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What is a Complex System, After All?

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Abstract

The study of complex systems, although an interdisciplinary endeavor, is considered as an integrating part of physical sciences. Contrary to the historical fact that the field is already mature, it still lacks a clear and unambiguous definition of its main object of study. Here, I propose a definition of complex systems based on the conceptual clarifications made by Edgar Morin about the bidirectional non-separability of parts and whole produced by the nature of interactions. Then, a complex system is defined as the system where there is a bidirectional non-separability between the identities of the parts and the identity of the whole. Thus, not only the identity of the whole is determined by the constituent parts, but also the identity of the parts are determined by the whole due to the nature of their interactions. This concept allows, as shown in the paper, to derive some of the main properties that such systems must have as well as to propose its mathematical formalization.

Keywords Philosophy of physics · Complex systems · Edgar Morin · Interactions · Discrete vs. continuous

1 Introduction

Asking any practitioner of "complex systems" analysis about what a complex system is, will almost surely trigger a reply that she does not need such a definition to recognize what it is when she has one in front. Physicist Tamas Vicsek in a letter to Nature (Viscek, 2002) stressed that *"to say that a system is complex is almost an empty statement*". However, this statement contrasts with the huge, and ever increasing, number of scientific papers studying systems which are claimed to be complex. Possibly this is a consequence of the fact that*"if a concept is not well defined, it can be abused*" (Viscek, 2002) or to the fact that indeed there are many systems out there which are complex. Therefore, we need a definition of what a complex system is because without it, not only the term "can be abused", but also we may enter into contradictions about the same object that we are talking about. For instance, while we can read (Chiesa et al., 2012) that "*a modern airplane is without any doubts one of the clearest and most convincing example of "complex system"*" we can also find (Amaral & Uzzi, 2007) that a Boeing jet *"is a complicated but not a complex system*".

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This situation reminds me a short story written by Edgar Allan Poe in 1833 with the title "*MS. Found in a Bottle*", (Poe, 1833) where a passenger on a doomed ship describes the structure of that strange vessel by saying: *"What she is not, I can easily perceive —what she is I fear it is impossible to say*." Does this should be the case for complex systems?

It seem that we can recognize some systems as not complex (apparently not the aircraft), and we can also identify others for which we can say that they are complex. However, if we are asked for a clear and unambiguous definition of what a complex system is, we can get into murky waters. Philosophers Ladyman and Lambert and mathematician Wiesner collected some of the statements used by scientists working on this field to refer to complex systems (Ladyman et al., 2013). They ranges from more cryptic statements like *"complexity means that we have structure with variations*" to the more frequent enumeration of properties that such systems should have. Among these properties they found "*nonlinearity*", the existence of many components interacting within it, "*emergence*" of properties, among others. For instance, in a Resource Letter to the "*American Journal of Physics*" physicist Mark Newman (2011) honestly recognized that) "*there is no precise technical definition of a "complex system"* but that *"most researchers in the field would probably agree that it is a system composed of many interacting parts, such that the collective behavior of those parts together is more than the sum of their individual behavior*s." This definition-by-enumeration of features has become such a main stream in the field that it appears today in the textbooks used for teaching complex systems to students. In the textbook "*Modeling Complex Systems*" physicist Nino Boccara (2010) considers a complex system as one that: (i) consist of a large number of interacting agents; (ii) exhibit emergence–a self-organizing collective behavior difficult to anticipate from the knowledge of the agents" behavior; (iii) their emergent behavior does not result from the existence of a central controller. Enumerative list of properties in a "definition" of complex systems appears in almost every context. For instance, Richardson (2005) in his essay "The hegemony of physical sciences: an exploration of complexity systems" states that: "A complex system is comprised of a large number of non-linearly interacting non-decomposable elements. The interactivity must be such that the system cannot be reducible to two or more distinct systems, and must contain a sufficiently complex interactive mixture of causal loops to allow the system to display the behaviors characteristic of such systems (where the determination of 'sufficiently" is problematic)." We find more examples of enumerative definitions in an essay written by the Editors of the Journal of Physics: Complexity (Bianconi et al., 2023) to celebrate the 2021 Nobel Prize in Physics awarded "for groundbreaking contributions to our understanding of complex physical systems" to Syukuro Manabe, Klaus Hasselmann and Giorgio Parisi. Accordingly, we find that "a complex system is formed by many interacting elements that give rise to emergent phenomena" (Bianconi); "a complex system is a distributed set of entities with many interconnections (usually networked), where each entity self-operates locally with its neighboring entities, and exhibiting globally emergent behavior" (Arenas); "I usually list properties (many interacting constituents, collectivity, nonlinearity, feedback mechanisms, emergent phenomena) that are always, and properties (hierarchical organization, ordering, adaptivity) that are often present in them, and I make clear the difference between complicated and complex systems" (Kertesz); "Complex systems are formed by many agents interacting with each other in nonlinear ways, thus yielding complex phenomena that cannot emerge from the simple sum of the agents" (Lü); "A main requirement of a complex system is that it has large number of interdependent variables and/or it is composed by a large number of interacting elements" (Masoller); a complex systems "(i) is made up of interacting component parts and (ii) exhibits dynamical behavior that cannot be inferred from the behavior of the parts themselves" (Motter); "Systems composed of many interacting units (usually in a non-linear fashion) whose macroscopic behavior cannot be explained by the behavior of individual components" (Sales-Pardo), among others. However, as Ladyman, Lambert and Wiesner have shown, Ladyman et al. (2013) most of the features used in the "definition" of complex systems are neither necessary nor sufficient for complexity. The list of properties that can be excluded from the definition of a complex system because they are neither necessary nor sufficient include: *"nonlinearity*", *"feedback*", *"spontaneous order*", *"robustness and lack of central control*". In any case these definitions-by-enumeration seem to be not recommendable if we agree that: Morse et al. (1996) *"(D)efinitions must be clear, not circular, neither too broad nor too narrow, should not include accompanying features*".

In closing, after many years of development of the science of complex systems, which include the previously mentioned award of the 2021 Nobel Prize in Physics, we cannot find a *"clear, not circular, neither too broad nor too narrow"* definition of the object of study which does *"not include accompanying features*". It is my intention to approach such a definition here. Before, I will analyze some of the facts that may have impede the development of this definition, first in some of the ideologies dominating very much the field of research and second on the own nature of the field of study. Here I use the term "ideology" not in a pejorative (political or ideological) way, but in the sense given at Honderich (2005) of being "a set of beliefs or philosophies attributed to a person or group of persons, especially those held for reasons that are not purely epistemic". Therefore, my goal here is to attempt a definition of complex system fulfilling those requirements stated by Morse et al. (1996). Here I will not approach the problem of quantifying how complex a system is. Such quantification can be approached by different mathematical methods like it happens for many other (physical) concepts, in which there is one definition and several ways of quantifying it.

2 "Complex Systems" in the Philosophy of Science

Philosophy should represent a valuable approach for reaching the goal of defining what a complex system is. This is because philosophy has tools needed by other branches of sciences but not belonging to them. They include for instance: conceptual analysis, accuracy of expression, detection of gaps in standard arguments, spotting conceptual weak points, and the search for alternative conceptual explanations, among others. I agree with physicist Carlo Rovelli when he has written that: "*philosophy can provide methods for producing new ideas, novel perspectives, and critical thinking*" (Rovelli, 2018) (see also Laplane et al. (2019)).

The topic of "complex systems" has been previously treated in the philosophy of science literature. One important example is the extensive and thoughtful book "*Philosophy of Complex Systems*" (ed2, 2011). The book is full of examples of complex systems in a wide variety of real-world scenarios. It also details a deep analysis of many of the properties that such systems must have. Even so, the book misses the important point of reaching a unified, global and unambiguous definition of what a complex system is. However, we can find some individual (personal) working definitions of what some authors understand by a complex system. For instance, in the chapter written by Snyder et al. (2011) on page 469 they declare that "*A complex system is composed of interconnected parts that as a whole exhibit one or more properties not present in the individual parts alone. Examples of some potential features of complex systems include unpredictability, emergence,* *interactions between system components, simultaneous order and disorder, heterogeneity, chaos, nonlinearity, feedback loops, and hysteresi*s." Thus, we see again the enumeration of individual properties which are neither necessary nor sufficient. We will see that saying that "*A complex system is composed of interconnected part*" is equivalent to say that "*a complex system is a system*". Then, on the chapter written by Rickles (2011) we find again that "*by a complex system I mean one made up of a large number of parts that interact in a nonsimple way. In such systems, the whole is more than the sum of its parts, not in an ultimate, metaphysical sense, but in the important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole*". Notice that a few pages before, other authors in the same book (Wolkenhauer & Muir, 2011), have claimed that "*A key problem is that in a complex system the whole is more than the sum of its isolated parts*." Thus, this property is in both the problem and its solution! The same authors end up by claiming that "*a complex system is by definition too complicated to be comprehended by just using everyday common sense*." (Rickles, 2011) also claims that some necessary conditions for a system to be complex are that it: (i) "*must contain many subunits (the exact number being left vague)*"; (ii) that "*these subunits must be interdependent (at least some of the time)*" and (iii) that "*the interactions between the subunits must be nonlinear (at least some of the time)*." Again, the insistence on the nonlinearity which has been found explicitly to be not necessary/sufficient for complex systems. Some interesting questions and statements are also found across the book. Apart from these attempts to define complex systems there are some questions asked in the book that will guide our search in this work. One example are those asked by Bishop (2011) such as: "*Can a complex system somehow be identified as a distinct individual from its environment?*" "*Can various hierarchies of a complex system be individuated from each other?*"

The concrete task of approaching a definition of what a complex system is was considered by Ladyman et al. (2013). They defined a complex system as "*an ensemble of many elements which are interacting in a disordered way, resulting in robust organization and memory.*"[1] Due to the methodological importance of this work I will consider it in a separate section of the current work. In the essay "*Complex Systems: The Science of Interacting Parts*" (Pessoa, 2021) considers simply a complex system as a diverse community of interacting players. However, he made a very important remark which is fundamental for the current work: "*Not only do we need to consider interactions, but we need to describe them richly enough for collective properties to be unraveled.*" The problem of interactions was also considered by Strevens (2005) in a paper in which he asked *"How is it possible to understand the behavior of extremely complex systems?*" His proposal is to consider what he calls "*nondecomposable systems",* namely those *"made up of many fairly independent, but strongly interacting, parts*", where "strongly interacting" implies that the "*parts sometimes interact in ways that have potentially radical consequences for the interactors*". More recently, philosopher (Rathkopf, 2018) extend this criterion of *non-decomposable system* to one in which the behavior of any given component part, even over a short time period, depends on the behavior of many other individual components. Later on in this work I will show how these concepts are not sufficient for defining a complex systems, but they can be derived in a more precise way from the new definition given here.

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[1] Here the authors refer to a set of many entities, not to an ensemble in the statistical language.

3 The "Why Not?" Ideology

In the previously mentioned paper by Rovelli (2018) the author considers a sort of ideology which emerges in (physical) sciences on the basis of assuming that "*any new idea deserves to be studied, just because it has not yet been falsified; any idea is equally probable, because a step further ahead on the knowledge trail there may be a Kuhnian discontinuity that was not predictable on the basis of past knowledge; any experiment is equally interesting, provided it tests something yet untested*". This "*Why not? ideology*" has produced mountains of useless theoretical and experimental works (Rovelli, 2018). We can figure out that: if a "power grid", the "World-Wide Web", the "neuronal system of *C. elegans*" are complex networked systems, "Why not?" are so: "the client", "education", "economy", "health care", "organization culture", "engineering education", "crowds", "central chemoreception", "organizational learning", "humanitarian network", "Cu3N with Lithium", "brain", "innovation in manufacturing", "earthquakes", "water and mankind", "interaction", "driver-network system", "workplace", "airports", "the Earth", "law".[2]

Once an object of study has been identified as a "complex system" its investigation focuses only on those structural and dynamical properties which depends on its "distinctive" new characteristics, for instance, on its networked structure. Here the "*Why not?*" ideology is playing what Rovelli remarks as a disastrous methodological confusion produced by the combination of Kuhnian and Popperian ideas (Rovelli, 2018). Basically, this ideology assumes "*that past knowledge is irrelevant when searching for new theories*". This is manifested in its most basic form when the only properties of the system which are considered are those depending on the interactions of its entities, removing any influence of what happens in its individual components. Although I will analyze this in detail later on in this work, let me just mention here one example. In considering a dynamical process on a neuronal system, such as synchronization, the only characteristics of the system taken into account are the interconnections between the neurons, forgetting that "signals" or "chemicals" must be processed inside the neurons before being sent to nearest neighbors. This implies that there is no functional role of the neurons or brain regions. That is, the interior of these regions (nodes) are assumed to play no role in the dynamics, reducing to zero the function of neurons and/or entire regions of the brain as if the processes occur only by jumping from one region to another in instantaneous ways. This is a consequence of forgetting the "*past knowledge*" about the dynamics in the continuous region inside a neuron (see for instance Pasemann, 1993), just to concentrate on the "*new theory*" of brain connectome (see for instance Ódor and Kelling 2019).

More recent manifestations of the "*Why not?*" ideology can be seen in the consideration of "complex systems" as systems of "higher order" interactions (see Battiston et al., 2021 for a recent revision of the topic). This is the case of considering complex systems as "simplicial complexes" in which some regions of the system are simplices interconnected among them. It has been claimed that simplicial complexes are a better tool to map the real organization of many social, biological and man-made systems. But a simplex is a region of continuous space, thus a social 2-simplex (triangle) is formed not only by the three individuals but also by all the inner space covered by the triple of edges. What is this "continuous space" of interaction between three individuals? Is the expected collective behavior of the individuals not better described by a "social hypergraph" already described

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[2] These are terms found in Google Scholar under the term "complex system"

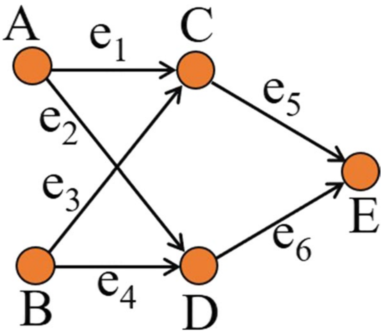

Fig. 1 A simple network representation of a series of chemical reactions

by Wasserman and Faust (1994) in their classic textbook? We need two points of clarification here. The first is that there are physical systems in which the representation as a simplicial complex is not only useful but necessary. For instance, I can think of the case of three interacting proteins. Every individual protein is kept in its three-dimensional structure by a set of covalent and noncovalent (electrostatic, hydrophobic, hydrogen bond, etc) interactions. When two proteins interact with each other they do so by similar noncovalent interactions as the mentioned before. Therefore we can consider the space inside the three interacting proteins as a continuous region of interaction forces which “belongs” to the new protein complex formed. Then, it is plausible to consider it as a 2-simplex. This situation can hardly be justified in a social triad. Secondly, I have to emphasize that it is not the same to consider a set of data points as a simplicial complex for the sake of analyzing them, than to consider that the structure of a given complex system IS a simplicial complex. The first is frequently done in topological data analysis (TDA) (see Carlsson, 2020 for a review) where these data points are agnostic in the sense that it does not matter for the TDA (Carlsson, 2020) which (complex) system they represent. This does not mean that the system from which such data comes from has a given simplicial complex structure. This is similar to the difference between using a hyperbolic geometry (see Boguna et al., 2021 for a review of the field) to extract useful information about a network like for the analysis of the Internet (Shavitt & Tankel, 2008) or confusing it with the geometry of a network.

Questioning the use of this ideology in its strongest form may be replied by its proponents with a classical “*Shut up and calculate*” (Kaiser, 2014). This lethal combination of ideologies has already brought some problems in the area of “complex networks”. Let me show one example. If a series of chemical reactions: $A + B \rightarrow C + D$ and $C + D \rightarrow E$ is formed by individual entities (chemical species) which transform to each others (chemical reactions), “*Why not?*” to represent them as a network like in Fig. 1.

Asking about whether there was a “*past knowledge*” which was more appropriate for representing this system, e.g., directed hypergraphs (Gallo et al., 1993), was not in place because what it was important was to show that these “reaction networks” display the properties of the “*new theory*”, like the “small-worldness” and “scale-freeness”. They indeed have them! For instance, Wagner and Fell (2001) reported that metabolic networks constructed in the previous way are small-world and Jeong et al. (2000) studied in 2000 the metabolic networks of 43 organisms representing all three domains of life, determining that “*these metabolic networks have the same topological scaling properties*”, i.e, power-law distributions of their node degrees. According to Jeong et al. (2000) this universality “*may indicate that metabolic organization is not only identical for all living organisms, but also complies with the design principles of robust and error-tolerant scale-free networks*”.

If the reaction networks are small-world then the shortest paths may have some biological relevance, such as in form of metabolic pathways or synthetic routes for obtaining important products. The same can be said from the fact that they contain "hubs" (nodes of extremely large degree resulting from the scale-freenness of the networks), which support the pass of many shortest-paths among them. But, if the representation of the metabolic systems is not correct, the shortest paths found in them must be biologically meaningless. For instance, one of the shortest path connecting the reactant A with the final product E is: A, e_1, C, e_5, E, which indicates that the product can be obtained in two reaction steps from the reactant A. The same is concluded by starting at the other reactant B. But, these reaction paths are completely meaningless because there is no transformation $A \rightarrow C \rightarrow E$ occurring in these reactions, but A has to react with B to form C, and C has to react with D, to give the final product. "*Shut up and calculate*". This attitude made that biologists immediately trigger criticisms against this approach *"because the shortest paths in metabolic graph generally contain irrelevant inter-connections between reactions*" (see Bourguignon et al., 2008 and references therein). For instance, Croes et al. (2006) have found *"that the shortest paths computed between pairs of reactions in the raw graph bear little resemblance to the metabolic pathways as known by the biochemists*." According to them "*the reason for this is obvious: since in this graph any compound can be used as intermediate between two reactions, most paths contain invalid shortcuts via pool metabolites like H2O, NADC, ATP*."

3.1 The Irruption of "Big Data"

In recent years a new term has irrupted in the scientific literature: "Big Data". It is common nowadays to find assertions like (Turk-Browne, 2013; Escobedo et al., 2020; Tan et al., 2013): *"Functional Interactions as Big Data in the Human Brain*"; *"Behavioral biology has recently become a 'big-data science'*" or that "*Understanding social networks evolves into a big data problem (...)*". Pushed to the extreme we found extravagances like in the article "*The End of Theory: The Data Deluge Makes the Scientific Method Obsolete*" (cited more than 3250 times so far) where physicist and entrepreneur (Anderson, 2008) states that (the reader can approach some debates in refs. Succi and Coveney, 2019, Mazzocchi, 2015):

"*Correlation supersedes causation, and science can advance even without coherent models, unified theories*" or that "*Correlation is enough. We can stop looking for models. We can analyze the data without hypotheses about what it might show. We can throw the numbers into the biggest computing clusters the world has ever seen and let statistical algorithms find patterns where science cannot.*"

Thus, at this level, "big data" can be considered as an extreme limit of the "*Shut up and calculate*" ideology (Kaiser, 2014). The question which remains here is on what extension it is also motivated by the "*Why not?*" ideology. To gain some insights about this I consider here the existence of two different approaches to deal with "big data" (notice that I have avoided the problematic attempt to define what "big" means, because what is massive today surely will not be so in the near future):

(i) a purely data-driven approach in which a researcher interrogates a database "*and let statistical algorithms find patterns where science cannot*";
(ii) a hypothesis-driven approach.

The first of these two approaches is purely driven by the "*Why not?*" ideology and it can bring all the problems that such ideology have, as previously analyzed. In the second one, a researcher has a model, equation or hypothesis and she interrogates a database to falsify it. I have to say that many of the approaches that I have read in the literature with the title "data-driven" are really "hypothesis-driven" as the researchers do not use a blind interrogation of the datasets but they typically have a model in mind to which fitting the data.

The main problem with the purely "*Why not?*" ideology of "big data" is the following. It has been proved mathematically that very large databases have to contain a large proportion of arbitrary correlations. In the paper "*The Deluge of Spurious Correlations in Big Data*", Calude and Longo (2017) used classical results from ergodic theory, Ramsey theory and algorithmic information theory, to demonstrate that these correlations appear only due to the size, not due to the nature, of data. Such correlations can be found in "randomly" generated, large enough databases, which implies that most correlations are spurious! As they have remarked (Calude & Longo, 2017) that: "*Too much information tends to behave like very little information.*" Their final lesson is illuminating: "*The scientific method can be enriched by computer mining in immense databases, but not replaced by it.*" Adapting this quote to our current work it means that "*The definition of what a complex system is can be enriched by computer mining in immense databases, but not replaced by it.*" This enrichment can be obtained only by applying transparent analytical methods, based on sounded scientific hypothesis, to allow us transforming such data into information and information into knowledge about complex systems.

I would like to remark that it is not all gloom and doom with the use of "*Why not?*" strategies to the analysis of "complex systems". This way of approaching to new questions has been successfully used in initial and exploratory stages of the development of new areas of research. The problem emerges when, as pointed out by (Rovelli 2018), we forget everything done in the past to focus only on the new.

4 What Systems Are?

Any attempt to define what a complex system is, should start by recognizing that it is a system in itself. Therefore, we should first explore the concept and definition of system. The reader will be surprised by the fact that although systems theory is older than "complex systems" as a discipline, there are many definitions of "system". As expressed by metrologist (Ruhm, 2010): "*Searching definitions of the term system is really amazing. If we exaggerate, we could claim that they differ altogether and in many respects. This fills whole books and leaves us disoriented and inclined to abandon the topic.*" Some examples of the definition of "system" are the following:

- "*a system is an assembly or set of related elements*" (Gigch, 1991);
- "A general system is an ordered pair (M, R) of sets M and R, where $\emptyset \in R \subseteq P\left(\cup_{n\in<Ord} M^n\right)$, such that for any relation $r \in R$ and any element $\alpha \in R$,there exists an ordinal number $n = n(r, \alpha) \in Ord$ such that α is a function of n in M, the number n is denoted by $D(\alpha)$ and is called the domain of α. The range of α, which is a subset of M, is denoted by $R(\alpha)$" (Yang, 1989);
- "$S = (T, R)$ *denoting system* S, *set of things* T *distinguished within* S *and a relation* R *(possibly a set of relations)*" (Klir, 1991);

- "*S is a (general) system if and only if S is an ordered pair* (M, R), *where M is an (abstract) set and R a set of some relations defined on M*" (Lin & Ma, 1993)*;*
- A system is "*a set of entities with relations between them*" (Langefors, 1995);
- A "*system is a set of interacting units or elements that form an integrated whole intended to perform some function*" (Skyttner 1996);
- *"a system is a set of interacting units with relations among them*" (Miller, 1995);
- "*A system* $S = (M, R)$ *is the pair formed of a set object Mand a set of binary relations, in such a way that* $R \subset P(M \times M) = P\left(M^2\right)$*.That is to say:* $\forall r \in R/r \subset M \times M$ *where:* $r = \left\{\left(x_1, y_1\right), \left(x_2, y_2\right), \ldots, \left(x_i, y_i\right) \in M \times M\right\}$" (Lloret-Climent et al., 1998);
- considers a system "*as a set M, and a non-empty set R of relations on M, satisfying that* $|M| \geq 2$ *and that from every member of M there is a path to every other member of M*" (Backlund, 2000);
- "*an integrated set of elements and assemblies that accomplish a defined objective*" (INCOSE, 2000);
- "*A system is an arrangement of parts or elements that together exhibit behavior or meaning that the individual constituents do not*" (Dori et al., 2019).

There are two common elements in all of these definitions of "system", namely that they are formed by an ensemble of parts and by their interconnections. Based on them I propose the following.

Definition 1 A system is a nonempty ensemble V of interconnected entities, and their interconnections, which together form an integrated whole exhibiting distinctive behavior or meaning from those of its individual components.

Before proceeding I am obliged to make a pedantic clarification here. It is necessary to clarify and properly define what are the parts which we will consider as the entities forming a given system. That is, the parts forming a given system may also be formed by other subsystems. However, for defining a given system S we should focus only on those parts forming the ensemble V which are interacting to each other, i.e., forming the set of interactions given by a subset of the Cartesian product of V to itself $E \subseteq V \times V$. In this sense, we should forget about the internal "systems" that V may contain. Let me consider an example here. Suppose that we are considering a system formed by an ensemble of cells interconnected to each other forming a cellular tissue. The entities of this system are the individual cells, independently that inside each of them we can find thousands of biomolecules, which are interacting to each other, and forming other biological (sub)systems.

It is important to remark here that the saying that a "complex system" has the property that the whole is different from the parts in any of its versions is simply wrong. This is obviously a characteristic of every system, not necessarily complex. An airplane as a whole is different, and surely more, than the list of its parts.

4.1 Previous Definition of Complex System

The essay "*What is a complex system?*" by Ladyman et al. (2013) has an invaluable methodological importance due mainly to the following. In this work the authors considered a large set of the attributes commonly assigned to "complex systems". They analyzed whether these attributes are necessary and/or sufficient to define a complex system.

Because most of the previous attempts to define a complex system have rested on the enumeration of attributes I will briefly resume some of the major findings of Ladyman et al. (2013). Accordingly,

- Nonlinearity is neither necessary nor sufficient condition for complex systems;
- The presence of feedback in a system is not sufficient for complexity;
- Large number of parts and of interactions seems to be necessary but not sufficient condition for complex systems;
- Hierarchical organization of system and subsystem seems necessary for complexity;
- Lack of a central control is a necessary but not sufficient condition for a complex system;
- Robustness seems to be necessary but not sufficient for complexity;
- Some kind of spontaneous order is a necessary condition for a complex system;
- Emergence in all epistemological senses is necessary, but it is not sufficient, for complex systems.

I will not make more emphasis in the case of the first two attributes, which are clearly defined as not necessary/sufficient by Ladyman et al. (2013), and the reader can find there the arguments given by these authors. I will focus on the other attributes in which some claims of necessity have been made by Ladyman et al. (2013). The first is about what they call "numerosity", namely the necessity of having a large number of parts and interactions. Including such kind of attributes into any attempt of definition is always problematic. The trouble immediately emerges when you ask "how many parts are a large number?" Is a system formed by a subdivision of the brain into its two hemispheres not complex just because of this number of components? I do not think that numerosity is a necessary attribute for complexity, not even that it should be mentioned as an attribute in (complex) systems in general.

The case of hierarchical organization needs more clarification. In Ladyman et al. (2013) this kind of organization is understood in terms of a Russian doll where a system contains subsystems, and they are organized in some hierarchical way. In my point of view this is mixing two aspects of the structural organization of a system which are not necessarily interdependent. For instance, it is true that the fact that a system is formed by subsystems is a characteristics of systems in general, not necessarily of complex ones. However, such organization not necessarily implies a hierarchy, whose inclusion in the definition of a complex system could be problematic. Let me give an example here. In Fig. 2a I illustrate (some of) the organs of the different systems in a human, e.g., nervous, respiratory, endocrine, cardiovascular, etc. It is true that every of these organs is formed itself by cellular tissues, which are systems in which cells are organized in certain types of structures as illustrated in Fig. 2b. Each cell in these cellular tissues is per se a complex system formed by millions of interacting macromolecules in a crowded cellular environment (see Fig. 2c). Similarly, every biological macromolecule, like DNA, RNA and proteins, are complex systems of molecular (covalent and noncovalent) interactions. In terms of the Russian doll we can easily see that some systems contain others like in going from left to right in the Fig. 2. But this nestedness does not imply a hierarchy. According to Oxford Dictionary a hierarchy "is a ranking system ordered according to status or authority" or "an arrangement according to relative importance or inclusiveness". How can we say that one of the systems in Fig. 2 is more important than others? We can think that if there is a hierarchical organization it could be some entities at the top of the hierarchy, which necessarily will be more important and possibly will exercise some control over the lower-hierarchy parts. But in a

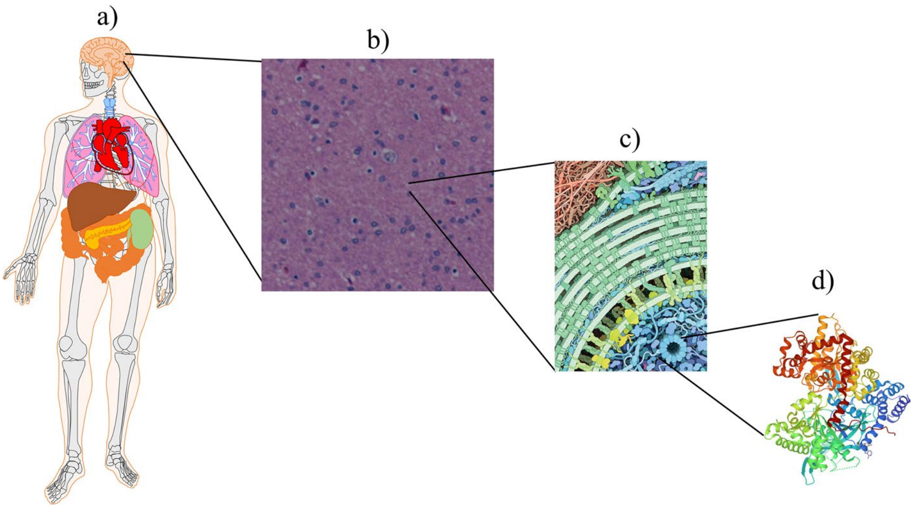

Fig. 2 Illustration of the nestedness of complex systems existing in a biological systems of a human: **a** organs; **b** a cellular tissue; **c** the interior of a cell; **d** a macromolecule like a protein

complex system such as the ones in Fig. 2 what happens is that there are feedback loops. It is true that some orders arise at the organs level and go down to the cellular or molecular ones, but others are exerted from these "lower" levels up to the very system of organs.

It is easy to confuse "nestedness" and "hierarchy" in a complex system. For instance, Wu and Loucks (1995) has stated that "*In hierarchically structured, patchy ecological systems, the phase change of individual patches at local scales and the pattern change in patch mosaics at broader scales together give rise to system dynamics. Thus, the dynamics of ecological systems are composed of the dynamics and interactions of constituent patches on different scales; this is an emergent property in that it is not simply the sum of the individual patch dynamics"*. Additionally, they point out that *"In a patch hierarchy, the interconnection between levels, through downward and upward influences, decreases with the number of intervening levels.*" The authors are right about the existence of a nestedness of patches and the "patch mosaic", i.e., a landscape network, but as they also recognize there are dynamical aspects that flow from the patches to the network and others flowing in the other direction (see Estrada et al., 2020 for a quantitative examples of this trade-off between patches and the network in a landscape network in Madagascar). Therefore, there is no hierarchy. Additionally, if, as stated in the next attribute, the "lack of a central control is a necessary" condition for a complex system, then we can find a contradiction with a hierarchical organization. Therefore, I do not consider neither of these two attributes as necessary for a complex system.

"Robustness" and "some kind of spontaneous order" suffer from the same problem as "numerosity", namely the lack of a proper quantitative definition of how much robustness and how much spontaneous order are needed for a system to be complex. Also, robustness is an ambiguous term as we can have many different kinds of robustness and arguably any system, complex or not, display certain level of robustness to some kind of perturbation. Emergence is an attribute that certainly needs more attention. As Ladyman et al. (2013) recognized it "*is a notoriously murky notion with a long history in the philosophy of* *science*". Therefore, I will let it to the subsection of this work immediately after the definition of complex system.

The second important methodological contribution made by Ladyman et al. (2013) was to show that a proper definition of "complex system" is possible without necessity of appealing to mystical/cryptic statements. In their essay they have the following.

Definition 2 A complex system is "*an ensemble of many elements which are interacting in a disordered way, resulting in robust organization and memory*" (Ladyman et al., 2013).

Let me disentangle this definition by analyzing its constituent parts. First, it is said that a complex system is "*an ensemble of many elements which are interacting"*. This is obviously saying that a complex system is a "system" as we have seen here by the proper definition of system. Although not stated explicitly in the definition they consider that "*interactions can be either exchange of energy, matter, or information*". I dislike this restriction because it allows to consider an internal combustion engine–where the interactions are the exchange of energy and matter–as a complex system.

The next integrating part of the definition refers to the assumption that the system should be "disordered". That is, the authors consider that "*disorder is a necessary condition for complexity simply because complex systems are precisely those whose order emerges from disorder rather than being built into them*". This is not a clear cut definition, and it alludes again to an attribute found in some systems. The main problem with this attribute is that it seems to refer to initial stage on the evolution of certain system not the system per se. Finally, it is not clear to me what it can be referred to as *"robust organization"* and *"memory"*. Here again the authors make use of some attributes of some complex systems, which are not necessarily present in all of them. Also, it would be a matter of discussion what it means to have a robust organization, robust to what?, in which amount?, etc. The attribute of having "memory" is even farther of being possible to define unambiguously for the general case.

Let us then consider the following situation. Suppose a chemical substance which is found in a disorganized way, such as in gas state. It is obviously formed by "*an ensemble of many elements"*. Let us now allow for this substance to crystallize. In the crystal state "*an ensemble of many elements which are interacting"* and because they have come from a more disorder state we can add that it is "*an ensemble of many elements which are interacting in a disordered way"*. It is obvious from its physical properties that the crystal is robust, e.g., it keep being a crystal for a wide range of temperatures. Even if we dissolve it (breaking down its crystalline structure) and left it to crystallize again, it will crystallize again in the same form as before. Thus, it has memory and we can say that it is "*an ensemble of many elements which are interacting in a disordered way, resulting in robust organization and memory*". But, is a crystal an example of complex system? Surely you agree it is not.

5 Towards a New Definition of Complex System

5.1 Edgar Morin and the Nature of Interactions

I have to recognize that I remained in the obscurity in relation to the fundamental role of the interactions for the definition of complex systems until I read the book "*The Nature of*

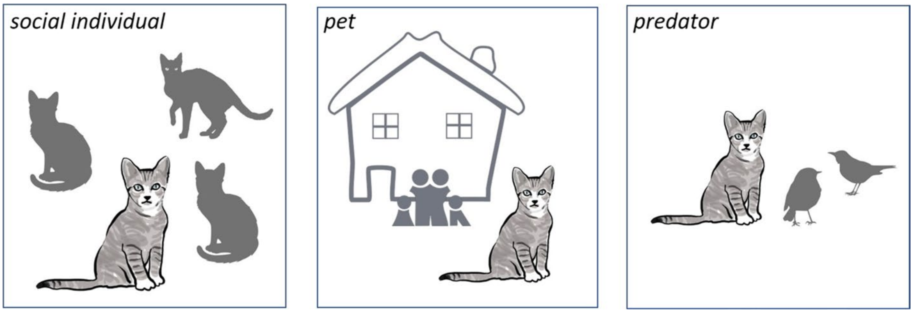

Fig. 3 Illustrations of a cat in different scenarios which are defined by the kind of interactions that it has with other entities. In the left panel it interacts with other cats forming a colony and distinguishing it as a social entity. in the center it interacts in a family environment becoming a pet. Finally, in the right panel it interacts with other species transforming it into a predator in a food-web

Nature" by philosopher (Morin, 2022). Then, digging in his papers I found particularly illuminating: "*From the Concept of Systems to the Paradigm of Complexity* (Morin, 1992)". There are many fundamental philosophical questions in these texts by Morin, which I possibly will instill in the rest of this text (as the proper Morin say "*we have the tendency to forget those who inspired us*"), but that for the sake of space I will not detail explicitly here. However, I consider the following statement as a fundamental pillar for any definition of what a complex system is Morin (1992). It is that *"whole-parts relations must necessarily be mediated by the middle term of interactions. This term is all the more important given the fact that most systems are composed, not of "parts" or "components", but of actions among complex units which are themselves composed by interactions*". This statement reconnects with what Pessoa (2021) has expressed by saying that "*Not only do we need to consider interactions, but we need to describe them richly enough for collective properties to be unraveled.*"

I will elaborate further these philosophical ideas to develop what I will call the concept of "Morinian interaction". I understand "interaction" here in the Morin sense of being (Morin, 2022) *"reciprocal actions that modify the behavior or nature of the elements, bodies, objects or phenomena which are present or that they influence*". That is, interactions as transformers of the nature of the interacting objects and of the whole formed by them. This will be the key to define a complex system. Let me start with the following.

Definition 3 Let A and B be two elements of a set of entities V. A *Morinian interaction* between A and B is a relation $\longleftrightarrow$, such that $\overleftrightarrow{AB}$ is different from the mere union of A and B. This necessarily implies that the interaction has changed the own nature of the interactors and of the whole they produced.

Let me illustrate the concept of Morinian interaction with some examples. A cat is a domestic species of small carnivorous mammal forming the species *Felis catus*. We can say many things about the cat as a species, but I will focus on a series of distinctive aspects of cats mediated by their interactions. Although cats are not very sociable they form groups with other cats in which the behavior of the individuals depends on the interactions with the other members of the group. The same cat, however, can be perfectly integrated into a human family, where it plays the role of a pet. Finally, the same cat belongs to an ecosystem where it can predate other species, e.g., insects, birds, small reptiles, and in certain places it could be the target of other predators. The three scenarios are illustrated in Fig. 3. In these three scenarios the same individual acquires different roles which are dictated by the own nature of its interactions, which define its own identity and the own identity of the system. There is no doubts that the three scenarios represent "systems", where several individuals form a whole by means of their interactions.

In the first case the cat forms a colony (Crowell-Davis et al., 2004), which is a new kind of entity with some characteristic features which are not inherent to the cat as species. For instance, the colony is matrilineal, where the affiliative and cooperative relations between females provide the social structure of the group. The size of the group will depend on the availability of food with large colonies existing only where food is abundant. There is members vs. non-members discrimination, with aggression exhibited against non-members of the colony if they approach too much to members. There are also some kind of preferred associates inside the colony, where cats can be found close together more frequently than they are found with non-preferred ones. There are also some signaling behaviors such as nose-touch, allogrooming, tail-up, sounds like growl, yowl, snarl, hiss, spit and shriek, which are part of the communication between group members (Crowell-Davis et al., 2004). There are dominance relations between group members and specific male-male, female–female and male–female interactions, all of which determine the specific identity of the whole. That is, the social interaction between cats is a Morinian interaction which modifies the own identity of the individuals (from a member of the cat species to a social animal) and the whole (from a group of cats to a colony). In plain words, the cat-cat interaction has transformed every individual into a social agent, and the group of separated cats into a colony. New identities for the entities and the whole emerged just from the nature of interactions.

In the second scenario we have another kind of Morinian interaction defined between the cat and humans (Merola et al., 2015), and possibly other pets. Cats were originally domesticated 10,000 years ago as predators of rodents and lived near human habitations. In the modern human-cat relations, cats use their sense of smell, hearing, touch, and eyesight to communicate with humans. It has been shown that cats avoid or select gaze with humans depending on the social context, spend more time in locomotion/exploration when accompanied by their owners, and exhibited higher alert behavior when accompanied by strangers (Merola et al., 2015). Humans have also modifications of their behavior as a result of these interactions. For instance, when cat-owners are depressed cats rubbled against their owner more frequently, which is beneficial for humans in terms of being less stressed, less anxious and healthier (Koyasu et al., 2020). These bonds also represent more and better food, and more security, for the pets. In closing, we have another kind of Morinian interaction which defines a new identity for the individuals and for the system as a whole.

The last scenario asks about the relations of our cat with the wildlife. In a study (Woods et al., 2003) carried out in Great Britain in 1997 during a 5 months period, it was estimated that a population of 9 million cats have brought their homes about 92 million prey items, including 57 million mammals, 27 million birds and 5 million reptiles and amphibians. This new kind of interactions, i.e., predator–prey, defines a new identity for the cat, i.e., a predator, and defines the identity of the whole, i.e., a food-web.

It is true that there would be interrelations between the three different systems in which we have integrated the cat. The same can always be said about any system. This has been well explained by O'Neill et al. (1986) by expressing that:

"*(D)epending on the spatiotemporal scale or window through which one is viewing the world, a forest stand may appear (1) as a dynamic entity in its own right, (2) as a constant*

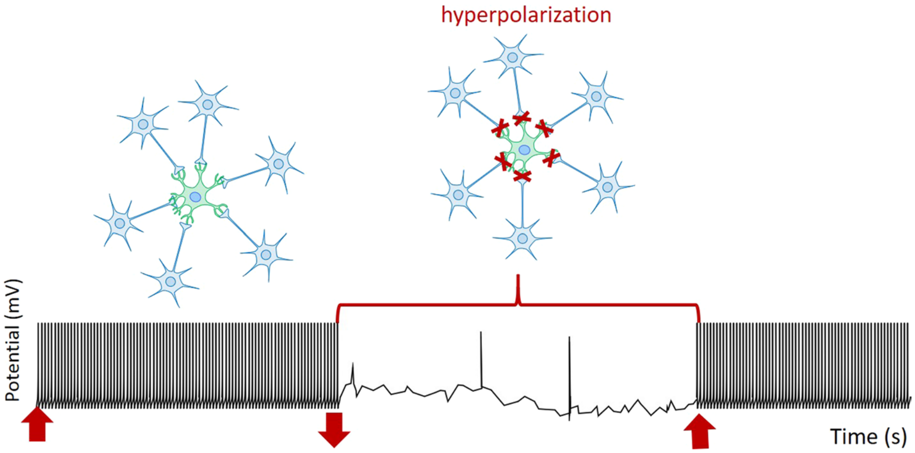

Fig. 4 Illustration of a type I neuron, whose firing was necessary for sensory-evoked initiation of the pedal wave motor program. The first upward arrow indicates the stimulation of one anterior tentacle with salt which caused accelerated type I neuron firing. Hyperpolarizing the type I neuron below threshold (downward arrowhead) caused slow down. When the type I neuron was released from hyperpolarization (second upward arrowhead), bursting in both nerves resumed. the diagram is based on the results of Fredman and Jahan-Parwar (1983)

(i.e., nondynamic) background within which an organism operates, or (3) as inconsequential noise in major geomorphological processes."

In the case of the cat, if we open very much our frame, it is possible to capture the three scenarios as it can socialize with other cats, predates other species and being part of its human family. In this case, the Morinian interaction defining the global behavior of the cat will be a combination of its social, pet-like and predator interactions, which can be considered all together in an aggregate form or separately in the form of a multiplex (Boccaletti et al., 2014; Kivelä et al., 2014) (notice that the notion of a new kind of representation of the complex system has emerged from the own definition of the object of study). For instance, cats belonging to households that provided food for birds brought home significantly lower number of birds and herpetofauna, although the number of bird species was greater than those not providing bird food. This is a clear interaction of the pet-like system and the cat-as-predator one.

In closing, what is important here is that if we ask a general question about what is the systems-identity of an "individual cat", we cannot reply it without knowing what is the "whole" in which this individual is embedded. It could be either the "social"-, or the "pet"-, or the "predator"-cat, or even an "integrated-social-pet-predator"-cat.

Let me show a second example of Morinian interactions. Experimental biologist (Fredman & Jahan-Parwar, 1983) identified a group of neurons in *Aplysia californica* that are excited by stimuli evoking locomotion *in vivo*. That is, intracellular stimulation of those individual neurons at physiological frequencies initiates and maintain pedal wave bursting (see Fig. 4). However, when the same neurons "*are removed from the neuronal circuits by hyperpolarization, the same stimuli fail to initiate the locomotor program*". This experiment indicates that the isolated pedal neuron is not a "*command neuron*", i.e., its firing does not evoke the locomotion of *Aplysia,* but it become so when it is interacting with other neurons in the cerebral ganglion of *Aplysia*. This "interaction" changes the own nature of neurons possibly through the interchange of neuromodulators, like neuropeptides (Strand, 1999), which in general regulate motivated behaviors like locomotion. Then, the motor system (the whole) acquires its identity due to the existence of "command neurons", but these neurons (the parts) acquire their identity only when they form part of this whole. That is, the Morinian interactions between the neurons are those which give rise to their functions and to the definition of the system as a whole.

Finally, I provide a third example which comes from the area of complex social systems, a field to which much attention have been paid in the (physics) complexity area (Castellano et al., 2009; Sen & Chakrabarti, 2014; Jusup et al., 2022). This would easily be the first example as we all have several different "labels" in our everyday life to distinguish the nature of our interactions. We wake up in the morning as a "family member", then transform into a "colleague" at work, possibly with relations of "boss-subordinate" and of "collaborators", then we can be transformed into a "team member" of some sport or just a "fan" of a given artist or sport club. Every of these different interactions transform the agents into different social entities and the nature of the groups formed in each of these scenarios is different. This was not unnoticed by social scientists and Emile Durkheim already in his classic "Les Règles de la mèthode sociologique" (Durkheim, 1894) (translated as "The Rules of Sociological Method" (Durkheim, 2014)) stated that the changes arising within the social environment "whatever the causes, have repercussions on every part of the social organism and cannot fail to affect all its functions to some degree". If we accept that the social environment is determined by the nature of the interaction between individuals, then the changes in the social environment are changes in the nature of the social interactions. These changes have repercussions not only on the "functions" of the group but also on "every part of the social organism", that is, on its own nature, modifying "all its functions" and its nature. Therefore, these social interactions are Morinian in the sense defined in this work. But here I want to push the definition of social Morinian interaction to its limits. That is, Can we falsify this definition in a Popperian way? That is, can we find such "labels" that individuals are claimed to have as a result of their different kinds of Morinian interactions? The answer is yes.

The labels that we have according to our different social interactions are recorded in our brain, particularly in our "social brain" (Brothers, 1990). The social brain is a collection of brain regions which are involved in a variety of social behaviors and cognitive processes, such as processing social stimuli, understanding, and acting upon other people's beliefs and intentions, judging and responding to interpersonal norms, and efficiently navigating the intersubjective social world as a whole (Frith, 2007). For instance, Bickart et al. (2014) have found significant correlations between the strength of intrinsic functional connectivity of three different parts of the social brain and the size of the social networks of the individuals. That is, the size of your social network is recorded as a label in your social brain, the larger the social network the strongest the functional connectivity of these regions. But this does not distinguish between two different types of social interactions. So, I will provide just another evidence. In the field of social network analysis it is frequent to find situations in which two individuals have a "positive" relation, such as a friendship, collaboration, alliance, etc. On the other hand, other type of interactions could be of a "negative" nature, such as enmity, social exclusion, etc. Typically these two types of interactions are represented by assigning a sign to the edges of the social network (Girdhar & Bharadwaj, 2017), e.g., positive for social inclusion, and negative for social exclusion. It has been found (Schmälzle et al., 2017) that the social brain register the differences between social inclusion and social exclusion via an increased connectivity within a set of regions previously identified as a mentalizing system during exclusion relative to inclusion. Therefore, the answer is yes, we can find such labels distinguishing situations in which the Morinian interactions change the own nature of the interactors and of the whole system they produce.

Let me give now an example of a non-Morinian interaction. I will consider the case of an internal combustion engine (ICE). This is an example where many parts interact with each other giving rise to an integrated whole exhibiting distinctive behavior from those of its individual components. This example is a simplification of the one of the aircraft which was used in the Introduction, so the analysis here is extensible to that object in a similar way. Among these parts or components we find the crankshaft, exhaust camshaft, inlet camshaft, piston, valves, cooling water jacket, spark plug, and many others. The "integrated whole" is characterized by being a heat engine in which the combustion of a fuel occurs with air in a combustion chamber. Let me focus on one of its component parts, namely the spark plug. It is a device for delivering electric current from an ignition system to the combustion chamber. Its function is to ignite the compressed fuel/air mixture by an electric spark, while containing combustion pressure within the engine. The spark plug is also a system, as it is formed by several interconnected parts which give rise to its unique function. Among these parts there is the terminal, insulator, ribs, central electrode, and others. The identity of the spark plug–as well as of all the other parts of an ICE–is completely independent on whether it is integrated in an ICE or not. We can connect a light bulb to a spark plug creating a new system, but the spark plug will continue having the same identity and function. If we ask about the identity of a spark plug we will not need to know about the whole system in which it could be integrated to understand it. Returning to the example of the labels that I have provided before for the social interactions we have the following. A spark plug has a label indicating that it is a "spark plug". But this label is always the same, independently on the fact that it is in a box without any use or it is found as an integrating part of an ICE. We do not need to know the other parts or the nature of the interactions in which it takes place to identify it as a spark plug. This does not happen with the Morinian interactions as we have seen before in the previous three examples provided. This fundamental difference in the "*bidirectional non-separability*" of parts and whole is what I think characterizes a complex system. The aircraft, as mentioned in the Introduction, or the ICE, are a complicated systems because they has many different interconnected parts, but they are not complex due to the lack of Morinian interactions between their parts.

5.2 Definition of Complex Systems

I am now in conditions of proposing the following.

Definition 4 A system is said to be complex if there is a bidirectional non-separability between the identities of the parts and the identity of the whole. Then, not only the identity of the whole is determined by the constituent parts, but also the identity of the parts are determined by the whole due to the Morinian nature of their interactions.

Let me explain how Definition 4 embraces some of the properties which are typically associated with a complex system. I will focus mainly on the ones that Ladyman et al. (2013) have claimed as necessary and sufficient conditions for complexity. However, due to its importance I will also consider other properties such as "emergence".

"Emergence" according to Nicolis and Nicolis (2009) refers to the appearance: *"at some level of description, of new qualitative properties not amenable to those of the individual subunits*". One classical example is the emergence of order out of chaos, for instance by considering how an increase in the **quantity** of participating chemical species (such as polypeptides) leads to the spontaneous emergence of the new **quality** of autocatalysis. This notion of "emergence" appears to be formulated by the first time in mid XIX century by Hegel (1970) as the "*law of the transition from quantity to quality*", recognizing the existence of: *"cases in which the alteration of existence involves not only a transition from one proportion to another, but also a transition, by a sudden leap, into a...qualitatively different thing; an interruption of a gradual process, differing qualitatively from the preceding, the former state*". Philosopher (Carneiro, 2000) in his inaugural contribution as a member of the National Academy of Science recognized that the law of *"the transition from quantity to quality*" has been enormously useful in his attempts to understand the changes that occur in social evolution, clearly a complex system under our current definition. According to this law, adding more entities to a system makes that a new quality eventually appears. This important concept is implicit in my definition of complex system as the own interaction between two parts already produces a new quality, which may grow in complexity by the interaction with many more parts.

Other properties of complex systems, such as the "non-decomposability" stated in the works of Strevens (2005) and of Rathkopf (2018) can be derived from the definition given here for complex systems. First, I have to remark that the definition of nondecomposable complex system as given by Strevens can give rise to confusion. The use of this concept of non-decomposability allows to consider as complex systems "*the systems studied by statistical physics, such as gases, and ecosystems*" (Strevens, 2005). The statement that a gas is a complex system took me by complete surprise. But according by Strevens it is so, because "*(A)t any given instant, two molecules are unlikely to affect one another's direction of travel, speed, mode of vibration, and so on. But when they do interact—that is, when they collide—they stand to change completely all of these properties."*(Ladyman et al., 2013) clearly point out that "*a gas has emergent properties but it is not a complex system*". In light of the new definition of complex system given here we can find the reason to explain why a gas is not a complex system but an ecosystem is. First, in a gas, the component parts (molecules) are not modified in their category (that of being molecules) when they are in the gas. Suppose that we introduce oxygen (O_2) in the gas form in a recipient. Let us introduce in the same recipient molecules of nitrogen (N_2) also in the gas form. The molecules of O_2 continue being identifiable as O_2, and the molecules of N_2 continue being identifiable as N_2. Also, the gas continues to be a gas. On the contrary, in an ecosystem, an animal (species) is transformed by the animal-animal interactions taking place, making them "social animals" (in a pack, fish school or a flock) or a "predator/prey" in a food web. The interactions taking place here are obviously Morinian as they transform both the individuals and the whole. In this case, the system has the property of "*non-decomposability*" (Rathkopf, 2018) as an immediate consequence of having Morinian interactions.

I will turn now my attention on the necessary and sufficient conditions given by Ladyman et al. (2013). The first of them is that complex systems must be "ensembles of many elements". As I have stated before, it is never clear what "many" means. Thus, what I will say is that for the own definition of system we need the existence of "elements" in a number larger than unity. This condition is of course trivially derivable from my definition. The second of these conditions is also trivially derivable from my definition of complex systems. Namely, the existence of interactions. According to my definition we do not need to specify the class of interactions acting on the elements of the system, but they have to have a given nature: being Morinian on the basis of the definition given here. Thus, they can be "exchange of energy, matter, or information" as mentioned by Ladyman et al. (2013), but we do not need to specify so.

Before I have mentioned the properties claimed by Ladyman et al. (2013) as necessary in terms of "robustness" and "memory". I have shown how the combination of these properties with the previously analyzed ones allows to conclude that a crystal is a complex system. Because, the physical interactions between the molecules in a crystal are not of a Morinian type, i.e., they do not transform the quality of the own molecules, so that we cannot consider the crystal as a complex system. The robustness is a necessary but not sufficient condition for a system to be complex as previously stated by Ladyman et al. (2013) and can be derived from the current definition by the fact that Morinian interactions give rise to stable organizations which should display certain memory to small perturbations applied on them.

Finally, I will refer to the "hierarchical" structure of complex systems claimed by Ladyman et al. (2013). As we have seen before the term hierarchy properly defined implies an order "according to status or authority" or an "arrangement according to relative importance". Herbert (1962) has considered that *"a hierarchic system is one that is composed of interrelated sub-systems, each of the latter being, in turn, hierarchic in structure until we reach some lowest level of elementary subsystem. Such hierarchies do not necessarily imply subordination among sub-systems*". But this kind of organization in a system is better described by considering it as a nested one, which is a property inherent to the nature of Morinian interactions. Let me explain. For two entities to interact through such kind of transforming interaction they necessarily have to have a complex internal structure. Such internal structure is most of the time also a complex system, showing a nested hierarchy.

5.3 Topological Explanations

The most common explanatory category in science is the consideration of the causes of a given event, phenomenon, state of affairs, etc. That is, when we explain a phenomenon we: "*generally consider how the system from which it is a property, an outcome, a characteristic or a consequence behaves*" (Huneman, 2010). A new explanatory category emerging from the discrete mathematical representation of complex systems is not straightforwardly causal, but it is "topological". According to philosopher (Huneman, 2010):

Definition 5 A "topological explanation" is an explanation in which a feature, a trait, a property, of the outcome X of a system S is explained by the fact that it possesses specific topological properties T_i.

This definition implies that we have to define a topological space E for the system S. This could be defined by the discrete representation of the system *per se* (network, hypergraph, simplicial complex, multiplex) or by means of the phase space of a dynamics in S. Once we have such space we can find topological properties which are invariant under some continuous transformation, and which will determine equivalence classes between all structures S'' homotopic to the variety S' of S in the space E. I will show later some current findings about how to generalize this concept to all complex systems.

Now, I can provide some examples that the reader will immediately recognize as topological explanations (see Estrada (2011) for definitions and examples). The existence of "small-world" properties, "scale-freeness" or more general "fat-tailness" degree distributions, the presence of "modularity" and communities, existence of "degree assortativity", of "clustering", etc., are all nowadays classical examples of non-causal but topological explanations in complex system. Topological explanation does not need to be divorced from causal explanation. An excellent example is provided by Ramírez et al. (2018) in the study of ice/water transition by considering the network of hydrogen bonds near the region of the phase transition. Although the authors found a topological explanation in terms of the discontinuity of several network properties while approaching a phase transition region, they connect such explanation with the well-known changes on some thermodynamic properties in the same region, which represents a causal explanation. The search for topological explanations in complex systems has triggered a frenzy search for new mathematical invariants of graphs, hypergraphs, multiplexes and simplicial complexes, which has had an important impact in several areas of mathematics ranging from graph theory, to geometry and topology.

5.4 The Individual-in-the-Whole Representation

Returning once again to Morin I recognize his battle against the dissociation between individual-species-society (Morin, 2022), which according to him "*breaks the permanent and simultaneous relation among them*". In the case of human beings, in which Morin focuses his attention, the existence of this "trinity" is clearly revealed by the existence of sciences that center their attention only on the individual, e.g., psychology, while others center them on the species, e.g., biology, anthropology, or in society, e.g., sociology. This division is similar to the one used in the example of cats illustrated previously in this work. The study of groups of individuals forming social networks has been claimed as a holistic approach to the analysis of complex social systems. However, this approach which considers nothing about the individual and put all the emphasis on the interactions is as reductionist as the one which focuses only on the individual. They are two reductionist sides of the same coin.

The same situation occurs in most of the other areas of study of complex systems, some of them as a consequence of the "*Why not?*" ideology. In neuroscience, for instance, we encounter with the neuron doctrine which focuses only on the individual neuron as the structural and functional unit of the nervous system, while the neural network models assume that neural circuit function arises from the activation of groups or ensembles of neurons (see discussion in Yuste, 2015). While the first approach excludes the neuron-neuron interactions as a fundamental part of the theory, the second excludes the processes taking place inside the neurons. The extension of the "system paradigm" to the study of the brain includes the consideration of the networks of interactions between anatomical or functional regions in a parceled brain, without any consideration of the processes taking place inside those regions. Moving from these areas of research to others the reader can find her own examples of mutual exclusion. But, why is this important for understanding complex systems?

Let me consider an example of a process which is ubiquitously used in the study of complex networks: random walks (RW). Although problems related to random walks can be traced back to the XVII century (Masuda et al., 2017) it was the statistician Karl Pearson who coined the term on July 27, 1905 (Pearson, 1905). In his short note in *Nature* he wrote "*A man starts from a point O and walks l yards in a straight line; he then turns through any angle whatever and walks another l yards in a second straight line. He repeats this process n time*." I have copied this formulation just to signify that there was no interaction at all between the man and any object that makes him to *"turns through any angle*". This situation changed when (Einstein, 1905) studied the motion of pollen grains in water by means of the collisions of the first with water molecules. However, here the interaction between the Brownian particle and each water particle is instantaneous on the time scale of

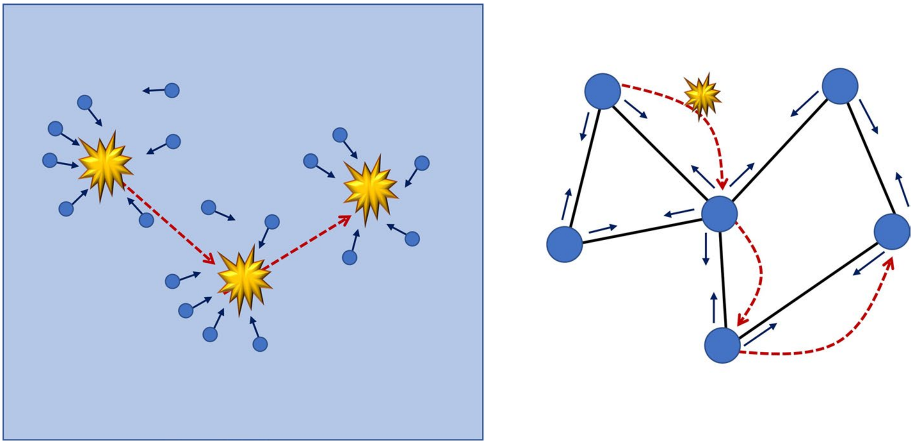

Fig. 5 Illustration of the random walk followed by a pollen particle in the continuous setting of a water environment (left panel) and in the discrete setting of a network (right panel)

the Brownian particle. Then, when the random walk model was "implemented" on the discrete space of graphs, it was assumed that "*a man starts from a node O and walks to any of its nearest neighbors with equal probability*". For instance, this is exactly the formulation of Göbel and Jagers (1974), where they clearly remark that the state space for the random walker is the set of vertices of a connected graph, and "*for each vertex the transition is always to an adjacent vertex, such that each of the adjacent vertices has the same probability*". Although this work is not so cited like those of Doyle and Snell (1984) or the one of Lovász (1993), it is possible one of the first in which a random walk is implemented on a graph. In all these works in which RW have been considered in discrete space, it has been assumed that there is no interaction between the "walker" and the nodes of the network (see Fig. 5).

Among the plethora of areas in which RW have been used to understand properties of real-world complex systems (as cited by Masuda et al., 2017) let me pick just two of them: "*the dynamics of neuronal firing*" and the "*locomotion and foraging of animals*" (see the references in Masuda et al., 2017). In these two systems (as well as in all others in which a RW model in considered for studying complex systems) the "walker" has no interaction at all with the nodes. It means that, a calcium ion or a neurotransmitter, enters a neuron or a brain region and just walk away to a nearest neighbor with a probability that only depends on the number of connections that that neuron/region has. It is like if the interaction between these particles and a neuron is instantaneous, like in the Brownian motion. In the case of the foraging of animals in a landscape it means that the animals only spread from one patch to another without foraging inside them. All of this is a consequence of the fact that the nodes (neurons or landscape patches) are just structureless points.

The previous situation is necessarily corrected by the definition of complex system given here, where the nature of the interactions change the own category to which the entities of the system belongs to. However, it seems also to contradict the proper definitions of what a system is. If a "*system is a set of parts*" as Leibniz (1880) claimed, then the parts (neurons/brain regions, landscape patches, etc.) must remain in the formulation of the system. "*A system is a set of unities with relationships among them*" (Bertalanffy, 1968) or it is "*the resulting unit of the parts in mutual interaction*" (Ackoff, 1971), but we have killed the parts to save just the relations. Therefore, we are obviating that "*The idea of complex unit will take on form if we realize that we cannot reduce neither the whole to the parts, nor the parts to the whole, nor the one to the multiple, nor the multiple to the one, but that it is necessary to conceive together, in a way that is both complementary and antagonistic, the notions of whole and parts, of one and diverse*" (Morin, 2022). Therefore, to make effective the plan in which the Morinian interactions take place, we need to go beyond simple networks of interactions. This is because by mean of these interactions there are reciprocal actions that modify the behavior or nature of the entities in the system as well as of the whole. Therefore, we need mathematical objects in which the internal structure of the entities is taken into account at the same level than the interactions among these entities. Then, we have the following (Estrada et al., 2020).

Definition 6 A complex system can be represented by a triple $\mathcal{S} = (\Upsilon, \mathcal{H}, \mathcal{T})$ where $\Upsilon = (V, R, \mathcal{I}, \omega)$ is a 4-tuple consisting of a discrete system (V, R) in which V is the set of entities of the system and R is a set of binary relations between these entities, $\omega = \{\Omega_j\}_{j=1}^{k}$ is a set of locally compact metric spaces Ω_j with Borel measures μ_j, and $\mathcal{I} : V \rightarrow \omega$. Additionally, the tuple $(\mathcal{H}, \mathcal{T})$ represents a dynamical system on Υ, where $\mathcal{H} = \left\{H_v : L^2(\Omega_{\mathcal{I}(v)}, \mu_{\mathcal{I}(v)}) \rightarrow L^2(\Omega_{\mathcal{I}(v)}, \mu_{\mathcal{I}(v)})\right\}_{v \in V}$ is a family of operators such that the initial value problem $\partial_t u_v = H_v(u_v)$, $u_v|_{t=0} = u_0$, is well-posed, $\mathcal{T} = \{T_{vw}\}_{(v,w) \in E}$ is a family of bounded operators $T_{vw} : L^2(\Omega_{\mathcal{I}(v)}, \mu_{\mathcal{I}(v)}) \rightarrow L^2(\Omega_{\mathcal{I}(w)}, \mu_{\mathcal{I}(w)})$ and E is a set of edges to which the pair (v, w) belongs.

The set of relations in R are restricted here to the case of binary, i.e., pairwise case, only for the sake of simplicity. However, these relations can be of a k-ary nature where $k \geq 2$. In this case we will be in the presence of metaplexic hypergraphs or metaplexic simplicial complexes in which the nodes contains an internal continuous space but the relations are not necessarily of a pairwise nature. In the formal definition the mapping $\mathcal{I} : V \rightarrow \omega$ is in charge of assigning a continuous space to the interior of every node. That is, we are zooming in inside the nodes to "see" what there is inside them. These continuous spaces could represent actual physical spaces like the interior of a cell, or the region inside a landscape patch, or can be abstract spaces like the "psychological continuum" (Ashby, 1983) where a random walk model allows to predict the two choice reaction times in decision problems in Psychology.

As a matter of example let us consider the (binary) metaplex illustrated in the Fig. 6 in which (V, E) is a network representing the skeleton of a complex system and in which each node is represented by the unit disk $B(0, 1) \subset \mathbb{R}^2$. In this case $\omega = \{B(0, 1)\}$ and $\mathcal{I}$ is constant. The endo-structure of this metaplex is given by the internal structure inside the unit disks, and its exo-structure is given by the connectivity of the nodes in the graph. The internal structure of the nodes is continuous, although nothing impedes that it could also be discrete. That is, ω is a set of open domains $\Omega_j \subset \mathbb{R}^n$, each endowed with the Lebesgue measure. However, the structure of the nodes could be of any kind, including irregular shapes like in the case of landscape patches or of neurons. The important thing is that we can couple an internal dynamics inside the nodes with the external dynamics between them. In the context of the RW this means that we will have a walker that navigates inside the continuous space of the node i controlled by a Brownian motion, and once certain conditions are fulfilled it will be transported to any of the nearest neighbors of i in a similar way as in the RW on graph.

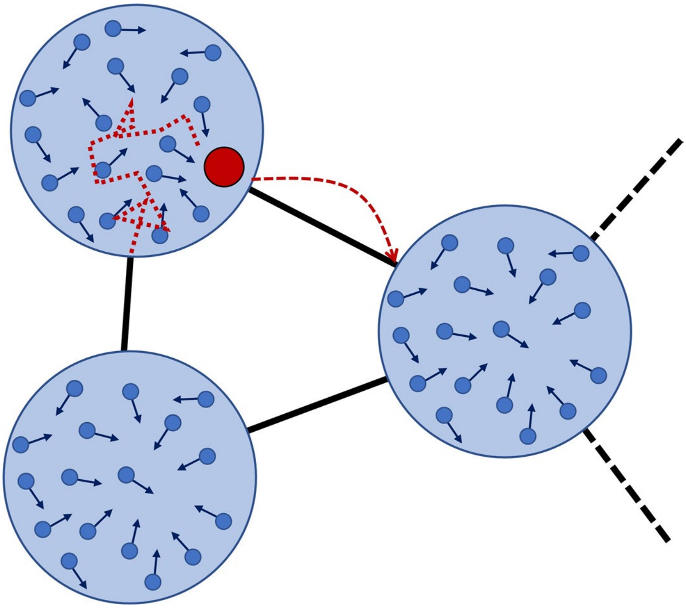

Fig. 6 Illustration of a metaplex in which inside the circular nodes there is a continuous space where a particle follows a Brownian motion and then it is transported through the network by jumping to adjacent nodes

Morin has claimed that interactions are a source of "organization" in systems (Morin, 2022). He also claimed that the number and richness of these interactions increases when they occur among entities which per se have more complexity than that of simple "particles". But this increase in organization necessarily implies an increase of order of the system. In Morin's scheme this is compensated by the fact that interactions are created by encounters, and encounters are facilitated by *"disorder (agitation, turbulence)*" (Morin, 2022). The current metaplexic scheme also allows that the increase in order emerging from organizations created by the interactions between the entities of the system is compensated by an increase in internal disorder produced by the dynamics inside the nodes. This reminds Ilya Prigogine statement that "entropy production contains two "dialectical" elements: a disorder-creating element, but also an order-creating element. And the two are always linked" (Prigogine et al., 1998). The metaplex, of course, generalizes the case where the internal structure of the regions is hidden and replaced by a weight that captures some of its inherent complexities. For instance, (Teza et al., 2018) introduce a measure of internal complexity from a Shannon-like measure of entropy for the nodes and relate it to local and global macroeconomic indicators, like export growth and GDP pro capita. The article links the level of internal complexity and diversification within the nation expressed through an entropic measure with the level of global growth by emphasizing the role of the internal structure of the economic metaplex.

6 Conclusions

The goal of this work has been to approach the concept of “complex system” from the perspective of a practitioner of the field and using the tools of the philosophy of science. I have carefully avoided any mention to the properties that a complex system must have in its definition as well as to any physical quantity which can be derivable for such systems. Thus, my definition of complex system is based on the distinctive nature of the interactions between the entities of a system as the only ingredient for defining its complexity. The importance of the nature of the interactions has been claimed in several publications by practitioners of complex systems analysis as well as philosophers of science who have approached this concept from different angles. These interactions must be transformers of the nature of the interacting objects and of the whole formed by them in order to form a complex system. I have coined here the term “Morinian interactions” for such transformative class of interactions. Then, a complex system is like any system composed by entities and interactions. However, the distinctive characteristic that make them complex is that such interactions are “Morinian interactions”. In this case, complex systems are, as they should be, a subclass of the class of systems, where there is a bidirectional non-separability between the identities of the parts and the identity of the whole, such that not only the identity of the whole is determined by the constituent parts, but also the identity of the parts are determined by the whole due to the Morinian nature of their interactions.

I have insisted in this work on some of the impediments which I think that have existed to avoid or delay a clear definition of the concept of complex system. More than the impression that “*a complex system is by definition too complicated to be comprehended by just using everyday common sense*”, I think it is the fact that some ideologies predominant in the physical sciences as claimed by Rovelli (2018) have permeated the field for long time. These “*Why not?*” and “*Shut up and calculate*” ideologies are two sides of a coin. On one side they have allowed the advance of certain areas of the study of complex systems by exploring new territories, but on the other side they have kept these searches blind, without a guiding concept to orient any new exploration. Many scientists in this field claim that such philosophical approach is not needed, that such a clear and unambiguous definition of complex system is unnecessary. I simply will repeat here what (Rovelli, 2018) has pointed out about the fact that: *“the scientists that deny the role of philosophy in the advancement of science are those who think they have already found the final methodology (...). They are the ones trapped in the ideology of their time*”.

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