COMPLEXITY AND INNOVATION

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Summary

The work in the area of complex adaptive systems has been able to help in creating a general theoretical framework for innovation in the general context of evolutionary and adaptive learning processes. It also provides a paradigm that can lead to practical and new approaches to anticipate and manage innovative processes. The general tendency of

complex adaptive systems to self-organize into emerging super-structures that indirectly benefit participating sub-structures also gives us a strategic outlook about the type of innovative approaches that will be able to lead to sustainable modes of organizational behavior on a global scale.

1. Introduction

Concepts and universal principles of complex adaptive systems can be found in a large number of scales and areas of application. One of them is related to evolution and can be interpreted as "innovation” on different hierarchical levels both in natural as well as in artificial and social systems. In this article the claim is made that complex systems can provide a general framework for exploring the phenomenon “innovation” and within which innovation in the more traditional sense can be embedded as one specific manifestation.
In order to prepare the arguments in the following sections, different meanings of the terms “discovery", "invention”, and "innovation” are briefly recalled in the following. These terms are related but also differ significantly in their context and application. They do not necessarily imply each other, but often discoveries lead to inventions which then (sometimes) lead to innovations. In a discovery one increases the understanding of one or a group of previously unrelated phenomena.

This improved understanding often but not always can be used to construct a gadget that is novel and specific enough to be patented. For instance the discovery that burning gas expands and during the expansion can perform work eventually led to the invention of the internal combustion engine. On the other hand the discovery of the “beauty" quark has not -- and quite possibly never will -- lead to any invention. Sometimes inventions like Bell's telephone change the world but it probably is fair to say that most inventions never lead to a commercial product, although some of them might be marketed as “Chindogu" (Japanese for the art of useless inventions).

In contrast to those examples, the term “innovation" is usually reserved for "Any idea, practice, or object that is perceived as new by an adopter. These can be processes as well as tools." [Fichman, 1992, Doheney-Farina 1992, after [STTT, 1999]]. Another definition is "the situationally new development and introduction of knowledge-derived tools, artifacts, and devices by which people extend and interact with their environment" [Tornatzky & Fleischer's, 1990, p. 10 after [Prescott & Van Slyke, 1997]]. This definition implies that the innovation is "useful” in some sense for the adopter. Sometimes goal-directed behavior is required as well but here a weaker definition is adopted: it is only assumed that there exists a value function on the space of possible behaviors and that adopting the innovation increases this function value.

1.1. Generalized Fitness Functions

In different contexts the function that assigns values to types of behavior has been known under different names: In genetics it represents fitness, utility in economics, error functions in engineering, performance indices in motor learning, payoff in game theory , and power in politics. Some of these functions might not be rigorously defined but as long as each agent follows a local decision rule that will improve the generalized fitness value no explicit definitions are necessary. Of course these local decision rules that evolved through past evolution might not guarantee survival in a changed environment especially if those changes happen rapidly compared to evolutionary time scales.

Note that the words "maximize/minimize" have not been used specifically since such a strategy often is quite risky on longer time scales. For instance in natural evolution "super predators" such as saber- toothed tigers emerged at different times and independently on different continents. But apparently they all became extinct within a very short (on evolutionary scales) time. It seems to be a general rule that the more chaotically an environment changes the more successful are sub-optimal but less brittle evolutionary strategies.

The general rule for improved performance of a complex adaptive system seems to be that it is better to increase the probability of a desired behavior by assigning it a higher value for the fitness function than trying explicitly to specify any procedure that the system should follow. In Tom Ray's Tierra model computer programs were produced without specific design rules and with significant levels of errors but under the constraint of a fitness parameter (here utilizing computer resources). The surprising result was that after a relatively small number of generations, programs emerged that solved certain programming problems more efficiently than those written by human programmers did. It is interesting that the performance improvements were not simple monotone functions of time but showed similar behavior to other evolutionary systems sometimes referred to as "punctuated equilibrium".

1.1.1. Innovation and Evolution

In this paper the connection between innovation and learning is emphasized and the different time- scales that are characteristic for different stages in this process are discussed. In a very general way complex adaptive systems can be characterized by their capability of evolving in the sense of adapting to a changing environment. During evolutionary processes selection mechanisms favor those systems that have a higher rate of survival and reproduction. Although traditional biology worked under the assumption that those mechanism only apply to individuals, more recent evidence supports the claim that epigenetic traditions can emerge in animal as well as in human societies that support formation and selection of groups and larger social organizations.

1.1.2. Influence of Noise and Chaos

It is an interesting phenomenon that the degree of chaos in the environment itself can lead to adaptive changes: It is known that mutation rates (or error rates in transcribing DNA) for certain species change depending on the rate at which environmental conditions change. For environments that are fairly stable, reproduction errors decrease and higher levels of adaptation to the stable environment can be observed. In terms of technical innovations very similar patterns can be seen: Mobility and change in a country like Switzerland are very different from corresponding parameters in the US. Correspondingly one would not expect that innovations like mobile homes that would support a fast changing life style would be made in a country like Switzerland.

The feature of self-organizing computer programs like Tierra to be able to improve under the influence of stochastic fluctuations seems to be especially relevant in the domain of nano-computers where error rates are naturally much higher than in conventional electronic computers. There is very strong evidence that external fluctuations not only are tolerated by complex adaptive systems but that they are even systematically exploited to improve the system's generalized fitness parameter. For instance, in the phenomenon of stochastic resonance, signals received by sensory hair cell receptors of lobsters could be shown to display a higher performance in a noisy environment. This concept has been generalized to spatio-temporal stochastic resonance in which moving visual patterns can be enhanced in a noisy environment.

Deterministic chaotic dynamics can sometimes be actively used in strategies to simulate stochastic environments: Learning of patterns by neural networks can be accelerated using chaotic learning strategies. The performance of such a strategy can sometimes even be better than the stochastic strategy itself (simulated annealing) if the chaotic dynamics has been adapted to the intrinsic dynamics of the system using the concept of "dynamical key". In the context of organizational learning strategies including a limited amount of chaos can reduce the degree of predictability for competitors.

The perspective presented in this paper is admittedly very broad and goes well beyond the above mentioned, more specific definitions of the concept of innovation that is restricted to human behavior and organizations. From the perspective of complex systems there is no difference in innovations as the result of careful and methodological planning of intelligent inventors and those that are triggered by random events. As a matter of fact, even in innovations that were rewarded by the Nobel Prize chance events often played a crucial role.

1.2. Example from Physics: Bubble Chamber

One out of many examples is Donald Glaser’s invention of the bubble chamber to detect elementary particles for which he received the 1960 Nobel Prize in physics. He tells the story of how he got the main idea for his invention while he was watching how bubbles formed when he opened a bottle of beer. Of course most people could watch bubbles forming in beer bottles for a lifetime without inventing any new device. But in a way Glaser's brain was prepared for this discovery for two reasons: He was working on the problem of visualizing tracks of elementary particles and he had detailed experience in working with Wilson cloud chambers. The working principle of a cloud chamber is in a way opposite to that of a bubble chamber but the mechanisms of both devices are closely correlated.

During the fifties the elementary particle physics environment had changed by introducing more and more powerful particle accelerators, which required larger and larger cloud chambers to detect the traces of the reacting particles. It became clear that a continuous increase in the performance of the cloud chambers (by increasing their size) was not a sustainable strategy once they reached a size of tens ore even hundreds of meters in diameter. Thus there existed a large "evolutionary pressure" for the elementary particle physics community to come up with a qualitatively new concept, an innovation to solve the urgent problem.

Glaser's innovation started a new period of continuous improvement with a corresponding growth in size and mechanical complexity of bubble chambers. As a student in 1975 the present writer worked on the Big European Bubble Chamber (BEBC), probably the climax of that evolutionary branch. The sheer amount of the highly flammable liquid hydrogen (BEBC had reached the size of a comfortable living room) created enormous technical problems. This went all the way to the need for a hot line to the local airport to warn pilots in the case the hydrogen had to be released into the air. This size problem and especially the inflation of the number of tracks that needed to be analyzed built up the evolutionary pressure again until it was resolved with the invention of the electronic Charpak chamber, another innovation that was awarded a Nobel Prize.

This example illustrates the progression as an alternation of continuous improvement and intermittent innovations. The time-scales associated with both processes typically are quite different.

2. Innovation and Learning

In this paper innovation is discussed in the general context of learning. To this end some of the basic definitions of those terms are recalled here. Innovation can be understood as a novel way to solve a problem. Here the word "novel" is understood in a qualitative way: Any type of behavior can show a large variability and still be categorized into a discrete number of qualitatively different classes of behavior. For instance in general it is not difficult to discriminate "walking" from "running" as two classes of distinct types of behavior that each individually can have a vast multitude of variations. A technical innovation involves a qualitatively different method of solving problems and is not just an improved way of performing a previously existing process. There are certainly examples where this distinction is not very clear-cut. The fact that qualitative changes take place on all scales is one of the characteristic features of complex adaptive systems and is related to fractal structures and self-similarity.

The above definition of innovation can be applied at a multitude of levels and often involves the creation of new, specialized problems that need to be solved in order to improve the solution of a more general problem. For example the problem of producing extremely pure silicon crystals simply did not exist until it was recognized that this problem could be correlated to the age-old problem of improving the quality and speed of communication between humans over large distances. This example illustrates the multi-level complexity that is universally present for any innovative process.

The concept of learning as a persistent change of behavior is more general in the sense that it does not require novelty in the method of problem solving. In most cases learning will lead to a gradual improvement of the performance within the class of one existing strategy or behavioral pattern. It is claimed, however, that in any learning process some form of problem solving is involved and that performance of different behavioral patterns can be compared and measured with respect to a given task. In other words: Learning and innovation will not take place if there is not a payoff of some sort. This means that there exists a fitness function that assigns a single value to each behavioral pattern. This value measures its fitness in the context of the current environment.

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Biographical Sketch

Gottfried Josef Mayer holds a Ph.D. in theoretical physics from the University of Stuttgart. Dr. Mayer is a prolific author and leading thinker in the complexity sciences. Since 1995, he has served as Adjunct Associate Professor of Kinesiology at Pennsylvania State University and as a Visiting Professor at the Institute of Medical Psychology and Behavioral Neurobiology at the University of Tuebingen. Dr. Mayer also holds memberships at the Sante Fe Institute and the New England Complex Systems Institute. He is a past member of the editorial board of the *Princeton Series in Complexity* and is a founding editor of *Complexity Digest*, an on-line journal of timely information devoted to complexity issues (www.comdig.org).