Prologue and Introduction

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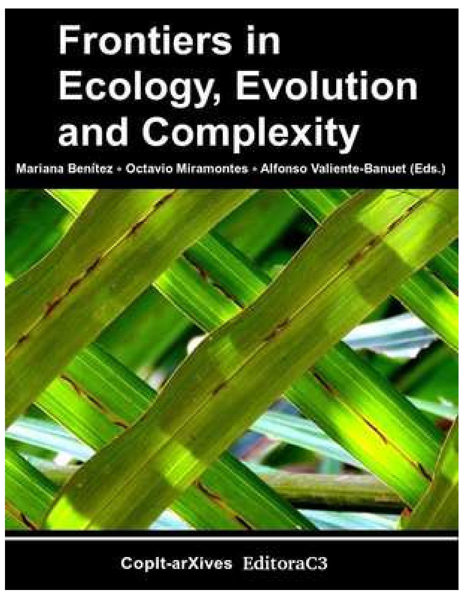
Frontiers in Ecology, Evolution and Complexity

Mariana Benítez, Octavio Miramontes & Alfonso Valiente-Banuet (Editors)
CopIt-arXives, 2014
Mexico City
ISBN: 978-1-938128-05-9

http://scifunam.fisica.unam.mx/mir/copit/TS0012EN/TS0012EN.html



Prologue

Right now, the understanding of life on Earth, its origins and dynamics, is going trough a deep transformation rooted in the major breakthroughs of the sciences of complexity. This transformation is so important and transcendental that it is challenging most of what biologist knew just a few decades ago. At its center is the realization that order in life emerges spontaneously from the interaction processes of their components. Bio-molecules self-assemble to form new entities with properties that are not reducible to the separate components and the same happens at different levels of organization, from the genes, the cells, the individuals and the communities. This is a new fascinating paradigm that is being explored and whose frontiers are being pushed forwards by a generation of mostly young scientists. This book is an example of this. Here the authors are exploring and sharing their intellectual excitement on different fronts, about a new kind of science that explains how complexity and self-organization drives living phenomena. Ecology and Evolution are two topics where fertile ideas are flourishing. One is the science of interactions among individual living entities at its many levels of organization and the other, the science of the origins and changes of these entities and their interactions. Major breakthroughs in ecological theory include the understanding that interactions have a non-linear nature and that these interactions can be understood as complex networks; and that emergent spatial order are present in driving patterns of biodiversity and distribution. This new ecological vision is extremely important for a world who is in an urgent need of novel approaches for ecosystems and biosphere sustainability and restoration. Self-organization is an undisputed major principle of nature. At the present we see how complexity scientists are busy extending Darwin's theory of evolution to incorporate it as a major driving force. This requires a visionary thinking and certainly, the authors of this book are not intimidated on demonstrating it. A mixture of recent findings in biology, physics, chemistry and mathematics have been assembled together to give the readers a fascinating look on the problems and perspectives of the new emergent and cutting edge theory of biological evolution.

Stuart A. Kauffman
Vermont, 2014

Introduction

All in this book is about doing a new kind of science. It is the collective effort of 44 authors from five countries who have generously agreed in writing an authoritative book in an open access format. This is also a new form of communicating science where knowledge flows freely to the general audience without the barriers, restrictions and imprisoning of commercial contracts of the “free”-trade society. Readers world-wide are allowed to freely copy and distribute this book for their personal use.

The Sciences of Complexity are a new whole scientific paradigm where biological phenomena are viewed and explained as emergent properties of interconnected networks out of equilibrium. This is a highly interdisciplinary view of nature that requires the concurrent participation of biologists, mathematicians, physicists, chemists, etc. Over the last decades, a world-wide mesh of scientists with visionary attitudes have been challenging our current knowledge of how life originated and has evolved into the natural wonders we see today on this planet. All authors participating in this book are part of this challenging effort.

Self-organization is a natural phenomenon of major importance in Biology, it might be the source of many ordered patterns we see; however it has been largely overlooked, until now. Theories and concepts integrated in the Modern Evolutionary Synthesis have been central to explaining the changes and transformations that living forms have been going through since the origin of life on Earth. But it has been argued that essential components are missing in this tradition; it has become more and more clear that this framework has to be extended in order to fully understand the origination, development and evolution of organisms phenotypes and ecological structures. A key component to explain the emergence of biological order is self-organization. This idea, together with recent major breakthroughs in evolutionary biology, is shaping a new face of biological evolution.

Evolutionary and ecological processes and phenomena occur in a wide range of spatiotemporal scales, in which a variety of biological, geological and human agents interact with each other in a non-linear way. Adding to this complexity, over the past few decades, experimental and field data have shown that phenotypic plasticity might be central for the generation of inheritable phenotypic variation, and that the development and evolution of organisms largely shapes their own niche, placing the organism-environment interactions in a central position in contemporary evolutionary biology. Also, advances in molecular biology, phylogenetic inference, remote sensing, systems biology, bioinformatics, non-linear science and other fields have rendered a great amount of data that remain to be integrated into models and theories that are capable of accounting for the complexity of ecological systems. It is thus necessary to provide a solid basis to discuss and reflect on these and other challenges derived from the study of ecological systems and their evolution, both at the local and global scales.

Many different topics are addressed in this book, initiating from species diversity patterns, primarily regarded as the product of local, regional processes and historical events. In this sense, a macroecological approach pretends to fill the gap between local and regional processes to explain diversity patterns with different methodological approaches, as presented in their chapter by Villalobos and Rangel. A conceptual framework for plant community ecology is proposed considering both historical biogeographical processes and biotic interactions discussing the ways these two components evolve in mutual response to each other. Understanding the assembly of communities would be the only way to explain the sixth major extinction in the history of life and to transit towards sustainable practices, as proposed by Valiente-Banuet *et al.* Flower complexity, studied as the fractal dimension of the corolla outline, provides a useful and standardized way to understand the factors underlying plant-pollinator communication and mutualistic interaction networks. This shows that the highest number of pollinators visiting flowers occurs in the intermediate region of the range of flower complexity, suggesting that pollinators face a tradeoff when deciding the types of flowers they visit. This is the central idea in the chapter by Medel *et al.*

In their contribution, Alcántara and Rey discuss the importance of the temporal patterns of change in abundance and composition of natural assemblages of species, and the mechanisms behind these changes. They emphasize that these are fundamental aspects to understand the structure, function and stability of biodiversity. Their essay shows that some of the dynamic properties depend on the structure of the interaction matrix considering strongly connected components. In the same line, the relevance of restoration practices, as far as present disturbance human activities are not intensified, constitute a paramount for biological conservation. Therefore, it is possible to use plant-pollination interactions to evaluate the success of restoration practices, as discussed by Ceccon and Varassin. On the other hand and in the context of the present biodiversity and alimentary crises, it is necessary to develop and promote agricultural practices that contribute to food security and biodiversity conservation. The use of dynamical complex networks is presented by Benítez *et al.* as a way to study sustainable agricultural practices in the Mesoamerican polycrop known as *Milpa*.

Bacteria is by far the largest gene repository know on the planet and its importance pervades any process on earth. The possibilities of using pangenomics as a workhorse is central to describe both taxonomical and functional diversity within bacteria, being this the central idea in Alcaraz's contribution. But the study of the unseen majority of ca. 10^{30} bacterial cells affecting any biological process, such as biogeochemical cycles pose a number of difficulties, as discussed by Escalante and Pajares, who present them as potential new venues to overcome delays in the advance of microbial ecology.

The necessity of an interdisciplinary program on cancer research, from fields such as physics, ecology and evolution -assuming that the human body is inherently complex- is opening novel perspectives for effective therapeutic interventions and shows clearly that metaphors based in the generic properties of complex systems such as ecosystems and cell tissues are not only useful but imperative to develop new approaches to deal with complex diseases, as shown by Keymer and Marquet.

Ecological science has emerged into the XXI century as one of the most complete and formalized topics in life sciences. It has benefited from the pioneering long tradition of bio-mathematicians that started in the early XX Century with the Lotka-Volterra formalism and into the Chaos theory of the 70s of the last Century. But it has entered a new and dramatic change in the last two decades: Modern ecological science is based, as never before, on the concept of non-linear interactions among components. But this is also a commonly definition given when explaining the nature of complex systems. Therefore simple computational complex systems displaying spatiotemporal self-organization are very useful to put on test the emergent nature of ecosystems dynamics. On its chapter, Caballero *et al.* have used Conway's *Game of Life* model as a metaphor for studying simple ecological interactions.

Non-linearity pervades population ecology and complex phenomena such as chaos, self-organization, or criticality arise when deterministic population models are analyzed, as discussed by Martorell. Moreover the dichotomy between determinism and stochastic has been recently revisited and so the biological relevance of chance an its role in biology, and specifically in evolutionary biology, is under review in the light of advances on dynamical systems theory. This reevaluation of determinism and chance, and their role, provides new elements to perceive how biological phenomena may be operating in nature. This is the contribution of Pedro Miramontes.

The mapping of genotypes into phenotypes is a central challenge of current biological research, which historically has assumed a linear causation scheme in which the non-genetic character of developmental dynamics has been neglected, as discussed by Davila-Velderrain and Alvarez-Buylla. However, in the post-genomic era, a systems-view based on nonlinear (network) assumptions is increasingly adopted, showing that evolutionary dynamics can be studied using simple dynamical models of gene regulatory networks.

Under an evolutionary framework, most organisms cope with a huge spectrum of perturbations and the inherent disruptions such as genetic mutations. Therefore, they must be flexible enough as to develop new phenotypes in order to keep up with new environmental challenges. Under this scenario, the central question is to determine how organisms reach this equilibrium between phenotypic robustness and phenotypic innovation, leading to the concept of dynamical criticality, as discussed by Sandoval-Motta *et al.* Although phenomena at the molecular and cellular levels, as well as environment interactions during evolutionary processes, have been studied independently from each other. With the advent of new theoretical and technological approaches for biological system research, multi-scale models allow rapid progress in their study, as shown by García and Azpetia.

Despite that some morphological traits have been commonly interpreted as adaptations maintained and modified just by natural selection, self-organization processes are able to determine the characteristics of the basic building units of organisms, relegating natural selection to a secondary role, this the central idea explored by Álvaro Chaos in his contribution. On the other hand, modularity is a common feature of biological systems and there are several evolutionary paths to explain its evolution, as noted by Espinosa-Soto. Luque and Bascompte remark that self-organization processes play an important role as a source of evolutionary novelty and causes the emergence of complex structures, while natural selection operates on the existing ones.

In the opinion of Miramontes and DeSouza, cooperation –and not competition– has played a central role in social evolution. In order to elaborate a modern view and theory of social evolution, concepts such as group selection and those from the sciences of Complex Systems must be integrated together along with the Darwinian tradition.

Analogies between biological and linguistic evolution are deep to the point that both evolutionary systems can be studied by using models of biological evolution. This allows to explore a number of questions related to the origin, causes, development, interaction, and fate of languages, as discussed by Capitán and Manrubia.

All chapters in this volume aim to delineate an integrative and interdisciplinary view highlighting new avenues in research and teaching, critically discussing the scope of the diverse methods in the study of complex systems, and pointing at key open questions expanding the program of evolutionary ecological studies. This book arises with the aim to provide students and specialists with a collection of high quality essays that will contribute to integrate Ecology, Evolution and Complexity in the context of fundamental biological research and possible applications.

We would like to express our gratitude to the Physics Institute and the Center for Complexity Sciences at the Universidad Nacional Autónoma de México for trusting on the relevance and success of the present publishing initiative (CopIt-arXives and EditoraC3). We also appreciate the enthusiastic participation of all contributors and reviewers who have devoted their time to a task –writing books– that is less and less considered and valuated in our present academic evaluation practices.

Mariana Benítez, Octavio Miramontes and Alfonso Valiente-Banuet
México, D.F. 2014