Position paper

A new approach to multi-scale complex systems and some open problems

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Multi-scale complex systems are ubiquitous in biology and in socio-economic areas. These evolutionary systems are 'multi-scale' in several ways: hierarchy of components of various complexity levels, multiplicity of internal regulatory organs, operating with different temporalities and different logics; however they maintain a global coherence, are able of some kind of learning and possess flexibility enough for adaptation to changes in the environment.

Usual models (based on non-linear differential equations, dynamic systems, graph theory, cellular automata, stochastic processes, or information theory) are well adapted to study local problems. However they cannot simultaneously take into account these different multiplicities, nor explain how the system can have both robustness and flexibility.

Thus new approaches seem necessary, in particular to treat the following challenging problems:

1. *Correlation between phenomena at different levels*: The system has a tangled hierarchy of components which may vary over time. How can an object of a given level 'bind' together (by self-assembly or under internal or external constraints) a pattern of lower levels objects, thus forming "a whole that is greater than the sum of its parts"? How to measure the 'real' complexity of an object? What are the interactions between objects emerging at each level? What makes possible the emergence over time of objects and processes of increasing complexity through successive "complexifications"?

2. *Self-organization*: The dynamic of the system is modulated by the cooperation/competition between a variety of agents, forming internal regulatory subsystems; each of these "co-regulators" has its own complexity and logic, and operates a stepwise process at its own rhythm. How can these co-regulators act cohesively in spite of their competition for the global resources and without any centralized control? How can the system develop higher procedural mechanisms or cognitive processes, and possibly act as an anticipatory system?

3. *Robustness* and f*lexibility of the system*: What are the characteristics which explain that the system can be both robust and flexible enough to be capable of storing and later recalling information on its environment and its inner processes, but also of adapting to changes in the environment? What is the role of the structural, temporal and energetic constraints in the genesis of critical events? How to anticipate failures and develop self-repair mechanisms?

To approach these problems, we have proposed (with J.-P. Vanbremeersch) a theoretical model, the *Memory Evolutive Systems*, based on a 'dynamic' category theory. I am going to sketch the main ideas, and to indicate the future developments needed for applications to real-world systems.

Category Theory

This theory, introduced by Eilenberg and Mac Lane[1] in the early forties, has a unique status, at the border between mathematics, logic, and meta-mathematics. It is a 'relational' theory with a foundational role in mathematics, and important applications in computer science. As an analysis of the main operations of the "working mathematician", it reflects some of the prototypical operations at the basis of science, explaining that it has applications in other scientific domains, for instance in the foundations of physics (quantum field theories and higher symmetries); or in biology (metabolism-repair model of Rosen[2]).

Let us recall the definition. A (directed multi-)*graph* consists of a set of vertices (its *objects*) and a set of arrows (or *links*) between them. A *category* is a graph equipped with a *composition law* associating to a 2-path (*f, g*) from A to B an arrow *fg* from A to B; this law is associative and each object has an 'identity'. It follows that each path admits a unique composite whatsoever its decomposition into successive 2-paths. In the application to systems, two paths which have the same composite will be thought of as 'functionally equivalent'.
The following examples show the ubiquity of categories: *monoids* are categories with only 1 object, a *preordered set* 'is' a category such that there is at most one arrow between 2 vertices; *groupoids* (or *groups*) are categories (or monoids) in which each arrow has an inverse; given any graph, the graph of its paths becomes a category if we take the convolution for composition.

Category theory is a still young active domain, open to the introduction of new notions adapted to specific problems, such as those raised by multi-scale complex systems.

Memory Evolutive Systems

A Memory Evolutive System (MES) gives an integrative model for a multi-scale complex system; it is doubly dynamic: because it accounts for the dynamic of the system, but also because it is not an invariant model but a flexible one, adaptable and in continuous evolution. I'll recall the main ideas in relation with the above problems; for more details, I refer to our book[3].

To account for its *global dynamic,* the system is represented not by a unique category but by a family of categories K_t indexed by time. K_t models the configuration of the system at *t* consisting of the states of its components and their interactions. The change of configuration from *t* to *t'*, by suppression of some components and addition of more or less complex new ones ("complexification process"), is represented by a partial 'transition' functor from K_t to $K_{t'}$.

The *hierarchy* of components is dealt with by dividing the components into a sequence of levels and imposing that an object C of level *n*+1 binds together a pattern P of linked components of strictly lower levels. The categorical "colimit operation" (Kan[4]) is well suited to represent this: C is modeled by the *colimit* of P, which is an object with the same functional role than the whole of P.
It follows that C has at least one top-down "ramification" to level 0. The smallest length of a ramification measures the 'real' *complexity order* of C, meaning the least number of steps necessary to re-construct C bottom-up.

[1] Eilenberg, S. & Mac Lane, S., 1945, *Trans. Am. Math. Soc*. 58, 231-294.
[2] Rosen, R., 1958, *Bull. Math. Biophys.* 20, 245-260.
[3] Ehresmann, A. and Vanbremeersch, J.-P., 2007, *Memory Evolutive Systems: Hierarchy, Emergence, Cognition*, Elsevier.
[4] Kan, D. M., 1958, *Trans. Am. Math. Soc.* 89, 294-329.

The property at the root of *emergence* and *flexibility* is characterized; it is the *Multiplicity Principle* (MP): there are patterns which are functionally equivalent while not structurally equivalent and not well interconnected. This property, first emphasized by Edelman[5] in neural systems ("degeneracy of the neural code"), is known to be ubiquitous in biology; it extends to systems in socio-economic areas. We show how MP allows for the emergence at each level of new properties, modeled by "complex links" which reflect global properties of its lower levels not observable locally at these lower levels. A consequence is that MP is necessary for going beyond a pure reductionism; without it, the complexity order of all the components would be 0 or 1; and It allows for the emergence of higher order processes through successive complexification processes.

To model the *self-organization* of the system, the dynamic of a MES depends on the cooperation/competition between a net of specialized subsystems of various complexities acting as co-regulators, with the help of a central memory to which the Multiplicity Principle confers both robustness and flexibility. Each co-regulator operates a stepwise process at its own rhythm: collect of the incomplete information accessible in its own "landscape", selection of a response, commands to effectors, and evaluation at the next step. The realization of the commands should be justifiable of classical models (e.g. in terms of differential equations).

However the local logics of the various co-regulators differing, the commands they send may conflict, and there is need of an "interplay" among the co-regulators. The Multiplicity Principle gives more flexibility to this interplay, the result of which may cause ubiquitous critical events, such as failures or dyschrony to some co-regulators; and they have to be self-repaired later. It follows that the system is "far from equilibrium" but adaptable to changes in the environment, with its global logic unpredictable on the long term.

An important *cause of failures* is the non-respect of the temporal and energetic constraints imposed by the propagation delays and strengths of the links. In particular we have characterized the *synchronicity laws* that the various co-regulators must satisfy for avoiding failures; they lead to a 'dialectics' between co-regulators with very different complexity and rhythm: a failure in one of them is able to be later reflected to others, themselves backfiring by sending a command to self-repair, for instance by re-synchronizing.

An application is given to a *theory of aging* for organisms[6] by a *cascade of re-synchronizations* of co-regulators of increasing levels (from molecular to cellular to organ levels), in agreement with known physiological phenomena.

In systems with higher order components, the flexibility resulting from the Multiplicity Principle makes possible the development of a *semantic*, and of a higher order subsystem of the which acts as a *flexible internal model* of the system; it allows for 'intentional' anticipatory processes leading to the formation of long term strategies. This is essentially explained in our model MENS for a neuro-cognitive system[7], which represents neurons at level 0 and "mental objects" obtained by binding synchronous (hyper-)assemblies of neurons at higher levels.

Open problems

The Memory Evolutive Systems propose an innovative rigorous scientific approach for analyzing complexity, emergence, self-organization and robustness/flexibility in multi-scale complex systems; in particular it highlights the role of the Multiplicity Principle and of the synchronicity laws in the behavior of "multilevel systems of systems of systems" with their critical events and their capacities

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[5] Edelman, G.M., 1989, *The remembered Present*, Basic Books, New York.

[6] Ehresmann, A.C. & Vanbremeersch J.-P., 1993, in *Cybernetics and Systems*, Tata McGraw Hill Pub., 190-192.

[7] Ehresmann, A.C. & Vanbremeersch J.-P., 2009, *Journal of Mind Theory* 0-2, 2009, 129-180.

for learning, self-repair and adaptation. However MES remains an evolutionary methodology, up to now essentially theoretical and more qualitative than quantitative. The long term research objective would be to develop real-world applications, in particular to bio-socio-technical systems and to ICT.

Above we have alluded to 2 applications of MES: an aging theory for organisms, and a model for neuro-cognitive systems. A better apprehension of them can suggest new methods for coping with aging impairments and neuro-degenerative pathologies such as Alzheimer or Parkinson, or with learning deficiencies such as dyslexia. Extended at the society level they could lead to new policies for education, to better strategies in business management for ubiquitous complex events processing, to new approaches in decision theory, or to the development of innovative scenarios in Future Studies (as we have shown in some recent papers[8]).

Now for dealing with real-world applications where large and heterogeneous data-streams have to be processed, MES should be more 'quantitative', and this raises the following problems, some of which are studied in the frame of the European project INBIOSA (to the Scientific Committee of which I participate):

1. *How to make MES amenable to computations?* Classical computations seem not able to account for the complexification process. A possible approach worth to undertake is through "spatial computing", such as the programming MGS language (Giavitto and Spicher[9]), or the "diagrammatic logics" specified by "sketches" (Lair and Duval[10]). Could it answer for the role of the Multiplicity Principle in the interplay among co-regulators?

Another possible approach, proposed in the frame of INBIOSA, is to enhance the MES with the capabilities of the *Wandering Logic Intelligence* that Plamen Simeonov[11] developed in relation with Internet.

2. *Introduction of supplementary structures.* In the interplay among co-regulators, the synchronicity laws account for temporal constraints; are there similar 'laws' accounting for spatial, energy, information or cost constraints?

More generally, Memory Evolutive Systems are based on the 'relational' dynamical structure of the system, consisting of its components and agents, and how they interact over time. In real-world applications it could be useful to add supplementary structures, for instance spatial structures, higher dimensional interconnections, or some kind of stochasticity. Theoretically this should be possible with the help of the notion of "enriched categories".

To conclude, the Memory Evolutive Systems propose a general frame, but a transdisciplinary cooperation would be necessary to develop it up to the stage of real-world applications.

[8] http://ehres.pagesperso-orange.fr
[9] Giavitto, J.-L. and Spicher, A., 2008, *Physica* D 237, 1302–1314.
[10] Duval, D. and Lair, C., 2002, Rapport de Recherche IMAG-LMC 1043.
[11] Simeonov, P., Thesis, 2002, http://www.simeio.org/pages/details/papers/dis/wli_dis_v12_last.pdf