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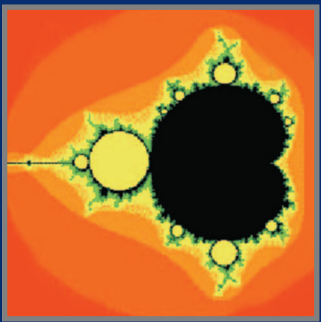
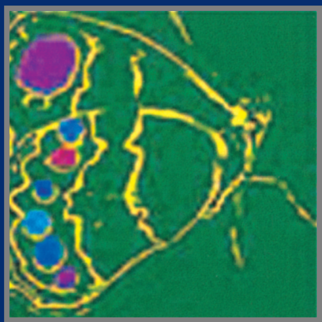


Research Article
: Complex adaptive systems
and a new thermodynamic 2nd law



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Research Article

Complex adaptive systems and a new thermodynamic 2nd law

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1. Introduction

Our universe has a very complex structure. It is structured through a hierarchy of galaxies, stars, planets, and finally elementary particles. The ecosystem is composed of various species interconnected through food chains. The economical system has a hierarchical structure from consumers up to giant international companies. These systems all share a common characteristic of a very complicated network of vast number of composing agents. These systems constantly change by themselves into new and more complex structures. Emergence of new advanced creatures by evolution in the ecosystem, emergence of complicated galaxies by evolution of stars, emergence of bigger money and financial markets by increase of trade in economical systems, are just a few examples [1].

Emergent properties can not be understood by simple linear summation of individual properties of participating agents. These are cooperative phenomena resulting from nonlinear summation over complex connections between agents. Complex systems are networks of many agents acting and reacting incessantly to each other. Without any master agent controlling the whole system, each complex system exhibits a coherent behavior. The brain, one of the most complex living systems, is composed of a huge number of neurons but does not have a master neuron unlike modern computers with central processing units. However, it still operates coherently by competition and cooperation among agents, which is ascribed to complex structures of synapses (connections between neurons). Patterns of connections between agents rather than agents themselves are crucial in emergent properties.

Complex systems have many levels of organizations or structures. Elementary

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particles form atoms, atoms form molecules, molecules form macromolecules, then living cells, organs, organisms, and the ecosystem. There exists a huge range of scales of structures and a typical scale of structures does not seem to be present. Moreover these structures in each level seem to be self-similar (or scale-invariant), which is characteristic of fractals [2]. The fractal structures can be found everywhere in nature; snowflakes, organic molecules, branches of trees, viscous fingers, lightening, coastlines, galactic distributions. These systems are not in equilibrium (or closed systems) but in non-equilibrium under the strong environmental influence (or open systems). Equilibrium systems can also exhibit a fractal structure but only at a critical point. Noncritical equilibrium systems cannot spontaneously organize themselves into being critical. Even equilibrium systems at criticality are different from complex open systems because they are inactive in the sense that they do not evolve into higher levels of complex structures. Complex open systems spontaneously organize themselves into criticality and incessantly increase the structural complexity through emergence of new and higher levels of structures. This dynamics can be characterized by two terms, *self-organization* and *adaptation*.

Self-organized criticality [3,4] is the main idea for explaining scale-invariant structures of open material systems in nature. However, living systems like the ecosystem and the economical system are ever-changing and developing into more complex patterns via adaptations to ever-changing environments. The key ideas for adaptations are prediction- reactions based on internal models and positive feedback of accidental events [5]. Living systems build internal models of their environments and react to them properly based on their internal models. For example, a consumer builds his own internal models of the economy via economic information acquired through mass media or schools, and predicts economical recession or improvement. He can then decide to buy a new product or invest at that time accordingly. These internal models constantly change into more complex models via learning and evolution for better economic life or survival. Living systems increase their complexity constantly via adaptations but the higher level of new structures seems to emerge abruptly as their complexity reaches a critical value. The punctuated equilibrium in the ecosystem [6,7] is a typical example. Emergence of new structures occurs via positive feedback dynamics. Most of changes diminish via negative feedback dynamics, but some changes are amplified sometimes accidentally or systematically and invoke enormous change of the entire structure. Increasing returns in economy are the positive feedback dynamics via adaptations and diminishing returns are the negative feedback dynamics [8,9]. The classical economic world of mass production and mass consumption which depends on resources is governed by negative feedback dynamics, but the modern economic world of technology which depends on know-how

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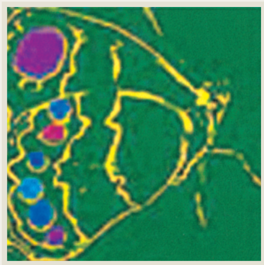
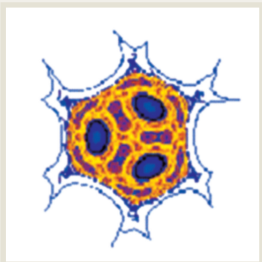
and knowledge is governed by positive feedback dynamics. The importance of adaptation in living systems leads to a new nomenclature of complex adaptive systems.

Cooperative phenomena, self-organizations and fractals, adaptations and internal models, and finally positive feed-back and butterfly effects are key concepts in the description of the dynamics of complex adaptive systems. In this article, I will give a brief account of these key concepts by taking well-known examples of complex adaptive systems.





2. Cooperative phenomena

Emergent properties of complex systems cannot be understood by simple linear summation of individual properties of participating agents. With the same participating agents, complex systems exhibit various different emerging properties depending on the surroundings. For example, material systems with low-temperature surroundings are in the solid phase. They are rigid, elastic, and ordered. As the temperature of the surroundings goes up sufficiently, a system undergoes an enormous change in its structure, i.e. the system goes into the fluid phase which is shapeless, viscous, and chaotic. The stability which is the emergent property of the solid is replaced by the fluidity. The emergent properties of complex systems depend on the structure of connections between agents rather than the agents themselves. These are called cooperative phenomena resulting from nonlinear summation over complex connections between agents.

Modern science has been brought up by reductionism. In order to understand the complex system, most scientists disorganize it into agents and study the property and the governing laws of the agents themselves. However, disorganization of the complex system into agents leads to the complete loss of its emergent properties in macroscopic scale. For example, life is the most intriguing emergent behavior out of materials. It is clear that life can not be maintained after dissolution into atoms. It is important to treat the complex system as a whole to understand its emergent properties.

3. Self-organizations and fractals

Living (and sometimes material) systems can spontaneously organize themselves into criticality where the fractal structures appear. At criticality, there are many levels of structures from microscopic to macroscopic. Moreover the structures in each level are self-similar. Correlation lengths between agents diverge in the fractal structure so the behavior of one agent exerts a non-negligible effect on all the other agents. So the critical systems respond very sensitively to the external stimulus and behave coherently as a whole.

Various fractals are classified by the fractal dimensions which represent the complexity of structures with fractional numbers [2]. For example, jagged coastlines are neither one-dimensional lines nor two-dimensional surfaces. The dimension of jagged coastlines is a fractional number between one and two. The size distribution of structures in fractals can be expressed in the form of a power law. The probability of finding structures with size L, P(L), is proportional to L^{-d} where d is the fractal dimension associated with those structures. Non-critical systems do not have fractal structures and their size distribution satisfies an exponential law, i.e. $P(L) \sim e^{-L/L^*}$ where a typical size of structures L* is present. In this case, the probability of finding a very big structure larger than L* is negligible. But, in critical systems, there is no typical size of structures and the probability of finding a very big structure is not negligible. So one should not ignore the possibility of abrupt appearances of giant structures in living systems.

Fractal structures have many levels of structures which are self-similar. Mathematical processes of creating fractal structures are iterations of simple rules on initial objects. Little mutations of simple rules create enormous variety of macroscopic patterns. Creativity of nature comes from these seemingly simple and iterative procedures.

4. Adaptations and internal models

Living systems are ever-changing and developing into more complex patterns via adaptation to ever-changing environments. They build internal models of their environments and react to them properly based on their internal models. The internal models constantly change into more complex models via interactions with environments. The concept of adaptation and internal models presents a crucial difference between living and material systems. For example, consider a learning process in the living systems. Through this process, numerous implicative predictions are carved on the brain. These predictions become building blocks of cognizance, which evolve and recombine themselves into higher-level cognitive structures by exploring the immense space of possibility via incessant trial and error to maximize the system's fitness to ever-changing environments. All complex adaptive systems build models to anticipate and predict their world, and constantly revise and rearrange internal models as they gain experience. This character is often worded as *Perpetual Novelty.*

5. Positive feedback and butterfly effect

Emergence of new structures occurs via positive feedback dynamics. Most of

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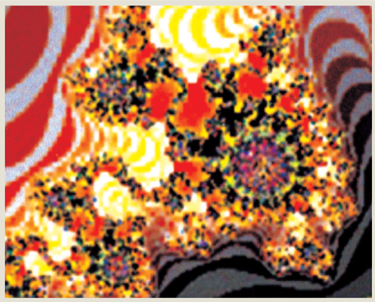
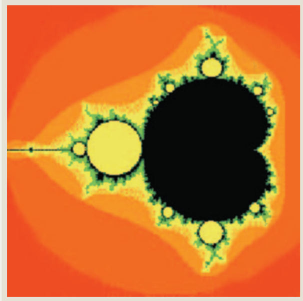
mutations and changes diminish via negative feedback dynamics, but some are amplified accidentally or systematically and invoke enormous change of the entire structure in a short period. Higher levels of new and complex structures emerge abruptly. The ecosystem evolves with both positive and negative dynamics but the emergence of new and advanced species is due to the positive feedback dynamics. So the ecological direction is governed by the positive feedback dynamics.

The increasing returns in modern economics are positive feedback dynamics via adaptations, and diminishing returns are the negative feed back dynamics. Diminishing returns govern the dynamics of the bulk processing economy, but the information processing high-tech economy is governed by the dynamics of increasing returns. Looking at the today's economy, new and complex structures seem to emerge under the rapidly changing society, politics, and culture. For example, Microsoft became one of the biggest world-wide





Positive feedback dynamics are closely related to the butterfly effects [10] in the modern chaos theory. Tiny variations of initial conditions can produce an enormous variety of complex patterns in the long time limit. Out of numerous patterns, some patterns with superior fitness to the environments are selected via adaptations and settle down as new structures. It is inherently impossible to predict precisely which variations or mutations will produce patterns with higher fitness later on. So it is important to leave each variation evolved spontaneously and look carefully at the dynamic behavior of each variation during some time period.

companies during a very short period and controls most of software industry in the world. Many other venture companies are trying to follow the example of Microsoft with competition and cooperation. But the Windows operation system of Microsoft, cars with gasoline engines, VHS system for video recorders are holding a big market share, not because of their technical superiority to their competitors, but because of some accidental historic events and tiny difference of initial market share, interchangeability and connections with other products. Selection among patterns with higher fitness can be determined by accidental events and tiny difference of initial conditions.

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6. Summary

Science of complexity tries to understand the universal dynamic behavior of complex open systems including living systems, especially the emergence of new complex structures and patterns. However, the concept of complexity, emergence, adaptation, and life is not well explored yet and the quantification of complexity seems an extremely formidable task. Two key questions in the science of complexity may be: Where does the complex adaptive system try to reach ultimately via evolution and what is the underlying force for this dynamics? Of course, these questions are not answered yet and even there is no concrete clue available up to now, except for some elusive ones. Complex adaptive systems under strong environmental influence spontaneously organize themselves into criticality and incessantly increase the structural complexity through emergence of new and higher levels of structures. The direction of this dynamics seems to be opposite to the well-known thermodynamics for the closed systems, governed by the thermodynamic second law which drives the system incessantly more disordered. Unfortunately, this opposite driving force is not well understood. The present situation is similar to the chaotic situation in the mid-19 century, when the concept of heat was not well established with intensely hot debates and the natural direction of heat flow was not understood on the fundamental level. This problem has been settled down finally by Boltzmann who microscopically quantified the degree of disorder with the introduction of *Entropy* at the end of the century. Hence, it is clear what our mission will be in order to resolve the issue of another broken time symmetry in complex adaptive dynamics: Quantify the degree of complexity microscopically (hopefully) and find a new thermodynamic second law involving this quantified *Complexity*. Even though the science of complexity is not yet on a solid footing theoretically, it can still provide many useful implications in various disciplines and recently it has rapidly grown into a fascinating interdisciplinary science.

7. References

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