# Systems, complex systems, and intelligence: An educational overview

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*Abstract:* - This contribution examines, for didactic purposes, the peculiarities of systems that have the ability to acquire, maintain and deactivate properties that cannot be deduced from those of their components. We evaluate complex systems that can acquire, lose, recover, vary the predominance of property sequences, characterized by their predominant coherence and variability, through the processes of self-organization and emergence, when coherence replaces organization. We consider correspondingly systemic epistemology as opposed to the classical analytic approach and to forms of reductionism. We outline aspects of the science of complexity such as coherence, incompleteness, quasiness and issues related to its modeling. We list and consider properties and types of complex systems. Then we are dealing with forms of correspondence that concern the original conception of intelligence of primitive artificial intelligence, which was substantially based on the high ability to manipulate symbols, and of those of a complex nature that consider emergent processes, such as inference, the learning, reasoning and memory. Finally, the recognition and acquisition of forms of intelligence in nature is explored, with particular reference to its emerging systemic processes.

*Key-Words:* - Coherence, Complexity, Emergence, Incompleteness, Intelligence, Quasiness, Self-Organization.

Received: July 17, 2021. Revised: February 24, 2022. Accepted: March 27, 2022. Published: April 21, 2022.

## 1 Introduction

The purpose of this article is to explore the concepts and problems of systems science using an interdisciplinary perspective, albeit at a good level of rigor, in order to enable an adequate dealing of problems of various types, such as those centered around interdisciplinary scientific education. The article concludes by hinting at the topic of intelligence, discussed in relation to complex systemic properties, up to the important subject of artificial intelligence. In this work, we consider the concepts of *system* and *complex system* that are widely used in everyday language, which involves the examination of diverse topics ranging from systemic pathologies to computer systems and mathematical systems; social issues with respect to banking, fiscal, legislative, and pension systems; and aspects of health such as nervous, cardiovascular, and digestive systems, and many others. The complexity of these systems is often misunderstood as referring to, for example, to the difficult manageability, comprehensibility, and reproduction. The complexity is considered to be negative attribute.

Systems are interesting because they may acquire properties that are not reducible to those of their components; for instance, in the *functioning* of electronic and electro-mechanical devices. Unlike *objects*, systems do not possess *definitive properties* such as a weight, or *results*, for example, cooking or a flame from the burning of a candle. The *engine* of systems is the process of *interactions* between its components, in which the *invariable links* in materials constituting *objects* are replaced by *interactions* replacing fixed relationships with variable, active, and interdependent (see *solid state physics* versus *condensed matter physics*) links. The result of latter is that the constituent elements have states that depend on that of the other elements. Systems are intended to acquire the *same* iterated property that characterize the whole system, i.e., electronic components when interacting establish a system having the same property such as of being a computer, a smartphone, or a television. When the composite elements cease to interact, the system *degenerates* into a set of components (Section 2).

Among the properties and constitutive processes of systems, *self-organization* and *emergence* are of particular interest as they establish complex systems, and they continually occur within them. Contrasting with systems, complex systems acquire a sequence of multiple properties that arise in variable ways and they have significant levels of coherence. Complex systems are established via multiple interactions, as in processes involving self-organization and emergence. In short, self-organization in the populations of interacting elements can be understood as the prevailing formation and maintenance of synchronizations in terms of interactions, while emergence can be understood as the prevailing formation and maintenance of multiple partial, local, and overlapping phenomena of self-organizations leading to coherences. *Coherence is intended to replace explicit organization*. The processes of self-organization and emergence are intended to be activated and maintained by the presence of particular environmental situations, for example, self-organization by topological constraints and dissipation for vortexes of liquids in pipes or the temperature differences in tornadoes, while emergence by properties of the interacting elements such as their available mobility, ability to fly, innate and cognitive abilities (Section 3).

The processes of emergence, and their acquired properties, are robust when perturbations are applied. These are able to re-emerge, adapt, and recur at different levels due to the dynamics between equivalences and the tolerance to temporal, recoverable losses of coherence that arises. The prevalent properties are the required *incompleteness* and *quasiness*, which create space for the occurrence of equivalences and partialities, in which the multiplicity of coherence is not reduced to a single synchronization. Examples are flocks of birds and swarms of bees that continuously present themselves in different forms, while maintaining their consistency and acquiring intelligent-like behaviors, for example in defense from predators. The topic becomes increasingly interesting when the area of study is not just about birds and insects, but the collective behaviors of people such as those observed in crowds, queues, markets, traffic congestion, and busy cities that acquire morphological, sociological, and territorial properties; the fact that systems of neurons acquire cognitive properties such as intelligence. One may then immediately consider the emergence of the property of being living. The emergence manifests itself in an innumerable variety of processes that correspond to the keeping of complex systems; to acquired variable, various properties to be considered in *dealing* (e.g., inducing, orienting, or merging) with them, such as coherence, correlation, scale invariance, power laws, network properties, chaotic properties, and polarization. The emergent nature of the acquired properties, which are attained by the complex systems, enables their robustness, thus they are able to resist perturbations, re-emerge, adapt, and recur at different levels (Section 4).

Among the properties that are acquired by complex systems, we consider forms of intelligence, such as the intelligence of collective behaviors in terms of the so-called *swarm intelligence* that are continuously present in different forms while maintaining their consistency; for example, implementation strategies in a defense from predators, such as the *predator confusion*. In particular, three options are mentioned, all are considered systemically in terms of the acquisition of intelligent behaviors, such as the phenomena of emergence that is mentioned above. As a second option, intelligence as a property of nature that enables, for example, the occurrence of chemical reactions, phase transitions, and constitute fields. Also of interest is the ability to establish fractality that allows for the availability of large surfaces in small volumes, for example, alveoli of the lungs. A third option to consider is emergence of generic intelligence, i.e., not related to specific behavioral factors but ones that are available to be applied to any problem or even to itself (Section 5). We conclude by a consideration of artificial intelligence and its intrinsic limits (Section 6).

## 2 Systems

The concept of a system is introduced by the biologist-mathematician Ludwig von Bertalanffy (1901–1972) in his most famous book [1]. The interest in systems may arise because such entities have the ability to acquire properties that are not reducible, meaning that they are lost following any collapse of the system into its components. The *engine* of systems is the process of *interaction* between these components. The interaction process between entities involves the properties and behavior of each component *depending* (either partially or completely) on those of the others. More precisely, the interaction can be considered as a relationship when specified by *fixed relationships* between the entities (such as temporal -synchronization- and quantitative -proportion-). One way to understand the interaction process is to consider it as an *ongoing interaction*, for example as an exchange of materiality in economics, or energy and information. In the case of the action-reaction effects, such as for the collisions between balls and activations via sensors, which can be described using fixed rules (not necessarily just deterministic, but also having a probabilistic nature), the interactions are a *contextualized* form of relationship (for example, the collision of two balls affected by their irregularities due to, for instance, wear). In the most specific case, the interaction is intended to occur between entities that are endowed with autonomy, when the inter-exchanged (both matter and energy) and information (either inter-exchanged or detected) is autonomously processed by the entities, such as when birds of a flock *cognitively decide* their reaction based on the reciprocal positions, speeds, and directions that they have detected. In this case, the interactions are established by the *interactors* and only partially by the relational rules furthermore respectable in a great number of ways. However, in the face of the same interchange, the reactions may not be the same. *Especially in complex systems, there are regular and irregular combinations of the various possibilities, in a multiple and time-varying way with different levels of equivalence until initiation of a new non-equivalent behavioral phase* [2].

The components are *considered as such* in the case of natural processes, which are either *intended* by the observer to be systems (for example, solar, digestive, ecological, reproductive systems, flocks, swarms, and anthills) or *designed* (components of electronic, mechanical, and hydraulic systems). The properties of the systems are not reducible to those of their components, thus they are not deductible from the latter, they are of a *different nature*, as in the previous simple examples and in Table 1a and Table 1b. Furthermore, the properties of the systems are not the *result* of energetic or biochemical changes, but rather they are *continuously* acquired. This is a matter of contrasting *transformation* with *interaction*. In the case of transformation, the elements (the components) change throughout the processes in terms of various phenomena such as thermal, chemical, and electrical. These are in reference, for example, to the science of materials (think of the flame of a candle). In the case of interactions, the interaction process is assumed to be of interest when it generates systemic properties. In fact, the interaction is presumed to be a *necessary* condition for the generation of systemic properties, but not *sufficient* (as in the case of the interactions between gas molecules and the Brownian motion), which remains such without acquiring new collective properties. In simple cases it can be said that the interaction process provides the *functioning* for devices, for instance, acquiring electronic characteristics. The interaction between the elements occurs via the power supply. When this ceases, the interaction process dissipates and the system *degenerates* into a set of the interconnected components, it becomes passive because it is no longer powered. The properties that were acquired become potential, are lost. Later, we will see the case of complex systems [3, 4], *in which the interactions between the components cannot be prescribed*.

The issues relating to the concept of *property* are a delicate one. We will limit ourselves to its use at the current level in cultural usage, as it is not the purpose of the article to extend it further. Let us mention that the detectability of the properties requires, in turn, the availability of properties and the ability to relate to them. Properties describes how one entity relate to another. For example, to detect existence it is assumed that existence is necessary. However, in mathematics, non-existent imaginary numbers ($i=\sqrt{-1}$) and non-computable, irrational numbers ($\pi$ and roots like $\sqrt{2}$) can be used, as treated only in terms of symbols. The theme of existence seems to be a problem of the observer, who presumptuously extends his cognitive need to fields of a completely different nature that are not accessible to him/her. For instance, existential and religion are fields which can consider higher levels of *generation of existence*. The idea of a physical world without properties is provided at an absolute thermal zero, i.e., the temperature at which a thermodynamic system has the lowest possible energy, at which no thermal energy is available for and from any molecular motion. In the classical understanding of the world, entities such as molecules are, in this case, completely isolated and no energy exchange between them is possible. This is about ideal environments without interactions. However, let us mention that at an absolute zero temperature the molecular motion does not completely cease, since molecules still vibrate with what is called a zero-point energy and quantum systems still have fluctuations in their lowest energy state. With systems, the important message is that properties are not determined and separable but they are understood with respect to their generating interactions, which are an integral part of the constitutive processes. Interactions are, in classical terms, considered often as *weak forces*, negligible details that leads at most to relativism. This is not the case, as we shall see, for complex systems [5].

| **Examples of system components** | **Examples of properties of the system components** | **Examples of systems consisting of interacting components** | **Examples of properties acquired by the system** |
|---|---|---|---|
| *designed* | *designed* | *designed* | *designed* |
| Electronic components (such as semiconductors, diodes, integrated circuits, resistors, capacitors) | Reliability, connectivity, consumption, stability | Electronic devices such as signal amplifiers, cell phones, televisions, videos | Functionality, availability, repairability, robustness, safety |
| Electrical generators (hydroelectric power plants, nuclear power plants, solar plants, wind turbines) | Reliability, consumption, pollution, safety | Networks of electrical generators | Availability, ability to avoid blackouts, programmability of restorability, safety |
| Words | Correct syntactic and lexical semantics | Phrases, poems, novels becoming systems when read | Overall meaning of phrasal semantics; enjoyment or not of reading; style |
| Individual musicians | Virtuosity in playing an instrument or singing | Playing orchestra | Interpretative ability, accuracy |
| Individual military | Individual properties of the military depending on their special training | Battalion, army in practice or in action | Ability to apply military tactics and strategies, and to react appropriately |

Table.1a – Examples of designed components, their properties, constituted systems, and their acquired systemic properties.

| **Examples of system components** | **Examples of properties of the system components** | **Examples of systems consisting of interacting components** | **Examples of properties acquired by the system** |
|---|---|---|---|
| *alleged* | *detected* | *alleged* | *detected* |
| Animals | Behavior, size, age, weight, quantity, gender | Schools of fish, schools, anthills, herds, swarms, flocks, termite mounds | Collective behavior (assuming patterns), collective intelligence for defense from predators, hunting strategies |
| Cell (morphological-functional unit of living organisms) and neuronal cells | Cell metabolism (unicellular organisms) | Living Beings | Cognitive abilities; *decided* behavior; ability to regenerate, repair, reproduce and evolve; ability to dissipate to keep away from thermodynamic equilibrium (death), ability to adapt |

Table.1b – Examples of alleged components, their detected properties, alleged constituted systems, and their acquired detected properties intended as systemic.

## 2.1 Systems epistemology

The interaction process has interesting generalizable aspects. There are *trivial systems*, in which the interactions between the elements (the components) are reduced to a linear, fixed, and regularly iterated relationship between the components. In short, the linearity can be understood as a *proportionality*. More properly the linearity, for example of a function $f(x)$, is given by the validity of additivity: $f(x + y) = f(x) + f(y)$ and the homogeneity: $f(\alpha x) = \alpha f(x)$ for each parameter $\alpha$. Everything else is nonlinear, such as an exponential and trigonometric equations. Trivial systems have fixed spaces of becoming (with few, limited *degrees of freedom*, i.e., in terms of variables such as speed, position, and temperature that are necessary to describe a phenomenon. In complex systems we consider a number of these variables, and their eventual change, in the course of the becoming of the phenomenon or process) and they have limited properties that can be acquired, which are few and in predefined sequences (this is the case of mechanical watches, and devices that are electronic or electromechanical, for which the concept of functioning applies).

There are also *non-trivial systems*, in which the interactions between the elements occur within very large spaces of becoming (there is numerous and variable degrees of freedom), there are numerous properties that can be acquired, and the components are identified as *appropriate* (suitable for constitute systems). Multiple and different interactions occur, which can be represented as sequences of irregular, linear and, mainly, nonlinear relationships. We will see later that this is the case for complex systems. However, at this point, we detect the peculiarities of systemic becoming with fundamental epistemological effects. Starting from what Bertalanffy previously wrote on the subject [1, p. 19]:

> "Application of the analytical procedure depends on two conditions. The first is that interactions between 'parts' be nonexistent or weak enough to be neglected for certain research purposes. Only under this condition, can the parts be 'worked out,' actually, logically, and mathematically, and then be 'put together.' The second condition is that the relations describing the behavior of parts be linear; only then is the condition of summativity given, i.e., an equation describing the behavior of the tota1 is of the same form as the equations describing the behavior of the parts; partial processes can be superimposed to obtain the total process, etc. These conditions are not fulfilled in the entities called systems, i.e., consisting of parts 'in interaction.' The prototype of their description is a set of simultaneous differential equations (pp. 55ff.), which are nonlinear in the general case. A system or 'organized complexity' (p. 34) may be circumscribed by the existence of 'strong interactions' [6] (Rapoport, 1966) or interactions which are 'nontrivial' [7] (Simon, 1965), i.e., nonlinear. The methodological problem of systems theory, therefore, is to provide for problems which, compared with the analytical-summative ones of classical science, are of a more general nature."

The classical analytical approach is based on the generic conceptual possibility that enables a breakdown into different parts, which are assumed to form the overall problem when recomposed through appropriate, assumed pre-existent, configurations of real and objective relationships. In this approach, the configuration of the relationships is intended as a network of cause-effects, which are presumed to be more controllable and manageable with the more detail we attain about the initial conditions. At this point, we can observe how non-trivial systems are not decomposable, non-linearly recomposable, and their properties are not attributable (for example, deductible) to those of their constituent elements. When the simplification of proceduralization (decomposition) is not applicable, the presumption that in the increasingly small, which is understood as a fundamental level without interactions, there is the *definitive* explanation in or dealing with the macroscopic systemic realm does not resist. However, we are indebted to the analytical approach, which has forged science for centuries and it is still effective for addressing non-systemic problems. It is also necessary to detect its inadequacy when it comes to systems or be used in a methodologically adequate way as for simplified, local, and temporary aspects. The problem on one hand is to *recognize* the systemic nature of the problems and properties while, on the other hand, avoiding consideration, approaches and models of systemic problems and properties that use non-systemic approaches, which are unsuitable, absolutely inadequate, and counterproductive [8]. *Operating conceptually and practically on a systemic level means considering the levels of description of the components and adequate (detected, supposed, inferred) interaction mechanisms (combinations of interactions, see [9]) that can possibly be multiple and variable. This is the case of quasi-systems, which are considered later for specific complex systems.*

While the analytical approach inherently contains the assumption of the existence of an optimal and objective level of description, this does not occur in the systemic approach. In the analytic vision, for example, a problem has different *aspects* and, thus, it should be treated accordingly in a multiple way, even if one seeks the predominance of one method over the others in the context of an objectivistic way of thinking (i.e., looking for how something *really is*). The systemic view considers the phenomenon under study, i.e., the system, as continuously being established by interacting structural multiplicities. *The analytical conceptual world has assumptions that are often considered as paradigmatic of the scientific approach itself*. And indeed, when it is not a question of systems and their acquired properties, they are. There are probably other cases in which such assumptions do not hold, beyond systems, as in the world of quantum physics, but this is not examined here. Some characteristic assumptions of the analytic conceptual world are, in addition to the decomposability, separability, reassembly, and consequent of strategies that search for truth in the infinitely small, those of general validity for the properties such as completeness, and therefore has complete precision and the solubility of problems as the only approach. Completeness can be understood as corresponding to the fact that a phenomenon or process has a finite number of degrees of freedom (which can be completely described by a finite number of variables) and a finite number of constraints (minimum and maximum values that can be adopted by the variables), that is, there is at least potential *completability* such as in so-called *grey systems* [10]. A completeness with an infinite number of degrees of freedom can be considered as corresponding to *incompletable* incompleteness. However, it should be considered how prescribing, for example, constraints can mean imposing innumerable (which is the incompleteness) ways to respect them (refs. [11], [12], pp. 47-51).

Speaking of incompleteness, we cannot forget to mention *fuzzy systems* for which the constituent elements can not only belong (or not) to the system but belong to different levels, which allow tolerances and approximations in problems with incomplete or imprecise information [13]. Examples include information engineering and theory, for example, in search engines that are tolerant to partial and incorrect search keywords. The problems, in principle, if we have been able to formulate them, could only be resolvable. Otherwise, it remains a problem that is waiting for a solution or will have extreme curiosity in the event of apparent irresolubility. This, the solubility, as Warren Weaver (1894-1978) said, for example in [14], concerns the problems of simplicity that can be completely described by a few variables (with limited degrees of freedom) and with a few differential equations, such as those of the mechanics of a pendulum and the motion of the planets. The abstraction of these problems made it possible to identify what were believed to be the *laws of nature*. This does not concern the *problems of disorganized complexity* that is considered for systems with numerous degrees of freedom, which are intractable considering the individual entities involved. Appropriate approaches were identified as those involving statistics and probability, of a macroscopic nature, with a search for adequate overall indices, as in thermodynamics in the study of gases in which the phenomenology of the interaction is *unspecified* (for this reason, Weaver speaks of disorganization). Accuracy was *transferred* to a consideration of suitable indices such as pressure, temperature, and volume. Accuracy would be recovered by redefining and transforming the problem.

Weaver then identifies a *great middle region* between the two identified cases given above, i.e., simplicity and disorganized complexity, and he refers to the problems of *organized complexity*, in which the many variables are "…interrelated in a complicated, but nevertheless not in helter-skelter fashion…" [14, p. 539]. The latter is within the context considered by Bertalanffy [1, p. 34], when he writes:

> "The theory of unorganized complexity is ultimately rooted in the laws of chance and probability and in the second law of thermodynamics. In contrast, the fundamental problem today is that of organized complexity. Concepts like those of organization, wholeness, directiveness, teleology, and differentiation are alien to conventional physics. However, they pop up everywhere in the biological, behavioral and social sciences, and are, in fact, indispensable for dealing with living organisms or social groups. Thus a basic problem posed to modern science is a general theory of organization. General system theory is, in principle, capable of giving exact definitions for such concepts and, in suitable cases, of putting them to quantitative analysis."

As we shall see, the quantitative analyzes to which Bertalanffy refers to are those containing variables that are, in populations of agents, *interrelated in a complicated, but nevertheless not in helter-skelter fashion* in terms of quantitative properties such as coherence, correlation, scale invariance, power laws, self-similarity, network properties, chaotic properties, and polarization (see section 4.5). We only mention here how this radically changed the naive concept of *law* considered in the *problems of simplicity*. In this regard, we cite what the great physicist Richard Feynman (1918-1988) wrote on the characteristics of physical law under the influence of the Greek approach to mathematics, based on the tendency to organize theories on an axiomatic basis, in contrast to the Babylonian one. Namely:

> "What I have called the Babylonian idea is to say, 'I happen to know this, and I happen to know that, and maybe I know that; and I work everything out from there. Tomorrow I may forget that this is true, but remember that something else is true, so I can reconstruct it all again. I am never quite sure of where I am supposed to begin or where I am supposed to end. I just remember enough all the time so that as the memory fades and some of the pieces fall out I can put the thing back together again every day" [15, p. 45].

> "In physics we need the Babylonian method, and not the Euclidian or Greek method." (Ibid., p. 47)

We mention later how this is combined, in mathematics, with the declining influence (due to the infrequent publication of new volumes) of the so-called *Bourbaki program* (1935-), see Bourbaki in the web references. This aimed at a completely autonomous treatment of the central areas of modern mathematics, based on set theory with an emphasis on axiomatics and formalism. The end of this project was a manifestation of the diminishing effectiveness of the role of classical mathematics, based on abstract definitions and axioms.

In organized complexity, there are phenomena and properties that are *invisible* to the analytical approach except as partial completeness, approximation, and imprecision, partial solubility or relativism. On the contrary, as we will see when dealing with complex systems, the incompleteness is required to allow for the establishment of innumerable equivalences, evolutionary options for the system, interchangeability of roles, multiplicity, simultaneity, overlap, dynamics of levels of loss, and recovery of properties, as necessary for the establishment of processes of emergence. Reducing complex systems, and the properties of organized complexity, to trivial systems or *problems of simplicity* is said to be a fact of *reductionism*. This is not a question of simplification, but an assumption of inadequate levels of description. This includes the validity of properties such as disassembly and reassembly of systems, the linearity (or in any case reversibility) in a context of relationships considered fixed, isolable, explicit, and, for example, always completely symbolically representable (see section 3.3, at the point *Computational Emergence*, for sub-symbolicity). In essence, this reductionism ignores and denies the establishment of properties by the interacting elements in the system that are not linearly attributable to the properties of the elements [16]. The incommensurable leap of nature between properties is denied or, in any case, considered *reconstructable*. Examples can be given by confusing acquired and possessed properties, by considering complex systems as non-complex when systems are considered as non-systems (objectality) [8]. The importance of confusion lies in the fact that its validity, such as acting on the symptoms, i.e., on the elements, is assumed and it is believed to act identically on the *system reduced to the sum, linear compositions, iteration, or amplification of the elements*.

We end this section with an epistemological reference to the contrast between objectivism and constructivism [17-19]. The above, in particular the incompleteness, multiplicity of equivalences, induction and orientation irreducible to solvability, systemic nature (in particular the emerging one that we will examine later) on the one hand, and reductionism on the other, are combined with two concepts: respectively the *constructivism* and *objectivism*. We only briefly mention these themes here, but they are treated by a great variety of authors. The objectivistic approach consists in retaining the *existence* of the objective reality, about which we must discover how it really is. The constructivist method identifies how *it is effective* to think how something is. Objectivism would, therefore, be a particular case. For objectivism, the experiments would attempt to discover how the reality of nature *really* is. While, in the case of constructivism, the experiments would be understood as questioning nature answering by being made to happen. Thus, the answers depend on the questions and without questions there are no answers. Furthermore, there are facts or events that can be understood as answers to questions that should be invented in such a way as to transform facts into answers. Objectivism conceives the knowledge as *independently* possessed properties and as infinite mines (theoretical completeness, but practically unattainable by human beings) of knowledge to be excavated and discovered, alongside ideal knowledge that relates to points of view and disciplines. It is in correspondence with the properties possessed by objectality, i.e., *the real*.

Constructivism conceives of knowledge as a human activity of interaction, which has emergent, acquired, and effective properties. Disciplinary relativism is replaced by a coherent and consistent multiplicity; the approaches are *spontaneously, inevitably interdisciplinary*. There is interdisciplinarity when the problems, solutions, and approaches of one discipline are used for others. For example, giving different meanings for the variables of a set of equations, even when problems are transformed from one discipline to another, as from algebraic to geometric, from energetic to social, from military to political and vice versa. In addition, again to address the intrinsic incompleteness of problems that cannot be exhausted by a single discipline, such as medical problems that are simultaneously physiological, biochemical, physical, psychological, social, cultural (for example, refusing treatment for any reason), hygienic, alimentary, religious, environmental, stress-related problems, and many others. It is not a question of *aspects* of the medical problem, as considered by objectivism, but of components establishing the *systemic medical problem* that cannot be *disassembled* in them, which must be addressed by avoiding the reductionist approaches. See the so-called *P4 Medicine* considering a paradigm of care that is simultaneously predictive, preventive, personalized, and participatory. *However, constructivism applies to itself when considering that, in some cases, it is effective to adopt a simplifying, temporal, and objectivistic approach as for when the Earth is considered flat by consulting a map for short distances*.

# 3 Self-organization, emergence, and complex systems

Let us begin with a quote from the English philosopher George Henry Lewes (1817-1878), who published a collection of five books between 1874-1879 under the general title: *Problems of Life and Mind*. He wrote:

> "Every resultant is either a sum or a difference of the cooperant forces; their sum, when their directions are the same - their difference, when their directions are contrary. Further, every resultant is clearly traceable in its components, because these are homogeneous and commensurable... It is otherwise with emergents, when, instead of adding measurable motion to measurable motion, or things of one kind to other individuals of their kind, there is cooperation of things of unlike kinds... The emergent is unlike its components in so far as these are incommensurable, and it cannot be reduced to their sum or their difference in so far as these are incommensurable, and it cannot be reduced to their sum or their difference" [20, p.414].

In 1923, the British psychologist, naturalist, and academic Conwy Lloyd Morgan (1852-1936) introduced the concepts of emergence and *emergent evolutionism* [21]. During the same period, the British philosopher Charlie Dunbar Broad (188-1971) introduced the concept of *emergent properties, present at certain levels of complexity but not at lower levels* [22, 23]. The issue of emergence was for a long time considered to be of particular relevance to the context of biology. Bertalanffy, himself a biologist, writes:

> "The meaning of the somewhat mystical expression, 'the whole is more than the sum of parts' is simply that constitutive characteristics are not explainable from the characteristics of isolated parts. The characteristics of the complex, therefore, compared to those of the elements, appear as 'new' or 'emergent'." [1, p. 55].

The 'emerging' attribute was considered as a synonym of 'new' and 'unpredictable', and underlines that, in the context of biological evolution, it is often possible to detect the 'becoming' of certain characteristics in a discontinuous, unpredictable way on the basis of those already existing. Subsequently, for example, Corning [24] published an article that attempted to refine the concept of emergence and he proposed the construction of a theory of emergence. The theme of the emergence can be considered to be introduced, linked, and subsequent to that of *self-organization* [25, 26].

## 3.1 Self-organization

*Self-organization processes* can be understood as consisting of a 'regular' sequence of property (such as behavioral) changes of the collectively interacting constituent elements, when their change over time is predominantly regular; for example, in cases when they have cyclicality and quasi-periodicity, in which *a single form of predominant coherence is detected* as reduced, for example, with respect to similar repetitiveness and synchronicities [27, 28]. The population of the interacting elements acquires a sequence of properties in an almost regular way, as if they follow an *invisible organization*. One can imagine the establishment of configurations of elements, their shapes, and overall behaviors, which are in turn *predominantly repeated and mainly synchronized with each other* (see Fig. 1). *Self-organization can be understood as a multiple and variable distorted (linearly and nonlinearly, as appropriate) amplification of a collective scale of overall individual behaviors*. Examples are the formation of liquid swirls in pipes via dissipation; eddies, in the context where ground and atmosphere have very different temperatures, such as during the formation of hurricanes; chemical reactions, in which the component molecules assume overall behaviors, such as oscillating chemical bonds characterized by strong variations in color; the establishment of regularity in the formation of queues in a traffic flow; *collective beings* [29], such as those given by the regular repetitiveness assumed by a swarm of flies around a fixed light and the behavior of seagulls that fly circularly around piles of garbage; and the regularity of shapes within organisms, such as snail shells.

Self-organization is linked to processes of *self-similarity*, in which the global properties are the *same* (precisely the *same* is only for geometric objects, otherwise with *high similarity* for those with a high approximation in nature) properties of the components. Such as the same precise properties of fractals, and approximated cases in nature such as leaves, flowers, broccoli, lung alveoli, and snowflakes. It is important to note that the interacting elements have usually the *same nature*, with reference to the previous examples this includes flies, gulls, vehicles, or molecules within liquids. This means that everyone (or everything) reacts in an 'identical' manner, albeit with differences in times and parameters, when certain external influences and constraints are applied, such as shape and sections of the pipes; shape, sections and height difference of the roads; and stable action-reaction for flies around a fixed light. *This is the main synchronization source*.

**Fig. 1.** An eddy is an example of self-organization, which is given by predominantly regular, synchronized, and repeated micro-molecular behaviors.

### 3.2 Emergence

The processes of emergence [30] can be understood as the occurrence of multiple, different, simultaneous sequences of self-organization processes partially and dynamically involving same elements, when the corresponding multiple acquired dynamic structures are coherent, i.e., they maintain the predominance of the same properties, despite the adoption of multiple local, simultaneous, and different coherences. In the case of emergence, the population of the interacting elements acquire sequences of properties in a correlated and coherent manner. As if the areas of the population of the interacting elements were self-organized in different ways, so that the same elements were simultaneously part of different self-organizations and some of the elements may not be part of any self-organization at all. The elements are set in temporal sequences, in which the self-organizing modes and the areas of application change, but they maintain the overall levels of coherence. One may imagine establishment of configurations of elements whose behaviors are partially repeated with partial, multiple, variable, overlapping, and intersecting synchronizations [31], see the example of Fig. 2. Basically, it is established such a coherence, which cannot be reduced to single synchronizations [32, 33] that is, to self-organization [34].

*The emergence we consider concerns the way in which systemic properties are acquired, maintained at different levels, replicated at different levels of equivalence, inhomogeneous, and lost and resumed. This allows for the incompleteness of tolerance, the establishment of thresholds, and the multiple and partial equivalences in variable structural dynamics, but they maintain sufficient levels of coherence that guarantee the forms of identity* (see section 4.6). *The interaction process is composed of multiple and variable interactions with irregular elements, having variable times and durations; interesting the same elements having to play different roles. The emergence gives rise to systems that are not just static systems, since they are not always the same system and also constitute other temporary systems, i.e., quasi-systems, see point* 2.2. *Like flocks and swarms that are constantly changing in structure.*

In short, this emergence [35] is the factor that characterizes the *formation* of complex systems and provides the nature of their *incompleteness* and *intrinsic undecidability*, that is, they cannot be prescribed by constitutive rules, except with unlimited degrees of freedom and constraints that are respectable in a large variety of ways. The considerable *level of complexity* for complex systems may be intended, for example, to be given by the dynamics and the quantity of detectable, simultaneous processes of emergence that occur within the system, by the properties of their sequences (such as regular, partially regular, and random), by their suspension and restoration, and by their simultaneous influence on other elements or their clusters [12, pp. 253-286]. Cases include collective systems, collective beings that are established by autonomous entities whose behavior, in addition to the context seen in self-organizations, is influenced by their own available structural available properties relating, for example, to the cognitive abilities (inducing similar processing of information and pursuing, in the most similar way, the same purposes), mobility, ability to fly, visual skills, and sensory abilities in general; to sensitivity to chemical signals or effects based on acoustics or optics (as for *stigmergy* introduced later), as in the following examples. Specific examples are anthills, termite mounds, flocks, swarms, cities, herds, schools of fish, and markets. These collective beings acquire properties such as shapes and behaviors, e. g, *swarm intelligence* considered later: sociological, ways of expanding and consuming resources by cities; and prudence, euphoria, or stability by the financial markets. *As we will see the emergence, the ability to set-up processes of emergence is the engine that makes up the complex systems.*

**Fig. 2.** Flock of birds emerging from micro structural available behavioral properties.

### 3.3 Notes on types of emergences

We now briefly list some cases of emergence:

- *Intuitive definition* corresponding to a first identification of 'emergence', which was novel and unexpected.
- *Weak emergence and strong emergence* corresponding to limited conceivability and deductibility, respectively; versus totally unpredictability from the lower levels [36].
- *Intrinsic emergence* refers to a process in which the occurrence of a certain behavior is not only unpredictable, but its existence gives rise to profound changes in the structures of the system, such as those that require the formulation of a new model system (this is symmetry breaking, see the point Symmetry breaking in section 4.5).
- *Phenomenological emergence* that cannot be prescribed, but only induced, which is sensitive to the environment (both external and internal) and dependent on the initial conditions, such as those due to the unique phenomena of dissipation of matter and energy (such as the maintenance of the vital state of the face in metabolic processes).
- *Radical emergence* refers to processes such as protein folding, acquisition of superconductivity, and superfluidity that require quantum physics models.
- *Computational emergence* arises when computing causes the acquisition of properties [37]. A simple case of computational emergence is provided by the emergence of shapes that derive from the step-by-step computation of Cellular Automata [38], as in the *Game of Life* [39]. Examples include properties that are acquired by artificial neural networks and all examples that involve the emergence of properties obtained from computational processes [40].

## 4 Complex systems

In this Section we consider three main constitutive aspects of complex systems: their theoretical incompleteness, their emergence, and their consequence of being quasi-systems. Furthermore, we list characterizing properties of complex systems and types of complex systems. We conclude with a note on the possibility to recognize a complex, collective system as *the same* over time despite its structural changes.

### 4.1 Incompleteness

The conceptual context in which the above-specified processes of emergence, equivalences, and multiplicity of levels of coherence can occur, is that of *theoretical incompleteness*. The theme of theoretical incompleteness [41, 42] is distinguished from the occurrence of incompleteness for any reason related to, in principle, *completable incompleteness*. The specification *theoretical* means that the incompleteness under consideration cannot be completed in principle, as considered and it has now been introduced in many disciplinary fields. Think, for example, of the *uncertainty principle* in physics: the well-known principle introduced in 1927 by Werner Heisenberg (1901–1976). This, referring to atomic or subatomic particles such as an electron, states that the more precisely the position is determined in an instant, the less precisely the momentum (mass multiplied by the speed) is known at the same instant, and vice-versa. The completeness makes the assumption of an alleged existing level which we would not be able to grasp, untenable. Another is the *complementarity principle* introduced in 1928 by Niels Bohr (1885-1962), according to which the corpuscular and wave aspects of a physical phenomenon will never occur simultaneously. Remaining with physics, we need to consider the theory in terms of fields rather than particles and the so-called quasi-particles that share the properties of traditional particles with the exception of localization [43]. Outside of physics, the incompleteness theorems introduced in mathematics by Kurt Gödel (1906–1978) must also be considered [44].

There is *theoretical completeness*, for example, when there is effective calculability, procedurability, and deductibility. There is effective computability when there are approaches to identify and use the computation methods that, on application of a certain input, enables the arrival at a complete result (whose precision cannot, theoretically, be incremented) in a limited time by use of limited resources (for example, calculation of the average prices and the average stock on a current account). This is the so-called

Turing computability. There is procedurability when a method is available, so that a problem can be completely divided into a finite and a limited number of sub-problems and, thus, can be addressed step-by-step (for example, a program to manage the logistics of a storage and a distribution system divided into various sub-programs that elaborate specific aspects, such as warehouse saturation, optimized use of means for the movement of goods, application of safety criteria, application of conservation criteria for goods, management of the personnel involved, etc.). In short, the analytical approach. There is deductibility when one can only pass from one current configuration to another (for example, in the Euclidean geometry of the plane, when a triangle has two sides of equal length then it can be deduced that it also has two equal angles); if a box contains only red balls and this colored ball is taken from this box, then there is the deduction that the ball is red.

Correspondingly, we can consider cases of theoretical incompleteness that, in principle, do not have the possibility of effective computability (such as calculating the square root of a number that cannot be expressed as a power of two, or calculating π); when a problem cannot be reduced to a procedure (we often talk about following the complete procedure, for example safety at an airport or at work, while this completeness only covers a significant percentage of possible cases). *Completeness applies completely only in abstract cases, such as in geometry and calculus, while in reality it is always a question of considering high levels of approximation. There would be nothing wrong with this, were it not for the fact that there are phenomena for which their approximation cannot be neglected, but they may even require it in order for them to happen*. These are, for example, phenomena that occur through innumerable modalities, with different levels of equivalence, of compliance with (incomplete) constraints, such as the flow of liquids in context which are very constrained, such as in a pipe, or a little constrained as in the bed of a mountain stream.

## 4.2 Emergent complex systems

In such partially (as they can be respected in countless ways) constrained spaces or, alternatively, whose constraints lie in the properties given by the very physicality available to the interacting components (agents, such as birds in flocks, mass displacements of people, and cars in vehicular traffic); environmental; and of a cognitive and social nature, there is the opportunity of unorganized complexity and organized complexity to occur, in particular in the emerging of complex systems. *We now examine processes and, in particular, processes of emergence and the establishment and maintenance of complex systems* [4, 45].

As introduced earlier, the multiplicity, the equivalences, and the structural dynamics of the processes of emergence require an incompleteness to be able to happen, in particular an incompleteness of the constraints. In this respect, we now mention how completeness-based influences have the same invasive and prescriptive nature as the prescriptions, *strong forces*, while the *weak forces* play the role of 'suggestions' to be processed by the complex system (for example, deciding between equivalences), rather than being substitutes with strong and contextless impositions. The incompleteness provides the system with the possibility to decide between equivalences and eventually acquire a coherence, as in the cases of acquisition of emergence in compliance with admissibility and compatibility. We mention the case of *metastability* as the potential to maintain or switch from one state to another in a response to small fluctuations, for example, a jug of water at a low temperature (very close to zero degree Celsius), freezes immediately if placed in contact with an ice cube. Furthermore, small fluctuations can break the unstable balance of any heavy bodies.

We characterize forces as ‘weak’ when they have a local range of influence, that is, they involve very few adjacent compositional elements, have a low intensity (for example, less than the lowest sized forces that are globally involved), and they are insufficient in changing the properties of the interactions in progress. To act on complex systems, it is a matter of proposing interventions as the application of weak forces and introducing constraints with various possibilities of being respected, suitably modified as inputs that must then be processed by the system, for example through adaptation. It is a question of considering the effectiveness of the weak forces that are capable of breaking equivalences, equilibria, initiating collapses, and establishing initial conditions; this is very important for chaotic systems that are very sensitive to their initial conditions (see section 4.4, point 3). Interventions with strong forces, in contrast, can destroy the complex system, i.e., the complexity, the emergence of the system, such as high dosages of pharmacological interventions, the increased pressure of liquids for which eddies can no longer form, and an increased speed of vehicular traffic.

Example of interventions with weak forces include taking a low dose of drugs in diluted times, changing the density of dissipated fluids, inserting traffic obstacles such as roundabouts, having beforehand an image of the defensive efficacy of wasp swarms that are collectively highly dangerous, but individually weak. The high frequency of weak forces replaces the possibly impossible and inappropriate single strong action, which also has the advantage of adaptation flexibility. These weak forces involve inducing non-traumatic variations to the processes of any nature that repetition can consolidate, such as affecting the movement of a flock with a weak flow of air that is unable to cause displacements but is a constant, or inducing medical, stock exchange, and ecosystem changes. *It is a question of convincing the complex system to work in a way that pursues the purposes we would like to prescribe, i.e., provide a suitable input to be processed*. Unfortunately, this is also the known approach for *manipulating* social systems.

Furthermore, the weak forces also *complete* any necessarily invasive interventions, such as repairs and replacements, and activate processes, for example, of adaptation. An interesting case is that of surgery, obviously invasive but inevitably incomplete. It leaves the operated body the role of *elaborating* the intervention, adapting it, or even rejecting it. The body is to be understood as a collective being [12, 29] of cells and other biological entities in continuous evolution, which partakes in regeneration, repair, replacement, degeneration, and reproduction. By being collective we mean, in short, a collective behavior that acquires its own emerging behavioral properties, which is autonomous (from the elements) such as flocks, markets, and networks such as the Internet. *Strong forces are inadequate for complex systems, they are not processable, inadequate, and they are like wanting to pay for a parking meter with a banknote or supplying electrical power with such a high voltage and amperage to burn out the electronic circuits*.

## 4.3 Complex systems as emergent quasi systems

In the scientific literature, there are several instances that are examples of the concept of quasi. We limit ourselves here to a mention of quasicrystals [46], quasistatic processes, quasiparticles, quasi-ergodic behavior [47, 48], and quasiperiodicity in mathematics. In systems science, quasiness relates specifically to the generic dynamics of the occurrence of incompleteness in phenomena of emergence, as mentioned above. *The modelling of quasiness converts abstract, complete (at the most probabilistic) models used in simulations into realistic models, which theoretically incorporate the structural dynamics (temporal variable, local, and multiple) of emergent phenomena*. It enables the possible consideration of the *process of quasification of models* [2]. Quasisystems are not always systems, not only systems, and not always the *same* systems, . They are partially systems, or multiple systems, and they have the ability to lose and recover properties that vary their predominance, such as their global and local coherences [12]. Quasisystems are assumed to model realistic systems and they require suitable approaches, which means considering and not neglecting their incompleteness as it is in processes of emergence of complex systems. In particular, the multiple sequences of the interaction mechanisms of emergence generate complex systems and quasiness is a main feature that occurs within them, which is intended to be partial, inhomogeneous, multiple local, occurring and reoccurring, a phenomenon of evolution and mutation, and the combinations of coherences.

We conclude this section by stating that we can identify complex systems as systems that are generated by the processes of emergence, in which various, multiple, overlapping processes of emergence occur in turn, with different coherences, that even involve same components in different instants. Therefore, *complex systems are quasisystems but quasystems are not necessarily complex systems*, since the necessary quasiness must also be accompanied by the acquisition of the characteristics (introduced in Section 4.5) of complex systems, such as long-range correlation, network properties, polarization, power laws, remote synchronizations, scale invariance, and self-similarity. These characteristics serve as the ideal representations (for simulations) of the *necessary* effects of combinations of multiple, different, partial, overlapping, and variable duration interactions. *In contrast, typically, simulated systems that have these characteristics may be not actually complex because the quasiness is not considered; the quasiness is ignored in the models assumed a real new reductionism*. The sufficiency (it is neither prescribed nor prescriptive, as prescribing means completing and, thus, extinguishing emergence and relative incompleteness. It can only be induced by varying the constraints that allow a great variety of possibilities to respect them) of models to represent complex systems can be established by a dynamic and incomplete but sufficient regularity of internal and external constraints. Similar to what occurs in collective beings such as flocks, swarms, and ecosystems. In the following section we mention various types of complex systems.

In the section 4.5 we examine some properties that are clues, or real manifestations, of complexity when they are accompanied by their quasiness.

### 4.4 Types of complex systems

At this point, we are able to list various *types* of complex systems:

1) Examples of complex systems that consist of coherent communities of living systems that are equipped with *cognitive systems*. It is matter of autonomous systems that are capable of *deciding* their own behavior, not only in an algorithmic way or pursuing, for example, optimization such as the trickle of water that makes the most efficient path to enter the river. In these cases, the decisions of the behaviors cannot be reduced to computational optimizations, since it is a process of emergence from a wide variety of aspects. In a nutshell, a cognitive system is understood, at various levels in nature, as a system of interactions between activities, such as those related to attention, perception, language, the affective and emotional sphere, memory and the inferential system, and logical activity. Examples of such complex systems capable of acquiring autonomous behaviors and properties with respect to that of the components include swarms; flocks; communities, industrial districts, industrial networks and clusters, markets, and social systems. The latter includes cities, schools, hospitals, businesses, families, and temporary communities, such as passengers, the public, vehicular traffic, and telephone networks. *In the case of sufficiently complex cognitive systems, there is the constitution of collective beings whose constituents are probably necessarily endowed with the same cognitive system. The collective being acquires its own emerging behavioral modalities* (see the *behavioral properties* point in section 4.5).
2) Examples of complex systems whose constituent elements are considered *without cognitive system* include cellular automata, ecosystems, the atmospheric system, specific electronic circuits, oscillating coherent chemical reactions such as the well-known Belousov–Zhabotinski reaction, nematic fluids (liquid crystals); and dissipative structures which in order to exist must dissipate matter-energy:
   - *living* such as amoeba and bacteria colonies; protein chains and their withdrawal, and cellular metabolism;
   - *non-living* such as vortices in fluid dynamics.
3) Another case of complex systems is constituted by *chaotic systems*, whose behavior is characterized by a very strong dependence on the initial conditions so that, in the face of minimal initial differences, the system acquires very different evolutionary paths. This system follows admissible evolutionary trajectories in the vicinity of an attractor. In short, an attractor (see the point *Attractors* in section 4.5) is a set of numerical values, for example, a single point or a finite set of points, a curve, and a manifold, towards which a dynamic system, starting from any manifold of initial conditions, tends to evolve. The shape of the attractors characterizes such systems. Evolutionary paths of the system, when close enough to the attractor, remain in the attraction basin even under the effects of perturbations. Examples include the climate system, the spread of smoking, specific electronic circuits, and the double pendulum. To also be considered are chaotic biological systems, as in the case of neuronal networks and economic systems (for example, in the time series of econometric indices). However, the considering chaotic systems as complex has controversial aspects, since chaos deals with deterministic systems whose trajectories diverge exponentially over time. Furthermore, this property is found in complex systems. Models of chaos are generally based on a few variables, while complex, non-chaotic systems have many degrees of freedom. The behaviors of the latter, however, are in some cases considered *high dimensional chaos*.
4) Another case for a complex system is given by systems *represented as complex networks* between constituent components, intended to be nodes, and where the links between the nodes are meant to represent interactions. Complex networks, considered by *network science* [49, 50], have properties that typical graphs, lattices, and non-complex networks do not possess, such as:
   - They are *scale-invariant*, which occurs when the network has a large number of nodes with a few links or a small number of nodes with a large number of links. In such networks, the probability that a randomly selected node has a certain number of connections follows a *power law* (see *Power Laws* in section 4.5). The property of a scale-invariance network is strongly correlated with its robustness, that is, the tolerance to perturbations. Examples include the internet and social collaboration networks.
   - They contain *small worlds* that are formed when most of the nodes are not closely adjacent (a few links away), but most of the nodes can be reached from any other node through a small number of links (the intermediate links). This property is also considered to increase the robustness of the network. Examples include networks of

electrical energy and networks of brain neurons.

- They have significant *aggregation coefficient values*, which measure the degree to which the nodes of a network tend to cluster together. In particular, it is a measure of the probability that any two nodes that have a common neighbor are themselves connected. An example is given by the social networks of friends, who generally know each other.
- Nodes have significant *degree values*, which act as the number of connections that they have with other nodes, and the degree distribution is the probability distribution of these degrees over the entire network. Examples are given by computer networks, networks of people of a given community, metabolic networks, and brain neuronal networks.

### 4.5 Properties of complex systems

*This is a matter of complex systems and not the causes that generate complex systems. Complex systems are generated by variable combinations, with different regularities, of different multiple interactions and suitable constraints in emergence processes.* Simulated systems that possess these properties *are not necessarily* complex systems. The properties offer significant *clues*, useful for recognition, partial simulation, and (in principle) not necessary for the treatment and generation of complex systems emerging from combinations of interactions. The difference is substantial when approaches must be adopted to deal with the emerging systems, while acting on these properties is like acting on symptoms [2]. We present below a list of prevailing properties [2] that characterize complex systems. However, individually they are neither sufficient nor necessary, but are recognizable in variable combinations, temporary dynamics, inhomogeneous, and at different intensity [30].

- Behavioral properties

We consider the behavior of configurations of interacting entities of types 1) and 2), given above. It is a behavior that cannot be *linearly reduced* to (that is, nonlinearly rebuildable from) that of the components. We examine properties, such as those of the dynamics of acquisition of sequences, with levels of regularity of collective patterns of the collective beings (in reality which entities are not this? Crystals perhaps...). Such collective beings emerge from the interaction between the composing elements and acquire forms of *behavioral autonomy* that are not only not reducible to that of the constituent elements, but also interpretable as manifested by an *ideal virtual collective cognitive system*. Examples of such acquired behavioral autonomy include the characteristics of school classes, markets, social of a city, and forms of the so-called *collective intelligence*, for which the collective being is able to implement strategies such as defense from predators and of territory, building perfectly organized hives, and to implement optimized research of food sources. In this regard, we recall the *stigmergy* that studies communication through the induction, detection, and use of environmental variations. This is defined as indirect communication that exchanges information through environmental modifications. It is of great importance to systematically read the territory, the environment, its uses, and its modifications. For example, this is widely used to study the evolution of cities and their social characteristics, while living and using its context as a communication. An important behavioral property is that of remaining coherent, since the correlated constitute the robustness of a collective being. Emergent systems keep their coherences and are robust to perturbations, are tolerant to noises thanks to their quasiness (their quasiness *absorb* noises, interpreted by the system as facts of quasiness).

- Synchronization

The classic concept of synchronization [51] in physics refers to the oscillatory phenomena, such as for single oscillators when in phase. The concept of synchronization has various disciplinary meanings, including those for swinging pendulums, marching parades, applause that become synchronized over time, and the emission of light (bioluminescence) in phase within a community of fireflies. As we saw in section 3.1, self-organization can be understood as prevalent continuous synchronization, which are predominantly and continuously repeated unless there are parametric variations, such as for liquid vortices. We also mention the implementation of *remote synchronization* based on the indirect transfer of information (when pairs of non-adjacent entities become substantially synchronized, despite the fact that there are no direct structural connections between them) and in a network as a system (type 4 as above), in which two nodes that contain the same symmetry have an identical phase, despite being distant in the graph [52-54]. It is also a question of synchronicities recurring over time, after periods of absence.

- Correlation

In statistics and probability [55, 56], the concept of correlation is closely linked to that of covariance [57]. Both measure the dependence between the variables under study. Covariance determines the extent to which two variables *covary*, that is, they both change in the same (or similar, depending on the threshold level adopted) manner. However, there are problems in comparing different covariances relating to variables of different nature, as they are evaluated on different scales. With an adequate mathematical approach, the various covariances can be *normalized*, making them dimensionless and therefore comparable; this is known as adopting the *correlation coefficient*. The correlation can, therefore, be considered on a common scale, or in a standardized form, of the covariance. Synchronization can be understood as a particular case of correlation, which occurs when changes over time are regularly repeated [58-60]. *Autocorrelation* refers to a consideration of the correlation of a phenomenon at a certain moment, with itself at another point, that is, the correlation with itself at different instants. This allows to reconstruct, or anticipate the values over time, by identifying the regularities. In the case of a population (of any number) of interacting phenomena or entities, the *correlation length* indicates the extension of the area or areas, and the number of elements of the subsets of the population in which the correlation is detectable.

- Coherence

In short, coherence arises when the correlation length identifies the entire population that makes up the system under study (*long-range correlation can be considered as identical to coherence*). The dynamics of a non-trivial complexity concerns the implementation of multiple coherences over time, interesting multiple systems with components in common, systems with components that have variable roles and belonging, at different scales (for example, positional, temporal, energetic, and others), and referral to various levels of coherence between the coherences. However, when dealing with complex systems, coherence concerns maintenance at different levels of admissibility and the recovery of the same (albeit considered as such, see section 4.3) collective properties, for example, the behavioral and the dynamics of acquired patterns [61-63].

- Power Laws

Power laws (*power* refers to, in the mathematical sense, the fact that the elevation to a power is considered) occurs when the frequency of an event varies at a power of some of its attributes. For instance, $Y = kX^{\alpha}$, where $\alpha$ is the exponent of the power law and $k$ is a constant. It is said that this power law relationship arises between the size and the number of corporations, the levels of wealth and the number of people considered, the magnitude and number of earthquakes, and the spatial size of cities and the size of their population. Power laws are scale-invariant [64].

- Polarization

In physics, the polarization refers to phenomena such as waves in liquids or gases that mainly oscillate in the direction of the wave's propagation, or to light that vibrates primarily in one direction. The theme can apply to the coherence of the flight of flocks of birds, with respect to the *anisotropy* (a property for which a phenomenon has characteristics that depend on the direction along which they are considered) of their behavior. Within a population of interacting entities, such as swarms or flocks, it is possible to consider the degree of global ordering that is measured, for example, by polarization. Instantaneous clusters can be considered, which are differently polarized and are composed of possibly dispersed not contiguous entities, but have, for example, the same direction. When the extent, or quantity, of the belonging entities coincides with the entire collective system, the population is all polarized.

- Scale invariance

Scale invariance is the characteristic of entities that do not change their properties, for example the geometric properties in morphologies, regardless of a change in size, for example, by scaling or by modifying the number of components. Scale invariance is a form of self-similarity, in which parts of the object are similar to the whole. A typical case is that of fractals in snowflakes, branches of a tree, leaves, and floral structures (which are typical examples in nature) [64].

- Symmetry breaking

The expression *symmetry transformation* denotes a transformation of suitable variables in the evolution equations of a given system. From a mathematical point of view, the solutions of dynamic evolution equations are invariant to shape with respect to symmetry transformations, such as rotation. However, this transformation can act both on the shape of these equations and on the shape of their solutions. S*ymmetry breaking* arises when a symmetry transformation leaves the shape of the evolution equations unchanged but changes the shape of their solutions. A typical example is given by considering matter, in which the form of the equations describing the motion of the constituent atoms is invariant with respect to the particular symmetry transformations that consists of spatial rotations around a given axis. The solutions of these equations also have the same invariance. However, for example, if ferromagnetic matter is exposed to an external magnetic field, whatever its direction, this will provide within the material an induced field aligned with the external one. The presence of such a field leads to the existence of a preferred alignment direction for the atoms, i.e., that of the induced internal magnetic field. Even if the shape of the equations that describe the motions of the atoms does not cease to be invariant with respect to the symmetry transformations constituted by the spatial rotations, their solutions do not; this is because the preferred direction breaks this invariance [65].

- Attractors

These are positions in the *phase space*, i.e., a space in which all the possible states of a system are represented. The evolution over time of a dynamic system can be represented by a graph in multidimensional space called a phase space, which is not the graphic representation of the geometric movement of the system. The phase space is an abstract space, in which each variable of the system is associated with a coordinate axis. For instance, the phase space of a pendulum is composed of two variables: the angular variable *p*, which identifies the position and moves on the circumference, and the velocity variable *v*, which can vary along a straight line. In this case, the phase space takes the shape of a cylinder. In short, an attractor is a set of numerical values, for example a single point, a spiral, interconnected and deformed spirals, or other towards which the evolution of a dynamic system represented in its phase space, starting from any variety of initial conditions, tends to evolve. The shape of the attractors characterizes such systems [66].

- Bifurcation points

This term denotes a change in the structure and topology of the system, and the number or *type of attractors* that results from small regular changes in the parameter values [67].

- Nonlinearity

To complete what is specified above (see section 2.1), we refer to changes in the forms of nonlinearity, when the equations describing the nonlinear behavior of the system change; for example, from trigonometric to exponential and their combinations. It is, therefore, the case of an evolutionary dynamic system described by variable combinations of parametric and structural variations, i.e., described by different rules. *It is of particular interest the process of transition between different nonlinearities*.

### 4.6 Note

We conclude this section with a note on the millennial philosophical theme, which regards the *recognition* of a process as the *same* over time in the face of its *continuous change*. It could be said that a process, and in our case a collective being, has a collective behavior that is recognizable as 'identical', if the components and the rules (such as the equations) that describe it are invariant, but the parameters are *admittedly* different; for example, without any phenomenologically *inadmissible*, *incompatible* jumps (which is not for quantum physics). If, on the one hand, this way of interpretation allows to identify the structural continuities that can be assumed as a representation of the *identity* (for instance, we are looking at *the same* flock over time...) but, on the other hand, it does not guarantee that we consider collective processes that are composed of equivalent indistinguishable but different elements and, however, having a behavior represented by the same rules. The very high improbability that *different* elements are found in the *same place*, and within adjacent temporality, that behave according to the same rules and parameters would have to be combined with the very high probability that it is the *same* process or collective being. Furthermore, at a certain moment, the same elements could interact in a structurally different way, which breaks symmetries and accords to different nonlinearities; this constitutes *another* process or collective being. The recognition of identity over time is linked to the appropriate approaches and levels of contextual representation that are used, *constituting admissibility* and *compatibility* of the temporal sequences. This deals with the problem of the identity of complex systems, collective beings, and collective behaviors. *However, we cannot shake off the probability*… (Parmenides vs. the *Panta rei* of Heraclitus).

## 5 Complex systems: their emergent intelligence or emergence as intelligence?

The human attitude has shown numerous times its presumptuous homo-centrism, well correlated, for example, with geocentric concepts and the instrumental relationship with nature. Thus, properties considered as characterizing humans have transferred from being uniquely human to being, often concessively, *also* recognized in other species.

As it is so for intelligence. For example, we consider the possibility of creating computers to behave in ‘intelligent' ways, *using the advantages of giving intelligence*. As with cognitive science it is matter of human beings studying themself, of science that studies itself, so it is for intelligence that studies itself, and once objectified it would be reproducible even artificially. Let us begin from this last aspect, to realize an approach for the systemic, multiple, and emerging identification of intelligence. First consider the context of artificial intelligence (AI). In this context, the acronym GOFAI (Good Old-Fashioned Artificial Intelligence) denoted until the end of the 1980s the oldest original approach to AI, based only on equipping computers with logical reasoning and problem-solving skills, all of which understood tout-court as intelligence. The acronym ‘GOFAI’ was introduced by John Haugeland (1945-2010) in [68].
The assumption was that intelligence consisted almost entirely of high-level ability to manipulate symbols with the predominant purposes of computation, *formal truth* seeking, formal problem solving, and optimization skills. It is interesting to note the conceptual correspondence with the Bourbaki research program (see section 1.1 and the web resources). The serious limitations of the GOFAI conceptual paradigm were subsequently realized, and new approaches were considered, such as a sub-symbolic one using tools such as artificial neural networks and cellular automata considered above, *when symbolic computation causes emergent properties to be acquired*, see [37], Furthermore, automaton theory, control theory, cybernetics, game theory [69], Gestalt approach, systems dynamics, catastrophe theory, chaos theory, sociobiology, natural computing algorithms [70,71], and the *general theory of systems* [1]. The underlying problem, however, is once again the *reductionist* interpretation of acquired properties, as in this case of intelligence, that can be considered separable from the others of the *intelligent living being* and, therefore, substantially without a need to emerge, but only to be appropriately possessed. *As for complex systems, knowing how to simulate systems that acquire properties of complex systems does not coincide with knowing how to simulate the emergence and the complex system itself. The formation and behavior of such systems, which is to know how to simulate artificial systems that acquire properties of intelligent behavior, does not coincide with knowing how to simulate the emergence, the constitution of intelligence*.
The complexity of the challenge for an intelligence capable of understanding itself has been examined by interdisciplinary approaches, such as that of the cognitive sciences. It is question of studying systems capable of *cognitive* (and not just intelligent) activities such as those that have the ability to make logical inferences and elaborate symbols; perform abduction (ability to invent hypotheses) as introduced by Charles Sanders Peirce (1839–1914), see ref. [72]; *manage* and not just *solve* problems, for example, adaptations, criminality, negotiations, and parasitism; have language skills, for instance, write different texts that have the same meaning; have, induce, and manage emotional influences; learn; make abstractions; decide and plan according to strategies; perform semantic processing; perform memory activity as an active *reconstruction process* (not only as storing and searching); and we mention at the end the ability to dream and to have an unconscious [73], and also *recognize properties such as intelligence.* Considering this list as theoretically incomplete is probably, on the one hand, a fact of intelligence and on the other related to believing intelligence is a property *continually and contextually emerging from a multiplicity of aspects of cognitive systems and not at least as a property possessed*, such as the shapes of complex systems like flocks and eddies.

## 5.1 Intelligence as a property of matter

Up until now we have not examined the problem of indicating what is meant by matter, which is the subject of endless discussions and controversies. In quantum physics, the quantum vacuum is an entity that precedes matter, so it must also precede space and time. In this way, the classical idea of matter as a substratum, as a metaphysical entity that allows physical existence, and one that possesses properties and allows them to be acquired, loses its consistency. As already mentioned in section 2 we could consider the approach considered in mathematics to not only *use* the imaginary, incomputable nonexistent number *i*, but identifying its properties. In this regard the Euler’s formula states that, for any real number *x*, we have $e^{ix} = cosx + i\ sinx$ where *e* is the base of natural logarithms and *i* is the imaginary unit. The Euler’s formula gives rise to the so-called Euler identity: $e^{i\pi} + 1 = 0$. From this it is possible the geometric interpretation of the formula, allowing complex numbers to be viewed as points in the plane. In conceptual correspondence (we don’t know the imaginary number as we don’t know matter) we could consider the intelligence of matter and its behavioral properties, such as its ability to perform chemical reactions, phase transitions, constitute fields, the cosmological dynamics, and the ability to establish and acquire emergent properties in conditions of theoretical incompleteness, such as coherence, long-range correlation, self-similarity, synchronization and remote synchronization, power laws, and life through dissipation that avoids thermodynamic equilibrium. The ability to *host* phenomena of emergence would be a form of intelligence, indeed emergence would be an original form [74] of intelligence. Intelligence should be understood as an implicit capacity, having pervasive aspects, present in the non-living and in the living (therefore, not as its specific property). Other examples include the assumption of fractality that allow for the availability of large surfaces in small volumes, for example, alveoli of the lungs. *We are talking here about intelligence of matter in its non-living phase*. Moreover, biotic matter could contain a continuous process of resilience and balancing (processes of self-repair, reproduction, and self-regeneration) and autocatalytic reactions (we refer, for example, to problems of genetic mutations and Neo-Darwinism).

### 5.2 Acquisition of intelligent behaviors as phenomenon of emergence

Just as we can identify properties of complex systems, so we can also recognize forms of intelligence about which we are tempted to have a reductionist approach, separating them from others, and understanding that it is autonomous and independently owned. Intelligence can be identified as an emergent property of sufficiently complex cognitive systems, and yet recognizable in various forms and levels in different phenomena. For example, we speak of *swarm intelligence* [75], distributed intelligence, or collective intelligence that can be considered as a property of non-intelligent agents, who collectively have (i.e., that the collective beings acquire) a behavior manifesting forms of intelligence. For example, consider the occurrence of a collective representation with individuals unable to formulate an abstract representation. This is the case with the behavior of ants in their search of food. When an ant detects a food source, it marks the path followed with a chemical trace (pheromone) and induces subsequent searches to follow such traces as for the stigmergy (is it a fact of intelligence?) introduced above. And then there are examples of collective defensive behaviors towards predators, such as the so-called *predator confusion*. Research shows, for example, that forms of collective groups of fish and birds change when they are under attack from a predator.

Furthermore, in the case of collective behavior, there is the possibility of repeating a collective action of collective attack, for example, sting or pecking, or implementing a collective defense strategy, for instance, light-reflecting herring giving predators the impression of being in front of a large being that is actually a collective. Here, high frequency of weak actions replaces the impossible single strong action; moreover, it has the advantage of the flexibility to adapt.

### 5.3 Emergence of intelligence

We refer to configurations, systems from which not only intelligent behaviors emerge, but particularly potential intelligence that is waiting to be applied, as an interdisciplinary, transversal systemic property, which *even studies itself*. We know that neural reticular activity is a central, necessary part of the cognitive system from which intelligence emerges in the form of a complex context of the brain, hosted in the living body. It is matter of intelligence that emerges from the cognitive system as described above. *We are talking about intelligence of matter in its living phase, which is able to study itself.*

### 5.4 Concluding remarks

We have briefly considered the marriage between complex systems and an emerging intelligence, but also intelligence as an intrinsic property of matter. Their dichotomy is richness: is it the second that transforms into the first and/or the first that mirrors and continues into the second, or are both in a continuous dynamic? The mission of Homo sapiens would be to understand (at least a little) Nature and itself, as the comprehensibility of the Universe promises (no wonder that father and son can understand each other), before such comprehensibility *was misunderstood as possession, and dominion over the understood* (Adam's fault in the Torah).

## 6 Artificial Intelligence

Does an understanding of intelligence provide us with dominion over intelligence? Can we extract it, separate it, and attribute it to artificial devices? Is there a possibility to delegate choices and decisions? Basically, can intelligence be simulated (neglecting its emergence) so that it can be supplied to artificial devices and applied to specific problems? In a limited form, yes. This is matter of *local intelligence* applicable to specific problems, such as *machine learning* of systems capable of learning from examples and training, and of generalizing (in particular based on neural networks), for example, in the following fields:

- Robotics;
- Games;

- Linguistics (translations, writing of texts);
- Profiling (behaviors), see for example [76];
- Chatbots (programs designed to simulate conversations with human users based on learning from previous conversations and interactions, i.e., *chatting robots*), for example as a virtual personal assistant and with vocal interactions with users, see for example [77];
- Vocal recognition;
- Image recognition;
- Driving of vehicles without a driver.

In reality, there are innumerable possible disciplinary applications. Examples of perspective research include image understanding, natural language understanding and processing; moreover, there is semantic processing such as for the so-called *semantic-AI*.

At this point, we can ask ourselves how far the generalization of local intelligence can go to attain the point of confining and affecting the conscience? The point of separation that we can consider is the meta-language of meta-thought [78]. A meta-language is a language that speaks of another language (object language). When the object language is a formal language such as a program, the corresponding meta-language is also said to be formal [79]. Meta-thinking is the process of thinking the thought; it could be interpreted as being aimed at maintaining a kind of coherence of ordinary thinking. The meta-logical modality, which controls the logical modality of thinking, has a meta-language as its formal language, which is not, however, algorithmic because it has no logical rules. The reason that computers cannot use a meta-language is because it is not algorithmic, since it has no logical rules; a computer cannot compute what is incomputable (i.e., non-Turing computability). *The non-reducibility of the complexity identified above, such as theoretical incompleteness and the quasiness of emergence, would therefore be represented and summarized in the role of meta-logic and the non-algorithmic nature of the meta-language.* The search remains open for determining properties that are acquired by computation (computational emergence), when the computation makes properties to be acquired, see section 3.3 and ref. [37], up to a consideration of the possible emergence of the unconscious [73].

# 7 Conclusions

In this work, we attempted to delineate the peculiarity of systems that have the ability to acquire properties rather than *possess* them. This fact contributes to the human capacity to create. In addition, another phenomenon was studied that relates to *emergence*, which involves the continuous self-constituting of complex systems; we outlined the types and properties of such systems. These peculiarities are such that, among the various properties complex systems can acquire, forms of intelligence can arise. This theme was elaborated in reference to artificial intelligence, which indicated the theoretical limits to its possibility relative to the intelligence of humans. These theoretical limits correspond to the theoretical incompleteness and quasiness that make complex systems irreducible in terms of their acquired properties. The presented themes were treated not in a technical manner but in a conceptual one, and yet there were sufficiently rigorous in order to allow the reader to adequately understand and properly use these concepts as in educational activity.

The present article is dedicated to the memory of Professor Eliano Pessa with whom these issues were under study and to celebrate his valuable interdisciplinary contribution and expertise in the science of complexity.

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**Funding: This research received no external funding.**
**Competing Interests: The author declares no conflicts of interest.**