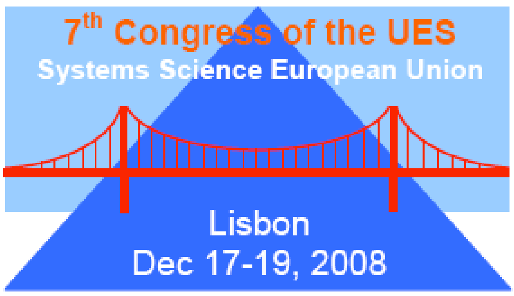
ISBN: 978-972-9059-05-6

Systems Science European Union
Union Européenne de Systémique
UES

APOCOSIS



Processes of structured and non-structured interactions, phase transitions, self-organisation and emergence

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Abstract

In the literature various approaches have been used to model and define processes presumed to characterize systems as *complex*. We agree with the approach which considers a system 'complex' when processes of emergence occur within it. We briefly compare and summarize some basic definitions and distinctions between processes render a system complex, including non-structured interactions, self-organisation and emergence. After considering processes of the establishment of collective behaviour as typical examples of complex systems, we mention some innovative approaches introduced in the literature for modelling phenomenological emergent complexity, such as the Dynamic Usage of Models (DYSAM), the use of *variations in ergodicity*, the concept of *logical openness* and the concept of Collective Beings as Multiple Systems. We then introduce a new research framework related to modelling emergence through *meta-structural* properties.

Keywords: Emergence, Ergodicity, Model, Phase-transition, Self-Organisation.

Introduction

In systemic literature there is a widespread use of systemic terms in an inconsistent and imprecise manner. This may be related to the fact that such terms represent complex processes of on-going multi-disciplinary refinements and conceptual redefinitions, rather than established results. Moreover, they are often used in a metaphorical rather than inter-disciplinary way thus producing inconsistent generalisations improperly claiming to be systemic. Examples include the usage of terms such as *systemic* itself, complex, structure, emergence and self-organisation to convey general, metaphorical, context-sensitive meanings rather than inter- or trans-disciplinary concepts. We recall that inter-disciplinarity deals with the study of the *same* systemic properties in *different* disciplines (e.g., openness, adaptability and chaos in physics, economics, biology and psychology) whereas trans-disciplinarity deals with the study of systemic properties *per se* and the relationships among them (e.g., models and simulations of openness, adaptability and chaos, and their inter-relationships). In this paper we attempt to contribute towards setting a more consistent framework of meanings for some of the terms mentioned above relating to current research activities. There is no presumption to providing a complete and finalised set of definitions which would be completely inappropriate *per se* for a multi-disciplinary, evolving context where coherence is dynamic by definition. Moreover, we believe that fuzziness may be creative until it produces inconsistencies and contradictions. Our aim is to contribute towards making future developments in Systemics based on the use of more robust and coherent terms for consistent rather than generic systemic generalisation.

Rather than focusing upon the various definitions of systems, we try to summarize what are considered *necessary conditions* for the establishment of a system distinguishing between the *homogeneous hypothesis* and the *heterogeneous assumption* related to elements necessarily interacting to *continuously* support the acquisition of systemic properties, different from states. We then consider *sufficient conditions* for the establishment of a system such as the interaction of elements in Structured, Self-organising, Non-structured but not self-organising, and Evolutionary ways. We then clarify the distinction between Systemic and non-systemic properties. On the basis of the clarification introduced we propose brief conceptual distinctions between transformations, such as phase transitions, self-organisation and emergence, suitable for modelling processes in complex systems.

1. Systems

In the scientific literature, a System has been defined in various ways. For instance as "A set of objects together with relationships between the objects and between their attributes" [1] or ". . . a set of units with relationships among them" [2]. A system has been intended as an entity having properties different from those of what are considered elements by the designer (for artificial systems) or by the observer (for natural systems). A set is an entity having properties different from those of its component elements (for example, the number of elements).

1.1 Necessary conditions for the establishment of systems

There is a general consensus that models adopted by an observer (for natural systems) and a designer (for artificial systems) explicating the process of establishment of a system are based upon, as a *necessary condition*, the interactions between elements, i.e., inter-relating elements. This emphasizes the conceptual nature of systems, as effective models. We may assume, in short, that two or more elements interact when *one's behaviour affects the other's* as observed by the observer. Examples of such interactions are processes of mutual exchange of energy (e.g., collisions and magnetic fields, where vector fields exert a magnetic force on magnetic dipoles or moving electric charges), matter (e.g., economic interchange) or information (e.g., prey-predator). Moreover, control devices are based on interactions between processes to regulate the value of a given variable (e.g., the Watt regulator using steam pressure and the induced speed of a rotating mechanism to keep the rate of rotation constant by adjusting the steam pressure). Interactions may occur in different ways. For example short and long-range correlations are interactions between elements on short or long time or distances scales (even simultaneously) which can display coherence as in the famous *binding problem* (regarding the *coherency* of the combination of information from distinct populations of neurons such as for visual, acoustic, olfactory, tactile or memory systems establishing a unified perceptual experience). Coherence is a concept having several disciplinary meanings. For instance, in physics, the coherence of two waves relates to how well correlated they are, allowing the possibility to predict the characteristics of one wave by knowing the characteristics of the other. Examples of other disciplinary meanings relate to usages in philosophy when considering the consistency of concepts, in cognitive science for cognitive states, and in linguistics with reference to semantics. In Systemics we consider coherence, as in the binding problem and collective behaviour, as the dynamic establishment and perpetuation of a property *continuously* established by interacting components. For instance, the property of a set of boids establishing a flock is continuously established and this *continuity* is considered as the coherence of the collective or coherent behaviour of boids. It should be stressed that systemic properties are not the *result* of interactions. Systems and their properties are established by the *continuous* interaction among elements (e.g., an electronic device acquiring a property when powered on, leading to interactions amongst the component elements) and not as a *state*, as in the formation of a new colour by mixing primary colours (e.g., Red-Green-Blue), weight or age.
By referring to the concept of *level of description*, i.e., the disciplinary knowledge and the scaling used by the observer to model a phenomenon in an effective way, systems may be intended as *models* to design or to represent phenomena [3]. Because multiple representations are possible, the Dynamic Usage of Models [4] has been introduced. A very important distinction considered relates to the particular kind of elements which are assumed to establish a system through their interactions:

a) Elements assumed as indistinguishable (*homogeneous hypothesis*). In this case elements are assumed to be particles. Their interaction may be modelled by mathematical equations and often by very simple rules. An example is given by gases consisting of particles and adopting systemic properties such as pressure and temperature. The hypothesis applies even when interacting elements are autonomous systems, i.e., provided with cognitive systems, all being considered as equal in a simplified, reductive, way. This is, for example, the case for models based on agents interacting according to a few, simple rules (e.g., eco-systems and markets).

b) Elements assumed to be different, and distinguishable (*heterogeneous assumption*). In this case each element interacts in a different way. This is the typical case of autonomous agents *processing* interactions and not simply reacting. Here, the processing is performed by the cognitive system and is computed *each* time. A typical example is given by families of human beings. Human beings establish systems, in this case families, assuming sociological properties different from those of its components, such as decisions emerging from discussions, i.e., interactions, regarding educational choices for children and economic behaviour. In some cases the cognitive system is so elementary that it is possible to simplify, by adopting a suitable particle representation, as for swarming and flocking modelled by assuming elements react according to very simple rules.

1.2 Sufficient conditions for the establishment systems

A sufficient condition for the establishment of a system is that elements interact by respecting suitable relationships, or modelled as such, in some particular ways. Moreover, it must be stressed that at the moment there is no way of demonstrating that the following ways (see Sections 1.2.1-1.2.4) of establishing systems are the *only* ones. This point is particularly important given that new levels of description have emerged, such as the quantistic one, requiring new conceptual approaches in which the very concept of interaction needs to be properly redefined.

1.2.1 The structured way

In the *structured* functional way of establishing organised systems, organisation is intended as a network of pre-established functional relationships which control the manners of interacting. Rules of interaction are determined by a) following a design or b) are *constructivistically* intended as such by the observer. In both cases they are *sufficient conditions* for establishing systems. Structured rules define *completely* the way in which elements interact, i.e., they define *all* the degrees of freedom possessed by interactions between elements, at the specified level of description. Examples of case a) include mechanical devices, such as machines, and electronic devices, such as circuits. Examples of *non-designed* systems, as in case b), are natural entities modelled as organised systems by the observer, such as organs performing given functions in living beings and eco-systems.

1.2.2 Self-organising way

In a so-called *self-organising* way, i.e., when a structure or a change in structure is acquired or lost, as in phase transitions due to environmental perturbations (e.g., change of temperature or pressure) and in *collective phenomena* such as swarming and flocking (see Section 4 for usage of the term in the scientific literature and Section 2 for our proposed conceptual definition). Changes are not prescribed from the outside, as in theoretical models of phase transitions, by adopting the homogeneity hypothesis. The same theoretical model adopted for phase-transitions is used to model self-organisation by identifying *order parameters* as in Synergetics [5, 6]. Examples of systems modelled in this way are flocks, swarms, industrial districts, lasers, ferromagnetic and superconducting systems. In any case, the use of Dynamical Systems Theory approaches based on the *homogeneity assumption*, i.e., neglecting *any differences* between the components, whether they be particles, planets or molecules, has been very successful in science. *Emergence* deals with a generalisation of such processes by considering the *heterogeneity assumption* and the process of hierarchically acquiring new properties as properties of systems of systems. Examples of models based on Dynamic Systems Theory and proposed for modelling emergence are Noise-induced phase transitions and Spontaneous Symmetry Breaking (SSB) in Quantum

Field Theory. Such models are *unsuitable* because emergence has to be considered in this case as arising from a suitable combination of dynamical rules and fluctuations, e.g., produced by noise, quantum effects, impurities or other effects instead of using *heterogeneity-based* models when considering differences between components such as in biology, e.g., life, or for cognitive systems, e.g., learning [7]. Examples of this kind for modelling emergence are Agent-based systems, Artificial Life, Neural Networks, and Immune Networks.

1.2.3 Unstructured, non-self-organising way

In an *unstructured* although non self-organising nor emergent way, i.e., when an interaction does not follow structure nor models of self-organisation nor emergence. In the case of a) autonomous systems, i.e., provided with cognitive systems, interaction is due to the processing of input by cognitive systems. In this case interaction derives from the cognitive processing modifying, for instance, information, emotions, knowledge, inference and the making of decisions, which can affect the behaviour of the autonomous systems. In these cases the system is produced by the way of processing and affecting behaviour. One processing affects the other. In case of suitable cognitive systems, coherence is ensured by the cognitive processing and this is a sufficient condition for the establishment of a system. Examples are social systems (e.g., families, classrooms, and micro-communities such as an audience). When the cognitive system is very simple (e.g., as in the case of ants) the process may be simulated by a particle system having structured or self-organised interactions. In the case of b) non-autonomous systems, such as systems in physics, new systems and corresponding new systemic properties occur by spontaneous symmetry breaking when the system acquires properties such as superconductivity or superfluidity. Such processes are modelled within the theoretical framework of Quantum Theory [8] and are considered by some physicists not only as non-structured, but also as the real models of self-organisation [9, 10]. Moreover, as mentioned above, they are unsuitable for the heterogeneous case.

1.2.4 Evolutionary way

In an *evolutionary* way, i.e., through a process considered for species, when elements of a specific species interact amongst themselves (e.g., competing for food or territory, and for reproduction), with individuals of other species (e.g., prey-predator or establishing symbiotic processes) and the environment, for instance, by adapting and modifying their behaviour. In this case the focus is not on the properties acquired by the established collective systems (e.g., ecosystems and prey-predator systems), but on changes produced in single systems to better accomplish the process of interaction. We may distinguish the cases where the process of interaction is ruled by a) fixed evolutionary rules establishing a system acquiring a new property with reference to components. For instance, ants possess fixed evolutionary rules corresponding to a simple cognitive system having a very limited or no ability to learn, i.e., to improve it. An anthill displays multiple but non-evolutionary acquired properties, such as shape, food recruitment, defence strategies and an *ant cemetery* [11]. Evolutionary rules are b) variable, for instance, through processes of mutation and learning. Previous cases may not only occur in well-separated, well-defined ways and at different times. They may also occur in any combination and at any time, e.g., simultaneously, alternately, or in short- and long-term correlations. Theoretical approaches towards this multiple combination in the establishment of systems have been introduced, for instance, with the concept of Collective Beings based on Multiple-Systems [4]. We recall that a *Multiple System* (MS) is a set of systems established by the *same* elements interacting in *different* ways, i.e., having multiple simultaneous or dynamical roles. Examples are the Internet where different systems play different roles in being used in continuously new ways (e.g., the same software codes and services can be used to perform different tasks) and dynamic infrastructures of electric power networks adopting emergent properties (an unfortunate example being the black-out). *Collective Beings* (CBs) are particular MSs established by autonomous agents possessing the *same* cognitive system allowing them to decide different, simultaneous or dynamic belonging to the various simultaneous or dynamic systems. Examples of multiple, *alternative* belonging can occur when human beings give rise to different systems in temporary communities, such as passengers on buses, audiences at performances, and queues in general. Examples of multiple, *simultaneous* belonging occur when *same* human beings give rise to different systems over time as for workers in a company, families, traffic on motorways, and mobile telephone networks. In these examples workers in a company are also *simultaneously* (i.e., they behave as components of a system simultaneously considering they belong to other systems) members of families, of traffic on motorways and of mobile telephone networks. Moreover, the *same* elements interacting in *different coherent* (see above) ways may establish a *single* system like cells in biological systems interacting in electrical and chemical ways, elements of an ecological system interacting in acoustic, visual, olfactory ways, human beings in social systems interacting in linguistic (through text, voice), pictorial (through images) and sounds. In this case a system is established by Multiple Coherent Interactions acting on vectorial elements, as in the binding problem mentioned above. Another theoretical approach has been introduced by considering the *combined* effects of evolution and self-organisation [4, 12, 13].

2. Systemic and non-systemic properties

What are *non-systems*? Depending on the level of description and on the model adopted by the observer, an entity is not a system when its properties are ***states***, *considered as not necessarily being supported by a continuous process of interaction amongst its components*. Systems are thus entities assumed to be *continuously acquiring* systemic properties. Non-systems are entities *possessing* non-systemic properties. Only systems may acquire systemic properties, while systems and non-systems may possess non-systemic properties. The novelty is that systems may *acquire* themselves or collectively (i.e., through systems of systems) *new* further systemic properties through processes of emergence at different levels. Examples are given by the establishment of properties such as cognitive abilities in natural and artificial systems, collective learning abilities in social systems such as flocks, swarms, markets, firms, and functionalities in networks of computers (e.g., on the Internet). *Evolutionary* processes establish properties in living systems. Properties are detected by an observer using a level of description as introduced above. We consider properties within the framework of the constructivist approach. In this view we do not find properties *as they are* in an objectivist view. To clarify this point, we can metaphorically say that we design experiments, intended as *questions* to Nature, and Nature *answers* by making them happen. There are no answers from Nature without questions. Effects may be intended as answers waiting for the proper questions able to model and make them usable. Repeatability of experiments, i.e., the receiving of *same* answers, is a confirmation about the consistency and appropriateness making knowledge possible. Knowledge has been developed, such as uncertainty principles, fuzzy theory, incompleteness, entropy, ergodic behaviour, statistical mechanics, and emergence, to model non-linear answers. What is a property? In general a property is intended as a *characteristic* of an entity detected at some level of description. Examples are the numbers of the Periodic Table of elements introduced by the Russian chemist Mendelejev; the Avogadro number; the speed of light; the pressure-temperature where water is transformed into ice and the period of the earth's orbit around the sun. The ideal is to consider properties as *context-independent*, i.e., having universal and constant values. Non-dependence upon the context of observation, i.e., the level of description, is the objectivist view and it is often confused with the *stability* of the context adopted. The problem is that there are no properties without a level of description, no statements without a language. It is not merely a *relativistic* point of view, but a *generative* one, assuming reality has to be linguistically generated as for constructivism [15, 16]. The approach may be understood as the *translation* (not *transposition*) of a property at one level of description to another. The observer is expected to have available a model of the *hierarchy* of levels of description. In an objectivist world the perspective is to make the model *coincide* with the phenomenon. Systemic *properties* are intended as characteristics which can *only* be taken on by entities, i.e., systems, established by interacting components, when they are designed or modelled as such by the observer. Systemic properties are not the *result* of the interacting components, but supported, as a *necessary condition*, by the continuous interaction of components. Examples of systemic properties, adopting a suitable level of description, are: adaptiveness, chaos, dissipation, life, learning and openness. Examples of non-systemic properties, adopting a suitable level of description, are: weight, age, geometric measurements, spatial position and speed in classical physics, and numeric properties in calculus. Non-systemic properties may *become* systemic when they *coherently change* or become inter-related and their changing gives arise to new properties. How can we distinguish systemic from non-systemic properties? Non systemic-properties do not need to be supported by the continuous interaction of components, they are constructivistically modelled by the observer as *stable or unstable states* to be detected and measured. Systemic properties are supported by the continuous interacting of components. A system may have non-systemic properties, while only systems may have systemic properties. Moreover, it is possible to *simulate* not only systems, but also *effects* of systemic properties reducing them in this way to non-systemic properties (e.g., music reproduction and movies). *Falsification* of Systemics can be considered equivalent to the possibility of finding systemic properties as properties of non-systems [17]. The reason why we distinguish between systemic and non-systemic properties is that there are different approaches for managing them at different levels of description. A reductionist view is based on considering a systemic property as non-systemic, i.e., using an inappropriate level of description. Can processes of emergence establish non-systemic properties? It depends on the level of description adopted. For instance, emergent cognitive properties may be considered as properties *tout-court* of living systems when focus is placed, for instance, on managerial or economic issues. Properties have to be considered as systemic when dealing with illnesses and how to cure them. In this latter case, the observer must have available a model of the process establishing a system through the acquisition of such systemic properties.

3. Systemics

Considering systemic issues in general (such as the usage of the concepts of system, interactions, inter-disciplinarity, trans-disciplinarity, and systemic specifications and properties often defined within specific disciplines) and not at a specific level of description/theorization has given rise to the more general aspects of the approach known as *Systemics* in English, *Systémique* in French, *Sistemica* in Italian and Spanish, intended as a *cultural generalization* of the principles contained in *GST*. The point is illustrated in Table 1. The term is widely used, although not precisely defined, even in the titles of journals and books.

Table 1: A general overview on Systemic issues.

Systemics This term is used to denote a *corpus* of systemic concepts, *extension* of systemic principles by using, for instance, analogies and metaphors.
Systemic Approach This expression is used to denote the general methodological aspects of Systemics, considering, for instance, identification of components, interactions and relationships (structure), levels of description, processes of emergence and role of the observer.
General System Theory This expression has been introduced in the literature to refer to the theoretical usage of systemic properties considered within different disciplinary contexts (inter-disciplinarity) and *per se* in general (trans-disciplinarity). It also refers to applications in specific disciplinary fields. Current research identifies it with the *Theory of Emergence*, i.e., acquisition of properties.
System Theory This expression, often inappropriately used as shorthand for *General System Theory*, relates to First-order cybernetics and Systems Engineering for applications such as Control systems and Automata.

4. Towards a General Theory of Emergence

In the literature it is also possible to find different definitions related to different kinds of emergence which will not be discussed here, including *strong* and *weak*, *computational* and *phenomenological* emergence [4, 18, 19, 20, 21, 22, 23]. A short overview of the *emergence of the concept of emergence* has been previously published [4, 24]. Some approaches are based on considering the concept of emergence related and, almost, identified with that of *self-organization*. In physics, processes of so-called *order-disorder transitions* have been identified as *self-organization* processes [25] and, thanks to the works of I. Prigogine, related, for instance, to *dissipative structures* [26] and of H. Haken, related, for instance, to *Synergetics* [27], the terms *emergence* and *self-organization* being considered as synonyms. Distinctions should be made between:

1. Phase transitions relating to changes in structure, e.g., water-ice-vapour transition and ferromagnetism.
2. Processes of self organisations considered as phase transitions when a new acquired structure is dynamic and stable, i.e., repeated in a *regular* way. Examples are non-perturbed swarms, i.e., synchronised oscillators, established by suitable initial conditions, reaching stationary states in a non-perturbed way such as populations of synchronized fireflies [28].
3. Processes of emergence may be understood as phase transitions when newly acquired dynamic structures *coherently* change over time. The process of emergence relates to changes in dynamic structures over time. This way of understanding processes of emergence is suitable for modelling collective behaviours of entities provided with cognitive systems allowing the collective system to process internal and external perturbations. The active role of the observer is fundamental detecting, representing and modelling emergent properties. Coherence is a property primarily generated by the cognitive system of the observer [4].

It should be recalled that changes in the ergodicity of a system is a useful index for detecting the establishment of processes of self-organization, such as structural changes in phase transitions [29].

4.1 Emergence as the *acquisition* of new properties

Processes of the establishment of hierarchies occurring in emergence is of a general, abstract, nature such as the establishment of acquired, hierarchical properties, one being based upon interactions with the other as for physiological-psychological-mental levels, Multiple Systems or Collective Beings [4, 30]. In this view complex systems and complexity may be intended as referring to the ability of systems to acquire new properties through processes of emergence, focusing on the transformational ability of systems.

4.2 The theoretical role of the observer

In the systemic literature the concept of *logical openness*, as opposed to *thermodynamic openness* [4, 31, 32] has been introduced. Logical openness relates to the constructivist role of the observer generating *n-levels* of modelling by assuming *n* different levels of description, representing one level through another and modelling a strategy to *move* amongst them, and considering simultaneously more than one level as in the Dynamic Usage of Models (DYSAM). With reference to the concept of systemic complexity, i.e., the occurrence of the acquisition of new properties within a system through processes of emergence or multiple dynamic roles of components, as for MSs and CBs, the number of levels, *n*, of modelling adopted by the observer can be considered as a *measure of the complexity* of a system [32]. An implementation of DYSAM based on Neural Networks was introduced by Minati and Pessa [4]. The DYSAM approach [4, 33] was introduced to deal with the dynamical emergent properties of complex systems. While a dynamical system is defined by the existence of a set of suitable state variables describing it, dependent upon time and evolution laws specifying how the values of these variables change, DYSAM relates to the dynamics of emergent properties of a system and to properties of MSs and CBs as well. DYSAM is based on approaches already considered in the literature having the common strategy of not looking for a unique, correct, optimum solution. Strategies not based on such a simplistic approach are, for instance, the well-known Bayesian method, Pierce's abduction, Machine Learning, Ensemble Learning and Evolutionary Game Theory. The concept of DYSAM relates to situations in which the dynamical adoption of properties by the system is such that any single model is, in principle, unsuitable to model such dynamics, because single models are assumed to model a specific system. DYSAM is composed of a repertoire of different possible models and a strategy for selecting, on the basis of general and momentary goals, the more suitable one and on modelling interactions between the adopted models (for instance, though representing and learning). A further theoretical approach to modelling processes of emergence is under investigation and based upon considering *meta-structures*, i.e., on mathematical properties adopted by sets of *mesoscopic and global variables* used by the observer to model collective behaviours [34]. In this approach we consider *coherence* generated no longer by dynamics between *state variables* related to components, but by properties of mesoscopic and global variables and of their inter-relations. Making reference to collective behaviours established by agents, examples of suitable mesoscopic and global variables changing over time are: *D*, density; *V*, volume; *Su*, surface; *Mx-Mn* maximum-minimum distance between two agents; N_k number of agents having the *same* value of some variables and levels of ergodicity of the sets of values adopted by single mesoscopic and global variables in a given timeframe.

Conclusions

The aim of this paper is to contribute towards the on-going process of clarification of concepts such as self-organisation and emergence. In our opinion, this is a fantastic opportunity for the systems community to deal with such topics in a trans-disciplinary way, i.e., in a general, non-disciplinary way. Disciplinary research is more and more systemic, and dealing with crucial topics may display the power of systemic research enabling it to have, in the future, a prestigious academic role which specific scientific disciplines currently enjoy. This includes the development of graduate programs, dissertations and research on systemic issues *per se* including the modelling of processes of emergence and acquisition of new properties.

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