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INTRODUCTION

Complex dynamics of life at different scales: from genomic to global environmental issues

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This introduction to the Theme Issue, *Complex dynamics of life at different scales: from genomic to global environmental issues*, gives a short overview on why the ideas and concepts in complexity and nonlinearity are relevant to the understanding of life in its different manifestations. Also, it discusses how life phenomena can be thought of as composing different scales of organization. Finally, the articles in this thematic publication are briefly commented on in terms of their relevance in helping to understand the complexity of life systems.

Keywords: life systems; complexity; living organisms; life organization; nonlinearity in life dynamics

1. Introduction

One of the most intricate and dynamically rich processes in nature is surely life. While, to a certain extent, it is easy to be intuitively identified, a clear and rigorous characterization and classification of all its features is far from being an accomplished task. Big questions related to partial aspects of the phenomenon of life, such as: the evolution of species; the biochemical organization at the distinct levels (from cellular to complex nervous systems); the variety of possible interactions between the different individuals; the ability to form groups with distinct purposes; the relation of organisms or groups of them with the environment; and the many stages of cognitive development; just to cite a few, all are subjects of intense research, nevertheless yet incompletely understood.

The study of life processes embraces a broad variety of fields, such as biochemistry, psychology, economics or meteorology, which are traditionally separated disciplines. Alternatively, the study of life as a whole is taking its first steps. To describe the many 'sides' of life in terms of ideas and concepts

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from complex systems, as will be discussed below, may be an alternative and useful way towards modelling and hopefully comprehending these very hard, but fundamental, problems in a unified framework.

In very general terms, complexity arises from relatively simple interactions among numerous mutually interacting parts. Despite the simplicity of the governing rules, a rich collective dynamic emerges which is quite distinct from that of the individual elements. Hence, the more traditional approach of analysing the parts of the system to build a picture of the whole must be re-examined to deal with such a scenario, where more appropriate conceptual and theoretical tools become necessary.

At the core of complexity is nonlinearity, directly associated with the lack of proportionality (hence linearity) between the causes (the forces over and among the smallest constituents) and the consequences (the phenonemon global properties). As a matter of fact, nonlinear responses may give place to a variety of emergent behaviours. Furthermore, in a nonlinear system, the possibility of chaos—i.e. the strong sensitivity to rather small perturbations and to slight changes in the initial conditions—may even add a certain degree of unpredictability and randomness to the dynamics.

From the above observations, it is natural to regard life from the perspective of complex systems. Indeed, how could one guess what a superior organism can do and accomplish based only on the study of its basic units, the cells? How to infer the huge potential transformations in a planet, including entire biome reshaping, just from an increase in the concentration of a single gas, carbon dioxide CO_2, in its atmosphere? How to distinguish the exact individual aspects defining human 'culture'? On the one hand, the study of life processes at diverse scales encompasses the broad spectrum of fields mentioned above. On the other hand, owing to the fact that life can only, in a very rough approximation, be studied at a single level, a deeper understanding of its entangled aspects may require approaches contrasting with the usual reductionism of science. Moreover, by its multi-disciplinary nature, it most probably needs to be addressed by researchers of different fields working in close interaction. Then, life, still one of the great challenges to science, may find proper answers from the point of view of complexity science.

2. The scales of life

Given a sort of hierarchical or multi-level organization of complex systems, they behave differently at different (spatial, temporal, energetic, etc.) scales of observation. Moreover, scales are intertwined such that the dynamics taking place at one level can influence all the others. This is so because of the feedbacks among 'layers' of interactions, settled on a structurally and functionally complex network of correlations. Then, to assess various layers of details is required for a full description of the system.

Let us illustrate it with an extremely self-organized human creation: the academic world. It can be a small College or a very large University, like the huge and relatively localized (the major part in a single city) Universidad Nacional Autômana de México, or also the large but scattered campuses system of the University of California. In any case, the organization is quite branched. There are separated departments, which may or may not belong to larger centres (e.g.

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Institutes), but each department may have within it laboratories, research groups and graduate programmes, shared by other departments. Also, there can exist central offices responsible for different matters, such as for helping to obtain graduate student scholarships or to establish agreements with the private sector for financial support (in exchange for some directed or even classified research). These offices are, in principle, independent, but often interact very closely. Regarding the different activities, students, professors, technical, administrative and support staff all follow their many particular duties. For instance, professors should teach, advise and move forward their research groups, while technical staff should take care of computers, laboratory equipment, etc. Each group plays its own role. Moreover, researchers do their job without a tight regulating control, namely, usually without following organograms, hierarchical structures (with supervisors, managers, etc.) and fixed schedules in traditional companies. Thus, in a university, all the parts constitute different levels of activities and distinct degrees of expected accomplishments in a web of interactions. Nevertheless, they depend on each other to meet the purposes of what we like to call 'Academy' since Plato's time. In summary, a good example of the many features at the large scales of organization of living beings.

This is exactly the case at the small spatial layers too. For instance, there are intricate components and interactions at any scale of observation of the cells (from the intracellular realm, to tissues, organs and organ systems), constituting an individual organism that in turn may form communities.

Furthermore, we can also refer to different time scales that are characteristic of life evolution, going from the metabolic biochemical reaction times, the organism lifetime, to the many generations necessary for natural selection.

At the same token, in the reciprocal interaction of organisms or groups of them with the environment, it is noteworthy that human intervention has crucial consequences, for instance, strongly modifying the pre-existing time scales, as in accelerating extinction processes. Be it with pre-determined goals (such as in genetic manipulations) or as a by-product (global environmental changes), it adds further critical feedback, which of course needs to be understood at the different layers of functioning mentioned.

3. An historical overview

Over a period of a few decades, major advances have been made in addressing life from the perspective of complex systems with the aim of understanding and predicting it at different levels. Starting with more 'traditional' tools, such as cellular automata (CA), or systems of differential equations, diverse novel concepts and techniques have been developed for the study of complexity, such as multi-agent models, evolutionary programming or complex networks. Also, the build-up of computational technologies, allowing us to explore huge databases (like the full genome or large phylogenetic trees), help to simulate emergent behaviour to be confronted with their real-world counterparts, thus strongly contributing to the progress of the area.

But this whole evolution followed an interesting historical path, perhaps itself a complex phenomenon. First steps in modelling the essence of living organisms by simple mathematical constructions were given by John von Neumann & Stanislaw

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Ulam in the 1940s, by the introduction of discrete systems named CA (von Neumann 1966). Later in the 1970s, CA became popularized by Gardner with John H. Conway's Game of Life (Gardner 1971, 1985). Since then, CA were further sophisticated and became useful tools to model a diversity of natural and man-made processes. Even earlier, in the 1920s, von Neumann created the foundations of game theory, today an important way to understand the actions of organisms, societies, etc., either in competition or, more 'friendly', in cooperation for common goals.

These discrete (in space and time) models have, as a counterpart in the continuum limit, systems of differential equations, such as in reaction–diffusion models (Nicolis & Prigogine 1977), among which is noteworthy the pristine work by Alan Turing on morphogenesis (Turing 1952). As a further outstanding example, Ilya Prigogine's theory of dissipative structures describing thermodynamic systems far from equilibrium (Nicolis & Prigogine 1977) leads to pioneering research on self-organization, helping to introduce complexity in biology.

Self-organized criticality (SOC), proposed by Bak (1996), which was also formulated on the basis of CA, mixes two apparently essential ingredients of complex systems: self-organization, that is formation of spatio-temporal patterns without external tuning, and criticality that, as in the critical point of phase transitions, is characterized by power-law scalings and divergent susceptibility-like quantities, allowing the system to react drastically to changes in its environment. Employed to describe a wide variety of phenomena, SOC could be one of the mechanisms yielding complex behaviour in nature.

In fact, to envisage life as being very plastic, in the sense of quick and even strong responses to the surrounding changes, has its roots in nonlinearity. In the 1970s, first work by researchers such as Robert May, George Oster, James York, among others, on the logistic equation for population dynamics, found the rich realistic phenomenology taking place when deterministic chaos is a key factor in biological systems. Moreover, since its development by Mandelbrot (1983), the concept of fractals has become very useful to interpret different biological processes (Kauffman 1993; Kaandorp 1994; Losa *et al.* 1994), from morphogenesis, to allometry in metabolism, going from patterns in cardiac rythms to the properties of the time series from brain signalling.

In former times, system components have been modelled as being identical, which is at odds with the typical heterogeneity of realistic complex systems. The introduction of non-identical characteristics, either in the components of the system, in their mutual interactions or in the way they interact with the environment, has been shown to be an essential step towards explaining many emergent features. As a historical example, we can mention random-walk models, like the simplest standard Brownian motion, initially used to describe limited properties of animal movement at the beginning of the twentieth century (Pearson 1905; Rayleigh 1905). However, to take into account a great number of relevant aspects associated with living-organism locomotion, including those associated with complex behaviour, nowadays much more sophisticated random-walk models need to be considered (Codling *et al.* 2008).

Another important model ingredient that has been introduced lately is related to the topology of the interactions between components. Up to a recent past, dynamical processes have been commonly studied in regular networks. This is the

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case of systems of coupled oscillators (e.g. to model biochemical reactions or firefly blinking). Interesting enough, the idea of treating a life system from network concepts is as old as the 1930s, with the pioneering work by Jacob L. Moreno, who created simple quantitative methods in social-network analysis. However, real networks (e.g. genetic networks, the nervous system or the World Wide Web) are neither completely regular nor totally random (Watts & Strogatz 1998). Actually, in many cases created by self-organizing processes, they can display scale-free distributions of connectivities (Barabási & Albert 1999). The incorporation of complex topologies have proved to be useful in modelling living systems, although real intrinsic networks and evolution rules are often still unknown.

Of course, it is beyond our purposes here to cite all the exhaustive names that have historically contributed to the study of complexity of life (see further suggested bibliographic references in Mosekilde & Mosekilde (1990), Kaneko (2006), Nowak (2006) and Special Online Collection (2009)). Our goal was just to give a synthetic (and illustrative) panorama about the historical developments of some of the main ideas in such a field, which is always in continuous progress.

4. This Theme Issue

This Theme Issue is devoted to recent works in complex-systems research focusing on life and its organization at different scales. It does not have the intention to exhaust the theme. Nevertheless, the issue selects problems that are very representative of how complexity concepts may turn out to be powerful in explaining the different aspects of life. Thus, besides furnishing new relevant results on different topics, the works presented here provide an overview of different methodological approaches, where a common factor is a proper balance between realism, predictability and simplicity. The selected works comprehend the following themes:

— viral quasi-species, genetic regulatory dynamics;
— cellular signalling, blood flows;
— neuronal response, the brain;
— population dynamics and epidemics;
— social and economical systems; and
— the environment.

Aside from the interest of the treated problems and the relevance of the results, which are already properly presented and discussed in each individual paper, we would like to highlight here, throughout the following comments, the methodological strategies and technical protocols used to uncover the intricate behaviours observed in life systems.

The usefulness of simplified approaches is illustrated, for instance, through the reduction of a quasi-species model, a system with a very large number of nonlinear coupled equations, in terms of ‘error classes’ (Alonzo & Fort 2010), or the introduction of minimally nonlinear ingredients, such as positivity constraints in genetic-regulatory networks (Hanel *et al.* 2010).

The fundamental role of non-uniformity and heterogeneity on systems’ collective response is shown in the works on calcium signalling (Solovey & Dawson 2010) and on ensembles of excitable neurons (Pérez *et al.* 2010), respectively.

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Schelin *et al.* (2010) study the dynamics of particles transported by blood flow in the presence of irregularities in the vessel walls. This mimics stenoses or aneurysms, which generate abnormal flow patterns. Beyond this particular relevant heath-related problem, the generality of the approach makes it applicable to other biological processes, e.g. the coexistence of plankton species. Thus, allowing interesting analogies between seemingly disparate systems.

The complex-network approach that has recently received considerable attention, yielding new insights as commented above, is employed to study the emergence of hierarchical order in functional brain networks (Gleiser & Spoormaker 2010).

In passing from the 'inner' to the 'external' aspects of life organization, it is interesting to analyse the motion patterns of mobile organisms in their environment. Boyer & Walsh (2010) go beyond the standard random-walk approach and use (learning-)agent-based models in random media to analyse whether memory can be advantageous for exploiting resources in heterogeneous and changing environments.

Likewise, going from the individual to the collective character of live systems, Araujo *et al.* (2010) study population outbreaks in a spatial predator–prey CA as a function of the predator home-range size, also performing the analysis from an evolutionary point of view. Furthermore, the spread of infectious diseases is another relevant and related problem. Pinho *et al.* (2010) show how mathematical models can help in determining the proper stage of epidemiological control policies.

Modelling human life at the level of sociopolitical and economical systems is also considered in the present Theme Issue. Starting from very simple principles of geopolitical theory and geographical considerations, Kuperman (2010) proposes a model with competition ingredients, which succeeds in explaining the general features related to the actual process of geopolitical division. Given that financial markets display universal features and are made up of many subunits and traders, who interact with positive and negative feedbacks (producing herd effects, crises, etc.), they become a paradigm of complex systems. This is strengthened by the huge amount of available data. Since the traders decisions, hence markets, are driven by fluxes of information that can be currently obtained from search engines like *Google*—another complex system—it is interesting to investigate the correlations between search volume and financial-market index fluctuations, which is precisely the goal of the work of Preis *et al.* (2010).

Finally, the environment is also addressed here in the work by Kiss & Jánosi (2010), analysing the time-asymmetric fluctuations (common attributes of dissipative systems operating far from the equilibrium) observed in daily mean temperature changes as well as in total-column ozone.

5. Conclusion

Following the goal pursued by this Theme Issue, the selected papers cover different questions under the focus of many current studies in life systems. Also, different techniques and theoretical approaches are employed. Therefore, this survey may help to gain insights on the complex dynamics of life, as well as on the methodological tools to tackle its study. Moreover, it might serve as a 'guide'

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pointing to possible new directions of research, relevant problems that still need deeper analysis, and what kind of new methodologies and concepts need to be developed to grasp life at its different levels of organization and also as a single (whole) complex phenomenon.

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