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How do heterogeneous levels with hierarchical modulation interact on a system's learning process?

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Abstract

In former Baden-Baden Conferences, the authors have presented a mathematical model, based on Category Theory, for natural open self-organizing systems, such as biological or sociological systems, and more specially neural systems. The dynamics of such a Memory Evolutive System is modulated by the competitive interactions between the global system and a series of internal more or less specialized Centers of Regulation (CR) with differential access to a hierarchical Memory, in which complex units are obtained by integration of more elementary ones. Each CR, at its own complexity level and time-scale, forms an internal representation of the system (its 'landscape') and elaborates strategies on it through a trial-and-error learning process. Conflicting strategies may lead to fractures in some landscapes, to be resolved later on.

Here the goal is to study how this 'dialectics' between heterogeneous CRs might generate higher order cognition. The tentative idea is that it provides the means for Semantics to arise through pattern recognition developing into conceptual learning thanks to categorization of memorized items. Then, in neural systems, fractures in a higher level CR lead to an increase in awareness which permits backtracking into lower levels in the scope of the CR 'actual present' to detect the causes of the fracture and devise strategies to reduce it, thus creating a re-entry process of the type by which Edelman characterizes consciousness.

Keywords. Systems. Categories. Memory. Neural system. Semantics. Consciousness

1. Memory Evolutive Systems.

Memory Evolutive Systems are a mathematical model for autonomous systems with a hierarchy of more or less complex components, which change in time but preserve their overall structure, and are able to use their preceding experiences to get a better adaptation to the environment. The model is based on Category Theory, which allows to characterize a complex object as the coherent binding ('inductive limit') of the pattern representing its own internal organization, to study the interactions between various imbricated complexity levels, and to describe in a computational setting the evolution of the system under the 'complexification' process accounting for the four archetypal changes: creation/annihilation of components, formation/decomposition of complex objects.

The model has been developed in (Ehresmann and Vanbremeersch, 1987, 1989, 1991), summarized in three papers presented to the preceding Baden-Baden Conferences organized by Professor Lasker in 1988, 1989 and 1990 (denoted EV1, EV2, EV3) to which we refer. Here we only outline the necessary notions to go deeper into the nature of a complex system and its cognitive abilities; we will emphasize the ideas rather than give technical details (to be published elsewhere).

In a MES, the state of the system at a given time is modelled by a category, formed by its components and the interactions between them. The arrows (or links) toward an object A correspond to the aspects of the system observable from A, or causal factors for A. The links going out of A model the effects of A on other components, e.g. transfers of informations, energy or constraints.

The system has an organizational hierarchy, with its objects separated into various complexity levels: an object of level $n+1$ is the cohesive binding of a pattern formed by its own components C_i of the lower level n and some specific links between them; the pattern operates as a synchronous coherent assembly of which the complex object is but the integration; the distinguished links are essential since they impose the shape of the complex object and make the difference with the amorphous aggregate (or 'sum') of the C_i . (Cf. EV1)

The evolution of the system, represented by transition functors between successive state-categories, depends both on internal modifications and on informations, exchanges or constraints originating from the environment. While 'black box' models center on the correspondence 'input-output', we try to characterize the functioning of the black box as it occurs from an internal point of view. ence in a MES there exists a Command Hierarchy Hformed by a family of internal regulatory organs called Centers of Regulation (CR), each with its own complexity level and propagation delay. These CRs operate in parallel by a trial-and-error learning process with eventually conflicting strategies to modulate the general dynamics of the system. In the lower levels, specialized CRs receive direct informations from the environment; in the higher levels more associative CRs with longer propagation delays supervise several other CRs. But all the CRs have a differential access to a central hierarchical Memory, which they concur to develop in time; its development dispenses from multiple analyses of the same situation, and allows for more adapted and quicker answers. (Cf. EV3)

While space does not intervene *per se* in this scheme (that is very different from the most usual mathematical models based on differential equations), Time, seen as Change, takes a great importance, for the emergence of complex behaviours will result from the interplay between the time-scales of heterogeneous CRs. Indeed, the learning process for each CR is done stepwise, according to a scale of time in which the length of the steps depends on the propagation delay of the peculiar CR and determines its 'actual present'. At each step, the CR, as an observational organ, constructs its own internal representation P of the global system, called its *actual landscape*. As a command organ, it selects a strategy on P consisting in the addition or subtraction of some elements, disassociation of some complex objects, strengthening of some patterns so that they acquire an identity by their cohesive binding into a new complex object of a higher level. The anticipated landscape P' at the end of the step should be the 'complexification' of P with respect to this strategy. However, since there is a competition between the CRs and each one has only a distorted view point of the whole, the strategy may not be enforced and there will be a difference between P' and the 'real' landscape. As a control organ, the CR measures this difference (by the comparison functor) and concurs to memorize the strategy and its result for ulterior use. (Cf. EV2, EV3)

2 . The dialectics between heterogeneous centers of regulation.

The strategies of the different CRs are only repercuted to the system with a distorsion and they are competitive. Hence conflicts may arise and block the operation of some CRs: we say that there is a *fracture* for a CR when its present step must be interrupted before its normal completion, because a change of strategy is imposed by constraints from the environment or from other CRs. These fractures modulate the general evolution of the system; though they are disruption factors, they are also a source of informations since they reflect the irruption of the exterior in the 'closed' description given by the CR landscape; to surmount them can be a creative process, leading to a better adaptation.

The distorsion enforced by the fractures will be measured by a comparison functor from the *total landscape* to the system. The total landscape **P** is constructed by glueing (in a technical way we cannot detail here) the landscapes of the different CRs and their correlations at a given date, so that each CR has the same landscape in the system and in **P**. Though this construction is purely abstract, it englobes the informations gathered by all the CRs, and reflects the functioning of the Command Hierarchy as it is shaped by the dialectics between the various CRs; in particular, it helps recognize the following specific features of a complex system.

Two CRs are *heterogeneous* if their complexity levels and time-scales are very different. so that there are a great number of steps for the lower landscape during one (macro)step of the higher one. (Micro)modifications will be ignored at the higher level up to the time their accumulation causes a fracture in its landscape. During the macrostep, the dynamics of the higher level CR will be similar to that of a simple physical system (for instance it might be described by partial differential equations depending on some parameters). But it represents only an approximation of the total system, valid locally (at this CR level) and temporarily (up to the fracture). After that, the higher CR will have to modify its strategy, leading to a new approximation for the system (described by a change of parameters after a Thom's 'catastrophe'). (Cf. EV3)

This process emphasizes the difference between *simple* (physical) systems and *complex* (biological, sociological or neural) systems (cf. Rosen, 1985): the same physical laws govern all these systems, but they have to be applied only between strict local and temporal bounds for complex systems. It also transcends the *determinism/indeterminism* problem. Even if, at each step, a unique strategy is available for a CR on its landscape (determinism), this strategy may be interrupted at an unforeseen date because of a fracture created by the differences between time-scales. So the dialectics between heterogeneous CRs may generate chaos or disorder in the macro-description, making long term prevision impossible. Remark that the situation is more complex than a complementarity between two descriptions (of the kind wave/particle), since there is a whole family of interacting competitive CRs, not only two. 'Free will' would take another meaning in a MES: even if a CR seems to have some latitude of choice with respect to those CRs which it knows of, it is possible that its operations are restricted by lower CRs of which it receives no direct informations, except via fractures.

And the *reductionnism/holism* problem takes another formulation: in the brief term, the evolution essentially depends on lower levels, since the behaviour of a complex object depends on that of the coherent assembly it binds; but this functional reductionnism is contradicted by the irruption of fractures caused at the higher levels by an accumulation of microchanges; these fractures force a change of strategy to the higher levels to maintain their homeostasis, and this change is repercuted to the lower levels, modulating the long term evolution. Roughly, the higher levels with longer time-scales are more stable, but their fractures are more dangerous for the system, since they will retroact on the levels which they supervise. In Section 3 we try to defend the (we hope not too preposterous!) thesis that the dialectics between CRs might explain the emergence of higher cognitive processes in neural systems, up to consciousness.

3. Higher cognitive processes.

Here we assume that the MES models a neural system, as it is described in EV2 and EV3. Though this hypothesis is not essential, it will help state the results in a more comprehensive way, and compare them with the theory of (Edelman, 1989). We recall that such a MES is based on the category of neurons: its objects represent neurons, their links are classes of synaptic paths with the same strength; successive complexifications lead to the addition of more and more complex units, called *'category-neurons'* (or orchestra-neuron in EV2). A category-neuron represents a synchronous assembly of interconnected neurons in
the sense of Hebb (neuronal group for Edelman), the activation of which corresponds to a particular mental process (perceptual experience, motor command, cognitive process...). One of the advantages of our categorical model, compared to other neural system approaches, is the explicit construction of the links between category-neurons (by the complexification process, cf. EV2). It gives an algorithmic description of the MES and leads to the construction of an 'algebra of mental objects' (in the sense of Changeux, 1983).

In the Command Hierarchy the CRs represent more or less specialized sub-systems of the brain in charge of some operations (for instance, particular visual or motor centers). Various dissociative syndromes have proved that specific types of informations are effectively handled by such separate modules. In the higher levels, more associative CRs supervise several lower CRs. The actual landscape of a CR at a date t acts as its working memory; it has been constructed (cf. EV3) by gathering aspects of the system observable by the CR during its 'actual present'; that an aspect be observable or not depends essentially on the strength of the corresponding link. Learning consists in modifying the strengths of some links, in particular to reinforce assemblies of neurons and transform them into new category-neurons. This process leads to the development of the Memory by formation of a hierarchy of category-neurons. Though the CRs participate in this development, the memory is a central system, to which each CR has only a differential access.

The dialectics between CRs exploits the flexibility of the model deduced from the following double *degeneracy* property (in the sense of Edelman, 1989, p. 50): - 1. several patterns in the memory may have the same category-neuron N as their cohesive binding, so that N is 'activated' (or retrieved) as soon as anyone of those patterns, say Π, is activated. Then Π retroacts on a particular CR by the activation of the more or less large pattern π in its actual landscape P consisting of those aspects of Π observable in P. The pattern π (or its cohesive binding in P) will be called the *trace* of N in P; the trace depends on the choice of Π. Two different category-neurons may have isomorphic traces in P while their traces in the landscape of another CR are not isomorphic. Whence a *'categorization'* of category-neurons with isomorphic traces, specifically depending on the CR. - 2. Conversely, the same pattern may participate in more than one category-neuron (for a physiological confirmation, cf. Meyrand et al, 1991). It follows that a pattern π in the landscape P of a CR can be the trace of several category-neurons, say N_i. If π is selected by the strategy of the CR, which one N_i is 'really' activated after repercution to the system will depend on the global situation, e.g. on the strategies repercuted by the other CRs. - These properties are essential to explain the dynamical formation of the following evolutionary sub-systems of the memory.

A. Perceptual Memory. At each of its steps, a particular CR will analyse its actual landscape to sort out new activated patterns of aspects, and search if similar previous experiences are memorized. In the affirmative, it will retrieve, from its (aspects of the) memory, the strategies already associated to them, and select the more appropriate one in the actual landscape context. If part of the present perceptual experience has not yet been encountered, its storage as a category-neuron will be programmed in the following strategy. The storage process is made in parallel by the different CRs, but on the different aspects of the situation they perceive and with their own time-scale. The global result consists in the strengthening of assemblies recruited through the different landscapes, so that they become category-neurons added to the central memory, to memorize the corresponding perceptual experiences. The *'percepts'* so defined form a special evolutive sub-system of Memory, called *Memp*. Learning leads to more and more complex percepts being stored, by cohesive binding of patterns in *Memp* .

Two percepts will be classified as 'the same percept' by a particular CR if their traces in its landscape are isomorphic; as we have said, it is possible even if they are not isomorphic in *Memp*. Perceptual invariances will result from such a classification in higher CRs.

B. Procedural Memory. Strategies are stored by a similar process, through the CRs, and they form another sub-system of the central Memory, called *Strat*. It develops from an innate kernel, consisting of some neurons or category-neurons corresponding to inherited behaviours or instincts. The objects of *Strat* model what Edelman calls a global mapping; they could also be compared with the schemas considered by several authors (e.g. Piaget or Arbib), or with Minsky's frames (their adaptability coming from the degeneracy properties).

The activation of a complex strategy Σ after its selection under one of its aspects σ through a particular CR requires a multiple coordination: first it activates some pattern of strategies σ_i admitting σ as its cohesive binding in the CR landscape ; which specific pattern is activated will depend on the global situation; and each strategy σ_i may itself retroact on other CRs to activate other patterns. For instance, the voluntary command to lift some object with the hand will activate the general 'prehension strategy' whatever be the object; but the scope of the motion, hence the patterns of effectors activated in lower motor centers, will depend on the exact location, shape and weight of the object which are determined via sensori-reafferences arriving through lower CRs. Moreover, the difference between the CRs time-scales helps explain how the same situation may elicit responses at different levels: if it is directly recognized by lower CRs with short propagation delays well equipped to answer, it will be settled before higher levels with longer propagation delays be even informed. So automatic or even reflex behaviors may replace voluntary ones, once they have been thoroughly learned and as long as no new factor interfers (think of the motorist who speaks while conducting).

The choice of strategies depends on their *evaluation*, hence on the storage and ponderation of the results of anterior experiences. The needs of the organism are measured in each CR through the strength of the links from a category-neuron representing the need to an evaluation-object +/- (example: the hunger center in the hypothalamus). Strategies will be ordered according to their ability to reduce the needs. For that, the result of a strategy Σ in a situation S (represented by an object of *Memp*) will be memorized by a link from the sum of S and Σ to the corresponding +/-. Fractures occur when the evaluations made by different CRs are conflictual.

C. Semantics. Thanks to the objects in *Memp*, the animal will be able to recognize the corresponding stimuli if they occur at a later time. But to interfer in a creative way with its environment, it is necessary that these objects acquire a 'meaning', and natural selection leads to the development of another evolutive sub-system of the central Memory, *Semantics*; its objects are called 'concepts' (this term does not assume that there is a language). A *concept* is a category-neuron C categorizing a class of items in the Memory which are relationally and functionally equivalent (technically, they have similar links toward other concepts, so that they all admit C as their 'free object' into *Semantics*). Basic concepts may also be defined either via the common features of their several representatives, or according to their similarity with a particular 'prototype'. An animal has some innate concepts, serving as a preliminary basis for comparison. Then it develops new concepts in connection with its sensori-motor behaviour. For higher animals, *Semantics* has a hierarchical structure, the concepts being themselves categorized into classes of more abstract concepts (for instance: the concept of 'dog' is a basic one, while a 'teckel' is a lower one and a 'mammal' a higher one). The links between concepts are the basis for the 'beliefs'.

In the case of man, language associates to each concept a word, so that *linguistic signs* are formed uniting a concept and its name ('signifié/signifiant' in Saussure, 1983). They also constitute an evolutive sub-system of Memory (connected to the Broca and Wernicke areas in the cerebral cortex). The categorical model gives another approach to some problems on the development of language by interaction between the sensori-motor experiences of a child and the vocal reactions of the humans with whom he communicates.

D. Consciousness. The dialectics between multiple heterogeneous CRs and the creative role of fractures might explain the development of more and more precise kinds of consciousness for a higher animal, thus making more explicit some ideas emitted in (Changeux, 1982, p. 227). We tentatively assume that an experience becomes *conscious* through a fracture generated on the actual landscape P of a higher CR by lower level (unconscious) CRs. The process could be as follows: A fracture in P increases the awareness of the animal, with the consequence that more aspects become observable by the CR; the CR may then *backtrack* in its expanding working memory to pinpoint the exact date and occurence F of the fracture. Then using the informations contained in *Semantics* and in *Strat*, the CR will search for the most probable causes of the fracture (in the categorical model, they are obtained as a free object in the field of F). This backtracking could be physiologically implemented by the re-entrant loops on which Edelman bases his theory of (primary) consciousness. And it agrees with Nietzsche's definition: to become conscious of something is to uncover motivations for it!

The emergence of consciousness gives a selective advantage in the long run. Indeed, while the usual operation of a CR tends to restrain the *effects* of a fracture, consciousness returns to its *causes*, so that the responses get more adapted (even if, in some circumstances, a less than optimal but quicker response is more efficient). Moreover, the memorization of these causes makes possible *projection into the future*, consisting in the search of a admissible strategies for several steps instead of only one, and also evaluating the risks of fractures. Language makes the prevision all the more efficient since it helps to represent complex items by a unique word, so that a greater number of informations are handled up in the working memory. Then thought could emerge from the dialectics between multiple (dualism is transcended!) CRs as the outflow generated by iteration of the back and fore movement of consciousness to overcome a sequence of fractures in a higher CR.

Consciousness with the oscillation between its two processes of backtracking and projection would amount to an internal integration of the temporal dimension (not apprehended by the lower 'unconscious' CRs). And self-consciousness could arise from the overlapping of successive conscious actual landscapes, set against this temporal perspective. Compare with Merleau-Ponty, for whom consciousness constitutes time, while, for Kant, time is the shape of our internal state. In fact, many philosophical problems may be formulated in our model; even if it does not help to solve them, at least they become more intelligible for us!

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