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# EMERGENT PROPERTIES FOR COMPLEX SYSTEMS

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**ABSTRACT.** The theory of Memory Evolutive Systems, already presented in former Baden-Baden Conferences, could be classified as a Rational Emergentism in the sense of (Bunge, 1979). It presents a model for natural open self-organizing systems, such as bio-sociological or neural systems, in which the dynamics is modulated by the competitive interactions between the global system and a family of internal Centers of Regulation (CR) with differential access to a central hierarchical Memory. Each CR operates at its own complexity level and time-scale, so that their respective strategies might be conflictual, whence the emergence of dialectical functional loops between heterogeneous CRs.

Here we show how this theory gives a unified frame to consider several emergence problems: emergent properties for a complex object obtained by the cohesive binding of more elementary ones, e.g. synchronous assemblies of neurons representing mental objects; emergence of higher order repair mechanisms (SOS system in bacteria, de/resynchronization in aging theory) ; differentiation between 'simple' physical systems and 'complex' biological or socio-political systems (organisms, enterprises, societies); functional development of complex cognitive processes, e.g. in neural systems, leading to the formation of a procedural memory, to the emergence of Semantics, and consciousness.

**KEYWORDS.** Emergence. Complexity. System. Agregation. Semantics. Reductionnism

## 1. Introduction

From Aristote on, emergence seems a ubiquitous and somewhat ambiguous notion related to complexity, with variant definitions, emphasizing either the formation of new processes or their sudden manifestation to others.

For (Rosen, 1982), emergence manifests "some kind of qualitative difference between what the system is doing now and what it did in the past". M. Bunge proposes a 'rational emergentism' that "combines an acknowledgement of emergence with the thesis that emergence is explainable and predictable within bounds" (Bunge 1979, p. 251). He defines an emergent property of a thing $x$ as a property gained by $x$ and not possessed by any of its precursor components.

Webster's dictionary defines to emerge as "to come out from anything", while the Collins Thesaurus gives as synonyms both to appear and to become apparent. In the French Larousse, emergence is a sudden apparition, while the Quillet says it is an obscure notion, which denotes a thing that comes out another one without being properly produced nor caused nor explained by it.

For (Bohm, 1983), the mechanistic order dominant in Physics unfolds from the universal 'implicate order'. In the dissipative structures of Prigogine (Prigogine and Stengers, 1982), order emerges from chaos. Biologists speak frequently of emergence for a new property of a molecule, a cell... , or the advent of a new organ or a new species in Phylogenetics. Social norms are also emergent, as well as new ideas or concepts, e.g. liberty in the XVIIth century, tolerance in the XVIIIth century (Larousse's examples).

Is it possible to give an operative definition encompassing these various meanings? Here we propose to study this problem in the framework of a general theory for complex systems, the theory of *Memory Evolutive*

*Systems* (MES) which we are developing since 1986 and have already exposed in Baden-Baden.

The overall idea is to define emergence as the sudden apparition, by materialization and/or functionalization, of a complex object with specific new properties, integrating an internal lower level organization which has slowly developed. It requires that actors and observers assign it at least a functional significance. Though intended to increase the efficiency, to offset a fracture or to adapt to changes in the environment, it may subsequently cause a fracture to another level. We'll distinguish three main types of emergence: with respect to association, to classification and to organization (though all are formally reducible to the first one). In each case, the emergence is related to a specific setting, and it is said: 'functional' (*f-emergence*) for some objects when it is manifested through its effects on them; 'ontological' (*o-emergence*, or simply emergence) if there is materialization of new objects or processes in a system; 'epistemological' (*k-emergence*) when such objects become apparent to some actors, either at the same date or at different times, while they were not before. An o-emergence in a system is also a f-emergence, and a k-emergence for some objects.

## 2. Bref outline on MES.

The MES represent a mathematical model for natural self-organizing systems, based on Category Theory (Mac Lane, 1971). We just recall the necessary notions and refer for details to the papers listed in the References (denoted by EV) and to the Proceedings of the 5 preceding Baden-Baden Conferences (denoted by BB 88-92).

The state of the system at a given time, formed by its components and the interactions between them, is modelled by a *category* K. An arrow (called *link*) from A to B will be considered either as an action (transfer of informations or energy...) performed by A, or as a factor (message or constraint) affecting B. The objects are hierarchically organized into complexity levels, so that an object A of level $k$+1 is a compound represented by the cohesive binding (= inductive limit in K) of a pattern $\Pi$ of linked objects of level $k$.

Emergence concerning the formation of such compounds, we recall that a *pattern* $\Pi$ in K is a family of objects $A_i$ with some specific links between them. A *collective link* from the pattern to an object B consists of a family of links from each $A_i$ to B, correlated by the specific links of the pattern. The *cohesive binding* of the pattern is an object A whose links to any object B are in 1-1 correspondence with the collective links from the pattern to B. Then A is considered as a complex object admitting $\Pi$ as its internal organization.

The change of states is represented by *transition functors* between successive state-categories. This dynamics is regulated by a net of subsystems, called nternal *Centers of Regulation* (CR), which have a differenitial access to a central *Memory* in which past experiences are stored for a better adaptation.

Each CR, at its complexity level and with its own period, operates a stepwise trial-and-error learning process. During a step, the CR constructs its internal (more or less distorted) representation P of the global system, called its *actual landscape*. Its actors select a *strategy* on P consisting in the addition or deletion of some elements, dissociation of particular compounds, cohesive binding of some patterns for them to emerge as new (complex) units of a higher level. The anticipated landscape at the end of the step should be the *'complexification'* of P with respect to this strategy (BB 88). However it might not be so (and the CR measures the difference), because the actual strategies of all the different CRs are repercuted to the system where they enter into competition. Whence the risk of a *fracture* for some CRs, and the emergence of a *dialectics between CRs* with contrasting complexity levels and periods, which modulates the global evolution of the system and makes it unpredictible on the long run.

## 3. Emergence by association.

The first type of emergence is the *emergence of compounds by cohesive binding*. It is the most important, since the other types will formally be reduced to it. It develops in three stages, corresponding to increasing complexity levels: transitory f-emergence of a collective action, emergence of a coherent assembly and its cohesive binding, emergence of a complex object with its own identity.

1. Let us consider a pattern Π in a MES, and suppose that a collective link is formed from this pattern to an object B at a given time (think of a group of people cooperating for a specific task). This collective link represents a collective action of the components $A_j$ of the pattern, which could not be performed by them separately and necessitates that all the components coordinate their actions along their specific links. For instance, the cumulative firings of an assembly of neurons may be necessary to activate a neuron B. When it occurs, this collective action causes the f-emergence of the pattern for B, and eventually its k-emergence for other actors when it becomes apparent in their landscape. However it may be only temporary.

2. *Emergence of a coherent assembly and its cohesive binding.* If the cooperation between the $A_j$'s is pursued, it becomes more efficient, the specific links of the pattern strengthen, synchronizing the actions of the components and eventually specializing some of them, and the collective links multiply. Such a change is either engineered directly by the pattern (e.g., people wanting to develop a common action), or forced by external events (formation of a synchronous assembly of neurons, in the sense of (Hebb, 1949), memorizing a stimulus), or required by the strategy of some CR. For instance, under stressful circumstances, some unicellulars form colonies, in which external cells specialize for motion, internal cells for metabolism.

This transformation of the pattern into a *coherent assembly* is actualized by the o-emergence of its compound as a new higher order unit, say A, which integrates the pattern (by complexification), and becomes its cohesive binding in the system or only in a particular landscape. As the links from A to any object B are in 1-1 correspondence with the collective links from the pattern to B, they represent the f-emergent properties of the pattern. The novelty of the emergence, that is the difference between the operations of the coherent assembly and the actions performable by the $A_j$'s acting separately, is measured by the *'comparison link'* (BB 88) from S to A, where S represents what would be the amorphous amalgam (= sum) S of the components $A_j$ if their specific links were omitted. For instance, Hemoglobulin is the cohesive binding of the pattern representing the spatial conformation of the tetramer, and the comparison link measures the difference between its cooperative fixation of $O_2$ and the oxygenation rate of its 4 separate units (Di Cera, 1990).

3. *Emergence of a complex object.* The compound A has emerged as the cohesive binding of the pattern Π in the system itself, or only in some landscape. Thereafter it might remain dependent of the pattern, in the sense that its successive states will be the cohesive bindings of the successive states of Π, and its functioning ceases if the pattern is disrupted. For instance a mechanical object (say a clock) will break if some parts cannot function. In this case, the emergence of A only represents the transformation of the pattern into a coherent assembly.

However in complex systems such as bio- or socio-systems, A may emerge as a higher order object *per se*, taking precedence over its components by developing an existence of its own, in that it perdures and maintains its identity while its components vary. For instance, a cell remains itself up to its death though there is a turnover of its supra-molecular components and its metabolic activities change in time: or an organ may adapt to new functions during the Evolution. The formal reason for this flexibility is that distinct patterns, e.g. a pattern and its 'representative' sub-patterns (EV 1987), have the same cohesive binding.

To model this situation, we have defined the *stability span* of a complex object as follows (EV 1987): the stability span of A at the time $t$ is the longest period $\tau$ such that, for each $t'$ from $t$ to $t+\tau$ (not included), there exists a pattern $\Pi t'$ admitting the state $At'$ of A at $t'$ as its cohesive binding, and the transition from $\Pi t$ to $\Pi t'$ is an equivalence (in the categorical sense). Roughly, the composition of A may vary, with the possible loss, addition and replacement of some of its components, as long as the 'sketch' of its organization remains unchanged. A may be considered as a materialization of this sketch, and A maintains its identity up to the time where its stability span tends to 0.

The emergence of A as such a complex object of its own (called a *category-neuron* in a neural system) transcends the emergence of the pattern as a coherent assembly, and gives it a duration longer than that of its components. For instance, an association is initially created by some persons, but it will really emerge as a new institution only when it will have been legalized and doted with specific statutes which ensure that it keeps functioning if its founders are replaced or its activities partially modified.

This o-emergence of A ensures that A also f-emerges for all the objects to which it is linked. But A may suddenly k-emerge in the landscape of a specific CR only later on, even if it is much earlier f-emergent for some objects of this landscape, and so affects its evolution up to become one of the causes of a fracture (e.g., neuropathies caused by the conscious resurgence of a forgotten trauma). We have explained in (EV 1989) how complex systems differentiate from 'simple' physical systems (having their dynamics determined by initial conditions and laws) by the irruption of such fractures caused to a higher level CR with a longer period by an unseen slow accumulation of small changes at a lower level.

The k-emergence of A for a CR may also result from an extension of the landscape following the emergence of other new objects (more powerful telescopes have permitted the discovery of farer stars), or from the efforts of the CR to counteract a fracture (up to the development of new scientific theories, e.g. Relativity Theory to overcome discrepancies in the Newtonian scheme, Catastrophe theory (Thom. 1990) to understand morphogenesis via attractors and bifurcations).

4. *Emergent processes.* The emergence of new objects is accompanied by the emergence of new processes, and eventually their later k-emergence for some CR. The *processes* are represented by the specific links between complex objects (in an adequate complexification), defined as follows (EV 1987). A *cluster* between two patterns $\Pi$ and $\Pi'$ is a family of links between their respective components, well correlated by their specific links; this cluster binds into a link between their cohesive bindings. Now for complex objects *per se*, there are also *complex links* from A to A', obtained by the combination of binded clusters $A \to A^1 \to \ldots \to A^n \to A'$, but with the flexibility added by considering each $A^i$ as the cohesive binding of 2 different patterns to define its 2 adjacent arrows.

By iteration, patterns of complex objects and complex links lead to the emergence of still more complex objects (and links), corresponding to coherent *'super-assemblies'*, then to coherent 'super-super-assemblies'..., intermixing objects of several levels and generally not reducible to large assemblies of a specific level (EV 1987). This fact explains that the theory of MES is a *rational emergentist reductionnism* (Bunge, 1979), offering a compromise between pure reductionnism and holism, and allowing for explicit computations.

## 4. Emergence by classification.

The basic mechanism is the same as in the preceding section, except that we consider the dual situation (formally, the system is replaced by its opposite, obtained by inverting all the links), so that emergence will concern the collective reactions of the pattern instead of its collective actions, and the emergent object will be the (projective) limit of the pattern instead of its cohesive binding.

More precisely, let $\Pi$ be a pattern. A *joint trigger* of the pattern consists in a family of links from an object B to the components $A_j$ of $\Pi$, correlated by their specific links. The formation of such a joint trigger implies that the pattern f-emerges for B. If it persists, the pattern is strengthened and synchronized as above, leading to the emergence of a new object L which represents its *limit*, i.e., the links from an object B to L are in 1-1 correspondence with the joint triggers issued from B. Finally this limit may emerge at a higher level as a complex object *per se*, and eventually become k-emergent for other CRs.

This situation has been applied in a neural system, to explain how Semantics emerges (BB 92). Indeed, let us take the pattern of actors $\Pi$B induced on a given CR by an object B, defined as the image of the base functor from the comma-category B↓CR to CR; in particular there is a joint trigger from B to $\Pi$B. Two objects B and C are said to have 'the *same CR-shape*' if their induced patterns $\Pi$B and $\Pi$C are isomorphic; it means that they both impose the same constraints on the CR. Hence $\Pi$B characterizes the class of the objects having the same CR-shape as B, which, in a neural system, represents the *invariance class* for a CR-attribute (say, the class of blue objects for a CR-color).

If there exists a higher CR in the landscape of which this 'acted' classification is k-emergent, it might lead later to the emergence of the limit LB of $\Pi$B, called (BB 89) the *CR-concept* of B, and which acts as a broad prototype memorizing the invariance class of B. It is triggered as soon as one of its tokens B is activated, and conversely its activation may activate anyone of these tokens.

The CR-concepts, for the different CRs, their canonical links, and more abstract concepts emerging from them by cohesive binding form a sub-system of the Memory. This *'Semantical Memory'* contains a sub-system, the *Procedural Memory*, formed by the concepts of memorized strategies. The emergence of such a memory increases the interplay between the CRs' strategies (BB 92).

## 5. Organizational emergence.

It concerns the emergence of *sub-systems* of the system K *with some specific organizational properties* (e.g., a new organ for an animal). It is doubly related to the preceding kinds of emergences: 1. It requires the preliminary emergence of more and more complex objects and processes (as their links, cf. §3), which will organize at higher levels and operate on a longer time-scale, with productive interferences between levels. 2. It might be interpreted as an emergence by association if we place ourselves in a more abstract 'epistemological' setting, namely the general evolutive system of all the systems of a particular type, their components and their sub-systems (contained in Popper's World III); when it develops (e.g., during the embryogenesis), the new sub-system of K will first f-emerge as a sub-pattern of K in this general system, then it increases its functions and emerges as the compound of a coherent assembly, or even as a complex object *per se*. Let us consider some applications.

1. In *neural systems*, we have already seen examples of this process, namely the emergence of a semantical or of a procedural memory, following the emergence of higher CRs able to memorize the invariance classification 'acted' by lower CRs.

Another example is the emergence of *consciousness* for a CR, by integration of the temporal dimension. We have defined such a CR (BB 91) as a higher level CR having the following properties: 1. It extends its landscape after a fracture through the retrieval from the working memory of lower level processes usually not observable by it (thanks to functional loops, of the kind considered in (Edelman, 1989), activated by increased attention); 2. then it back-tracks in this extended landscape to find possible causes of the fracture (so operating by abduction); and 3. it may feed-forward and planify for several steps ahead. If such a CR k-emerges to itself, we have *Self-consciousness.*

The emergence of *Language* could also be described as the emergence of new sub-systems for phonetics, syntax, and 'symbols' associating a concept and a word (signified/significant).

2. *Repair mechanisms*: Other kinds of sub-systems which may emerge are repair mechanisms, e.g. the SOS system in a bacterium (Radman, 1975), or a centralized organization in a too diversified enterprise. These systems will be triggered by a higher CR in case a lower CR is blocked, to impose a repair strategy (the SOS system is a complex which intervenes when the DNA replication is interrupted because of the obstruction of the lower repair mechanisms by too many errors, and it allows to pursue the replication, eventually with a mutation (EV 1989)).

Another kind of repair mechanism (though it is more difficult to explicitly explain its emergence in terms of formation of compounds and/or sub-systems) is the *de/resynchronization* of a CR when it cannot maintain its temporal constraints which impose that $p \ll d \ll \tau$, where $d$ is the period, $\tau$ the mean stability span and $p$ the mean propagation delay in its landscape (EV 1993); it consists in altering the period, by increasing it in a phase of decline, decreasing it in a development phase. We have proposed a *theory of aging* for organisms (unifying known physiological theories) based on the emergence of a cascade of such de/resynchronisations for higher and higher CRs.

3. *Taxinomies.* Organizational emergence also accounts for the emergence of a new population, as a new species or sub-species,.... This population is characterized by the emergence of a new feature (organ, sub-system, strategy,...); we may describe the emergence of this new 'organization' as above, at the individual level. But we may also consider the system of all biosystems and of their populations; the emergence of a new species or a sub-species (for instance, sparrows adapted to town-life) is then a 3-step process at the population level: formation of a small pattern with the new feature (which has emerged as above after an environmental change or by mutation); this pattern slowly expands into a more steady pattern, hence emerges as a coherent assembly; finally the new (sub-)species emerges when the feature is hereditarily transmitted (phenotypically or genotypically). However in both cases, there is some difficulty to date the emergence and to circumscribe exactly the bounds of the species. This problem is well-known (cf. papers in *"Biology and Philosophy"*). An example is the emergence during the glaciation of a semi-speciated population of vivipar lizards which can still interbreed with ovipar lizards, but with a less effective score (Heulin).

## Conclusion.

The dynamics of a complex system, modelled by a MES, is entirely dependent on emergence processes. Indeed, its evolution is regulated (cf. §3): 1. at a given time by the interplay between the competing complexifications directed by the CRs on their landscapes, and these complexifications ensure the emergence of more and more complex objects and complex links; 2. on the long term, by the dialectics between heterogeneous CRs which is partially generated by the fact that an emergence at some level may k-emerge at another level only later and through a fracture partially caused by its earlier f-emergence; and to repair this fracture, other emergences will be produced, with new risks of fractures.

In large systems, the (generally non-hierarchical) net of CRs decomposes into hierarchical sub-nets, in which higher CRs coordinate several parallel lower CRs, and these sub-nets interact as parallel worlds. So the 'vertical' dialectics between CRs is enriched by a 'horizontal' dialectics between these parallel worlds, since the emergence of a new process in one of them will retro-act on the others. For instance, in an ecosystem each species develops its own world, and a change in the world of a species will retroact on the other worlds, e.g., on the world of man, which will react by acting on another world.... with unwanted effects emerging at each step (desertification, depletion of the ozone, resistance developed against antibiotics).

The significance taken by emergences/fractures in complex systems warns against planifying local changes without care of their later distant implications. For instance, the physician should treat the whole person and not an isolated organ, and be cautious of the interferences of drugs; a social reorganization, or a change of paradigm in Science, asks for a thorough examination of its effects...

Finally, let us remark that the distinction between o-emergence and k-emergence is somewhat blurred, and often depends on philosophical options. For instance, a higher order cognitive process has been represented by a (complex) category-neuron (BB 90-92). The statute assigned to this category-neuron has to do with the mind-brain problem: is it to be considered as a 'real' *physical* object which is k-emergent in our model ('identity theory') or as a purely *'conceptual'* object, which is o-emergent only for our MES of neurons ('dualism')? It seems that a 'simple' category-neuron, integrating an assembly of neurons, might be said identical to a physical neural state; but a 'complex' category-neuron, involving complex links, is a more flexible neural process, although it may be explicitly described by an inductive construction from simple category-neurons (cf. end §3). So our model is a kind of monism in which mental functions are emergent activities of brain, as for (Bunge, 1979); but this emergence lends itself to computations, so that it allows to develop a 'real' *algebra of mental objects* (BB 91-92), as called for by Changeux (1983).

## References.


Bohm, D. (1983); *Wholeness and the implicate order*; Ark Edition, London.

Bunge, M. (1979); *Treatise on Basic Philosophy*, Vol. 4; Reidel, Dordrecht.

Changeux, J.-P. (1983), *L'homme neuronal:* Fayard, Paris.

Di Cera, E (1990), *Il Nuovo Cimento* 12 D (p. 61).

Edelman, G.M. (1989); *The remembered Present*; Basic Books, New York.

Ehresmann, A.C. & Vanbremeersch, J.-P. : (1987), Hierarchical evolutive systems: a mathematical model for complex systems; *Bull. Math. Biology*, 49 N°1 (pp. 13-50). — (1989), Modèle d'interaction dynamique entre un système complexe et des agents; *Revue Intern. Systémique* 3 (pp.315-341). — (1991), Un modèle pour des systèmes évolutifs avec mémoire, basé sur la Théorie des Catégories; *Revue Intern. Systémique* 5 N°1 (pp. 5-25). — (1992), Outils mathématiques pour modéliser les systèmes complexes; *Cahiers Top. et Géo. Diff. Cat.* XXXIII (pp. 225-236). — (1993), Memory Evolutive systems: An application to an aging theory, in *Cybernetics and Systems* (Ghosal & Murthy, Ed.); Tata McGraw-Hill Pub. C° New Delhi (pp. 90-92).

Hebb, D. O. (1949); *The organization of behaviour*; Wiley, New York.

Mac Lane, S. (1971); *Categories for the working mathematician*; Springer, Berlin.

Prigogine, I & Stengers, I. (1982); *La nouvelle alliance*; Gallimard, Paris.

Radman, M. (1975); SOS repair hypothesis; in *Molecular mechanisms for repair of DNA* (Hanawalt & Setlov, Ed.); Plenum Press, New York (pp. 355-367).

Rosen, R. (1982); *On complex systems*; Dalhousie University; Halifax.

Thom, R. (1990); *Apologie du logos*; Hachette, Paris.



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