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Introduction to Self-Organization

Self-organization is not an invention; nor was it developed by an engineer. The principles of self-organization evolved in nature before we finally managed to study and apply these ideas to technical systems. The first articles on self-organization date back to the early 1960s. Ashby (1962) and von Foerster (1960) analyzed self-organizing mechanisms and Eigen and Schuster (1979) finally made the term 'self-organization' popular in natural and engineering sciences. Meanwhile, various application scenarios for self-organization methods have been identified. Nevertheless, the term 'self-organization' and its context and meaning are still often misused or misunderstood.

One common ambiguity is the essentially different meanings of 'self-organization' and 'bio-inspired'. We will discuss this difference in more detail in Section 4.3. In short, self-organization is a general paradigm for operation and control of massively distributed systems. We can observe many examples of self-organization in nature and many proposed solutions in this domain have their roots in biological mechanisms, and thus can be named bio-inspired. Nevertheless, self-organization is only one example of bio-inspired algorithms. Additionally, not all self-organization techniques are related to bio-inspired research. An introduction to bio-inspired methods in the context of self-organization is provided in Part V.

In the domain of networked computers, different control concepts have been developed. Starting with monolithic, centralized controlled systems, the demand for improved scalability and simplified deployment strategies was growing. The research domain of distributed systems is working on such solutions. Novel approaches lead to control and collaboration paradigms that show the same behavior as that described for self-organizing systems (Gershenson and Heylighen 2003). Their common objective is to reduce global state information by achieving the needed effects based on local information or probabilistic approaches only. Most of these solutions are using, whether explicitly or implicitly, methodologies similar to biological systems. Even though bio-inspired algorithms represent a novel research domain, first reviews and surveys of such approaches are already available (Dressler 2006b; Prehofer and Bettstetter 2005).

The main goal of this chapter is to analyze the concepts behind self-organization, its applicability and its limitations. Additionally, we develop a comprehensive definition of

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'self-organization' out of various former approaches. This clarification, together with a summary of properties and capabilities of self-organizing systems, will hopefully lead to a deeper understanding of self-organization in general and its applicability in the context of Sensor and Actor Networks (SANETs) in particular.

1.1 Understanding self-organization

The term 'self-organization' refers to a specific control paradigm for complex systems. Eigen and Schuster (1979) investigated the main concepts behind self-organization in the context of natural – mostly biological – systems and tried to transfer methods and techniques to control mechanisms for technical systems. Basically, he discovered that systems consisting of huge numbers of subsystems need some kind of controlled autonomy that enables a proper functioning in a highly scalable system. Similarly, self-organization mechanisms are required if systems need to face changing environmental conditions or have to adapt to previously unknown application scenarios. If a system is able to fulfill the described requirements, i.e. if it is scalable and adaptive (we will later discuss the meaning of scalability and adaptivity in detail) and if it does not rely on external control, the system is said to be self-organizing.

One of the first definitions of self-organization by Yates *et al*. (1987) characterizes self-organization as follows: 'Technological systems become organized by commands from outside, as when human intentions lead to the building of structures and machines. But many natural systems become structured by their own internal processes: these are the self-organizing systems, and the emergence of order within them is a complex phenomenon that intrigues scientists from all disciplines.' Thus, he already discovered some of the hidden properties of self-organization: completely decentralized control, emerging structures and a high complexity of the overall system.

A particular feature of self-organizing systems was discovered by many researchers in this field: the operation principles always lead to a globally visible effect – the creation of patterns. Depending on the application scenario (we will discuss some basic scenarios in the next subsection), such patterns might be directly visible based on observations of the environment. In other cases, such patterns appear if the system and the environment that it operates in are studied more closely in order to see effects such as the – pattern-like – change of system parameters or environmental conditions.

There are many examples visible in our everyday life. The most cited examples are perhaps the oscillating reactions of the Belousov-Zhabotinskiy reaction (Winfree 1972). The oscillation occurs due to two simultaneously conducted processes: reaction and diffusion. These processes cause a system in which the concentrations of reactants and products oscillate temporally and spatially. These oscillations lead to the creation of spectacular patterns, such as those shown in Figure 1.1.[1]

Based on the described observations, Camazine *et al*. (2003) developed the following definition for self-organization:'Self-organization is a process in which pattern at the global level of a system emerges solely from numerous interactions among the lower-level components of a system. Moreover, the rules specifying interactions among the systems'

[1] http://www.swisseduc.ch/chemie/orderchaos/

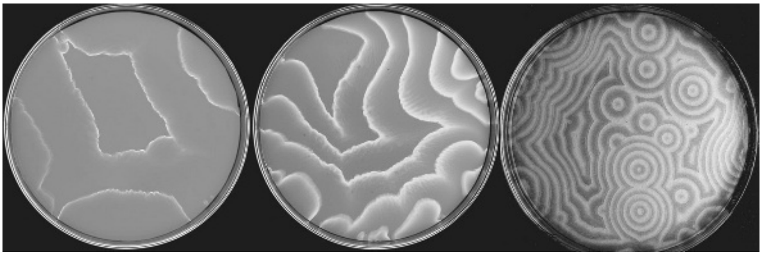

Figure 1.1 Pattern formation in the Belousov-Zhabotinskiy reaction [Reproduced by permission of Juraj Lipscher]

Table 1.1 Properties of self-organizing systems

Property	Description
No central control	There is no global control system or global information available. Each subsystem must perform completely autonomously.
Emerging structures	The global behavior or functioning of the system emerges in the form of observable patterns or structures.
Resulting complexity	Even if the individual subsystems can be simple and perform basic rules, the resulting overall system becomes complex and often unpredictable.
High scalability	There is no performance degradation if more subsystems are added to the system. The system should perform as requested, regardless of the number of subsystems.

components are executed using only local information, without reference to the global pattern.' This definition takes into consideration that the effect of self-organization, i.e. the result of the interactions between the systems' components, can be described by an observable pattern. Additionally, it explicitly denies global state information that would allow each system to analyze the current (global) pattern and to modify its internal parameterization according to an overall goal.

So far, self-organization was discussed in a fairly sketchy way. In order to understand the meanings of self-organization and how to develop self-organizing systems, a more detailed discussion on principles, mechanisms and operation methods is necessary. Nevertheless, some outstanding properties of self-organizing systems can already be summarized as shown in Table 1.1.

1.2 Application scenarios for self-organization

Self-organization can be found in every stretch of our life. Essentially, self-organization as the key paradigm applies to all aspects of system control. Nevertheless, there are many scenarios in which self-organization is not the optimal solution. Before discussing the limitations of self-organization in a further section, we will try to become more familiar with self-organization and its usual application scenarios.

Basically, it can be said that self-organization can be found in all kinds of system control whenever properties described in Table 1.1 must be considered. Generally, self-organization is always employed for the operation and control of complex systems that consist of numerous subsystems. Such systems can be individuals building a loose group or subsystems that cannot be separated without harming the global system.

Most often cited examples of natural self-organization are swarms of animals (Bonabeau *et al*. 1999; Kennedy and Eberhart 2001), the cellular signaling pathways studied in molecular biology (Alberts *et al*. 1994) and the mammalian immune system (Janeway *et al*. 2001). These natural application scenarios fit very well in the context of self-organization as the key paradigm for operation and control. Swarms of animals such as ants, bees or fishes represent loosely coupled systems of a huge number of subsystems. A control mechanism is required in order to enable the swarm to fulfill global tasks such as foraging. In this context, each individual works on its own intention but collaborates on a global task.

Differently, cells in an organism are tidily coupled. In this context, self-organization can be found in two system aspects. First, the development of the organism is said to be self-organizing because there is no central control that determines which cell has to be created at which time. Secondly, the communication between the cells, i.e. the so-called signaling pathways, is strongly self-organizing. Without a global communication plan such as well known paths, signals are efficiently transmitted to appropriate destinations. This enables the cellular system to perform common tasks without reference to each other.

The mammalian immune system also represents a massively distributed detection device that searches for known and unknown anomalies and attacks against the body. After a successful detection, countermeasures are initiated. All these activities are done without direct reference to a global goal and without expensive coordination. Nevertheless, biology is not the only domain in which natural self-organization can be found. Examples can be found in physics or chemistry as well (Winfree 1972).

As this book aims to support and improve the understanding of self-organization in more technical domains, the application of self-organization should be extended to technical systems. Independently from the specific application scenario, self-organization helps if huge numbers of subsystems are to be managed and controlled and if there is no possible way to provide global state information, e.g. due to limited communication pathways. A well known example that is obviously self-organizing is the Internet. The increasing number of end systems, which are efficiently participating on a loosely coupled compound of autonomous networks, is supported. With yet higher numbers of inter-networked systems and less reliant communication media, the demand for self-organization techniques is increasing. Ad hoc networks, wireless sensor networks, and sensor and actor networks represent such systems. The common objective is to reduce global state information by achieving the needed effects based on local information or probabilistic approaches only. Thus, the inter-networking between huge numbers of devices with possibly limited communication resources increases the demand for well understood self-organization techniques.

Similarly, the robotics community searches for adequate methods to control the behavior of the robot systems. In addition to the requirements for the communication between the individual machines, task and resource allocation algorithms are needed to operate a distributed system consisting of several robots.