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COMPUTATIONAL DARWINISM AS A BASIS FOR COGNITION

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Abstract

In this work we attempt to distinguish, in a biological frame, adaptation from cognition. Ontogenetic adaptation arises as a second order (sensorimotor) loop on the ground of the operational closure that provides autonomy and reproductive identity to the living system. Adaptation ensures the functional correlation between metabolic-motor states and the states of the environment. Later, cognition is carefully distinguished from the ontogenetic adaptive mechanism of the living system in that instead of a control on metabolic-motor processes, it effects a control on information. This is achieved by the construction of a network formed by patterns of meta-stable components (symbols), which is, in its turn, controlled by the system from another level (rules). In this sense, a new idea of biological computation is presented, necessary to distinguish cognitive processes from the adaptive ones. This account of cognitive processes makes it possible to distinguish and correlate its semantic (sensorimotor), syntactic (computation of discrete results) and pragmatic (motor action) levels in an autonomous frame.

Keywords: Biological Computation, Cognitive Primitives, Adaptation, Autonomy, Sensorimotor Loop.

Résumé

Dans cet article nous essayons de différencier, sur une base biologique, adaptation et cognition. L'adaptation ontogénétique intervient comme une boucle du second ordre (sensori-motrice) liée à la clôture opérationnelle responsable de l'autonomie et de l'identité reproductive des systèmes vivants. L'adaptation assure une relation fonctionnelle entre états métaboliques-moteurs et états de l'environnement. La cognition

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se différencie des mécanismes ontogénétiques adaptatifs du système vivant, dans la mesure où elle crée non pas un contrôle des processus métaboliques-moteurs, mais un contrôle informationnel. Ce contrôle est obtenu par construction d'un réseau de composants métastables (symboles) qui sont à leur tour contrôlés, à un autre niveau (règles), par le système. Ainsi, une nouvelle conception de la computation biologique est présentée, amenant à différencier processus cognitifs et processus adaptatifs. Cette conceptualisation des processus cognitifs permet de spécifier et de corréler les niveaux sémantique (sensori-moteur), syntaxique (computation discrète) et pragmatique (action motrice), dans une perspective autonomique.

1. Introduction

From a biological point of view, a definition of cognition faces the difficulty of telling among the set of relations of the organism with its environment, which are the ones that should be properly considered cognitive. The aim of this work is to show the difference between the notion of adaptation – in an ontogenetic sense – and cognition.

Given the variability of the ecological niche where they live, organisms develop mechanisms of adaptation to preserve their living functions. On a phylogenetic scale the solution to this fundamental problem is given by evolutive mechanisms. But we see that when organisms are focused as individuals, each one has as well mechanisms of adaptation – non-hereditary in this case – to changes of the environment. Even the simplest organisms known at present possess some sort of "sensor organ" that performs evaluations of the physical parameters of its environment that are functionally relevant for them to subsequently produce structural or behavioral changes that ensure a suitable performance of their living functions.

Yet, even if in the biological domain it is often thought that cognition is a type of adaptivity, it seems clear that it implies phenomena that are more specific than those involved in simple individual adaptation. The idea we are defending here is that the functions that are usually considered cognitive are the result of a specialised subsystem of the organism continuously reconstructing patterns that are functional or referentially correlated with certain changes occurring in the environment. This set of patterns makes up what we usually call "representations" and it is built up during the existence of each cognitive organism, but disappears with it. Obviously, every adaptive process on an individual scale starts with some kind of perceptive action over changes taking place in the organism environment.

Then, while non-cognitive organisms respond to those changes only by means of metabolic-motor actions, the cognitive ones, in addition to that, specifically process the information obtained from perceptive action.

2. Is every living organism an ontogenetically adaptive system?

If we only think about present forms of life, the answer will be yes. But, when we analyze the minimal criteria for defining life as a whole phenomenon, probably some phylogenetic or evolutive capabilities of adaptation might be sufficient to successfully face the changes in the environment. In fact, even when we refer to individual living beings, a definition of life has to consider its dimension as a global phenomenon: life as a recursive network formed by living units whose collective interaction produces the necessary conditions for the viable existence of the units themselves. Phylogenetic adaptation studies the changes undertaken by individual units in the context of the operation of the whole network of living systems.

When we place ourselves in this viewpoint, a living unit is defined so that the operations for the self-maintenance of the individual entity (a network of molecular components) involves self-reproduction (Csanyi & Kampis, 1985; Moreno, Fernandez & Etxeberria, 1990). As a development of ideas suggested by von Neumann (1966), Pattee (1977, 1982) has contended that only a network of components that constitute themselves in two complementary levels – dynamic and informational – allows a viable reproduction of this kind of systems (*fig.* 1). Thus, the minimal condition for the appearance of an evolutive process by mutation and selection is the formation of autocatalytic networks with functional and informational components operationally entangled through a mechanism of coding. This kind of system (genetic loop) ensures a mechanism of adaptation on a phylogenetic scale.

It seems reasonable to suppose that populations of individuals of this kind of "minimal living system" would appear presenting some drift of metabolic plasticity. These, in fact, represent different alternative solutions to successfully face sudden changes in their environments. In this way, every set of newly born living organisms can mean the appearance of a variety of metabolic-motor responses, sufficient to ensure the survival of at least a percentage of the whole population. Given that these minimal biological systems might be only phylogenetically adaptive, the appearance of ontogenetically adaptive organisms must have taken place with the arousal of a new informational-dynamical closure (the sensorimotor loop), which does not define the identity of the system, but its mode of relation with the environment (*fig.* 2).

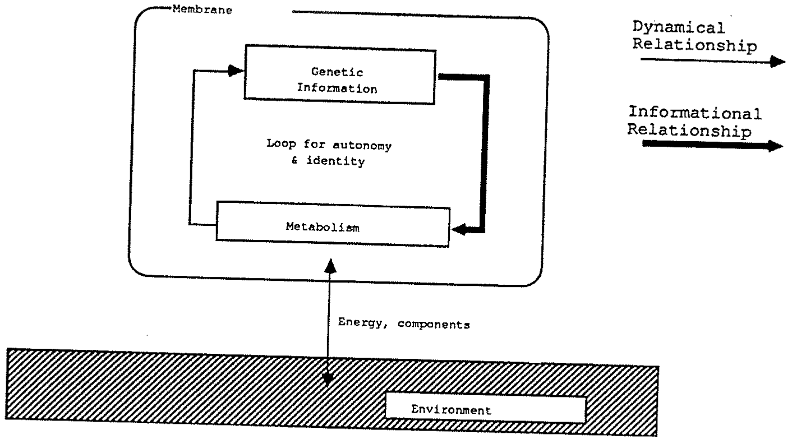


Figure 1. A minimal biological system.

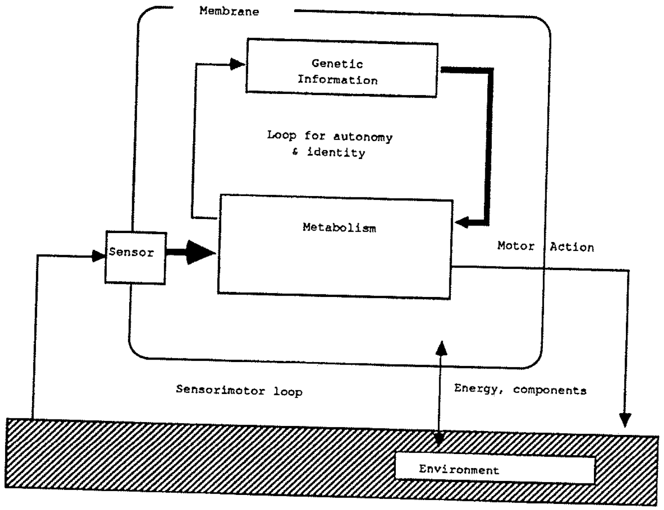


Figure 2. An ontogenetically adaptive system.

3. How did the sensorimotor loop appear?

The main theoretical questions are raised precisely in the most primitive forms of life. How can we determine in what consists a perception? Where

do "sensors" begin and where do they end? How can a perceptive action be distinguished from a motor one?

Perception has been defined as an act by which a system establishes an intentional relationship with its environment. But if we ask what perception is from a physical point of view, we can see that it is a phenomenon equivalent to measurement (Pattee, 1982; Conrad, 1988). In other words, it is a many-to-one mapping starting from a physical state that is assumed as continuous and a discrete or meta-stable state that is functionally interpreted (Rosen, 1978; Minch, 1988). This operation must be in addition repeatable. What structures will meet the appropriate conditions to act as sensors at the level of elemental organisms (e.g. bacteria and other unicellulars)? Only certain macromolecules, situated at the system boundaries and capable or steric recognition and non-linear pattern change seem to be the suitable candidates. In the most primitive forms of life, however, the existence of membrane proteins only can be considered to be generically functional, for it does not exist any subsystem or mechanism capable to interpret these functions as "perceptions" or "motor actions".

Therefore, to assert that there exists an elemental perceptive function it is not enough to look for certain structural requisites that could ground it. We have to ask as well what kind of organization or network is required so that the organism interprets in an autonomous way some physical changes of its boundary as perceptive information. A capacity to functionally correlate certain changes in the sensors with specific metabolic actions is also involved. If what defines the living being is the fact that it is constituted by a network whose operations ensure its autonomy (in the sense of a capacity to establish by itself its own functional needs), then every interaction between the minimal network and its environment acquires a functional meaning ("good" or "bad" for the network). In other words, the existence of a minimal network that ensures the autonomy of the organism brings about the possibility of having a way of testing the correlations between changes in the sensors and metabolic actions; the testing minimal network is placed in a "meta-network" frame. This is, in fact, what happens in all organisms known at present, even in the most primitive ones whose sensors are simply certain membrane proteins that change their conformation or pattern in the presence of physical or chemical variations of the environment.

Anyway, to be able to talk of test or evaluation it is not enough to refer to the principle of functional action implicit in the described mechanism. Every evaluative activity requires the existence of a source of variety on which the selective mechanism operates. At this elemental level, variety means a repertory of metabolic plasticity that is compatible with the maintenance of the identity of the organism. We could point out a series of general principles of selection, like the tendency to shorten paths and redundant processes or to maintain a balance between an increase of the energetic costs of reproduction (as the complexity of the system increases) and the adaptive advantages of the more complex systems. But at the end, the key to the problem is that all correlations have to satisfy the genetically prefixed conditions for the self-maintenance of the network.

Therefore, it will be the network of genetic information, acting as a test mechanism, what allows the arousal of a new informational network. As it provides a principle for testing the perceptive-metabolic correlations, the selective search of the functionally adequate correlations will be in fact the result of a trial and error procedure.

Ontogenetically adaptive systems are endowed with two types of loops: the genetic one, that ensures the maintenance and reproduction of the identity of the system, in the form of a blueprint or instructions with a self-referential meaning (Moreno, 1986); and another, sensorimotor, originated by physical changes of the environment that are recognized by the membrane proteins and has functional or motor effects. There are fundamental differences between the two of them. In the first case, genetic information is self-referential, because its semantic referent coincides with its causal action. Given its function it usually remains unchanged along the lifetime of the individual. In the second, the referent of perceptions – some physical changes of the environment – is different from the domain where its causal action – a metabolic functional control – is performed. Because of their epistemic character, perceptions are created and disappear in the lifetime of the individual organism, and they constantly change according to variations of the environment (*fig.* 3 *a* and 3 *b*).

4. Differences between Adaptation and Cognition

Once epistemologically outlined the adaptive mechanism (from here to the end we use "adaptation" only to refer to processes occurring at an individual scale), we are prepared to pose the following question: can perceptive-functional organisms whose adaptive processes are based on an enzymatic control be considered really cognitive? Although phenomena such as taxia, as they are primitive forms of perception-action, can be considered generically cognitive, the usual sense we give to the term is related to the development of learning[1], memory and anticipatory behavior. To realize this functions it is simultaneously required a big increase of elaboration of perceptive

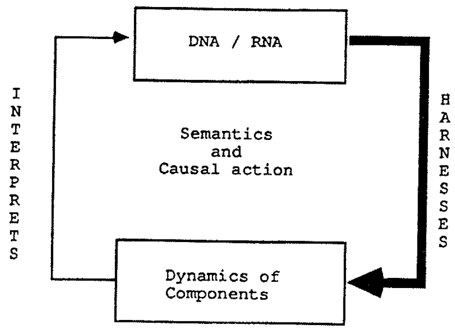


Figure 3 a. Genetic loop.

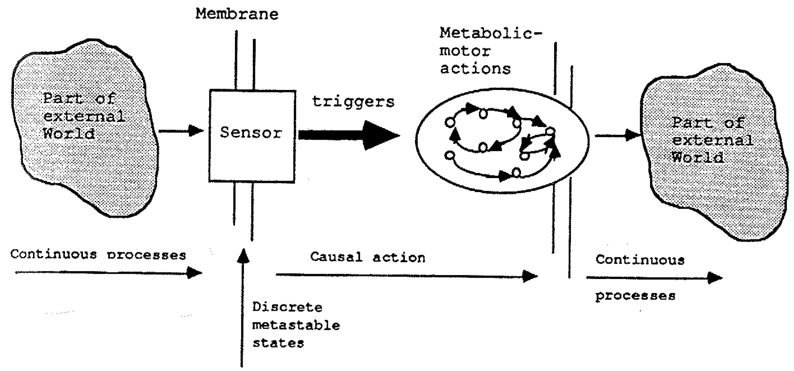


Figure 3 b. Sensorimotor loop.

information, a complex process of transformations and reorder of information, and a sophistication of the motor device (that is to say, of the final expression of information in physical and chemical actions).

Our hypothesis is that the appearance of what we call cognitive capacities was only possible when in the course of evolution some organisms developed a specialized system of elaboration, processing and expression of perceptive information. Thus, in contrast to the previous types of adaptive response, exclusively based on the control exerted on metabolic processes, cognitive functions are based on the control on information (*fig.* 4).

While in purely adaptive organisms perceptive information is, as we said before, the direct cause of functionally-adaptive metabolic-motor actions, in cognitive organisms the physical patterns impinging on sensors are trans-

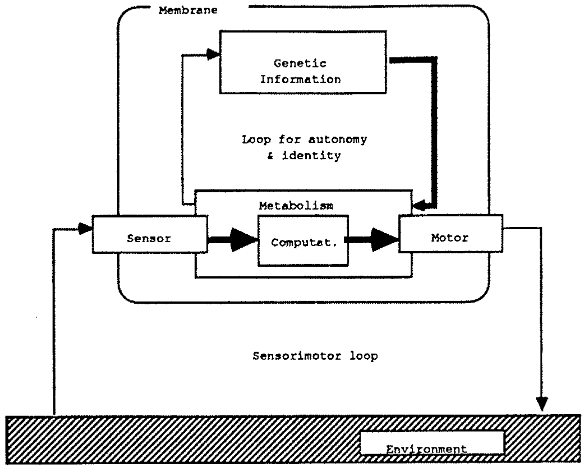
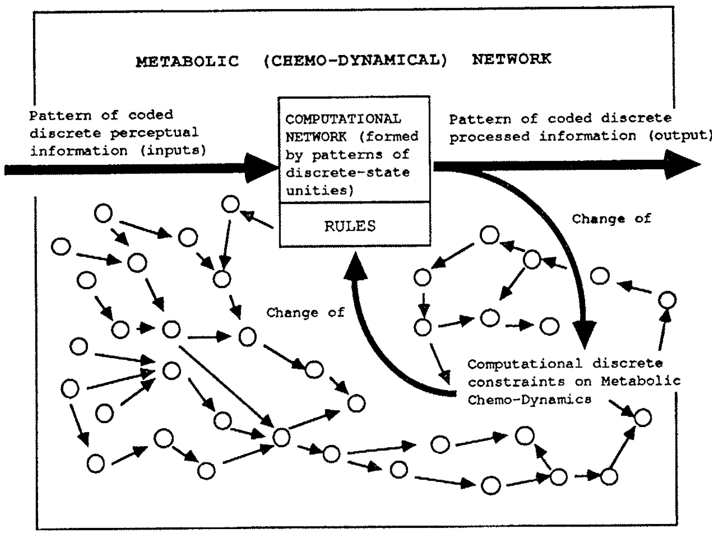


Figure 4. Metabolic and informational processes in Cognitive Systems: a model.



Detail of Figure 4.

formed in trains of discrete sequences that modify the dynamics of a network of information processing. It is from this viewpoint that it can be interpreted that certain informational patterns of that network are "representations" of processes of the environment. Very clearly the biological function of these informational patterns is to ensure the maintenance of an adequate relationship between the activity of the organism and changes in the environment.

There is a main reason why only those organisms whose interaction with the environment is performed through a specialized system of processing the information coming from perception can exhibit a fully cognitive evolution. Because the construction of cognitive maps is detached from the other global metabolic functions, cognition makes possible a minimization of the energetic costs of the mechanism of selection of representational patterns by trial and error. As a consequence of it, cognitive organisms can construct and control a potentially unlimited variety of representations of the environment. All the functioning of the cognitive system is based on a strong selective process of the high number of the available informational patterns[2]. But, at the same time, the bigger it is the number of informational patterns or configurations of which the system gets rid, the bigger will be also the knowledge it acquires.

This selection can be achieved either by 1) a modification of the processes that control the relations between discrete informational states, 2) a modification of sensor organs, and/or, 3) a modification of motor organs. Nevertheless, this does not mean that the whole cognitive system has homogeneous plasticity levels. Organisms are the result of a long evolutive process that structures in the course of phylogenetic changes several cognitive levels, some deeper and more stable, others more plastic.

All this shows that the key concept to explain the differences between the respective epistemic capacities of the purely adaptive systems and of the properly cognitive ones is that of "information processing". Anyway, it is important to clarify that the opposition we have placed between the notions of control on metabolism and on information does not intend to deny the fact that all biological processes can be basically described in physico-chemical terms. The point is whether a description in those terms is useful to study phenomena that involve complex representational operations, and we think it is not. This case is similar to the one of introducing an informational vocabulary to study living autocatalytic networks in opposition to the non living ones. Therefore, we are in fact claiming for the necessity of introducing a new frame of description to understand the specificity of the cognitive phenomenon. And, as will be explained in the next section, this new frame is articulated around the idea of computation.

5. Artificial and Biological Computation

Given the multiple, often vague and ill-defined meanings attributed to the term "computation", it is important to briefly explain our reasons to introduce it here and the differences we find between its use in artificial systems and in the natural (biological) ones. "Computation" usually refers to that process in which a system goes through a number of steps, from an initial state to a final one, that is considered a "solution"[3]. The main point about computation and what essentially distinguishes it from any other system based on the harnessing of dynamic processes, is that the computational path has a non-inherent physical character, it depends on rules acting on discrete tokens – symbols – (Moreno, Fernandez & Ibañez, 1989). From the physical perspective, a computational system is a highly constrained type of dynamic system, where 1) certain meta-stable states are functionally treated as discrete and 2) the action of an external programmer is a different dynamics applied on those discrete states. When these applications produce well specifiable and repeatable actions among discrete states, this level is functionally equivalent to rules. In this way, through the action of rules on symbols, any logically possible action is realizable and it is possible to construct "formal" universes physically within the limits of the space, time and energy resources of the system.

To talk rigourously of the existence of computational processes in living organisms, it is important to understand that the primitives of computation –symbols and rules – must be recognizable in the frame of the autonomy of the system itself, and not in the one of the external observer/programmer. This involves three basic methodological conditions:

1) It has to be justified that the functionality of the system authorises to consider some of its meta-stable states as symbols for computational operations. That is why these discrete states taken for symbols should be connected to sensor and motor organs.

2) A recognition that the relations among discrete elements depend on mechanisms that are equivalent to transition rules, and therefore, repeatable and modifiable by a level external to the operation of computation itself (but not external to the organism).

3) Mechanisms found responsible for change of rules have to be autonomous in respect to the functioning of the computational process and depending on the functional evaluation of the sensorimotor loop[4].

For these reasons, it is somehow paradoxical to talk about biological computation. It is a phenomenon that takes place in systems where the network of dynamic, rate dependent interactions of components of the lower level let the functioning of part of their structure at an upper level be assimilated to a rate-independent processing of discrete tokens. At this level, any form of intrinsic dynamics among discrete elements is suppressed, and the operations undergone by them are fixed guide-lines at another level of the system. But, on the other hand, the action of this other level cannot be completely external and independent in regard to the rest of the organism and its sensorimotor relationship with the environment. Then, as the computational network itself is part of the whole organism, the result of the computational operations is executed through constraints on a continuous dynamics. This one is evaluated once it is in contact with the environment by the sensorimotor loop. Evaluation causes a selective pressure on diverse parts of the system; at the computational level, this selective pressure modifies the information processing rules. Thus, the only possible way for a biological system to function in a "computational/syntactic" way is, paradoxically, through the self-transformation of its own rules. In other words, the results of the computational operations can exist biologically only if they lead the system/organism to functionally modify the level (rules or program) that governs these operations, which involves a syntactic self-modifying capacity (Detail of Figure 4).

6. Limitations of Artificial Models

In the last years a great effort has been made to overcome the evident differences between natural cognitive systems and models inspired in classical computational machines (von Neumann architecture). This has brought about the construction of new models that try to artificially simulate more and more the autonomous character of cognitive processes in living systems (McLelland & Rumelhart, 1986; Langton, 1989; Langton *et al.*, 1991; Conrad & Rizki, 1989). A good recopilation of recent works on this area can be found in the monograph edited by Forrest (1990).

Nevertheless, it is precise to recognize that there are still certain very important problems. We will focus the following two in particular: the recognition of emergent processes in relation to the autonomy of a cognitive system and the problem of materiality. In regard to the first one, it is known that one of the subjects on which more questions can be posed is the creation of new meanings in the universe of computational simulations (Cariani, 1989). In some models implemented on digital computers presenting certain "emergent" capacities like recognition of forms (see, for example, models proposed by Atlan (1983) or Varela (1984) and their respective epistemological interpretations) the problem lies on deciding if it is possible to interpret those emergent properties as a creation of new primitives in the frame of the model or in the one of the observer. We find that the design of an artificial cognitive system that emulates the autonomy of the natural ones has to incorporate some kind of functional appliance on its own emergent behaviors. But a system like that should be based on different principles from Turing computation. For, within the framework of the latter every process – even those interpreted as "emergent" in other levels of description – is not but a deterministic and repeatable consequence of the initial conditions and the transition rules (Levy, 1986; Kampis, 1990).

There remains, finally, the problem of materiality. In computational simulations of dynamic systems it is assumed that their material specificity is irrelevant for the simulation (Ashby, 1962; Hofstadter, 1985). But a computational simulation of a natural cognitive system not only has to represent the causal processes of the material world in the formal universe of the model (Rosen, 1985), but also the non linear mapping processes of a physical level into a symbolic one, and inverse. That is to say, by a symbol system representing material relations it has to model how symbols emerge (measurements or perceptive information) from those material relations and the causal action of those symbols on the underlying material relations (control or motor-functional mechanisms) (Fernandez, Moreno & Etxeberria, 1990). Therefore, it does not seem that the principle of designing material systems on the basis of a radical separation between the logical (software) and the physical (hardware) structures will allow, by an exclusive implementation of formal relationships, an adequate representation of the referred interrelation of levels.

Besides, unlike digital simulation machines, cognitive organisms are systems where the material structure is deeply entangled in their informational structure. Even von Neumann (1966), when studying the problem of a machine capable of reproducing itself, was conscious enough of the problem of materiality to ask why living systems are constituted precisely of a certain kind of components. Conrad (1988) has recently suggested that the enzymatic recognition of a substrate – a phenomenon that grounds nearly every process that is relevant for life and cognition (Koshland, 1982) – only can be explained as a phenomenon that occurs in between the quantum and the classical worlds, because of the critical size of those macromolecular structures. It is regrettable that many of the enthusiastic followers von Neumann has today have forgotten his words to observe that by axiomatizing automata in this way half of the problem (referring to the material part) has been thrown out of the window, and it might be the most important half (von Neumann, 1966).

7. Conclusions: epistemological criteria to detect cognitive systems

We have claimed that among the range of all possible epistemic interactions of organisms with their environments, the ground for the development of cognitive capacities is constituted only by the appearance of living beings endowed with a computational network in the course of evolution. Thus, the existence of organisms with individual adaptive capacities is not in itself a sufficient condition to speak of cognition. But, what is the simplest arrangement of a computational network in living beings? In the previous pages we have avoided to explicitly talk about the nervous system, because even if it is true that it is the clearest candidate for it – because of its flexibility, functioning speed, and coevolution with sensorimotor organs – the existence of other computational network of a cognitive character cannot be discarded. Several authors (Farmer *et al.*, 1986; Varela *et al.*, 1987) have defended the idea that the immune system has a cognitive character as well, for it ensures a form of self-organized identity of the organism in the frame of a changing environment. Anyway, even if the immune system acts mainly on a molecular level it is not less complex than the nervous system in evolutive terms, nor does if raise the same consensus in its characterization as an essentially epistemic mechanism (and not genetically adaptive).

Several proposals presented in the last years (Conrad, 1984; Hameroff, 1987; Koruga, 1990; Marijuán, 1991) that tend to explain even the most elemental perceptive-motor processes on the basis of pretended mechanisms of molecular computation taking place at the intracellular level also deserve a comment. Their main problem from an epistemological point of view is a confusion of criteria to distinguish dynamic processes from the computational ones. The conceptual difficulties that appeared when we tried to characterize biological computation grow when we try to determine clearly of processes like the enzymatic control of the cellular metabolism or, at least, certain dynamic changes in the cytoskeleton have or not a computational nature. In all these cases it is extremely difficult to distinguish which level of the system plays the role of rules or self-modifiable programs, which acts as support of discrete signals and what is the meaning of the processed information. Confusion also lies on the fact that the molecular computation they are talking about consists, directly or indirectly, on enzymatic control actions exerted on the informational sequences of DNA or RNA (Bennet & Landauer, 1985). In the latter case the problem is that even if it might be correct to talk of information processing, it is genetic and not perceptive. Therefore it is doubtful that it is related to the appearance of a cognitive system at a cellular scale, because the idea of processing discrete sequences at the level of the genome is nothing but a phenomenon of self-control on a prefixed set of instructions to direct a process of self-reproducing construction.

It is not by chance that we find that serious difficulties of conceptual kind appear when we attempt the study of the most elemental forms of cognition. After all, the same happens in so significative fields as the origin of life or the study of elemental particles. That's why our purpose in this paper is to offer some general theoretical criteria that can help to clarify the basic research of cognitive phenomena. The conditions presented in what follows are therefore both an epistemological and a methodological proposal. In this sense, these criteria are offered on the one hand as an horizon where the respective research programs of Artificial Intelligence and Artificial Life (Langton, 1989) can ideally converge and, on the other, as a ground to conceptually and epistemologically distinguish cognitive science from its biological background.

Thus, these are the three essential criteria proposed to characterize a system as cognitive:

1) It must be possible to distinguish three autonomous subsystems in the system: sensors, which provide the semantic primitives for the system; a computational network, that operates syntactically on the information provided by sensors and, finally, effectors, that physically express the processed information.

2) At the same time, both in the evolutive scale and in the lifetime of each cognitive organism, there exists an interrelation among the processes that take place in the three mentioned subsystems.

3) There are three different levels of epistemic networks, starting from the first perceptive-motor organism to systems formed by complex hierarchies where networks at a certain level are at the same time units of a higher level: where what at a certain level is interpreted as discrete becomes continuous at another, and vice versa.

As a summary, organisms with cognitive capacities automously establish the frame and the level of their relations with the environment, assigning new functional meanings to the new computational patterns aroused within the system. In cognitive processes there exists a testing mechanism that, depending on the modifications imposed to the sensorimotor loop by the conditions of the environment, indirectly constraints the computational processes depending on the interaction with the environment and in accordance with the network that ensures the identity of the organism.

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Notes

1. Learning brings about a qualitative change in regard to adaptation, the most generic and simple form of optimization at an individual scale. Learning implies the idea of acquisition of new knowledge, in the sense that the organism links what formerly appeared unconnected before it and/or discriminates what appeared as an undistinguished whole. In other words, it means the capacity to change its own codes of meaning. Nevertherless, it is evident that to avoid a distruction of the previously acquired information by the creation of new meanings, the former must be functionally reinterpreted in the new codes.

2. Edelman (1987) has recently defended the idea that the principles governing all the selective processes of the cognitive system are similar to the ones proposed by Darwin to explain the evolution of species.

3. In biological systems the computational process is a set of operations grounded on a network type of functioning. Therefore to consider certain states as "initial" or "final" is only meaningful dependending on the interconnection of sensors and effectors, not on the dynamics of the network itself.

4. The last two points can be interpreted according to the non-programmability principle that Conrad (1984) considers a fundamental characteristic of biological computation. There is, anyway, an ambiguity in Conrad's formulation that does not permit to clearly decide whether his concept is compatible or not with the idea of "internal rules". The problem lies in the following: if rules are internal, then computation does not belong to the domain of the described system, but if we disregard the concept of rules, it is not easy to see how to distinguish between computational and dynamical processes (Pattee, 1989).

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