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EDITED AND REVIEWED BY
Andrea Rapisarda,
University of Catania, Italy

*CORRESPONDENCE
Maxi San Miguel,
✉ maxi@ifisc.uib-csic.es

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Frontiers in Complex Systems

Maxi San Miguel*

Institute for Cross-Disciplinary Physics and Complex Systems, IFISC (CSIC—UIB), Campus Universitat Illes Balears, Palma de Mallorca, Spain

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Introduction

In this paper I intend to give an answer to three entangled questions: What is a Complex System?, What are present research challenges in Complex Systems?, and What is the purpose of the new journal ***Frontiers in Complex Systems***?

What is a complex system?

Complexity comes from the Latin word “plexus” which indicates non-separability in components. Therefore, a good standard definition is that a Complex System is composed of many interacting units showing emerging properties that cannot be understood in terms of the properties of the individual isolated components. When we say that a system has emergent properties we mean that an effective theory of the system at some scale or level of organization is qualitatively different from the lower level scale. The slogan of Complex Systems is then that *the whole is more than the sum of its parts* (Aristole): Society is more than a collection of individuals, in the same way than brain and mind are more than a collection of neurons, or traffic a collection of cars. Complexity is not about things but about processes. It is about how order at large scales emerges from local interactions at small scales. Quoting the Nobel Laureate Phil W. Anderson (Anderson, 1972), *a reductionist hypothesis does not by any means imply a constructionist one:* One can then say that, as a change of scientific paradigm, Complex Systems Science is the triumph of emergence over reductionism. In this sense it is not so much defined by a subject or specific system of research, but as a way to approach the understanding of systems behavior: Systems in which emergent behavior transcends the characteristics of the units composing the system are ubiquitous in many branches of natural sciences, human sciences and technology.

A main important characteristic of Complex Systems behavior is that it is often associated with multiscale problems. Cities, the human body or economies have dynamics at very different scales. For example, coupled interactions in the brain cover nine orders of magnitude in spatial scales. How do we go from neurons, or below from the genome, to the brain functioning, or above, to human behavior? Being more than the sum of its parts implies the existence of long-range correlations. The physics paradigm for these situations is the critical point of a phase transition, characterized by the divergence of the correlation length and by self-similar (scale free) behavior. The more challenging physical problems are precisely those embracing all scales. The lack of a characteristic scale is what makes a standard reductionist approach inappropriate and what gives rise to fat-tails and self-similar distributions that are common in Complex Systems description (West, 2017). Additionally, a system in a critical point is at the threshold between order and disorder. The existence of a threshold indicates nonlinear behavior, and nonlinearity and half-way situations between order and disorder are also characteristics of Complex Systems.

Emergent phenomena are conditioned by interaction networks describing which elements of the system interact with a given element. These Complex Networks (Estrada, 2011; Dorogstev and Mendes, 2022) are the skeletons of Complex Systems and therefore an essential methodological ingredient for their description. Basic properties of these networks such as small-world (half-way between regular and random networks) or scale-free, share the complexity fingerprints of a critical point. Taking into account the dynamical adaptability as another characteristic of Complex System behavior, a mathematical definition of Complex Systems has been given as co-evolving multilayer networks (Thurner et al., 2018).

Another important characteristic of Complex Systems is that there are intrinsic limits for long time quantitative predictions of their behavior. The issue of predictability is a main link between the two parts of the 2021 Nobel Prize in Physics awarded "for groundbreaking contributions to our understanding of complex systems", with one-half jointly to Syukuro Manabe and Klaus Hasselmann (Earth climate) and the other half to Giorgio Parisi (disordered and random processes). Quoting Giorgio Parisi (Parisi, 1999), *in the study of Complex Systems the word prediction has a weaker but more general sense, so that the target field of Physics is much broader and Physics constructions (concepts, models, tools . . .) have much more applications.* Prediction in climate is now intrinsically probabilistic and based in realizations of different models which are, for the climate system, conceptually analogous to the "replicas" introduced by Parisi for disordered systems. Climate is also a particularly relevant example of a system with interactions at many different scales: from local variables to ocean-atmosphere coupling to planet level correlations.

What are present research challenges in complex systems?

Cybernetics, Systems Science, Synergetics, Global Systems, Complex Systems . . . , all these are key words found in the historical path of the efforts to improve our understanding of how the whole works. What is new in these efforts and what are the present challenges? I will classify the answers to this question in three groups: 1) Basic scientific level of complex systems research, including which are proper questions that can be answered and what statements of universal value can be made. 2) Specific fields of research that offer new challenges and opportunities, 3) Societal impact of this field of research. But to begin with, it should be emphasized that there are two aspects that set a new context in that historical path. A first one is the availability of massive data and new techniques to analyze data. A second aspect is the direct social relevance and short -term social impact of many of the research questions addressed. While data availability percolates those three groups of answers posing new fundamental questions, opening new fields of research and having a large social impact, the societal impact of present research is an important challenge in itself. Similar, complementary or different ideas about these challenges by different representative groups of researchers in Complex Systems have been collected elsewhere (San Miguel et al., 2012; Thurner, 2017; Bianconi et al., 2023).

Basic scientific level

- Classifying and cataloguing different types of complexity, emergent behavior and multiscale problems.
- Constructing a quantitative general theory, or generic conceptual framework, of emergent behavior: How do we quantify emergence? What is a general methodology to identify relevant and irrelevant microvariables for macroscopic emergent behavior? Is self-similarity generic? How do hierarchies emerge? Universality in emergent phenomena?
- Full development of a theory of Complex Hypernetworks including higher order interactions and going beyond the well-established paradigm of complex networks for pairwise interactions
- Big Data: Success in Complex Systems research requires the merging of theoretical deductive approaches with empirical inductivism. The question is, *How do we go from data to information to knowledge?* There might be specific aspects that need to be considered in different systems, but in general, the challenge is to identify mechanisms that allow the understanding of data. It is not only to infer behavior from statistical correlations, but to establish cause-effect relations for isolated mechanisms. It is about identifying underlying mechanisms beyond the description of patterns and to construct models that give understanding of data beyond modeling to reproduce data. In parallel there is the challenge of understanding how and why Artificial Intelligence techniques and Machine Learning algorithms are successful: What can we learn from black-box techniques in terms of mechanisms of interactions in the system?
- Limits of prediction: Complex Systems have intrinsic limits for long term prediction that need to be established. One reason is that many Complex Systems cannot be described in terms of ensemble averages, having a single contingent dynamical path. There are also many of these systems that might have different multiple optima. The challenge is to establish clearly what can be predicted in different systems, what are the limits for prediction and what are the conclusions in terms of the forecasting of possible scenarios. A theory of Complex Systems should provide an answer to the question of which dynamical outcomes are possible with certain probability, and how unexpected scenarios can occur given the available information on the system´s past.

Specific fields

Among the specific fields that today offer renewed challenges and opportunities within a Complex Systems approach, I would highlight, in random order:

- Socio-technical systems: Understanding the ecosystem of interconnected socio-technical systems is needed to forecast possible collective phenomena emerging from the interaction of humans and technology. These include interactions with passive Information and Communication Technologies, interactions with Artificial Intelligence developments, humans-robots interactions, human interactions with the Internet of Things (IoT) and interactions of online social networks with IoT, as well as interactions among technological outputs such as for example collective robot behavior.
- Complexity Engineering or harnessing complexity: Design, engineering and ***control*** of complex systems for specific purposes, as for example neuro-inspired devices for information processing or nonconventional computing such as Reservoir and Bio-inspired Computing (S Neves and Timme, 2021).

- Global change and System Earth: Climate studies have recently benefited by the use of Complex Networks methodologies (Dijkstra et al., 2019), but many challenges remain there. Climate is an emergent phenomenon in the system Earth, and the understanding and control of the Global Change requires proper modeling of the interactions and coupling of natural phenomena with human activities and feedback between them.
- Neuroscience: Dynamical models of brain functional networks are needed for the understanding of how our brain processes information. Properties of interest for us are the ones that we experience first-hand (perception, cognition, emotion, attention, memories …) but those are emergent properties difficult to anticipate without a Complex Systems approach. These studies are expected to play a decisive role in the comprehension of important diseases including Alzheimer, Parkinson, autism, epilepsy and others.
- Health sciences: Identifying the causes and defining a proper treatment for many diseases requires paying attention to a large number of interacting factors. This has become evident in a pandemic situation with the role of human mobility and social interactions, but at a completely different level it is also true for a personalized medicine. In addition, the availability of data on patient clinical records under different treatments opens new avenues of research using complex networks approaches, as well as for new approaches to hospital organization and management.
- Quantum Complexity: An important window of opportunity appears in the study of Complex Systems in the quantum domain, as for example Quantum Complex Networks, the Quantum Internet, Quantum Machine learning and Quantum Reservoir computing.

Societal impact

For Complex Systems researchers, it is clear that addressing the present challenges of our interconnected and global society requires being able to define proper questions and to use completely new scientific concepts and approaches, and that those are provided by Complexity Science. However, this idea is not yet well appreciated in general, and in particular by policy makers, having yet a small impact on mainstream social understanding. The biggest challenge is then in terms of communication, making society at large aware that the Complex Systems approach entails a scientific renaissance based in a different way of thinking with capabilities to transform society by transforming the way of thinking.

The message to convey for societal impact includes two different aspects that break the basic-applied dichotomy: 1) Fundamental science: Complexity Science deals with transversal problems, such as multiscale problems, which are deep, fundamental science at the frontiers of knowledge. 2) Complex Systems approaches are needed and are successful in dealing with many problems of immediate social impact such as Economic and Financial networks and crisis; Pandemics; political, cultural and migration conflicts; Socio-technical interactions such as social information processing with new technologies, Global change, Green transition and Sustainability, Urban and Transport problems, etc.

In addition, Complex Systems approaches provide a perspective and concepts which are absolutely needed in our daily life experiences and that defy common wisdom. For example, individual intentions cannot be inferred from observation of social aggregates, or an average quantity such as the mean income is a meaningless concept for many power-law distributions. In order that these concepts become general knowledge, we confront the challenge of constructing a new educational system in which students of all ages learn the new way to learn about reality: learning across disciplines, learning from data. This is possibly the safest path for complexity approaches becoming a key ingredient in decision making.

Cross-disciplinarity

A main asset of Complex Systems approaches is that it provides common and shared methodologies to explore cross-disciplinary boundaries. It is in the cartography and colonization of the cross-disciplinary land at the boundaries among established scientific fields where the most important scientific challenges and seminal progress occur, often giving rise to new emerging disciplines. The study of Complex Systems includes an essential effort to integrate different scales, interaction mechanisms, models and data, and also disciplines. The integration of disciplines is based in the transfer of concepts and methods among these disciplines, often giving rise to new disciplines. This integration is complementary to the multidisciplinary approach to a given specific problem. Examples of new disciplines that have emerged from the Complex Systems Cross-Disciplinary approaches include Computational Social Sciences (Lazer et al., 2009; Computational Social Science, 2021) or City Science (Batty, 2013). The challenge here is to find and develop such emerging disciplines and also to keep the enlightening feedback loop between those new disciplines and the development of new basic and general methodologies for the study of Complex Systems.

What is the purpose of Frontiers in Complex Systems?

The community of researchers in Complex Systems is itself an example of a Complex System in which the whole is more than the sum of its parts, with local interactions within a discipline and across disciplines, giving rise to global emergent behavior. Frontiers in Complex Systems is a service to this cross-disciplinary community that aims to become a natural and reference outlet for publications in the field, with a paper selection strictly based on scientific quality.

In the field of Complex Systems it has been often difficult to find the proper journal where the research topics and challenges discussed above are identified as the topics of the journal, and at the same time the journal reaches different disciplinary audiences for which this research is relevant: A great part of the research in Complex Systems is not recognized by any of the well-established disciplines, because it addresses problems which are beyond the realm of a single discipline, bridging among several disciplines. Frontiers in Complex Systems addresses this problem including topics at the core of this research such as Complex Networks or Physics based research, but not being limited to them. Rather, it provides a forum for cross-disciplinary communication with research papers on Complex Systems coming from different disciplinary fields including Physics, Mathematics, Computer Sciences, Artificial Intelligence, Engineering, Climate change, Economics and Finance, Social Sciences, Linguistics, Ecology, Neuroscience, Health Sciences, Epidemics, Mobility and Transport, City Science, etc. Beyond the impact on the complex systems community, enhanced visibility in different scientific communities is guaranteed by shared sections of the journal with other Frontiers journals specialized in different disciplines. Frontiers in Complex Systems also aims to become a standard reference for professionals looking for scientific results that merit being disseminated and communicated in social media.

Author contributions

MSM developed the conceptual content and wrote the manuscript.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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