THE SCIENCE OF SELF-ORGANIZATION AND ADAPTIVITY

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Contents

Summary

The theory of self-organization and adaptivity has grown out of a variety of disciplines, including thermodynamics, cybernetics and computer modelling. The present article reviews its most important concepts and principles. It starts with an intuitive overview, illustrated by the examples of magnetization and Bénard convection, and concludes with the basics of mathematical modelling. Self-organization can be defined as the spontaneous creation of a globally coherent pattern out of local interactions. Because of its distributed character, this organization tends to be robust, resisting perturbations. The dynamics of a self-organizing system is typically non-linear, because of circular or feedback relations between the components. Positive feedback leads to an explosive growth, which ends when all components have been absorbed into the new configuration, leaving the system in a stable, negative feedback state. Non-linear systems have in general several stable states, and this number tends to increase (bifurcate) as an increasing input of energy pushes the system farther from its thermodynamic equilibrium. To adapt to a changing environment, the system needs a variety of stable states that is large enough to react to all perturbations but not so large as to make its evolution uncontrollably chaotic. The most adequate states are selected according to their fitness, either directly by the environment, or by subsystems that have adapted to the environment at an earlier stage. Formally, the basic mechanism underlying self-organization is the (often noise-driven) variation which explores different regions in the system's state space until it enters an attractor. This precludes further variation outside the attractor, and thus restricts the freedom of the system's components to behave independently. This is equivalent to the increase of coherence, or decrease of statistical entropy, that defines self-organization.

1. Introduction

Science, and physics in particular, has developed out of the Newtonian paradigm of mechanics. In this worldview, every phenomenon we observe can be reduced to a collection of atoms or particles, whose movement is governed by the deterministic laws of nature. Everything that exists now has already existed in some different arrangement in the past, and will continue to exist so in the future. In such a philosophy, there seems to be no place for novelty or creativity.

Twentieth century science has slowly come to the conclusion that such a philosophy will never allow us to explain or model the complex world that surrounds us. Around the middle of the century, researchers from different backgrounds and disciplines started to study phenomena that seemed to be governed by inherent creativity, by the spontaneous appearance of novel structures or the autonomous adaptation to a changing environment. The different observations they made, and the concepts, methods and principles they developed, have slowly started to coalesce into a new approach, a science of self-organization and adaptation. The present article will first present a quick, intuitive overview of these developments, and then delve deeper into the abstract concepts and principles that came out of them.

2. The science of self-organization: a historical sketch

2.1. The thermodynamic paradox

The spontaneous emergence of new structures is easy to observe, both in the laboratory and in our day-to-day world. Perhaps the most common example is crystallization, the appearance of a beautifully symmetric pattern of dense matter in a solution of randomly moving molecules. A different example is the Bénard phenomenon, the appearance of a pattern of hexagonal cells or parallel rolls in a liquid heated from below. More complicated examples are certain chemical reactions, such as the Belouzov-Zhabotinsky reaction or the "Brusselator", where it suffices to constantly pump a number of ingredients into a solution in order to see the development of dazzling spirals of pulsating color.

What these examples have in common is *self-organization*: the appearance of structure or pattern without an external agent imposing it. It is as if the system of molecules arranges itself into a more ordered pattern. It was already noted that such a phenomenon contradicts the mechanistic worldview. But it does not fit into our intuitive picture of the world either. If a system, such as a flower, a building or a watch, shows organization we tend to assume that someone or something must have arranged the components in that particular order. If we cannot find a person responsible for the design, we are tempted to attribute it to some unknown, intelligent force. This intuition is confirmed by the second law of thermodynamics, which says that in a system left to itself entropy (disorder) can only increase, not diminish. So, the first step to explain self-organization must be to reconcile it with thermodynamics.

In the example of crystallization, the solution is simple. The randomly moving molecules which become fixed within the crystalline structure pass on the energy of their movement to the liquid in which they were dissolved. Thus, the decrease in entropy of the crystal is compensated by an increase in the entropy of the liquid. The entropy of the whole, liquid and crystal together, effectively increases.

In the case where the self-organizing system does not reach an equilibrium, the solution is less obvious. The Belgian thermodynamicist Ilya Prigogine received a Nobel Prize for his investigation, starting in the 1950s, of that problem. Together with his colleagues of the "Brussels School" of thermodynamics, he has been studying what he called *dissipative structures*. These are patterns such as the Bénard cells or the Brusselator, which exhibit dynamic self-organization. Such structures are necessarily open systems: energy and/or matter are flowing through them. The system is continuously generating entropy, but this entropy is actively *dissipated*, or exported, out of the system. Thus, it manages to increase its own organization at the expense of the order in the environment. The system circumvents the second law of thermodynamics simply by getting rid of excess entropy. The most obvious examples of such dissipative systems are living organisms. Plants and animals take in energy and matter in a low entropy form as light or food. They export it back in a high entropy form, as waste products. This allows them to reduce their internal entropy, thus counteracting the degradation implied by the second law.

2.2. Principles of self-organization

The export of entropy does not yet explain how or why self-organization takes place. Prigogine noted that such self-organization typically takes place in non-linear systems, which are far from their thermodynamic equilibrium state. The thermodynamicists' concrete observations of physical systems were complemented by the more abstract, high-level analysis of complex, autonomous systems in cybernetics. The first conference on self-organizing systems, held in 1959 in Chicago, was organized by the same multidisciplinary group of visionary scientists that had founded the discipline of cybernetics.

The British cybernetician W. Ross Ashby proposed what he called "the principle of self-organization". He noted that a dynamical system, independently of its type or composition, always tends to evolve towards a state of equilibrium, or what would now be called an *attractor*. This reduces the uncertainty we have about the system's state, and therefore the system's statistical entropy. This is equivalent to self-organization. The resulting equilibrium can be interpreted as a state where the different parts of the system are mutually adapted.

Another cybernetician, Heinz von Foerster, formulated the principle of "order from noise". He noted that, paradoxically, the larger the random perturbations ("noise") that affect a system, the more quickly it will self-organize (produce "order"). The idea is very simple: the more widely a system is made to move through its state space, the more quickly it will end up in an attractor. If it would just stay in place, no attractor would be reached and no self-organization could take place. Prigogine proposed the related principle of "order through fluctuations". Non-linear systems have in general several attractors. When a system resides in between attractors, it will be in general a chance variation, called "fluctuation" in thermodynamics, that will push it either into the one or the other of the attractors.

2.3. Various applications

Since the 1950s and 1960s, when self-organizing systems were first studied in thermodynamics and cybernetics, many further examples and applications have been discovered. Prigogine generalized his observations to argue for a new scientific worldview. Instead of the Newtonian reduction to a static framework ("Being"), he sees the universe as an irreversible "Becoming", which endlessly generates novelty. The cyberneticians went on to apply self-organization to the mechanisms of mind. This gave them a basis for understanding how the brain constructs mental models without relying on outside instruction.

A practical application that grew out of their investigations is the so-called "neural networks", simplified computer models of how the neurons in our brain interact. Unlike the reasoning systems used in artificial intelligence, there is no centralized control in a neural network. All the "neurons" are connected directly or indirectly with each other, but none is in control. Yet, together they manage to make sense out of complex patterns of input.

The same phenomenon, a multitude of initially independent components, which end up working together in a coherent manner, appears in the most diverse domains. The production of laser light is a key example of such collective behavior. Atoms or molecules that are excited by an input of energy emit the surplus energy in the form of photons. Normally, the different photons are emitted at random moments in random directions. The result is ordinary, diffuse light. However, under particular circumstances the molecules can become synchronized, emitting the same photons at the same time in the same direction. The result is an exceptionally coherent and focused beam of light. The German physicist Hermann Haken, who analyzed lasers and similar collective phenomena, was struck by the apparent cooperation or synergy between the components. Therefore, he proposed the new discipline of *synergetics* to study such phenomena.

Another example of spontaneous collective behavior comes from the animal world. Flocks of birds, shoals of fish, swarms of bees or herds of sheep all react in similar ways. When avoiding danger, or changing course, they move together in an elegantly synchronized manner. Sometimes, the swarm or shoal behaves as if it were a single giant animal. Yet, there is no "head fish" or "bird leader", which coordinates the others and tells them how to move. Computer simulations have reproduced the behavior of swarms by letting the individuals interact according to a few simple rules, such as keeping a minimum distance from others, and following the average direction of the neighbors' moves. Out of these local interactions a global, coherent pattern emerges.

2.4. Complex adaptive systems

Swarms are but one of the many self-organizing systems that are now being studied through computer simulation. Whereas before it was very difficult to mathematically model systems with many degrees of freedom, the advent of inexpensive and powerful computers made it possible to construct and explore model systems of various degrees of complexity. This method is at the base of the new domain of "complex adaptive systems", which was pioneered in the 1980s by a number of researchers associated with the Santa Fe Institute in New Mexico. These complexity theorists study systems consisting of many interacting components, which undergo constant change, both autonomously and in interaction with their environment. The behavior of such complex systems is typically unpredictable, yet exhibits various forms of adaptation and self-organization.

A typical example is an ecosystem, consisting of organisms belonging to many different species, which compete or cooperate while interacting with their shared physical environment. Another example is the market, where different producers compete and exchange money and goods with consumers. Although the market is a highly chaotic, non-linear system, it usually reaches an approximate equilibrium in which the many changing and conflicting demands of consumers are all satisfied. The failure of communism has shown that the market is much more effective at organizing the economy than a centrally controlled system. It is as if a mysterious power ensures that goods are produced in the right amounts and distributed to the right places. What Adam Smith, the father of economics, called "the invisible hand" can nowadays simply be called self-organization.

The biologist Stuart Kauffman studied the development of organisms and ecosystems. By computer simulation, he has tried to understand how networks of mutually activating or inhibiting genes can give rise to the differentiation of organs and tissues during embryological development. This led him to investigate the types and numbers of attractors in Boolean networks that represent the pattern of connection between genes. He proposed that the self-organization exhibited by such networks is an essential factor in evolution, complementary to Darwinian selection. Through simulations, he showed that sufficiently complex networks of chemical reactions will necessarily self-organize into autocatalytic cycles, the precursors of life.

Whereas self-organization allows a system to develop autonomously, natural selection is responsible for its adaptation to a variable environment. Such adaptation has been studied most extensively by John Holland, one of the complexity theorists associated with the Santa Fe Institute. By generalizing from the mechanisms through which biological organisms adapt, he founded the theory of genetic algorithms. This is a general approach to computer problem-solving that relies on the mutation and recombination of partial solutions, and the selective reproduction of the most “fit” new combinations. By allowing the units that undergo variation and selection to interact, through the exchange of signals or “resources”, Holland has extended this methodology to model cognitive, ecological and economic systems. These interactions allow simple units to aggregate into complex systems with several hierarchical levels.

Both Holland's and Kauffman's work have provided essential inspiration for the new discipline of *artificial life*. This approach, initiated by Chris Langton, has successfully developed computer programs that mimic lifelike properties, such as reproduction, sexuality, swarming, co-evolution and arms races between predator and prey.

3. Characteristics of self-organizing systems

The different studies which we reviewed have uncovered a number of fundamental traits or “signatures”, that distinguish self-organizing systems from the more traditional mechanical systems studied in physics and engineering. Some of these traits, such as the absence of centralized control, are shared by all self-organizing systems, and can therefore be viewed as part of what defines them. Other traits, such as continual adaptation to a changing environment, will only be exhibited by the more complex systems, distinguishing for example an ecosystem from a mere process of crystallization. These traits will now be discussed one by one, starting from the most basic ones, as a prelude to a deeper analysis of the principles of self-organization.

3.1. Two examples: magnetization and Bénard rolls

To make things more concrete, it is useful to keep in mind two basic examples of self-organizing systems. Perhaps the simplest such process that has been extensively studied is magnetization. A piece of potentially magnetic material, such as iron, consists of a multitude of tiny magnets, called “spins” (see Figure 1). Each spin has a particular orientation, corresponding to the direction of its magnetic field. In general, these spins will point in different directions, so that their magnetic fields cancel each other out. This disordered configuration is caused by the random movements of the molecules in the material. The higher the temperature, the stronger these random movements affecting the spins, and the more difficult it will be for any ordered arrangement of spins to maintain or emerge.

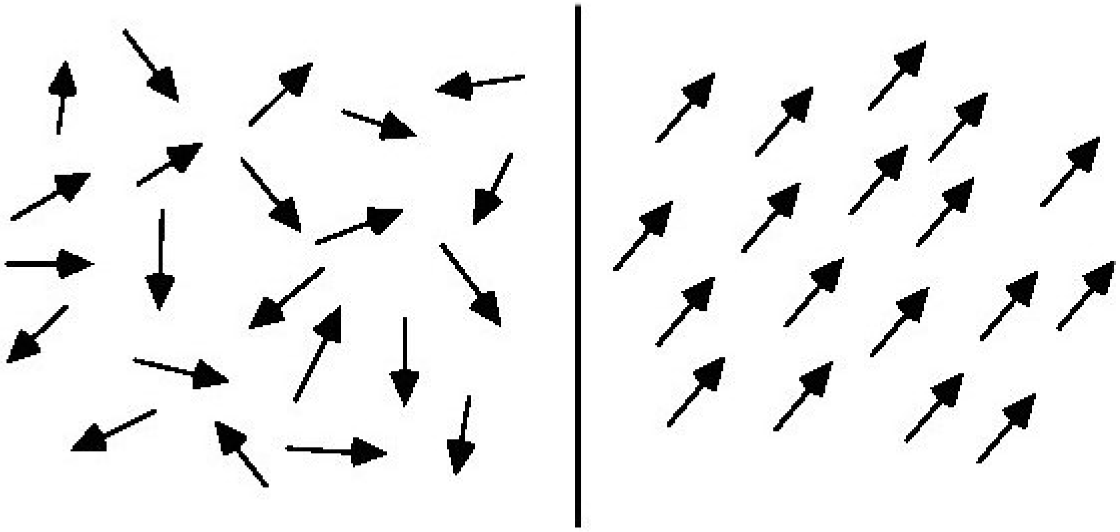

Figure 1: Two arrangements of spins: disordered (left) and ordered (right)

However, when the temperature decreases, the spins will spontaneously align themselves, so that they all point in the same direction. Instead of canceling each other, the different magnetic fields now add up, producing a strong overall field. The reason that the spins "prefer" this ordered arrangement is because spins pointing in opposite directions repel each other, like the North poles of two magnets that are brought together.

Spins pointing in the same direction, on the other hand, attract each other, like the North pole of one magnet attracts the South pole of another magnet. Magnetization is a clear case of self-organization, which can be used as a paradigm for a whole range of similar phenomena, such as crystallization (where not only the orientations but also the positions of the molecules become evenly arranged).

A somewhat more complex example will illustrate further characteristics of self-organization. In the Bénard phenomenon, a liquid is heated evenly from below, while cooling down evenly at its surface, like the water in an open container that is put on an electric hot-plate. Since warm liquid is lighter than cold liquid, the heated liquid tries to move upwards towards the surface.

However, the cool liquid at the surface similarly tries to sink to the bottom. These two opposite movements cannot take place at the same time without some kind of coordination between the two flows of liquid. The liquid tends to self-organize into a pattern of hexagonal cells, or a series of parallel "rolls", with an upward flow on one side of the roll or cell and a downward flow on the other side.

This example is similar to the magnetization in the sense that the molecules in the liquid were moving in random directions at first, but end up all moving in a coordinated way: all "hot" molecules moving upwards on one side of the roll, all "cool" molecules downwards on the other side (see Figure 2). The difference is that the resulting pattern is not static but dynamic: the liquid molecules remain in perpetual movement, whereas the magnetic spins are "frozen" in a particular direction.

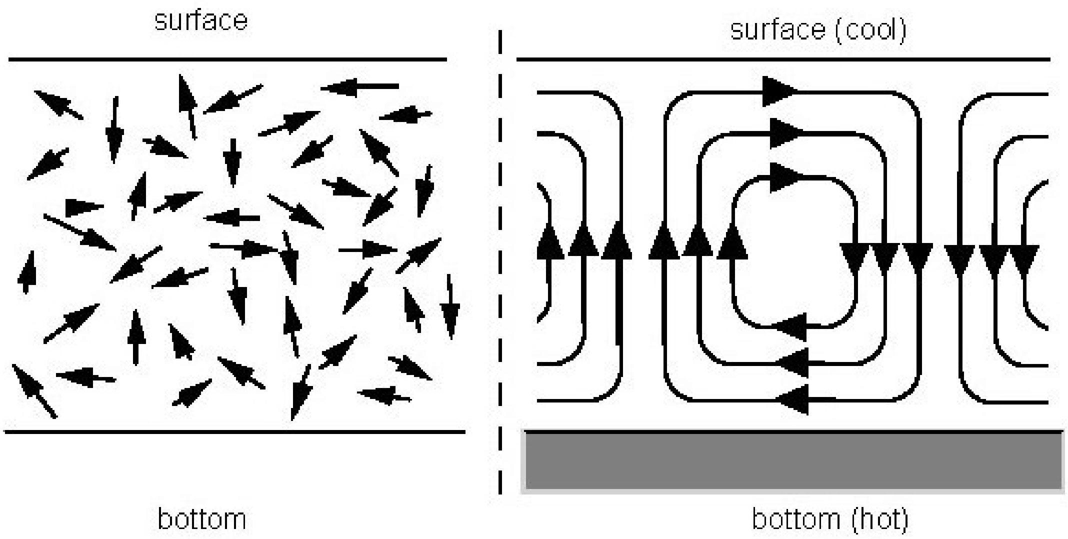

Figure 2: Two types of movements of liquid molecules: random (left) and in the form of Bénard rolls (right)

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Biographical Sketch

Dr. Francis Heylighen received his university degree in mathematical physics in 1982, and his Ph.D. in 1987, both with the highest distinction, from the Free University of Brussels (VUB). He is presently a Research Associate for the Fund for Scientific Research - Flanders and an Associate Director of the transdisciplinary research Center "Leo Apostel" at the VUB. He has been working at the VUB since 1982, first on the foundations of physics (quantum mechanics and relativity theory), then on the cognitive and systems sciences. The main focus of his research is the evolution of complexity, which he studies from a cybernetic viewpoint. He has worked in particular on the evolutionary development of knowledge and the creation of new concepts and models. More recently, he has extended the underlying principles to understand the evolution of society, and its implications for the future of humanity. Together with his collaborator Johan Bollen, Dr. Heylighen has applied this framework by implementing a self-organizing knowledge web, that "learns" new concepts and associations from the way it is used. As such, it forms a simple model for a future intelligent computer network, the "global brain". Dr. Heylighen has authored some 70 scientific publications, mainly in cognitive science, cybernetics and systems theory, including a monograph and four edited books. He is a member of the editorial boards of the Journal of Memetics, which he co-founded in 1996, and the journals Informatica and Entropy, and has been a referee for various other journals. He is editor of the "Principia Cybernetica Project", an international organization which attempts to consensually develop a cybernetic philosophical system on the web (http://pespmc1.vub.ac.be/). He has organized and chaired many international conferences, symposia and seminars, and is regularly invited to lecture about his work in different countries.