# FROM SIMPLE TO HIGHLY-COMPLEX SYSTEMS:
## *A PARADIGM SHIFT TOWARDS NON-ABELIAN EMERGENT SYSTEM DYNAMICS AND META-LEVELS*

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Abstract. The evolution of non-linear dynamical system theory and super-complex systems–that are defined by classes of variable topologies and their associated transformations–is presented from a categorial and generalised, or extended topos viewpoint. A generalisation of dynamical systems, general systems theory is then considered for the meta-level dynamical systems with variable topology and variable phase space, within the framework of an "universal", or generalised Topos–a logico-mathematical construction that covers both the commutative and non-commutative structures based on logic classifiers that are multi-valued (MV) logic algebras. The extended topos concept was previously developed in conjunction with dynamic networks that were shown to be relevant to Complex Systems Biology. In so doing, we shall distinguish three major phases in the development of systems theory (two already completed and one currently unfolding). The three phases will be respectively called *The Age of Equilibrium*, *The Age of Complexity* and *The Age of Super-Complexity*. The first two may be taken as lasting from approximately 1850 to 1960, and the third which is now rapidly developing in applications to various types of systems after it began in the 1970s after the works of Rosen, Maturana and others. The mathematical theory of categories–which began in the 1940s [44],[45] with a seminal paper by Eilenberg and Mac Lane in 1945 [45]– is an unifying trend in modern mathematics [40], and has proved especially suitable for modeling the novelties raised by the third phase of systems' theory, which became associated with applications to system super-complexity problems in the late 1950s and 70s [84]-[85],[2],[6],[8], [88]-[89]; it was continued by applications to logical programming involving categorical logic in computer science [58] , as well as the categorical foundations of mathematics [59]-[60].

Each phase is characterized by reference to distinct concepts of the *general* system and operational logic levels–including meta-levels, that were meant in many–but not all cases–to include classes of specific, actual, or concrete systems. The exceptions to such concrete cases are several, perhaps one of the most notable example being that of abstract metabolic-replication, or (M,R)-systems introduced by Robert Rosen in 1958 in terms of categories of finite sets [81]-[82]. Such categories were later shown to be part of the category of abstract automata or sequential machines [8],[100]. Rosen's abstract, relational approach to biological systems was then complemented by the (M,R)-system representations as dynamical systems with added mathematical structure [88]-[89] ; it was still clearly unable to include all classes of actual, concrete systems because of the paradigm shifts needed to do so: from simple to *complex* systems [91], and then again to extremely complex [46], or super-complex [19] and ultra-complex systems [22],[25] classes of systems. Furthermore, each subsequent phase generalised the previous one, thus addressing previously neglected, major problems and aspects, as well as involving new paradigms and also including the higher ontological levels. The second part deals with the deeper problems of providing a sufficiently flexible mathematical framework, and yet well-defined, that might be suitable for various classes of systems ranging from simple to super-complex, and beyond. As we shall see, this is something still in wait as mathematics itself is undergoing development from *symmetric* (commutative, or *natural*) categories and commutative homology to the non-commutative, higher dimensional structures of Non-Abelian Algebraic Topology [33], that are capable of representing dynamic *asymmetry*, and thus enabling the development of theories that are more general and much less restrictive than any static modelling. Among such novel mathematical constructs are those addressing problems associated with *multiple geometric structures* that are of great interest not only in mathematics (for example, in the case of "foliation bundles"), but also in applications to a variety of classes of non-linear dynamic systems that exhibit symmetry-breaking, ranging from super-conductors to percolating neural networks. Examples of the need for such non-Abelian theories are abundant in Complex Systems Biology, Population Genetics, Morphogenesis, Evolutionary Biology, Ecology, Neurophysiology and other biomedical sciences, Cognitive Sciences, Psychology, Algebraic Quantum Field Theory and Categorical Ontology. Its potential importance for the future of a human society without Mumford's megamachines, or the human use of human beings, is also pointed out.

## 1. Introduction

Poli's ontological theory of levels [69]-[75], following the tradition of Hartmann [55]–and to an extent also influenced by Husserl–asserts that the ontological world consists in the unity of a system comprised of 'levels' of reality.

These are specified in terms of Poli's ontological theory of levels [19] as follows:

a) coordination (integration) occurs among the categories governing some or all levels;

b) there exist forms of dependence among levels;

c) there exist forms of autonomy among levels;

d) there is a categorical closure, or 'completeness', of levels.

Such specifications can be also viewed within the context of *emergence*, *complexity*/non-linearity, and *genericity* properties of open and far-from-equilibrium systems (cf. Prigogine in 1980, ref. [79]). In this paper we will discuss several aspects of ultra-complexity, and consider the processes that induce passage, or transition from one level of reality to the next, higher levels. Here we are somewhat in tune with Poli's original claim [69] that there are three fundamental levels of reality comprising material (physical, chemical, biological), psychological and social phenomena. This paper will discuss the relations (1) among the layers of the material stratum, and those connecting the highest layer of the material stratum (biology or organisms) and the psychological stratum, leaving analysis of the social stratum for another occasion. It will result that among the levels considered there is an increasing of complexity. More complete details of our novel approach to the subject can be found in recent reports [20]-[25].

The next three sections present succintly the development stages of the general dynamic systems (GDS) theory, from its semi-empirical roots to the more abstract and formal stages that followed. Related concepts from the Ontological Theory of Levels will also be discussed in this context.

## 2. The Age of Equilibrium

The first phase in the evolution of the theory of systems depends heavily upon ideas developed within organic chemistry; *homeostasis* in particular is the guiding idea: A system is a dynamical whole able to maintain its working conditions. The relevant concept of system is spelt out in detail by the following, general definition, D1.

**D1**. A system is given by a bounded, but not necessarily closed, category, or super-category, of stable, interacting components with inputs and outputs from the system's environment.

To define a system we therefore need (1) components, (2) mutual interactions or links; (3) a separation of the selected system by some boundary which distinguishes the system from its environment; (4) the specification of system's environment; (5) the specification of system's categorical structure and dynamics; (6) a super-category will be required when either components or subsystems need be themselves considered as represented by a category, i.e. the system is in fact a super-system of (sub) systems, as it is the case of emergent super-complex systems.

Point (5) claims that a system should last for a while: a system that comes into birth and dies off *immediately* has little scientific relevance as a system, although it may have significant effects as in the case of *virtual particles*, *photons*, etc. in physics (quantum electrodynamics and chromodynamics). Note also that there are many other, different mathematical definitions of *systems* ranging from (systems of) coupled differential equations to operator formulations, semigroups, monoids, topological groupoids and categories that represent a formal rather than an ontological view of general systems. Clearly, the more useful formal system definitions include algebraic and/or topological structures rather than simple sets (discrete topological structures) or their categories [3],[21]. The main intuition behind this first understanding of dynamic systems is well expressed by the following passage: The most general and fundamental property of a system is the interdependence of parts or variables. Interdependence consists in the existence of determinate relationships among the parts or variables as contrasted with randomness of variability. In other words, interdependence is order in the relationship among the components which enter into a system. This order must have a tendency to self-maintenance, which is very generally expressed in the concept of equilibrium.

It need not, however, be a static self-maintenance or a stable equilibrium. It may be an ordered process of change, a process following a determinate pattern rather than random variability relative to the starting point. This is called a moving equilibrium and is well exemplified by growth [67].

*2.1 Selective Membranes, Boundaries and Horizons*

Boundaries are peculiarly relevant to systems. They serve to distinguish what is internal to the system from what is external to it. By virtue of possessing boundaries, a system is an entity for which there is an interior and an exterior defined for such an entity. The initial datum, therefore, is that of a difference, of something which enables a (characteristic or essential) difference to be established between a system and its environment.

An essential feature of boundaries of open systems is that they can be crossed. There are more open boundaries and less open ones, but they can all be crossed. On the contrary, a horizon is something that we cannot reach or cross. In other words, a horizon is not a boundary. As far as systems are concerned, the difference between inside and outside loses its common sense, *spatial* understanding. As a matter of fact, *inside* doesn't anymore mean "being placed within", but it means "being part of" the system. One of the earlier forerunners of system theory clarified the situation in the following way: *"Bacteria in the organism ... represent complexes which are, in the organizational sense, not internal, but external to it, because they do not belong to the system of its organizational connections. And those parts of the system which go out of its organizational connections, though spatially located inside it, should also be considered as being ... external"* ( p.81 in ref.[29]). In other words, internal and external are first and foremost relative to the system, not to its location within physical space. The situation is, however, less clear-cut in the case of viruses that insert themselves into the host genome and are expressed by the latter as if the viral genes *belonged* to the host genome. Even though the host may not recognize the viral genes as *foreign*, or *external* to the host, their actions may become incompatible with the host organization as in the case of certain oncogenic viruses that cause the death of their host. An even less obvious *externalization* occurs in the case of malignant cancer cells that are derived through neoplastic transformations from normal cells that originally were indistinguishable from their neighbors in terms of their being part of the internal organization of the original multi–cellular organism. The fact that some systems are able to enslave other systems or to exploit them might thus

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be treated as a form of *parasitism* which is a one-way relation as it benefits only the *parasite* organism at the expense of the host–if such systems were not actually really internal to the host; in such complex, special cases the *internality*, or *externality* is defined only by the *dynamic compatibility* of the intruder relative to that of the host organism; this compatibility can thus be described in terms of competing or conflicting attractors of the host and intruder, respectively. Let us add that internal and external can also be taken as features describing the difference between the world of *inanimate* things/machines and the world of organisms. In the mechanistic, *linear* order of things or processes, the world is regarded as being made, or constituted, of entities which are outside of each other, in the sense that they exist independently in different regions of space (and time) and interact through forces. By contrast, in a living organism, each part grows in the context of the whole, so that it does not exist independently, nor can it be said that it merely *interacts* with the others, without itself being essentially affected in this relationship. The parts of an organism grow and develop together. Unfortunately, this is also true of the malignant tumors that grow at the expense of the *host* (diseased) organism.

As soon as a boundary is established, both separating and connecting the system to its environment, a second type of boundary may arise, namely the one distinguishing the center of the system from its periphery (the former boundary will be termed *external* boundary, and the latter *internal*). The center, once established assumes control over the system's external boundary and can modify the boundary's behavior. Multi-modal systems may require a multiplicity of centers, for each of the relevant modalities. When different centers are active, a secondary induced dynamic arises among them.

Boundaries may be clear-cut, precise, rigid, or they may be vague, blurred, mobile, or again they may be intermediate between these two typical cases, according to how the differentiation is structured.

The usual dynamics is as follows. It begins with either vague, random oscillations or an original asymmetry. These introduce differences among the diverse areas of a developing, or growing, region. The formation of borderline phenomena (such as surface tension, pressure, competition) only occurs later, provided that the differences prove to be sufficiently significant. Even later there arises a center, or a node, whose function is primarily to maintain the boundaries.

Generally speaking, a closed boundary generates an internal situation characterized by limited differentiation. The interior is highly homogeneous and it

is distinct from whatever lies outside. Hence, it follows that whatever lies externally is inevitably viewed as different, inferior, inimical; in short, as something to be kept at a distance. A second consequence of closed boundaries is the polarization of the internal space of the system into a center and a periphery. The extent of this problem was already noted by Spencer, who accounted for it with his law of the concentration of matter-energy. Open boundaries allow instead, and indeed encourage, greater internal differentiation, and therefore, a greater degree of development of the system than would occur in the presence of closed boundaries. In its turn, a population with marked internal differentiation, that is, with a higher degree of development, in addition to having numerous internal boundaries is also surrounded by a nebula of functional and non-coincident boundaries.

This non-coincidence is precisely one of the principal reasons for the dynamics of the system. However, note that in certain, *chaotic* systems organized patterns of spatial boundaries do indeed occur, albeit established as a direct consequence of their chaotic dynamics. This non-coincidence is precisely one of the principal reasons for the dynamics of the system. Efforts to harmonise, coordinate or integrate boundaries, whether political, administrative, military, economic, touristic, or otherwise, generate a dynamic which constantly re-equilibrates the boundary situation. In these cases, the border area becomes highly active, and it is in this sense that we may interpret the remark by Ludwig von Bertalanffy that "ultimately, all boundaries are dynamic rather than spatial" [28], (p.37 of Bertalanffy, 1972, in ref.[28]).

Corresponding to such a logic of boundaries is a more or less correlative logic of centers. If to every boundary there corresponds a center responsible for its maintenance, the dynamics of boundaries reverberates in a corresponding dynamics of centers. The multiplicity of boundaries, and the dynamics that derive from it, generate interesting phenomena. Campbell was the first to point out that boundaries tend to reinforce one another (Campbell 1958). We quote Platt on the matter: The boundary-surface for one property ... will tend to coincide with the boundary surfaces for many other properties ... because the surfaces are mutually-reinforcing. I think that this somewhat astonishing regularity of nature has not been sufficiently emphasized in perception-philosophy. It is this that makes it useful and possible for us to identify sharply-defined regions of space as *objects.* This is what makes a collection of properties a *thing* rather than a smear of overlapping images; any violation of boundary-coincidence has an upsetting fascination for us, as in tales of ghosts, which can

be seen but not touched [68].

The following synopsis (modified from [71] and [75]) summarizes the main structural features of system boundaries:

- nature (external/internal)

- structure (gates, filters, selective, overlaps, connectivity, intrinsic or functional organization)

- cardinality (as a single boundary or as a border area)

- dynamics (changes in location, boundary exchange, variable topology with time)

- form (open/closed, mobile/static, flexible/rigid)

- maintenance (integrity, growth, destruction).

To these features, the so-called law of transposition should be added: a characteristic of all structures with an emerging structure at a higher level is that its boundaries can be revealed by transposition.

The analysis set out in this section has been conducted with the deliberate omission of any reference to levels of reality [69]-[75]. The inclusion of explicit consideration of the problem of stratification into levels will be shown to significantly increase complexity thus leading to *super–complexity*, as explained in Section 4 below).

## 3. The Age of Physical Complexity

After the Second World War, cybernetics, game theory, information theory, computer science, general systems theory, and other related fields flourished. Subsequently, there was also the first report of a categorical approach to complex biological systems which is Robert Rosen's seminal paper on the metabolic-replication, (M,R)-systems and the general, abstract representation of biological systems in the category of sets [84]-[85], in a purely functional, or organizational sense.

The main result achieved by the first phase of development of system theory has been the proof that the system as a whole is defined by properties

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not pertaining to any of its parts–a patently non-reductionist view. Global equilibrium (multi-stability, etc) are all properties of the whole systems, not of their parts. However, much more than this is required to understand system dynamics. The simplest way to see what is lacking runs as follows. According to some system theories, a system is the whole resulting from the interactions among its components. There are at least three hidden assumptions embedded in this definition. The first assumption is that all the components are given in advance, before the constitution of the system, or that they might be distinguished through some canonical decomposition (as in the case of sequential machines or automata). We shall discuss this problem under the heading of the system's *constitution*. The second assumption becomes apparent as soon as one asks what happens when components change: What happens when a component is no longer part of the system, or it fails? What happens when a new component enters the system or is generated internally? What happens when elements die out? These groups of questions can be summarized as the problem of the *reproduction* of the system, i.e. as the problem of the historical continuity of the system through time–though not in either a topological or strict dynamical sense–as distinguished and opposed to the continuity of its components, in the same historical sense. The third hidden assumption is that all the changes are placed on the side of the environment. What about systems that are able to learn and to develop new strategies for better dealing with survival or other problems they may run into? Systems endowed with this property will be called *adaptive*.

### 3.1 The Constitution, Reproduction and Adaptability of Systems

Two forms of constitution should be distinguished: the bottom-up type of constitution from components of the system (that are already available), and the top-down constitution from (a previous stage of) the system into its components. This latter form of constitution comes in two guises: (1) as constraints on initial conditions and the phase space of the system components, and (2) as the creation of new elements, i.e. the development of a new organizational layer, or layers, of the system.

### 3.1.1. Autopoietic Systems

The question of self-organization in a cellular network and how in open systems, dissipation induces order leading to evolution, was described by Capra in

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1996 as a means of connecting several theories, particularly those of Prigogine [79], and Maturana and Varela [65]. The dictum of the latter is that living systems are cognitive systems and the living condition/phenomenon itself is a process of cognition.

*Autopoietic* ('self-making') systems structure a living system as both open and closed–they are closed in their organization, but remain open to their environment. Such systems, structurally coupled to an environment, alter their structure in the way of *self-renewal* and the formation of new connections that amount to a special kind of learning mechanism. In this way, environmental interaction initiates structural changes and the living system reacts to environmental perturbations via its innate system of responses. Thus, an assimilation of inputs from the environment and a coordination of behavior in response, may be viewed as a basic premise for communication; it is only one mode in the continuous self-reproduction and self-organization of the living system throughout its ontogeny. Both the interplay between this continuous self-organization and response to environmental perturbations, may themselves be regarded as iterates of local procedures and induce network topology changes which subsequently may be geared up to emergence (see also refs. [21]-[25]).

### 3.1.2. Adaptive and Autopoietic Systems–Relations to Dynamic Genericity

We shall discuss first how and why adaptive systems possess or exhibit dynamic genericity and autopoiesis.

All adaptive systems seem to require at least two layers of organization: the first layer of the rules governing the interactions of the system with its environment and with other systems, and a higher-order layer that can change such rules of interaction; the changes that occur may be purely casual, or may follow pre-established, or acquired, patterns. In this regard, a hypothesis can be advanced which claims that the main difference between non-living natural systems on the one hand, and living natural systems, psychological systems and social systems on the other, is that the former present only one single organizational layer of interactions; the latter, more complex systems present at least two layers of organization: the one governing interactions and the one capable of modifying the rules of interaction. The persistence in time of the latter systems that are highly complex is made possible by dynamic multi-stability [3] –a source of their state-space, or state-genericity, a form of structural/dynamic/topological stability to perturbations that prevents the destabilization and rapid disappearance of such systems. Genericity replaces in highly

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complex systems the degeneracy characteristic of simple, physical systems with strictly deterministic causality and dynamics represented by systems of ordinary, or partial, differential equations. Genericity, multi-stability/homeostasis and autopoiesis may also be related to symmetry breaking or repeated symmetry breaking, as discussed next in further detail.

### 3.2. System Reproduction, Regeneration, and Repair

Autopoiesis (or regeneration) was previously defined as the capacity of a complex system to generate the components of which it is composed. The simplest mathematical models mimicking such biological capabilities are arguably Robert Rosen's (M,R)-systems in [84]-[85]. Their categorical construction from component objects and maps, using natural transformations and the fundamental Yoneda-Grothendieck Lemma [8] elicits their implicit algebraic structures, and furthermore allows their possible extension to more general categories and structures than Rosen's (M,R)-systems in the categories of sets, such as, the cartesian closed categories of generalized, algebraic (M,R)-systems [6]. Complex, molecular dynamic representations of both (M,R)-systems [88]-[89], and Rashevsky's organismic sets (developed in 1964-1969 [81],[83]) have also been constructed in terms of natural transformations of molecular biology systems [10],[12]-[15]. Such categorical, multi-level constructs of generalized, algebraic metabolic-repair/regenerating systems illustrate the hierarchical layers occurring in super-complex biological systems that will be further discussed here in the next sections.

### 3.2.1 Asymmetry Roles

An original asymmetry at the beginning of growth, following the fertilization of an ovum, seems to play an important role in determining the preferred growth axis (or axes); it seems also to be responsible for introducing constraints in the potentially possible variable topologies during embryogenesis/organismic development. Furthermore, the structural/anatomical asymmetry of the human brain between its left and right hemispheres, and also extends apparently to the mental *functions* correlated or supported at least in part by such hemispheres. Interestingly, the human brain appears to be rather unique in regard of its asymmetric structure(s).

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### 3.2.2 Reproductive and Economic Adaptations

It seems to be the case that humans are the ones that have been extensively capable of creating complex systems out of the reintegration of organismic reproductive and economic adaptations [12]. This is partly reflected upon in the life world principle of *two parallel hierarchies* (cf. Eldredge and Greene in 1992 [12]):

a) biological reproduction of the species;

b) ecological (or economic) reproduction.

### 3.3 Complexity as an Intrinsic Organizational Property

The overall outcome of constitution, reproduction and autonomy is complexity. The guiding connection changes from the system-environment connection to the connection between the system and its complexity. Not by chance, self-referential phenomena and systems have started to receive substantial attention. Summing up, complex systems are adaptive systems capable of regeneration of the elements they are made of, followed by topological/structural and organizational/functional transformations. As far as self-referential systems are concerned, the guiding relation is no longer the system–environment opposition or duality, but the system–system intra-relations, or automorphisms. Ultimately, the difference between openness and closure acquires a different meaning: now openness means exchange with the environment, whereas closure generates structure, a key attribute of the system which provides its identity by organizing the system as an integral whole, or a holon. The closure should be understood as operational closure and not in the sense of major restrictions placed on the system's exchanges with the environment.

### 3.4. From Structural Symmetry to Dynamic Symmetry Breaking:

A recognized path for the emergence of higher dynamical complexity levels is provided by dynamic symmetry breaking. The role of structural symmetry and dynamic symmetry breaking in changing levels and causing the emergence of increasing complexity levels can be further considered as shown in the following diagram (Figure 1):

**Figure 1.** The roles of symmetry breaking and the corresponding groupoids structures in the emergence of higher complexity levels of reality: repeated symmetry breaking leads at first to double groupoids, and then to multiple-groupoids in a higher dimensional algebra of highly complex dynamics characterized by multi-stability and genericity of states in super-complex (organismic) systems. The living states thus formed are both meta-stable and generic, achieving structural stability or resistance to external perturbations, unlike chaotically-complex systems that are neither generic nor meta-stable.
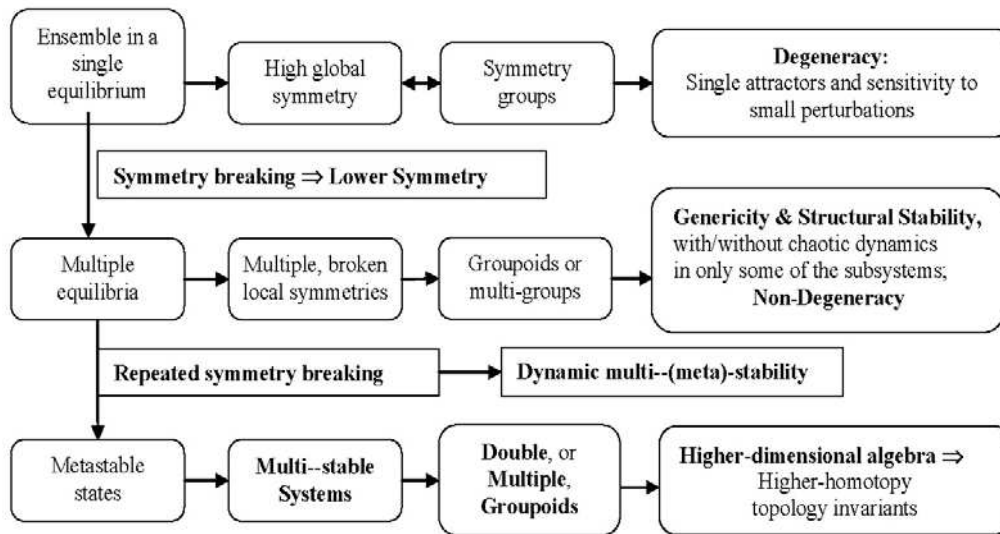


Figure 1: The roles of symmetry breaking and the corresponding groupoids structures in the emergence of higher complexity levels of reality: repeated symmetry breaking leads at first to double groupoids, and then to multiple-groupoids in a higher dimensional algebra of highly complex dynamics characterized by multi-stability and genericity of states in super-complex (organismic) systems. The 'living' states thus formed are both meta-stable and generic, achieving structural stability or 'resistance' to external perturbations, unlike chaotically-complex systems that are neither generic nor meta-stable.

The following provides a more detailed explanation of the interesting properties derived from such emergence phenomena. The super-complex systems that have thus emerged exhibit several properties considered essential to life

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and its maintenance/propagation: autopoiesis, self-repair capabilities (as for example in (M-R)-system models), and self-reproduction or sexual reproduction capability. Such highly complex systems also comprise logically heterogeneous classes that can be properly understood only in terms of their operating n-valued, LM-logics underlying their genetic networks/active genomes [9],[15],[21].

Obviously, not all initial, quantum/ multi-molecular systems are capable of emerging in this fashion through repeated symmetry breaking. One of the major tasks of any complete super-complexity theory is therefore to identify the initial conditions and quantum/ molecular components that must exist for the super-complexity emergence to occur starting from certain, either chaotic or quantum, systems; the latter seems the more likely class of candidates as quantum dynamics appears to quench chaotic dynamics and the extreme sensitivity to perturbations that chaotic-complex systems exhibit. A related, interesting but open question is if the emergence of the ultra-complex, meta-level of the human mind also involves repeated symmetry breaking and the corresponding, multiple-groupoid structures with their non-Abelian higher dimensional algebra. Considerations made elsewhere would seem to indicate that this is indeed the case, but additional conditions for the interactions among super-complex systems are also necessary for the emergence of the uniquely ultra-complex human mind [21],[24] ); emergent dynamic features such as meta-stable, generic states and multi-stability are, however, likely to recur at the meta-level of the human mind (see also for example, [3]-[5], [21]-[25]).

## 4. The Age of Super-Complexity (1968–).

Living systems (including among living systems not only biological systems but psychological and social systems as well) present features remarkably different from those characterizing non-living systems. We propose that super-complexity requires at least four different categorical frameworks, namely those provided by the theories of levels of reality, chronotopoids, (generalized) interactions, and anticipation. Furthermore, the claim is defended that novel logical frameworks [21],[24]) as well as a new conceptual/mathematical framework is required [21]-[25],[32].

*4.1 Strata of Reality*

The distinction is widespread among three basic realms or regions (or strata, as we will call them) of reality. Even if the boundaries between them are differently placed, the distinction among the three realms of material, mental and social phenomena is essentially accepted by most thinkers and scientists. A major source of discussion is whether inanimate and animate beings should be placed in two different realms (this meaning that there are in fact four and not three realms) or within the same realm.

From an ontological point of view, the problem about how many strata there are can be easily solved. Leaving apart universal categories (those that apply everywhere), two main categorial situations can be distinguished: (a) Types (Items) A and B are categorially different because the description (codification or modelling) of one of them requires categories that are not needed by the description (codification or modelling) of the other; (b) Types (Items) A and B are categorially different because their description (codification or modelling) requires two entirely different groups of categories. We term the two relations respectively as relations of over-forming and building-above (Hartmann 1935). Strata or realm of reality are connected by building-above relations. That is to say, the main reason for distinguishing as clearly as possible the different strata of reality is that any of them is characterized by the birth of a new categorial series. The group of categories that are needed for analyzing the phenomena of the psychological stratum is essentially different from the group of categories needed for analyzing the social one, which in its turn requires a group of categories different from the one needed for analyzing the material stratum of reality.

Over-forming (the type (a) form of categorial dependence) is weaker than building-above and it is used for analyzing the internal organization of strata (together with building-above and eventually other types of relation). Each of the three strata of reality has its specific structure. The case of the material stratum is the best known and the least problematic. Suffice it to consider the series atom-molecule-cell-organism (which can be extended at each of its two extremes to include sub-atomic particles and ecological communities, and also internally, as needed). Compared to the material realm, the psychological and social ones are characterized by an interruption in the material categorical series and by the onset of new ones (relative to the psychological and social items). More complex types of over-forming are instantiated by them.

The next step is to articulate the internal organization of each stratum (see also [70],[73]-[74] for additional details).

## 4.2. Levels and Meta-levels of Reality

System analysis requires framing ontology in the form of a theory of categories (Poli, 2008). We shall therefore adopt here a categorical viewpoint, meaning that we are looking for "what is universal" (in some domain or in general). In this regard, the most universal feature of reality is that it is temporal, i.e. it changes, and it is subject to countless transformations, movements, alterations.

The deepest access to the ontological theory of levels is achieved by adopting a categorical viewpoint. In short, a *level of reality* is represented by a group of (ontological) categories [75]. The next step is to distinguish universal categories, those that pertain to the whole of reality, from level categories, those that pertain to one or more levels, but not to all of them. The question now arises about how the material, psychological and social strata are connected together. The proposal defended by Poli in [70] and subsequent papers is that material phenomena act as bearers of both psychological and social phenomena. In their turn, psychological and social phenomena reciprocally determine each other. Psychological and social systems are formed through co-evolution, meaning that the one is the environmental prerequisite for the other [63].

Terminological considerations are here essential: Poli in [70] and [75] uses the term 'level' to refer in general to the levels of reality, restricting the term 'stratum' to building-above relationships and the term 'layer' to over-forming relationships, and we shall eventually use the expressions 'sub-layer' and 'sub-stratum' when analysis will require them. On the other hand, a meta-level is a term that emerged from the logical and mathematical analysis of categories of categories; to resolve antinomies in the mathematical theory of sets, such as "the set of all sets is not a set", the term class has been reserved for ensembles containing sets. Thus, a class is a type of meta-level of sets, and their existence still relies on the membership relation, that is, "an element belongs to a set". In category theory, a category of categories is, in fact, a meta-category or super-category [64],[68]. In both cases, that of a class and a super-category, one has in fact three levels: the 0th level is that of elements or objects, that belong respectively to sets or categories, the first level of sets or categories, and then the second level, or meta-level, of respectively classes and 2-categories (super-categories or meta-categories). Furthermore, the links, or

morphisms (arrows) between objects have distinct actions and properties at
the meta-level from those of the lower levels; 2-level morphisms are functors
between categories, and 3-level morphisms are natural transformations of func-
tors. Neither functors nor natural transformations (or functorial morphisms)
can be regarded as mere mappings; in fact, the meta-level morphisms–natural
transformations–are where most of the interesting action is in Category The-
ory, which is thus intrinsically meta-theoretical in character. The attribute
*natural* of 'functorial morphisms' also reflects their intrinsic type of symme-
try/property, called commutativity which is present in the square diagrams
that define them and that are natural (see for example, [66], [76] and [64] for
the rigorous definition of functorial morphisms involving such natural, square
diagrams.) In actual use, the term meta is employed in Category Theory
for meta-theorems that emerge in a similar form from the first to the sec-
ond level (2-category or super-category). Notably, the meta-levels do not stop
at the second level discussed here, but can go up higher to the n-th level,
with n being an integer. Thus, an n-category is still a meta-level category
of a higher order, and thus belongs to Higher Dimensional Algebra [30],[32].
One also notes that this feature of Category Theory and Higher Dimensional
Algebra is very attractive both as a logically-consistent tool and as a frame-
work for a relational approach to highly complex systems and their dynamics
(Baianu and Marinescu, in [2]; Baianu in [3]-[6],[14]-[22]). In the case of bio-
logical organisms–which are super-complex dynamic systems (cf. Baianu et al.
in [22]-[23],-their meta-level was represented by Organismic Supercategories
(OS) that required a special axiomatics (ETAS in [3]). Similar considerations
were made in Relational Biology by Nicolas Rashevsky in 1969 who consid-
ered both living organisms and human societies as Organismic Sets [81]–even
though such sets have only a discrete topology and no explicit connectivity,
organizational structure or links. It was only recently shown in [22], [24]-[25]
that the super-complexity level of organisms has emerged/emerges as a direct
consequence of their internal dynamics and ontogenetic development. In Ra-
shevsky's theory of organismic sets [81] the 0-th level is that of the genes (it
was thus conceived as a biomolecular level), whereas living cells of a multi-
cellular organism were considered to form the first organizational levels, and
then the multi-cellular, organismic level would constitute the second organi-
zational level. One notes here also that the multi-cellular, organismic level of
eukaryotes satisfies the three-level criterion for the existence of a meta-level,
that of the super-complex dynamic system of the eukaryotes, but that prokary-

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otic organisms like bacteria would not meet the three-level requirement for a
meta-level. In the case of human societies, the three-level criterion can always
be met, the suggested levels involved being the human organism, the mind
and the human society [22], [25], with the additional proviso that the human
mind can be 'in itself' considered as a meta-level of existence, above those
of the living human organism and cells, or genes/biomolecules. Thus, atoms,
molecules, organisms distinguish levels of reality because of the causal links
that govern their behavior, both horizontally (atom-atom, molecule-molecule,
organism-organism) and vertically (atom-molecule-organism). This is a first
intuition of the theory of levels. Even if the further development of the theory
requires imposing a number of qualifications to this initial intuition–such as
existence of meta-levels in the sense introduced here–the idea of a series of
entities organized on different levels of complexity will prove correct. Briefly,
the difference between levels of reality and levels of interpretation requires ac-
knowledging that the items composing levels of reality are endowed with their
own form of agency [74]-[75]).

*Mutatis mutandi*, the same kind of reasoning holds for meta-levels. Thus,
the molecular level–which is extremely rich in the number of different types of
molecules, more so than its sub-level of atoms–can be considered as a meta-level
of electrons and stable nucleons (protons and neutrons), because the latter are
thought to be 'made of' up (u) and down (d) quarks; thus, the mathematical
requirement of a meta-level for the existence of three consecutive levels is
satisfied in the case of the molecular meta-level of the quarks and electrons,
albeit by intertwining the 0th and first level. On the other hand, if the electrons
were to be found to have also a 'quark-like' substructure, then the three-level
requirement for the molecular meta-level would be exactly satisfied, without
any level intertwining. One notes however that the use of the term meta-
level in Logics and Mathematics is more restrictive and more sharply defined
than the flexible and broader meaning that we propose to employ here in the
ontological theory of levels (and also 'meta-levels'); therefore, one could avoid
potential semantic confusions by referring precisely to the latter meta concept
as ontic meta-levels.

Most details of the links connecting together the various levels of reality
are still unknown, because the various sciences had mainly been working on
causal links internal to their regional phenomena. The lack of a theory of levels
of reality has been the major obstruction to the development of the needed
theories. Proposal concerning the architecture of levels and their links will

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improve our understanding of the world and its many dependencies.

*4.3. Chronotopoids*

The theory of levels paves the way towards the claim that there could be different families of times and spaces, each with its own structure. We shall argue that there are numerous types of real times and spaces endowed with structures that may differ greatly from each other. The qualifier *real* is mandatory, since the problem is not the trivial one that different abstract theories of space and time can eventually be and have been constructed [74]-[75] ). We shall treat the general problem of space and time as a problem of chronotopoids (understood jointly, or separated into chronoids and topoids). The guiding intuition is that each stratum of reality comes equipped with its own family of chronotopoids (see [74] for further details).

*4.4. Causal Interactions and Dependencies*

The theory of levels of reality provides as well the natural framework for developing a full-fledged theory of causal dependencies (interactions). As for the case of chronotopoids, levels support the hypothesis that any level has its own form of causality/interaction (or family of forms of causality/interaction). Material, psychological and social forms of causality/interaction could therefore be distinguished (and compared) in a principled way. Beside the usual kinds of basic causality between phenomena of the same nature, the theory of levels enables us to distinguish upward and downward forms of causality/interaction (from the lower level to the upper one and vice versa). This acknowledgement provides the needed context for distinguishing material, psychological and social types of interactions.

*4.5 Anticipation*

An Anticipatory System is a system such that the choice of the action to perform depends from the system's anticipations of the evolution of itself and/or the environment in which it is placed (Rosen, 1985). Reactive systems, on the contrary, are such that subsequent states depends entirely from preceding states (usually, according to some law or rule). Anticipation comes in different guises: the simplest distinction is between strong and weak types of anticipation, where the former (the strong one) is meant as coupling between the system and its environment, while the latter (the weak one) is understood in the form of a (cognitive) model developed by the anticipatory system itself. As a straightforward consequence, evolutionary survival implies that all living systems are characterized by some form of another of strong anticipation, while some among the most evolved species may enjoy weak types of anticipation as

well.

Anticipation can therefore lie low and work below the threshold of consciousness or it may emerge into conscious purpose. In the latter form it constitutes the distinctive quality of causation within the psychological and the social realms. On the other hand, biological systems are better characterized by non-representative (model-based) types of anticipation [75].

Complexity, as usually and most likely incorrectly understood, is entirely past-governed and apparently does seem to be unable to include anticipatory behaviour. In order to distinguish anticipatory systems from entirely past-governed systems, the concept of super-complexity has been recently introduced (see Baianu 2006, special issue of Axiomathes dedicated to Robert Rosen; also with precise definitions and specifications by Baianu et al in ref. [22]).

A different but not opposite way to understand anticipation is to see the theory of anticipatory systems as providing a phenomenological, or first-person, type of description, while most of complexity theory is usually based on third-person descriptions. The theory of anticipatory systems can therefore be seen as comprising both first- and third-person information. The interactions between the two types of descriptions may result in many cases in a substantial reduction of the state space characterizing the dynamics of anticipatory systems.

Besides anticipation, living systems require the capacity of coordinating (again, intentionally or automatically) the rhythm of the system with those of its parts. In this respect, the anticipation of the system as a whole may diverge from those of its parts. Furthermore, living systems are multi-strata systems, composed by different types of components interacting at different levels of organization. Analysis is required of both their material and functional components.

The interaction among the three mentioned topics (anticipation, part-whole structure and levels of organization) provides a cue for better understanding living systems.

## 5. Mathematical Categories

From the point of view of mathematical modelling, the mathematical theory of categories models the dynamical nature of reality by resorting to variable

categories (i.e., toposes). The claim advanced by this paper is that mainstream topos theory suits perfectly the needs of complex systems. However, as soon as one passes from complex systems to super-complex systems, the theory of toposes requires suitable generalizations. Our proposal is then to adopt the framework provided by (a suitably generalized) topos theory for modelling super-complex systems. We have seen that the difference between complex and super-complex systems in based on at least four main issues: levels of reality, chronotopoids, (generalized) interactions, and anticipation. So far, none of them has been adequately formalized. However, considering that chronotopoids and interactions require (and therefore depend on) the theory of levels, and that the issue of anticipation has been advanced by Rosen in [88], subsequent sections will make reference to the issue of levels only. Furthermore, it is apparent that any step towards a proper formalization of the theory of levels (or any other of the mentioned theories) seems to require the development of a non-Abelian framework. Whatever other mathematical property will be required, the first mandatory move is therefore to pass from an Abelian, or commutative, framework [40]-[43], [44]-[45], [48], [54],[64],[66] to a non-Abelian one [33].

## 6. Living Systems Represented as Variable Categories.

One of the major road blocks to a successful dynamical theory of complex systems, and also of developmental, living systems, has been the lack of a flexible mathematical structure which could represent the immensely variable and heterogeneous classes of biological and social organisms. In the following subsection we propose to re-examine the representation of living systems in terms of such flexible mathematical structures that can vary in time and/or space, thus providing a natural framework for relational/theoretical biology, psychology, sociology or global theoretical constructs addressing environmental problems.

We have already mentioned that the problem of time, i.e. the problem of the dynamical nature of reality, is the main problem underling the philosophical theory of categories (see also [75]). This same problem has also been at the center of the mathematical theory of categories over the last six decades, and found a first outcome in the idea of variable category (be it in the form of variable sets, variable classes, etc). Furthermore, dealing with varying, or

variable, objects such as those formalized as variable sets, variable classes, etc. lead to a further generalization of this categorical approach that is founded in Logic, be it Boolean (as in the Category of Sets), Heyting-intuitionistic (as in standard Topos theory in [64]), or Many-Valued (MV or Lukasiewicz-Moisil [52] by Georgescu, as further applied in the new generalized version of Topos theory in [18],[21]. It is worth mentioning that some of the occasional pitfalls of the categorical approach in specific, logical or mathematical, contexts, as for in example in certain areas of Algebraic Topology or Algebraic Logic, were recognized early by topologists, who also branded this approach as "abstract nonsense", even though it continued to facilitate and be widely employed in the proof of general theorems. Their objection lies in the fact that the universal may, and does, have a few specific exceptions and counter-examples as one might of course expect it. Things that may appear to be *globally the same*, or *categorically equivalent*, may still differ quite significantly in their specific, local contexts.

## 7. Dynamic Equivalence, Analogous Systems and Similarity

A scientific and/or engineering strategy for dealing with complex systems has long been the analysis of simpler, more readily accessible models of a complex system. One often attempts to arrive at computable models with similar dynamic behavior(s) to that of the original, complex system. Computability of such simple models may often involve the use of a super-fast digital computer, and the models can be made indefinitely more and more complicated through iterated attempts at improved computer simulation.

A formal, categorical approach to analogous systems and dynamic equivalence of systems was first reported by Rosen in 1968 [84] from a classical viewpoint that is, excluding quantum dynamics; subsequently his approach was extended to the development of biological systems and embryology by means of adjoint functor pairs and weak (epimorphic) adjointness [7].

Returning now to the issue of computer simulation, one finds upon careful consideration that there is no recursively computable (either simple or complicated) model of both super-complex biological systems and simpler chaotic systems (see for example, [14] and the relevant references cited therein). Therefore, complex systems biology cannot be reduced to any finite number of simple(r) mechanistic models that are recursively computable, or accessible to digital computation or numerical simulation. This basic result does not seem,

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however, to deter the computationally-oriented scientists from publishing a rapidly increasing number of reports on computer simulation of complex biological systems. There is surprising enthusiasm and optimism, not to mention popularity, funding, etc., for computer simulations in both biology and medicine. Heuristic results are both attractive and stimulating, culminating with the aroused expectation of final answers to either biological or medical problems by means of digital super-computers. It seems, however, that super-computers are no match for super-complexity, or even for the simpler, chaotic dynamics, a result also widely recognized by many chaotic dynamic theorists.

Fundamentally, the limitations of digital computers that rely upon recursive computations are traced back to the Boolean (or Chrysippian) logic underlying the design of all existing digital computers, and also to the Axiom of Choice upon which set theory is based [64]). On the other hand, biological, super-complex system dynamics is governed by a many-valued (MV) logic characteristic of biological processes including genetic ones [9],[21],[24]. Such an MV-logic is both non-commutative (unlike the Boolean or the Heyting-intuitionistic logic of standard Toposes) and irreducible to Boolean or intuitionistic logics (of course, with the exception of the special cases of the category of centred Lukasiewicz-Moisil logic algebras that can be mapped isomorphically onto Boolean Logic algebras [50]-[52]). Unlike the well known result of von Neumann's for the Universal Automaton, super-complex biological systems are not recursively, or numerically, computable.

Although this limits severely the usefulness of all digital computers in complex systems biology and mathematical medicine, it does not render them useless for experimentation, data collection and analysis or graphics and graphical presentation/representation of numerical results. The limitations come in the final analysis where computer simulations of super-complex system dynamics may not claim a full, or complete, dynamical modelling of living systems as such a result has been formally proven to be unobtainable, in general, through recursive computation with algorithms, universal Turing machines, etc. [14],[89]. Furthermore, it may be possible to extend the recursive concept of numerical analogy to one of symbolic computation through conjugacy of dynamic state spaces [14] and similarity of the corresponding systems, as in the case of adjoint dynamical systems [7],[14]. Thus, non-recursive algebraic-topological computation is still possible, of course, for living systems and their essential subsystems, such as genetic networks, by employing non-commutative, irreducible MV-logics, either in a general context [52], or

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in more specific contexts, such as the controlled dynamics of genetic networks in biological organisms in refs. [9],[13]- [14],[16]-[18], [21]. Non-commutative super-complex dynamic modelling has just begun in biology and medicine, including diagnostics. Biostatistics based on such MV-logics has also just become a possibility [52]. The latter developments are also suggesting a paradigm shift occurring now in system theory  from Abelian to non-Abelian theories. This new paradigm has perhaps already began with the earlier introduction of non-commutative geometric spaces obtained through deformation as models of Quantum Spaces in attempts at formalizing quantum gravity by A. Connes ([35] and references cited therein).

## 8. Towards a Non-Abelian Systems Theory

One could formalize the hierarchy of multiple-level relations and structures that are present in super-complex systems in terms of the mathematical Theory of Categories, Functors and Natural Transformations (TC-FNT). On the first level of such a hierarchy are the links between the system components (or objects) represented as morphisms of a structured category which are subject to the ETAC axioms/restrictions of Category Theory [59]-[60]. Then, on the next, second level of such a categorical hierarchy one considers functors, or links, between the first level categories which compare two categories by associating objects from the first category to objects in the second category, and morphisms of the first category to morphisms of the second one. On the third level, one compares, or links, such functors using natural transformations in a 2-category (or meta-category) of categories. At this level, natural transformations not only compare functors but also involve mappings that associate elements of the first level objects (system components) thus *closing* the structure and establishing the universal links between items as an integration of both first and second level links between items. The advantages of this constructive approach in the mathematical theory of categories, functors and natural transformations have been recognized since the beginnings of this mathematical theory in the seminal paper of Mac Lane and Eilenberg in 1945 [45]. A relevant example from the natural sciences, e.g., neurosciences, would be the higher-dimensional algebra of processes of cognitive processes of still more, linked sub- processes [31]-[32]. Yet another example would be that of groups of groups of item subgroups, 2-groupoids, or double groupoids of groups

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of items. The hierarchy constructed above, up to level 3, can be further extended to higher, n-levels, always in a consistent, natural manner. This type of global, natural hierarchy of items inspired by the mathematical TC-FNT has a kind of internal symmetry because at all levels, the link compositions are natural, that is the all link compositions that exist are transitive, i.e., $x < y$ and $y < z$ then also $x < z$, or $f : x \to y$ and $g : y \to z; h : x \to z$, then also $h = g * f$. The general property of such link composition chains or diagrams involving any number of sequential links is called commutativity, or the naturality condition; this key mathematical property also includes the mirror-like symmetry

$$x * y = y * x$$

where $x$ and $y$ are operators and the star, '*', representing an operator multiplication. Then, the equality of $x * y$ with $y * x$ implies that the $x$ and $y$ operators 'commute'; in the case of an eigenvalue problem involving such commuting operators, the two operators would share the same system of eigenvalues, thus leading to equivalent numerical results. This is very convenient for both mathematical and physical applications (such as those encountered in quantum mechanics). Unfortunately, not all operators commute, and not all mathematical structures are commutative. A structure is called 'Abelian' if it commutes everywhere the composition '*' is defined. Thus, as a prominent example a commutative group is Abelian. The more general case is however the non-Abelian one; any structure that is not commutative everywhere, that is globally, is thus non-Abelian. A general example is that of the categories defined above; only a sub-class of such categories are Abelian. Another example is that of a non-commutative structure relevant to Quantum Theory the Clifford algebra of quantum observable operators [38] ; yet another, more recent and popular, example is that of C*–algebras of (quantum) Hilbert spaces; such structures, are of course also non-Abelian, with non-Abelianness being the weaker condition than global non-commutativity. Last but-not least, are the interesting mathematical constructions of non-commutative geometric spaces obtained by deformation introduced by Allan Connes in 1994 [35] as possible models for the physical, quantum space-time; such non-commutative geometric spaces are therefore also non-Abelian, as is also their category which is only locally, but not globally, commutative. Thus, not all diagrams of non-commutative geometric spaces and connecting homeomorphisms are commutative. However, it was shown that the property of Abelianness can be extended in the case of categories to a subclass of categories that satisfy six additional axioms (Freyd,

1964). Such Abelian categories have formally identical meta-theorems to those exhibited by the (Abelian) category G of commutative groups; therefore, one has G as the best mathematical model for any Abelian category (p. 2 of Popescu in ref.[76]).

Because, as explained above, both the (Clifford) algebra of quantum observable operators and the related C*-algebras of (quantum) Hilbert spaces are non-commutative structures, the microscopic, or quantum, fundamental (sub)levels of physical reality do not satisfy the Ab-axioms, or conditions for Abelianness, in TC-FNT the standard mathematical theory of categories (functors and natural transformations). Therefore, quantum theory itself is not Abelian, and it thus follows that a General Categorical Ontology which considers all items, from all levels of reality–including those on the 'first', quantum level (that are not commutative)–must also be non-Abelian on account of the fundamental quantum sublevels that are not commutative.

Moreover, mathematical, Non-Abelian Algebraic Topology [33] , as presented by Brown, Higgins and Sivera in 2010, as well as the non-Abelian Quantum Algebraic Topology (NA-QAT; Baianu et al. in 2006, in ref. [20]), and the physical, Non-Abelian Gauge theories may provide all the ingredients needed for a proper foundation of novel/non-Abelian, hierarchical multi-level theories of super-complex system dynamics. Furthermore, it was recently pointed out by Baianu et al in refs.[20]-[25]) that the current and future development of both NA-QAT and of a quantum-based Complex Systems Biology involve a fortiori non-commutative, many-valued logics of quantum events, such as the Lukasiewicz-Moisil (LMV) logic algebra [50]-[52], complete with a fully-developed, novel probability measure theory grounded in the LMV-logic algebra [52]. The latter work paves the way to a new projection operator theory founded upon the (non-commutative) quantum logic of events, or dynamic processes, thus opening the possibility of a complete, non-Abelian Quantum theory [see also, [36]). Finally, such recent developments point towards a paradigm shift in systems theory and to its extension to more general, Non-Abelian theories, well beyond the bounds of commutative structures/spaces and also free from the restrictions and limitations imposed by the Axiom of Choice to Set Theory.

9. The Emergence of An Ultra-Complex System of Processes

The term *ultra-complexity level* of reality is here proposed to represent *the mind meta-level*, or the mental level, that is, a certain dynamic pattern, or meta-process of layered sub-processes emerging to the most complex level of reality based upon the super-complex activities and higher level processes in special, super-complex systems of the human brain coupled through certain synergistic and/or mimetic interactions in human societies. In this respect we are proposing a non-reductionist, categorical ontology that possesses both universal attributes and a top level of complexity encompassed by the human consciousness [22],[25].

As a provisional, working hypothesis, one can formulate a (most likely incomplete) definition of human consciousness as an *ultra-complex* process that integrates numerous super-complex 'sub-processes' in the human brain that are leading to a *higher-dimensional, psychological level* capable of free will, problem solving, and also capable of speech, logical thinking, emotions, etc. including–but not limited to–'awareness', self, creativity, empathy, and a wide variety of *introspective* experiences. It may be possible to formulate a more concise definition but for operational and modeling purposes this will suffice, at least provisionally.

From a causal perspective, the social realm and mental realm inter–correspond *via* co-evolution and both are founded on the material realm. But these differ categorically. According to the theory of levels, a level of reality may comprise various kinds of dynamics and it is essential to distinguish between:

a) dynamics relative to the unfolding of reality;

b) dynamics relative to the processes among strata of reality by which a higher level emerges from a lower one (cf. Poli in ref. [73]).

### 9.1. Meta-processes of Processes, and Groupoids of Groups: Higher-Level Emergence via Symmetry Breaking

On the lower level, certain groups of transformations, such as the group of Lorentz transformations are well-established in physics- in General Relativity. Both classical physics and Quantum theories also abound with symmetry

groups. Let us consider next what happens on the higher, mental level of reality. Thus, at the higher levels of reality-both mental and social, much more complex, global structures emerge *via* symmetry breaking (see Figure 1), such as those formally represented by biogroupoids and HDA [18]-[22],[24],[30]-[32].

William James in 1890, in his *"Principles of Psychology"* (cited in [21]), considered consciousness as *"the stream of thought"* that never returns to the same exact 'state'. Both *continuity* and *irreversibility* are thus claimed as the key, defining attributes of consciousness. We note here that our earlier metaphor for evolution in terms of 'chains of local (mathematical) procedures' [21]-[24] may be considered from a different viewpoint in the context of human consciousness–that of chains of 'local' thought processes leading to global processes of processes..., thus emerging as a 'higher dimensional' stream of consciousness. Moreover, in the monistic –rather than dualist–view of ancient Taoism the individual flow of consciousness and the flow of all life are at every instant of time interpenetrating one another. Then, *Tao* in motion is constantly *reversing* itself, with the result that consciousness is *cyclic*, so that everything is –at some point– without fail changing into its opposite. One can visualize this cyclic patterns of Tao as another realization of the Rosetta biogroupoids that we introduced earlier in a different context– *relating the self of others to one's own self* in the formation of the concept of one's self [25], thus at once 'combining nature with nurture' [22].

The qualifier *ultra-complex* is thus mandatory and indicates that the ontological level of consciousness, or mental activities that occur in the conscious, '(psychological) state', is *higher* than the levels of the underlying, *super-complex* neurodynamic sub-processes leading to, and supporting, consciousness. From this point of view, although the mental level cannot exist independently without, or be existentially separated from neurodynamics, it is nevertheless distinct from the latter. This looks like a Boolean logic paradox which is avoided if one considers human consciousness and/or the mind as a *meta-system* of intertwined mental and neurodynamic processes; such a meta-system would have *no boundary* in the sense described in [75], but a horizon. This proposed solution of the 'hard problem' of psychology is neither dualistic (e.g., Cartesian) nor is it monistic–as in Taoism or Buddhism. Our novel view of consciousness disagrees with them because it contains a tertium datur claim, simply because reality is likely to be much more complex than the framework of crysippian/Boolean logic.

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## 10. Conclusions

By way of a conclusive synthetic summary, it is worth underlining that the proposal of higher-order complex systems crucially depends on two different and so far only partially overlapping threads. From one side, we have the ontological thread comprising levels of reality, chronotopoids, generalized interactions and anticipation. On the other side, several distinct mathematical frameworks are actually under active development, and are also gaining momentum. These include, but are not limited to, categories of Lukasiewicz-Moisil algebras, variable biogroupoids, and variable topologies. All of them are part and parcel of a wider movement towards substantially more general mathematical structures usually termed non-Abelian mathematics that may also include non-commutative structures. The former have been originally developed in the effort of understanding at high energy quantum physics, and are also promising candidates for addressing biological, psychological and social phenomena. Abelian structures, on the other hand, are patently far too rigid and/or too symmetric for smoothly modelling dynamic phenomena/processes as variable, rich and (super)-complex as those pertaining to life, mind and society. So far, the overlapping and mutual breeding between the ontological and the mathematical threads is still limited,not the least because many philosophers are not yet sufficiently familiar with the rather advanced mathematical subjects mentioned here, and many mathematicians are not yet sufficiently aware of all subtleties and difficulties posed by ontology.

However, the world is so complex and so widely differentiated–even though it is ultimately and intimately unified–that one cannot hope to solve most of the demanding real-world problems without both flexible enough mathematical structures and a deeper understanding of their ontological, multi-stratified and many-layered attributes than it has been presumed before.

## References

[1] Albertazzi, L. 2006. Immanent Realism. Introduction to Franz Brentano. Springer, Dordrecht.

[2] Baianu, I.C. and M. Marinescu. 1968. Organismic Supercategories: Towards a Unified Theory of Systems, *Bulletin of Mathematical Biophysics*, **30**: 148-159.

[3] Baianu, I.C. 1970. Organismic Supercategories: II. On Multistable Systems, *Bulletin of Mathematical Biophysics*, **32**: 539-561.

[4] Baianu, I.C. 1971a. Organismic Supercategories and Qualitative Dynamics of Systems. *Bulletin of Mathematical Biophysics*, **33**(3): 339-354.

[5] Baianu, I.C. 1971b. Categories, Functors and Quantum Algebraic Computations, in P. Suppes (ed.), *Proceed. Fourth Intl. Congress Logic, Mathematics and Philosophy of Science*, September 1-4, 1971.

[6] Baianu, I.C.: 1973. Some Algebraic Properties of (M,R)-Systems., *Bulletin of Mathematical Biophysics*, **35**: 213-217.

[7] Baianu, I.C. and D. Scripcariu. 1973. On Adjoint Dynamical Systems. *Bulletin of Mathematical Biophysics*, **35**(4), pp. 475-486.

[8] Baianu, I.C. and M. Marinescu. 1974. A Functorial Construction of (M,R)-Systems. *Revue Roumaine de Mathematiques Pures et Applique*, **19**:388-391.

[9] Baianu, I.C. 1977. A Logical Model of Genetic Activities in Lukasiewicz Algebras: The Non-linear Theory, *Bulletin of Mathematical Biology*, **39**: 249-258.

[10] Baianu, I.C. 1980a, Natural Transformations of Organismic Structures., *Bulletin of Mathematical Biology*, **42**: 431-446.

[11] Baianu, I.C.1980b, On Partial Order and Disorder in Biological Systems. Letter to the Editor. , *Bulletin of Mathematical Biology*, **42**: 601-605.

[12] Baianu, I. C.1983, Natural Transformation Models in Molecular Biology., in *Proceedings of the SIAM Natl. Meet.*, Denver, CO.;
Eprint: http://www.cogprints.org/3675/;
http://www.cogprints.org/3675/0l/Naturaltransfmolbionu6.pdf.

[13] Baianu, I.C. 1984. A Molecular-Set-Variable Model of Structural and Regulatory Activities in Metabolic and Genetic Networks, FASEB Proceedings, 43, p. 917.

[14] Baianu, I. C. 1986-1987a. Computer Models and Automata Theory in Biology and Medicine, in M. Witten (ed.), Mathematical Models in Medicine, vol. 7., Pergamon Press, New York, pp. 1513-1577; CERN Preprint No. EXT-2004-072:
http://doe.cern.ch//archive/electronic/other/ext/ext-2004-072.pdf.

[15] Baianu, I. C. 1987b. Molecular Models of Genetic and Organismic Structures, in Proceed. Relational Biology Symp., Argentina; CERN Preprint No.EXT-2004-067:
http://doc.cern.ch/archive/electronic/other/ext/ext20040

[16] Baianu, I.C. 2004a. Quantum Nano-Automata (QNA): Microphysical Measurements with Microphysical QNA Instruments, CERN Preprint EXT-2004-125.

[17] Baianu, I. C. 2004b. Quantum Interactomics and Cancer Mechanisms, Preprint No. 00001978
http://bioline.utsc.utoronto.ca/archive/00001978/01/
QuantumInteractomicsInCancer–Sept13k4E–cuteprt.pdf;
http://bioline.utsc.utoronto.ca/archive/00001978/

[18] Baianu, I.C., James Glazebrook, G. Georgescu and Ronald Brown. 2005. "Generalized 'Topos' Representations of Quantum Space-Time: Linking Quantum N-Valued Logics with Categories and Higher Dimensional Algebra.", CERN Preprint series EXT-2005.

[19] Baianu, I. C., ed., 2006. Robert Rosens Work and Complex Systems Biology, *Axiomathes*, **16** (1-2): 25-34.

[20] Baianu, I. C., Brown, R. and J. F. Glazebrook.2006. *Quantum Algebraic Topology and Field Theories: I. Non-Abelian Quantum Algebraic Topology (NAQAT)".* http://planetphysics.org/?op=getobj&from=lec&id=61.

[21] I. C. Baianu, R. Brown, G. Georgescu and J. F. Glazebrook, J. F. 2006. Complex Nonlinear Biodynamics in Categories, Higher Dimensional Algebra and Lukasiewicz–Moisil Topos: Transformations of neuronal, genetic and neoplastic networks, *Axiomathes*, **16** Nos. 1–2 (2006), 65–122.

[22] I. C. Baianu, R. Brown and J. F. Glazebrook.2007. Categorical ontology of complex spacetime structures: the emergence of life and human consciousness, *Axiomathes* **17**, (2007a), 223-352.

[23] Baianu, I. C. , Brown, R, and , J. F. Glazebrook. 2008. A non-Abelian, categorical ontology of spacetimes and quantum gravity. Axiomathes 17: 145–222. doi:10.1007/s10516-007-9012-1.

[24] Baianu, I.C., George Georgescu, James F. Glazebrook and Ronald Brown. 2010. Lukasiewicz-Moisil Many-Valued Logic Algebra of Highly-Complex Systems., *Broad Research in Artificial Intelligence and Neuroscience (BRAIN)*, vol.1: 1–11, (ISSN: 2067-3957).

[25] Baianu, I.C. and James F. Glazebrook. 2010. Complex Systems, Meta-Systems and Levels: The Emergence of Life, Human Consciousness and Society. *Broad Research in Artificial Intelligence and Neuroscience (BRAIN)*, vol.1: 119-207, (ISSN: 2067-3957).

[26] Bell, J. 2000. Continuity and the Logic of Perception, *Transcendent Philosophy*, 1, 2.

[27] Bell, J. 2005. The Continuous and the Infinitesimal in Mathematics and Philosophy. Polimetrica, Monza.

[28] Bertalanffy, L. von, 1972. The History and Status of General Systems Theory, in G. J. Klir (ed.), *Trends in General Systems Theory*, Wiley, New York, pp. 21-41.

[29] Bogdanov, A. 1984. *Essays in Tektology. The General Science of Organization.*, Seaside CA, Intersystems Publications, 1984 (first Engl. ed. 1980).

[30] Brown, R. 2004. Crossed complexes and homotopy groupoids as non commutative tools for higher dimensional local-to-global problems, in Proceedings of the Fields Institute Workshop on Categorical Structures for Descent and Galois Theory, Hopf Algebras and Semiabelian Categories, September 23-28, *Fields Institute Communications*,**43**: 101-130.

[31] R. Brown, R. Paton and T. Porter.2004. Categorical language and hierarchical models for cell systems, in *Computation in Cells and Tissues - Perspectives and Tools of Thought*, Paton, R.; Bolouri, H.; Holcombe, M.; Parish, J.H.; Tateson, R. (Eds.) Natural Computing Series, Springer Verlag, pp. 289-303.

[32] Brown, R., J.F. Glazebrook and I.C. Baianu. 2007. A Conceptual construction of complexity levels theory in spacetime categorical ontology: non-Abelian algebraic topology, many-valued logics and dynamic systems, Axiomathes. 17 (3-4): 353–398.

[33] Brown, R., Higgins, P. J. and R. Sivera. 2010. *Non-Abelian Algebraic Topology.*, EMS.
http://www.bangor.ac.uk/ mas010/nonab-a-t.html;
http://www.bangor.ac.uk/ mas010/nonab-t/partI010604.pdf

[34] Campbell, D.T. 1958. Common Fate, Similarity, and Other Indices of the Status of Aggregates of Persons as Social Entitites, Behavioral Science, pp. 14-25.

[35] Connes, A. 1994. *Noncommutative Geometry*, Academic Press: New York and London.

[36] Dalla Chiara, M., Giuntini R. and R. Greechie: 2004, Reasoning in Quantum Theory., *Trends in Logic–Studia Logica Library*, Vol. 22, Kluwer, Dordrecht–Boston–London.

[37] H. de Jong and M. Page. 2000. Qualitative simulation of large and complex genetic regulatory systems, in Proc. of Fourteenth European Conference on Artifical Intelligence, ECAI 2000, W. Horn (ed.), IOS Press, Amster-

dam , pp. 141–145.

[38] Dirac, P.A. M. 1962.*The Principles of Quantum Mechanics.*, Oxford
University Press: Oxford.

[39] Edelman, G. and G. Tononi. 2000. *A Universe of Consiousness.*, Basic
Books: New York.

[40] Ehresmann, C. 1965. *Catégories et Structures.*, Dunod: Paris.

[41] Ehresmann, C. 1966. Trends Toward Unity in Mathematics., *Cahiers
de Topologie et Geometrie Differentielle*,**8**: 1-7.

[42] Ehresmann, C.1959. Catégories topologiques et catégories différentiables,
*Coll. Géom. Diff. Glob., Bruxelles.*, pp. 137-150.

[43] Ehresmann, C. 2005. *Oeuvres complètes et commentées.*, Amiens,
1980-84., edited and commented by Andrée Ehresmann.

[44] Eilenberg, S. and Mac Lane, S.1942, Natural Isomorphisms in Group
Theory., *American Mathematical Society*, **43**: 757-831.

[45] Eilenberg, S. and Mac Lane, S. 1945. The General Theory of Natural
Equivalences, *Transactions of the American Mathematical Society*, **58**:231-294.

[12] N. Eldredge and M. Grene, *Interactions: The Biological Context of
Social Systems*, Columbia Univ. Press, 1992.

[46] Elsasser, M.W.1981, A Form of Logic Suited for Biology., In: Robert,
Rosen, ed., *Progress in Theoretical Biology*, Volume 6, Academic Press, New
York and London, pp 23-62.

[47] Freeman, W. J.1997. Nonlinear neurodynamics of intentionality., J. of
Mind and Behavior, 18: 143–172.

[48] Freyd, P.1964. Abelian Categories., Harper and Row: New York and
London.

[49] Gabor, D.1946. Theory of communication., J. IEE (London) , 93 (III):
429–457.

[50] Georgescu, G. and C. Vraciu.1970. "On the Characterization of Łukasiewicz
Algebras." J. Algebra, 16 (4): 486-495.

[51] Georgescu, G. and D. Popescu.1968. On Algebraic Categories, Revue
Roumaine de Mathematiques Pures et Appliquées., 13: 337-342.

[52] Georgescu, G.2000. N-valued Logics and Lukasiewicz-Moisil Algebras,
Axiomathes, 16(1-2), pp. 123-136.

[53] Golubitsky, M. and I. Stewart.2006. Nonlinear dynamics of networks:
the groupoid formalism, Bull. Amer. Math. Soc. 43, No. 3: 305–364.

[54] Grothendieck, A.1971. Revêtements Étales et Groupe Fondamental
(SGA1), chapter VI: Catégories fibrées et descente, Lecture Notes in Math.

224, Springer Verlag, Berlin.

[55] Hartmann, N.1935. Zur Grundlegung der Ontologie., Berlin, W. de Gruyter.

[56] N. Hartmann.1942. *The New Ways of Ontology* ('Neue Wege der Ontologie', in *Systematische Philosophie*, pp. 199–311), Chicago.

[57] Herre, H.2010. Ontology of Time in GFO. (in preparation).

[58] Lambek, J.1994. Some Aspects of Categorical Logic, *"Logic, Methodology and Philosophy of Science IX, Studies in Logic and the Foundations of Mathematics"*: **134**, Amsterdam: North Holland, pp. 69-89.

[59] Lawvere, F. W.1966. The Category of Categories as a Foundation for Mathematics., in *Proc. Conf. Categorical Algebra- La Jolla.*, Eilenberg, S. et al., eds.Springer–Verlag: Berlin, Heidelberg and New York., pp. 1-20.

[60] Lawvere, F. W.1963. Functorial Semantics of Algebraic Theories, Proc. Natl. Acad. Sci. USA, Mathematics, 50: 869-872.

[61] Levich, A. P and A.V. Solovy'ov.1999. Category-Functor Modelling of Natural Systems. *Cybernetics and Systems*, Vol.30 (6): 571-585.

[62] Löfgren, L.: 1968, An Axiomatic Explanation of Complete Self-Reproduction, *Bulletin of Mathematical Biophysics* **30**: 317-348

[63] Luhmann, N. 1995. *Social Systems*, Stanford University Press, Stanford.

[64] Mac Lane, S. and I. Moerdijk: 1992. Sheaves in Geometry and Logic A first Introduction to Topos Theory., Springer Verlag: New York.

[65] H. R. Maturana and F. J. Varela, *The Tree of Knowledge: The Biological Roots of Human Understanding*, Shambhala, Boston and London, 1998.

[66] Mitchell, B. 1968.*The Theory of Categories.*, Academic Press: New York and London.

[67] Parsons, T. 1951.*The Social System*, Free Press, New York.

[68] Platt, J, 1969. Theorems on Boundaries in Hierarchical Systems, in L. L. Whyte, A. G. Wilson and D. Wilson (eds.), Hierarchical Structures, Elsevier, New York, pp. 201-213.

[69] R. Poli, Levels.1998. *Axiomathes* **9**(1-2) :197–211.

[70] R. Poli.2001. The Basic Problem of the Theory of Levels of Reality, *Axiomathes*, **12** (3-4):261–283.

[71] Poli, R.2001b, Alwis. *Ontology for Knowledge Engineers.* PhD Thesis, Utrecht Univ.

[72] Poli R. 2004. Approaching Brentanos Theory of Categories, in A. Chrudzimski and W. Huemer (eds.), *Phenomenology and Analysis. Essays in*

*Central European Philosophy*, Frankfurt: Ontos Verlag, pp. 285-321.

[73] R. Poli. 2006. Levels of Reality and the Psychological Stratum, in *Revue Internationale de Philosophie*, **61**(2): 163–180.

[74] Poli, R. 2007. Three Obstructions: Forms of Causation, Chronotopoids, and Levels of Reality, Axiomathes, 17(1): 1-18.

[75] Poli, R. 2010. Ontology: The Categorical Stance, in R. Poli, J. Seibt and J. Symons (eds), *Theory and Applications of Ontology.* Vol. 1: Philosophical Perspectives, Springer, Dordrecht.

[76] R. Poli. 2009. "The Complexity of Anticipation", in *Balkan Journal of Philosophy*, 2009, 19-29.

[77] R. Poli. 2010. "The Many Aspects of Anticipation". *Foresight*, 7-17.

[78] Popescu, N. 1973. *Abelian Categories with Applications to Rings and Modules.* Academic Press, New York and London; 2nd ed. 1975.

[79] I. Prigogine.1980. *From Being to Becoming– Time and Complexity in the Physical Sciences*, W. H. Freeman and Co., San Francisco.

[80] Rashevsky, N.1954.Topology and Life: In Search of General Mathematical Principles in Biology and Sociology., *Bulletin of Mathematical Biophysics*,.**16**: 317-348.

[81] Rashevsky, N.1967. Organisms Sets and Biological Epimorphism., *Bulletin of Mathematical Biophysics*,.**29**: 389-393.

[82] Rashevsky, N.1968. Neurocybernetics as a Particular Case of General Regulatory Mechanisms in Biological and Social Organisms, Concepts de l'Age de la Science, 3: 243–248.

[83] Rashevsky, N.1969. Outline of a Unified Approach to Physics, Biology and Sociology., *Bulletin of Mathematical Biophysics*,. **31**: 159-198.

[84] Rosen, R. 1958a. A Relational Theory of Biological Systems, Bulletin of Mathematical Biophysics, 20, pp. 245-260.

[85] Rosen, R. 1958b. The Representation of Biological Systems from the Standpoint of the Theory of Categories, *Bulletin of Mathematical Biophysics*, **20**: 317-341.

[86] Rosen, R.1968a, 'On Analogous Systems', *Bulletin of Mathematical Biophysics*,**30**: 481-492.

[87] Rosen, R.1968b, 'Recent Developments in the Theory of Control and Regulation of Cellular Processes.', *Intl. Review of Cytology*, **23**: 25-88.

[88] Rosen, R.1971, 'Some Realizations of (M,R)–Systems and Their Interpretation', *Bulletin of Mathematical Biophysics*,.**33**: 303-319.

[89] Rosen, R.1973, 'On the Dynamical Realization of (M,R)Systems.', *Bulletin of Mathematical Biology*,**3**5: 1-9.

[90] Rosen, R.1985. *Anticipatory Systems. Philosophical, Mathematical and Methodological Foundations.* Pergamon Press, New York.

[91] Rosen, R.1987. On Complex Systems.,*European Journal of Operational Research.*, **30**:129–134.

[92] Rosen, R.1991. *Life Itself.*, Columbia University Press: New York.

[93] Rosen, R.2000. *Essays on Life Itself.*, Columbia University Press: New York., (also 2nd edn., 2004).

[94] B. Russell and A.N. Whitehead.1925. *Principia Mathematica*, Cambridge Univ. Press.

[95] Saunders, P.T. 1993. The Organism as a Dynamical System. in *Thinking about Biology.*, . SFI Studies in the Sciences of Complexity, Lecture Notes, Vol. 3., F. Varela and W.Stein, eds. Reading: Addison Wesley, pp. 41-63.

[96] Searle, J. R.1983. *Intentionality*, Cambridge University Press.

[97] Spencer, H.1898. *A System of Synthetic Philosophy*, Williams and Norgate, London.

[98] Wiener, N.1950. *The Human Use of Human Beings: Cybernetics and Society.*, Free Association Books: London, 1989 edn.

[99] Wilson, D. L.1999. Mind-brain interaction and violation ofphysical laws, *Journal of Consciousness Studies* **6**, No. 8–9: 185–200.

[100] Warner, M. 1982. Representations of (**M,R**)-Systems by Categories of Automata., *Bull. Math. Biology.*, **44**:661-668.

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