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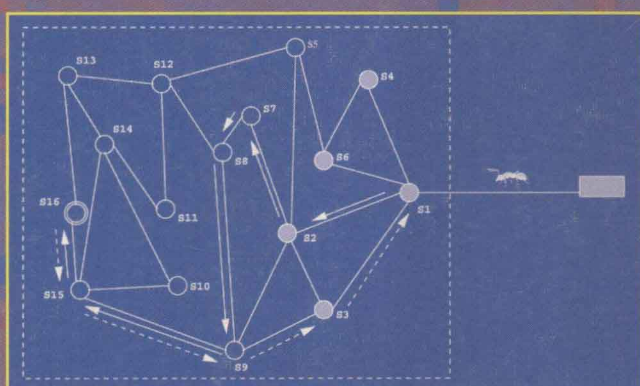
Giovanna Di Marzo Serugendo
Anthony Karageorgos
Omer F. Rana
Franco Zambonelli (Eds.)

Engineering Self-Organising Systems

Nature-Inspired Approaches to Software Engineering



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Nature-Inspired Approaches to Software Engineering

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Preface

The spread of the Internet, mobile communications and the evolution of traditional market models, such as the proliferation of e-commerce, has led to much existing IT infrastructure operating as a global dynamic system. It is therefore important that software that operates over this infrastructure adapt accordingly, to provide highly customised services to a huge user population. New maintenance requirements have to be met, for example software that cannot be stopped must still evolve. Furthermore, software must cope with changes in interconnectivity requirements, such as network topology workload fluctuations, mobility of devices, node failures, and interoperation of unreliable, possibly erroneous distributed code.

As information handling systems get more complex, it becomes more difficult to manage them using traditional approaches based on centralised and predefined control mechanisms. Over recent years there has been a significant increase in interest in taking inspiration from biology, the physical world, chemistry, or social systems to more effectively manage such systems – generally based on the concept of Self-organisation. This gave rise to Self-organising Applications (SOA) – generally applications that undertake problem solving (in a particular application domain) based on distributed interactions between uncoupled system components. Typical examples of such distributed interactions in SOA include systems that reproduce behaviours of social insects or multicellular organisms. Another example is multiagent systems that aim to reproduce behaviours found in human societies – thereby providing a useful paradigm for managing large, distributed information handling systems. In multiagent systems self-organising behaviour results from the autonomous behaviour of system components and the locality of their interactions. The key characteristic of all these applications is their ability to achieve complex collective tasks with relatively simple individual behaviours.

There is currently a consensus that modern applications can gain in robustness, management, and simplicity if they are developed according to the principles of self-organisation (which one finds in nature). The central question related to the engineering of SOA is how to specify the local behaviours of individual components to achieve the desired (self-organising) global system behaviour. This involves, in particular, defining a global goal, designing local behaviours and interactions that will result in the desired global behaviour. Subsequently, it is necessary to monitor system execution to verify the emergence of the correct system behaviour, and the achievement of the global goal. This is a difficult exercise because the global system behaviour is not directly predictable as the "sum" of the local behaviours. It is also important to note that self-organisation is not useful in all instances – as it may lead to "parasitic" and unwanted behaviours. The need to monitor the system as it evolves from some initial state is therefore an important requirement in many applications that make use of self-organising principles.

Traditional software engineering methodologies also make it possible to define a global behaviour only as a closed function of the behaviour of the various parts of the system. They involve techniques based on assumptions, such as interfaces fixed at design time and statically established ontologies, which therefore makes them insufficient for engineering self-organisation. Furthermore, traditional practices in multiagent systems have introduced basic techniques for autonomously interacting or retrieving information, such as agent coordination, service description, and ontology-based interaction. However, these techniques rely on preprogrammed interaction patterns, preventing large-scale adaptation to unexpected environmental changes.

Current engineering practices that directly address self-organisation primarily involve designing distributed algorithms according to natural life metaphors, such as the social insect metaphor and the immune system. More recently, appropriate interaction mechanisms and middleware technologies specifically targeting the development of self-organising applications have been introduced. However, many issues such as verification and systematic methodologies covering the whole engineering life cycle still remain open.

This book intends to serve as a reference and starting point for establishing the field of *Engineering Self-Organising Applications*. It comprises papers presented at the Engineering Self-Organising Applications (ESOA 2003) workshop (held at the Autonomous Agents and Multi-Agents Systems conference (AAMAS 2003) in Melbourne in July 2003), and selected invited papers from leading contributors in the self-organisation field.

The book presents the current state-of-the-art perspective on the field. Part I contains several papers related to self-organising applications: Di Marzo Serugendo et al. review natural self-organising systems and their interaction mechanisms and discuss several examples of artificial self-organising applications; Brueckner et al. present SWARMing principles applied to mobile ad hoc networks; Thompson then discusses the use of self-organising systems for agent-based implementations.

In Part II, translations from a diverse collection of natural-life metaphors are presented. Naghpal presents self-organising principles from multicellular organisms and their application to multiagent systems. Tateson et al. apply self-organising behaviour of cells in a developing fruit fly to wireless communication networks. Guo et al. present a genetic algorithm for designing self-assembling objects. This is followed by two papers inspired from ant-based behaviour properties such as indirect communication of interacting entities via the environment (stigmetry): Handl et al. apply ant mechanisms in data set clustering, and Hadeli et al. in manufacturing control. Foukia et al. combine ant-based behaviour and the immune system metaphor to build an intrusion detection and response system in a computer network. Ulieru et al. design logistics infrastructures based on the holonic structure of the Universe. Subsequently, Babanov et al. take their

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inspiration from evolutionary computation to build an additional layer on top of heterogeneous strategies in electronic markets.

Part III describes artificial self-organisation mechanisms specifically introduced for computer systems applications. Capera et al. propose an adaptive multiagent system theory for providing self-organising behaviour in mechanical design. Hales et al. propose the notion of tags, a marking attached to agents and observable by other agents, as an interaction mechanism for realising self-organisation. Yolum et al. then establish the notion of trust as a self-organising mechanism in referral networks.

In Part IV, self-organisation specific to coordination models is discussed by Menezes et al. in the case of the Linda-based systems. Along this line, Mamei et al. describe the TOTA coordination environment propagating tuples according to a propagation rule.

Part V concludes the book with methods and tools for engineering emergent behaviour. Airiau et al. discuss the COllective INtelligence framework for accessing shared resources among several users. Jelasity et al. describe simple components that can be combined to implement complex functions. Finally, Bernon et al. present the Adelfe methodology that guides a programmer during the design of SOA.

December, 2003

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Self-Organisation: Paradigms and Applications

Giovanna Di Marzo Serugendo, Noria Foukia, Salima Hassas, Anthony Karageorgos, Soraya Kouadri Mostéfaoui, Omer F. Rana, Mihaela Ulieru, Paul Valckenaers, and Chris Van Aart

Engineering Self-Organising Applications Working Group
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Abstract. A self-organising system functions without central control, and through contextual local interactions. Components achieve a simple task individually, but a complex collective behaviour emerges from their mutual interactions. Such a system modifies its structure and functionality to adapt to changes to requirements and to the environment based on previous experience. Nature provides examples of self-organisation, such as ants food foraging, molecules formation, or antibodies detection. Similarly, current software applications are driven by social interactions (negotiations, transactions), based on autonomous entities or agents, and run in highly dynamic environments. The issue of engineering applications, based on the principles of self-organisation to achieve robustness and adaptability, is gaining increasing interest in the software research community. The aim of this paper is to survey natural and artificial complex systems exhibiting emergent behaviour, and to outline the mechanisms enabling such behaviours.

Keywords: Self-organisation, self-organising application, emergence, collective behaviour, multi-agent systems.

1 Introduction

The study of self-organising systems is a field that has been explored at least since 1953 with the work done by Grassé [25], who studied the behaviour of insect societies. Many systems in nature demonstrate self-organisation, such as planets, cells, organisms and societies. All these systems exhibit recurrent properties inherent to self-organisation. The simplest form of self-organisation can be achieved by the arrangement of parts of a system in such a way as to be non-random. Considerable research has already been undertaken to study such systems. Self-organising systems are often encountered in many scientific areas including biology, chemistry, geology, sociology, and information technology.

A large number of software self-organising systems are designed based on natural mechanisms of self-organisation. Furthermore, recent research has been oriented towards introducing self-organisation mechanisms specifically for software applications, as well as entire development techniques supporting self-organisation [19]. This trend originates from the fact that current software applications need to cope with requirements and constraints stemming from the

G. Di Marzo Serugendo et al. (Eds.): AAMAS 2003 Ws ESOA, LNAI 2977, pp. 1–19, 2004.

increased dynamism, sophisticated resource control, autonomy and decentralisation inherent in contemporary business and social environments. The majority of these characteristics and constraints are the same as those which can be observed in natural systems exhibiting self-organisation.

This survey firstly defines self-organisation, and presents examples of self-organising systems taken from natural life. Subsequently, it describes the different mechanisms enabling social, natural and artificial organisations to achieve a coherent global behaviour. Finally, it reviews several software applications exhibiting a self-organising behaviour.

2 Self-Organising Systems

The notion of self-organisation is popular in many different research fields. Therefore, it is difficult to find a precise and concise definition of what is the meaning of the term self-organisation. However, it seems that similar properties are apparent and recurrent among the different definitions and research fields referring to self-organisation. The next sub-section defines what are the inherent characteristics of self-organisation. Subsequently, the following sub-sections describe a number of different types of self-organising systems. It is not the intention of this paper to provide an exhaustive review of all types of self-organising systems. Instead, self-organising systems are classified in three broad categories: physical, living and social systems. For each category a representative example is described.

2.1 Definition

Intuitively, self-organisation refers to the fact that a system's structure or organisation appears without explicit control or constraints from *outside* the system. In other words, the organisation is intrinsic to the self-organising system and results from *internal* constraints or mechanisms, due to *local interactions* between its components [11]. These interactions are often *indirect* thanks to the environment [25]. The system dynamics modifies also its *environment*, and the modifications of the external environment influence in turn the system, but without disturbing the internal mechanisms leading to organisation. The system evolves *dynamically* [9] either in time or space, it can maintain a stable form or can show transient phenomena. In fact, from these interactions, *emergent* properties appear transcending the properties of all the individual sub-units of the system [30]. One well-known example is that of a colony of ants sorting eggs without having a particular ant knowing and applying the sorting algorithm. The emergence is the fact that a structure, not explicitly represented at a lower level, appears at a higher level. With *no central control*, a complex collective behaviour raises then from simple local individual interactions. More generally, the field of complex systems studies emergent phenomenon, and self-organisation [8].

2.2 Physical Systems

A characteristic of physical self-organising systems is that many of them present a so called *critical value* in which the state of the system changes suddenly to another state under certain conditions (temperature, pressure, speed, ...). Thus, self-organisation is observed *globally* when the physical system moves from a chaotic disordered state to a stable one. For instance, a thermodynamic system such as a gas of particles has emergent properties, temperature and pressure, that do not derive from the description of an individual particle, defined by its position and velocity. Similarly, chemical reactions create new molecules that have properties that none of the atoms exhibit before the reaction takes place [8]. Moreover, the magnetisation of a multitude of spins[1] is a clear case of self-organisation because, under a certain temperature, the magnetic spins spontaneously rearrange themselves pointing all in the same direction thanks to a strong emerging magnetic field.

2.3 Living Systems

A scientific aspect in the study of living organisms is the determination of invariant in the evolution of natural systems. In particular the spontaneous appearance of an order in living complex systems due to the self-organisation. In the optic of biological research, the global emergence of a behaviour or a feature that can not be reduced to the properties of each system's component (molecules, agents, cells, ...) defines also the common meaning of self-organisation. One example described in [43] is the self-organisation of the cytoskeleton thanks to collective processes of reaction and diffusion of the cytoskeletal filaments. The cytoskeleton is the basis of the internal architecture of the cytoplasm of eukaryotic cells. Eukaryotic cells are cells of the higher organisms, containing a true nucleus bounded by a nuclear membrane. These cells are founded in animals and plants. Eukaryotic cells are often organised into organs to create higher levels of complexity and function thanks to metabolic processes. The obtained organ has a defined functionality that transcends all the functionality offered by each of its constitutive cells. These cells are the basic functioning units of life and evolve in step through external changes with the environment. These units of life (cells) have to use internal metabolic processes such as mutation or natural selection, to adapt to natural life's evolution. This is also the result of the self-organisation of cells. Other examples in human body are the human nervous system, or the immune system. Such living systems transparently manage vital functions, such as blood pressure, digestion, or antibodies creation.

2.4 Social Systems

Social insects organise themselves to perform activities such as food foraging or nests building. Cooperation among insects is realised through an indirect

[1] A spin is a tiny magnet.

communication mechanism, called stigmergy, and by interacting through their environment. Insects, such as ants, termites, or bees, mark their environment using a chemical volatile substance, called the pheromone, for example, as do ants to mark a food trail. Insects have simple behaviour, and none of them alone "knows" how to find food but their interaction gives rise to an organised society able to explore their environment, find food and efficiently inform the rest of the colony. The pheromonal information deposited by insects constitutes an indirect communication means through their environment.

Apart from animal societies, human beings organise themselves into advanced societies. Human beings use direct communication, they engage in negotiation, build whole economies and organise stock markets.

3 Self-Organising Mechanisms

This section presents the major self-organising mechanisms used in natural and software systems to achieve self-organisation.

3.1 Magnetic Fields

A self-organisation phenomenon has been studied in the structure of a piece of potentially magnetic material. A magnetic material consists of a multitude of tiny magnets or spins. The spins point in different directions cancelling their respective magnetic fields. At a lower level, the orientation of the spins is due to the random movements of the molecules in the material: the higher the temperature, the stronger these random movements of the molecules in the material. These molecular movements affect the spins making them difficult to orient in an ordered way. However, if the temperature decreases the spins spontaneously point in the same direction. In this case, the different magnetic fields now add up, producing a strong overall field. Magnetisation exhibits self-organisation because the orientation of the spins is variable and depends on the local neighbourhood. Under low temperature, the force between neighbouring spins is dominating and they tend to build order. Similar phenomena, are observed in the crystallisation from a liquid state, which is another common example of self-organisation.

3.2 Kohonen Neural Networks

Kohonen neural networks, also called self-organising maps, are useful for clustering applications [36]. They take their inspiration from brain cells, which are activated depending on the subject's location. Such a network is made of two neurons layers (input, and output), and usually follows a regular two-dimensional grid of neurons. This grid represents a topological model of the application to cluster. Indeed, the network maps similar data to the same, or adjacent, node of the grid, by projecting multi-dimensional vectors of data onto a two-dimensional regular grid, preserving the data clustering structure.