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Giovanna Di Marzo Serugendo
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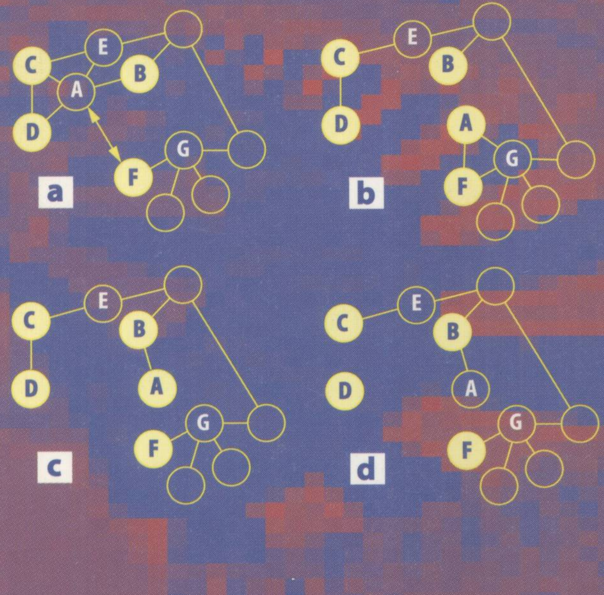
Radhika Nagpal (Eds.)

Engineering Self-Organising Systems

Methodologies and Applications



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Lecture Notes in Artificial Intelligence 3464

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Preface

The spread of the Internet, mobile communications and the proliferation of new market models, such as e-commerce, has resulted in the whole information infrastructure operating as a global dynamic system. The complexity and the inherent dynamism of the resulting global system require software capable of autonomously changing its structure and functionality to meet dynamic changes in the requirements and the environment without immediate human intervention. In particular, contemporary software applications must provide highly customised services to a huge user population by dynamically adapting to personal requirements. Furthermore, new maintenance approaches need to be followed, for example continuously running software should evolve on run-time to meet ever-changing user requirements. Finally, new ways for handling exceptions and component failure and replacement, as well as changes in the environment are required, for example as is the case in networks including large numbers of smart computing entities, such as ad hoc sensors and MEMs devices. In large interconnected software systems such tasks cannot be achieved by approaches involving direct supervision and centralised management.

A way to meet requirements of this kind is to utilise the emergent properties of distributed interacting software referring to concepts such as self-organisation, self-regulation, self-repair and self-maintenance. However, in artificial systems, environmental pressures and local interactions and control may lead to unpredicted or undesirable behaviour. Understanding how to engineer the correct self-organising behaviour is thus an issue of major concern.

Self-organising applications (SOAs) are able to dynamically change their functionality and structure without direct user intervention to meet changes in requirements and their environment. The overall functionality delivered by SOAs typically changes progressively, mainly in a nonlinear fashion, until it reaches (emerges to) a state where it satisfies the system requirements at the time, and therefore it is termed *self-organising* or *emergent* behaviour. Self-organising behaviour is often the result of the execution of a number of individual application components that locally interact with each other aiming to achieve their local goals, for example systems that are based on agents or distributed objects. The main characteristic of such systems is their ability to achieve complex collective tasks with relatively simple individual behaviours, without central or hierarchical control.

A major open issue is therefore how to engineer desirable self-organising behaviour in SOAs and how to avoid undesirable ones, given the requirements and the application environment. To address this issue, approaches originating from diverse areas such as nonlinear optimisation, knowledge-based programming and constraint problem solving are currently being explored. Furthermore, SOA engineers often take inspiration from the real world, for example from biology, chemistry, sociology and the physical world. Typical examples of SOAs are systems that reproduce socially based insect behaviour, such as ant-based systems, artificial life, or robots. Although the results achieved so far are promising, further work is required until the problem is sufficiently addressed.

This book is complementary to a sister volume published in 2003, which aimed at establishing the field of *Engineering Self-organising Systems* and it focused on the foundations of self-organising systems. This year the emphasis is on methodological aspects and on applications of self-organising approaches. The book comprises revised versions of papers presented at the Engineering Self-organising Applications (ESOA 2004) workshop, held during the Autonomous Agents and Multi-agent Systems conference (AAMAS 2004) in New York in July 2004, and selected invited papers from leading contributors in the self-organisation field.

Part I contains three papers related to state of the art of self-organising systems. Wolf and Holvoet review historical definitions of the terms self-organisation and emergence and provide new aggregated definitions of each term supported by examples. Subsequently, Bar Yam demonstrates the limitations of decomposition-based engineering for the development of highly complex systems using multi-scale analysis. Ulieru then discusses the characteristics of adaptive information infrastructures and their role in human/machine and hardware/software integration.

In Part II approaches to designing self-organising systems are presented. d'Inverno and Saunders provide a mathematical formalisation and discuss the advantages of using an agent-based approach to develop biologically plausible models of stem cell systems in the context of a case study. Subsequently, Bour et al. address the issue of the creation of visual ambiences based on the coordinated activity of tiny computing entities distributed randomly on a 2D canvas that can only change their own color and perceive their immediate neighbors. Edmonds argues on the use of adaptive approaches producing reliable self-organised software systems. The argument is supported by defining a class of simple multi-agent systems and showing that it can be evolved to perform simple tasks. Nowostawski et al. then propose an evolutionary computation model based on the theory of hypercycles and autopoiesis. Subsequently, Hales discusses the use of tag dynamics to realize adaptive node behaviour in P2P systems (selfish vs. altruistic) based on results of P2P simulations.

Part III describes applications of self-organisation in self-assembly and robotic systems. Mamei et al. present self-organising spatial shapes in mobile particles with minimal capabilities. Poulton et al. discuss a method for directed self-assembly of 2-dimensional mesoblocks using top-down/bottom-up design. Subsequently, Galstyan et al. present a stochastic model for adaptive task allocation in robots. Finally, White and Helferty discuss the application of division-of-labor principles to achieve emergent team formation in robot soccer.

In Part IV self-organisation models based on the use of stigmergy are discussed. Parunak and Brueckner discuss stigmergic learning for self-organising mobile ad hoc networks (MANETs). Karuna et al. propose a stigmergy-based approach for emergent forecasting in manufacturing coordination and control. Subsequently, Foukia takes inspiration from natural systems and proposes a self-organising approach for intrusion detction and response in networks. Along a similar line, Armetta et al. describe a self-organising model for managing dynamic flow in production chains.

Part V concludes the book with industrial applications of self-organising systems. Lauterbach et al. describe self-organisation and fault-tolerance issues in a wired peer-to-peer sensor network for textile applications. Subsequently, Brueckner and Gerth discuss the application of distributed adaptive optimisation techniques to digital car-body development. Finally, Graupner et al. propose adaptive service placement algorithms for autonomous service networks.

We are grateful to the Programme Committee of the ESOA 2004 workshop for their timely reviews, and their useful suggestions on improving the workshop. All papers submitted to the workshop were reviewed by three members of the Programme Committee.

December 2004

Sven Brueckner, Giovanna Di Marzo Serugendo
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Emergence Versus Self-organisation: Different Concepts but Promising When Combined

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Abstract. A clear terminology is essential in every research discipline. In the context of ESOA, a lot of confusion exists about the meaning of the terms emergence and self-organisation. One of the sources of the confusion comes from the fact that a combination of both phenomena often occurs in dynamical systems. In this paper a historic overview of the use of each concept as well as a working definition, that is compatible with the historic and current meaning of the concepts, is given. Each definition is explained by supporting it with important characteristics found in the literature. We show that emergence and self-organisation each emphasise different properties of a system. Both phenomena can exist in isolation. The paper also outlines some examples of such systems and considers the combination of emergence and self-organisation as a promising approach in complex multi-agent systems.

1 Introduction

In the context of engineering self-organising applications there are two very important concepts to consider: emergence and self-organisation. In many multi-agent systems and complex adaptive systems in general, a combination of the two concepts is often used. As a consequence, much literature describes emergence and self-organisation incorrectly as synonyms and this results in misconception about their meaning. When engineering such applications, using a clear terminology is very important. To clarify the distinction between emergence and self-organisation, this paper's goal is to propose a working definition of both concepts. This definition is supported by characteristics that most literature describes as essential for emergence or self-organisation.

Emergence and self-organisation each emphasise very different characteristics of a system's behaviour. Both phenomena can exist in isolation and they can co-exist in a dynamical system. The first two sections of this paper describe each phenomenon separately by giving a historic overview of the use of each concept, proposing a working definition, and outlining their important characteristics to explain and support the definition given. The third section relates emergence and self-organisation to each other by discussing their similarities and differences.

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This is illustrated with examples where each phenomenon occurs separately. After that, a section is devoted to the combination of both phenomena in a single system. Finally we conclude this paper.

2 Emergence

Typically, people describe 'emergence' as the phenomenon where global behaviour arises from the interactions between de local parts of the system. In most literature there is nothing more than this vague description. Examples of emergence around us are: global pheromone paths that arise from local path-following and pheromone-dropping ants, the swarming movement of a flock of birds, a traffic jam from the interactions of cars, etc.

The goal of this section is to develop a more detailed working definition for 'emergence'. First, a historic overview of the early use of the concept is given. The second part proposes a definition of emergence that is consistent with the given history and outlines the important characteristics found in literature.

2.1 Historic Overview

Emergence is not a new topic [1][1]. Conceptual constructs such as 'whole before its parts' (i.e. to consider an explanation in terms of the global behaviour more important than explaining how the system works in terms of local behaviour) and 'Gestalt' (i.e. a configuration or pattern of elements so unified as a whole that it cannot be described merely as a sum of its parts), which resemble emergence, can be found in western thought since the time of ancient Greeks.

However, 'whole before its parts' and 'Gestalt' refer to a pre-given coherent entity, whereas emergence is not pre-given but a dynamical construct arising over time. In the context of a dynamical system, the meaning of emergence is not new either. It was used over 100 years ago by the English philosopher G.H. Lewes in 1875. Lewes distinguished between 'resultant' and 'emergent' chemical compounds coming about from a chemical reaction [2]:

> (...) although each effect is the *resultant* of its components, we cannot always trace the steps of the process, so as to see in the product the mode of operation of each factor. In the latter case, I propose to call the effect an *emergent*. It arises out of the combined agencies, but in a form which does not display the agents in action (...). (italics added)

Lewes' term was borrowed during the 1920s to form the backbone of a loosely joined movement in the sciences, philosophy and theology known as emergent evolutionism or proto-emergentism [1]. The concept of emergence was hotly debated and mainly used against reductionism, which stated that a system can be reduced to the sum of its parts. Proto-emergentism had few answers when it came to understanding how emergence itself was possible, i.e. how the lower-level inputs are transformed to the higher-level outputs during emergence.

[1] The historic overview of emergence is based on [1].

A second movement, called neo-emergence or complexity theory [1], tries to address the lack of understanding emergence. The concept of emergence in complex systems has very diverse scientific and mathematical roots: cybernetics, solid state/ condensed matter physics, evolutionary biology, artificial intelligence, artificial life, etc. There are actually four central schools of research that each influences the way emergence in complex systems is studied:

- **Complex adaptive systems theory**, which became famous at the Santa Fe Institute and which explicitly uses the term 'emergence' to refer to the macro-level patterns arising from interacting agents (see [3], [4], and [5]);
- **Nonlinear dynamical systems theory and Chaos theory**, which promulgates the central concept of attractors, i.e. a specific behaviour to which the system evolves. One kind of attractor is the so called strange attractor that the philosopher of science David Newman (1996)[6] classifies as an authentically emergent phenomenon.
- **The synergetics school**, which initiated, among others, the study of emergence in physical systems. They describe the idea of an order parameter that influences which macro-level coherent phenomena a system exhibits [7].
- **Far-from-equilibrium thermodynamics**, which was introduced by Ilya Prigogine and which refers to emergent phenomena as dissipative structures arising at far-from-equilibrium conditions[8].

In short, the uses of the concept of emergence refer to two important characteristics: a global behaviour that arises from the interactions of the local parts, and that global behaviour cannot be traced back to the individual parts.

2.2 A Working Definition

It is important that the concept of emergence is used consistently in literature. In the first place we need to be consistent with the historic use of the concept, as outlined above. In current literature, this is not such a big problem w.r.t. emergence. There is a larger misconception about the meaning of self-organisation, which is discussed later. The definition that we propose as a working definition for emergence is:

> A system exhibits emergence when there are coherent emergents at the macro-level that dynamically arise from the interactions between the parts at the micro-level. Such emergents are novel w.r.t. the individual parts of the system.

The definition above uses the concept of an 'emergent' as a general term to denote the result of the process of emergence: properties, behaviour, structure, patterns, etc. The 'level' mentioned refers to certain points of view. The macro-level considers the system as a whole and the micro-level considers the system from the point of view of the individual entities that make up the system.

This definition resulted from an extensive literature study, which identified the most important characteristics found in literature. The remainder of this part outlines these characteristics in order to explain the different aspects of the proposed definition in more detail.

Micro-Macro effect [3, 9, 10, 1, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21]. This is the most important characteristic and is mentioned explicitly in most literature. A micro-macro effect refers to properties, behaviours, structures, or patterns that are situated at a higher macro-level and arise from the (inter)actions at the lower micro-level of the system. We call such properties 'emergents'. In other words, the global behaviour of the system (i.e. the emergent) is a result from the interactions between the individual entities of the system.

Radical Novelty [9, 11, 1, 22, 17, 19, 10, 20, 21, 13]. The global behaviour is novel w.r.t. the individual behaviours at the micro-level, i.e. the individuals at the micro-level have no explicit representation of the global behaviour. In terms of reductionism this is formulated as: the macro-level emergents are not reducible to the micro-level parts of the system (= non-reductionism). In literature there are various formulations: 'not directly described by' [9, 10], 'can not be reduced to' [11], 'neither predictable nor deducible from' [1], 'without reference to the global pattern' [17], 'the whole is greater than the sum of its parts' [13].

From [22] we learn that we must pay attention. Stating that emergents are not captured by the behaviour of the parts is a serious misunderstanding. Radical novelty arises because the collective behaviour is *not readily understood from* the behaviour of the parts. The collective behaviour is, however, implicitly contained in the behaviour of the parts if they are studied in the context in which they are found. Emergent properties cannot be studied by physically taking a system apart and looking at the parts (=reductionism). They can, however, be studied by looking at each of the parts in the context of the system as a whole.

Coherence [1, 14, 13, 12, 22, 16]. Coherence refers to a logical and consistent correlation of parts. Emergents appear as integrated wholes that tend to maintain some sense of *identity* over time (i.e. a *persistent* pattern). Coherence spans and correlates the separate lower level components into a higher level unity, i.e. correlations between components are needed to reach a coherent whole [22]. This coherence is also called 'organisational closure' [12].

Interacting Parts [13, 17, 18, 14, 12]. The parts need to interact - parallelism is not enough. Without interactions, interesting macro-level behaviours will never arise. The emergents arise from the interactions between the parts.

Dynamical [1, 12, 3, 13, 17, 10, 20]. In systems with emergence, emergents arise as the system evolves in time. Such an emergent is a new kind of behaviour that becomes possible at a certain point in time. Therefore, as a dynamical construct we can relate the appearance of emergents to the appearance of new attractors in dynamical systems, i.e. bifurcations [1, 12].

Decentralised Control [13, 12, 16]. Decentralised control is using only local mechanisms to influence the global behaviour. There is no central control, i.e. no single part of the system directs the macro-level behaviour. The actions of the