularly what he calls "strange loops", which are processes whereby the interaction of different levels (the higher level influences the lower level, while at the same time being determined by it) gives rise to the emergent phenomena of our brains, like ideas, hopes, analogies, etc.

Forrest's paper on emergent computation (Forrest, 1990) is one of the rare attempts to give an accurate definition of emergence in the context of emergent computation. She proposes a set of conditions that must be satisfied for emergent computation to take place:

(i) *A collection of agents, each following explicit instructions*;

(ii) *Interactions among the agents (according to the instructions), which form implicit global patterns at the macroscopic level, i.e. epiphenomena*;

(iii) *A natural interpretation of the epiphenomena as computations.*

She also suggests that the global patterns can influence the microscopic level. She stresses the fact that "*the explicit instructions are at a different (and lower) level than the phenomena of interest*". It must be noticed that the third condition strongly refers to an observer: the function that emerges (here computational abilities) is not considered intrinsic to the system under observation, rather everything happens as if it were following some computational rules: it behaves **in accordance with** computational rules, and the extent to which it does so is determined by the observer.

IV. OBSERVERS

Most of the definitions of emergence related to the idea of levels rely on the existence of an observer or of some device capable of observation. Such an approach is emphasized by Baas (Baas, 1992), for whom emergence is defined with respect to a set of "observational mechanisms': an property P is emergent if P is observed at one level using some observational mechanisms, and not at the level below using the very same observational mechanisms (in order to define the notion of level, he introduces n^{th} order structures which are derived from a $(n-1)^{th}$ order structure by a set of observational mechanisms proper to the level $n-1$ and a set of interactions between the elements of the $(n-1)^{th}$ order structure). Another conception of emergence needing an observer, more, referring to an observer's knowledge is Lorenz's (Lorenz, 1973), who uses the term "*fulguration*" (sudden appearance of a new property), and gives the paradigmatic example of an oscillator, whose property of generating electrical waves cannot be predicted by the knowledge of the individual components alone (essentially a coil and a capacitor).

But for some others, a definition of emergence must not include any reference to a cognitive observer, i.e. no mental states must be involved in the definition. This is not necessarily in contradiction with the use of "observational mechanisms", but such mechanisms must not be taken (appearence of new functions not reducible to combinations of old ones) because of the "structural plasticity of biological systems".

VI. EMERGENCE, COGNITIVE SCIENCE, AND ARTIFICIAL LIFE

When facing all these definitions of emergence, the issue is not that of finding which one is the right one, but finding the domain of application of each definition, some overlapping being likely to occur between the domains. Popper (Popper, 1987) suggests four levels of emergence, each level defining a particular set of phenomena: "*on the first level, there is the theory of emergence of heavy atomic nuclei in the center of big stars, and (...) the evidence for the emergence somewhere in space of organic molecules. On the next level there is the emergence of life. (...) On the next level, the next great step is the emergence of conscious states. (...) [And finally] on the next level, this is followed by the emergence of products of the human mind, such as the works of art; and the works of science; especially scientific theories*".

Several other classifications of emergence are proposed by Cariani (Cariani, 1989):

(i) In the first one, he separates physical emergence, from biological emergence, psychological emergence and social emergence. Physical emergence is related to the appearance of new physical structures, for instance at phase transitions. Biological emergence is related to the increase in morphological complexity and to the appearance of new functions in biological evolution. Psychological emergence is related to the appearance of new ideas. Yet another type of emergence is the one encountered in social evolution, which corresponds to the appearance of new social structures and cultural innovations.

(ii) In a more personal classification, he distinguishes computational emergence, which is mathematically-based (formation of new formal structures), thermodynamic emergence, which is physically-based (formation of new physical structures), and emergence relative to a model, which is biologically-based. Due to the finite specifications of computations, computational emergence does not offer open-endedness, a necessary condition for describing biological evolution. Another flaw of computational emergence according to him is the fact that computationalists see emergent behavior in the formal devices themselves. This flaw does not exist in thermodynamic emergence, where physicists try to model the formation of physical structures without seeing any emergence *in the equations* describing the physical system. Thermodynamic emergence may be considered a first step towards a theory of emergent functions, the main difficulty being to make the link between structure and function. Cariani goes further by building a connection between emergence and adaptivity: formal devices are nonemergent, adaptive devices have syntactic-emergent behavior (are capable of creating new linkage relationships between previously defined observables), and evolutionary devices have semantic-emergent behavior (in order to model such devices, it is necessary to add new observables). Semantic emergence corresponds to functional emergence.

The question of knowing whether or not computations can carry the full essence of biological evolution, i.e. can offer functional (or only structural) open-endedness [defined by Cariani as the inability to define and enumerate in principle all the possible functions available to the device], is in the center of a strong debate. For Rosen like Cariani, formal systems do not provide any interesting kind of emergence (Rosen, 1978): "*We (...) do not 'learn' about a formal system, beyond establishing the consequences of our definitions through the application of conventional rules of inference, and sometimes by modifying or enlarging the initial definitions in particular ways*". It seems that theories of emergence are the most important support of Artificial Life, as well as in the new connectionist trends of cognitive science, but these theories so far have been mostly mathematically-structurally-based. The preferred medium for "experiments" is usually the computer, and the main idea is that a macroscopic order can emerge out of a populations of microscopic (deterministically) interacting elements.

Rosen's (and some others') objection to that article of faith is that "*in all dynamical theories, there is simply no visible source for (...) new observables*" (Rosen, 1978). According to that view, in order to produce truly evolutionary devices, one needs to give-up formal systems and look for more "open ended" devices. But, claiming that computer simulations and other formal processes cannot in the thermodynamic limit (i.e. when the number of parameters or of elements tends to ∞) describe evolution with an arbitrary degree of accuracy is like a philosophical conjecture. If this is just a question of specification length, other media may constitute an alternative, which allow for infinite variability by themselves: it is these "side effects" of the medium on the computational process which will render it open-ended. As Pattee noticed (Pattee, 1989), "*there are extra features of the simulation medium that are not to be found in the system, and as in all metaphors, these extra features are essential for the simulation to be effective*".

Finally, Emmeche (Emmeche, 1992) draws a parallel between AI's formalists' motto: "*if you take care of the syntax, the semantics will take care of itself*", and AL's computationalists' motto: "*if you take care of the computational setup, living behavior will emerge by itself*". Pattee (Pattee, 1989) draws another parallel between Artificial Life and Cognitive Science: he believes that "*the concept of emergence in AL presents the same type of ultimate complexity as does the concept of consciousness in AI*". What is shown by these two criticisms – that can apply to both Cognitive Science and Artificial Life – is that a working concept of emergence is needed, that is to say, a set of definitions that lead to well-defined research and simulation methodologies, because "*the concept of emergence in itself offers neither guidance on how to construct such a system nor insight into why it would work*" (Hillis, 1988). Thus, once one considers one particular definition of emergence, the question comes to "how can one achieve this type of emergence?" Cariani's thesis (Cariani, 1989) and Forrest's paper on "Emergent Computation" (Forrest, 1990) constitute two important attempts to give an operational definition of emergence.

VII. CONCLUSION

In conclusion, we have presented a review of the various conceptions of emergence that we have found in domains related to Cognitive Science and Artificial Life, in a broad sense. Of course, we do not pretend that this review is complete, but we believe it to be a good introduction to the notion of emergence, which, owing to its widespread use, is of central importance. It remains to see if and how all these conceptions can be understood in a common way. A framework for characterizing emergence is needed, especially if one wants to go further than the simple awareness that things "emerge" in the world. A step in that direction can be found in (Bonabeau *et al.*, 1995).

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