Springer Complexity

Springer Complexity is an interdisciplinary program publishing the best research and academic-level teaching on both fundamental and applied aspects of complex systems—cutting across all traditional disciplines of the natural and life sciences, engineering, economics, medicine, neuroscience, social and computer science.

Complex Systems are systems that comprise many interacting parts with the ability to generate a new quality of macroscopic collective behavior, the manifestations of which are the spontaneous formation of distinctive temporal, spatial or functional structures. Models of such systems can be successfully mapped onto quite diverse "real-life" situations like the climate, the coherent emission of light from lasers, chemical reaction-diffusion systems, biological cellular networks, the dynamics of stock markets and of the internet, earthquake statistics and prediction, freeway traffic, the human brain, or the formation of opinions in social systems, to name just some of the popular applications.

Although their scope and methodologies overlap somewhat, one can distinguish the following main concepts and tools: self-organization, nonlinear dynamics, synergetics, turbulence, dynamical systems, catastrophes, instabilities, stochastic processes, chaos, graphs and networks, cellular automata, adaptive systems, genetic algorithms and computational intelligence.

The two major book publication platforms of the Springer Complexity program are the monograph series "Understanding Complex Systems" focusing on the various applications of complexity, and the "Springer Series in Synergetics", which is devoted to the quantitative theoretical and methodological foundations. In addition to the books in these two core series, the program also incorporates individual titles ranging from textbooks to major reference works.

Understanding Complex Systems

Founding Editor: J. A. Scott Kelso

Future scientific and technological developments in many fields will necessarily depend upon coming to grips with complex systems. Such systems are complex in both their composition—typically many different kinds of components interacting simultaneously and nonlinearly with each other and their environments on multiple levels—and the rich diversity of behavior of which they are capable.

The Springer series in Understanding Complex Systems (UCS) promotes new strategies and paradigms for understanding and realizing applications of complex systems research in a wide variety of fields and endeavors. UCS is explicitly transdisciplinary. It has three main goals: First, to elaborate the concepts, methods and tools of complex systems at all levels of description and in all scientific fields, especially newly emerging areas within the life, social, behavioral, economic, neuro- and cognitive sciences (and derivatives thereof); second, to encourage novel applications of these ideas in various fields of engineering and computation such as robotics, nano-technology and informatics; third, to provide a single forum within which commonalities and differences in the workings of complex systems may be discerned, hence leading to deeper insight and understanding.

UCS will publish monographs, lecture notes and selected edited contributions aimed at communicating new findings to a large multidisciplinary audience.

For further volumes:
http://www.springer.com/series/5394

René Doursat · Hiroki Sayama
Olivier Michel
Editors

Morphogenetic Engineering

Toward Programmable Complex Systems

Springer

Editors
René Doursat
Institut des Systèmes Complexes,
Paris Ile-de-France (ISC-PIF)
CNRS and Ecole Polytechnique
Paris
France

Hiroki Sayama
Department of Bioengineering
Binghamton University
State University of New York
Binghamton, NY
USA

Olivier Michel
Algorithmic, Complexity and
Logic Laboratory, Faculté des Sciences
et Technologie
Université Paris-Est Créteil
Créteil
France

ISSN 1860-0832 ISSN 1860-0840 (electronic)
ISBN 978-3-642-33901-1 ISBN 978-3-642-33902-8 (eBook)
DOI 10.1007/978-3-642-33902-8
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2012953376

© Springer-Verlag Berlin Heidelberg 2012
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Book Overview

Classical engineered products (mechanical, electrical, computer, or civil) are generally made of a number of unique, heterogeneous components assembled in very precise and complicated ways. They are expected to work as deterministically as possible following the specifications given by their designers. By contrast, self-organization in natural systems (physical, biological, ecological, or social) often relies on myriads of identical agents and essentially stochastic dynamics. Here, collective behavior and nontrivial patterns can emerge from relatively simple agent rules—a fact often touted as the hallmark of *complex systems*. Yet, the great majority of these naturally emergent motifs (spots, stripes, waves, clusters, and so on) are random and modified only by boundary conditions. They can be described with a few statistical variables, such as order parameters, but do not exhibit an *intrinsic architecture* like machines and industrial systems do.

Important exceptions to this dichotomy can be found in certain types of biological systems, which distinguish themselves by their strong "morphogenetic" properties and demonstrate the possibility of combining pure self-organization and sophisticated architecture. This is the case of embryogenesis and certain insect colonies, in other words: the self-assembly of cell masses into a detailed anatomy and the stigmergic collaboration of swarms of insects creating giant constructions. Multicellular organisms are composed of organs and appendages arranged in specific ways, yet, they entirely self-assemble in a decentralized fashion under the guidance of (epi)genetic information produced by millions of years of evolution and stored inside each cell. Similarly, termites, ants, or wasps are able to collectively build extremely complicated and well-organized nests without the need for an overall plan or grand architect.

In other words, all these examples testify to the existence of *programmable self-organization*—a concept not sufficiently explored so far, neither in complex systems science (for the "programmable" part), nor in traditional engineering (for the "self-organization" part). These natural examples trigger whole new questions: How do biological organisms or populations achieve morphogenetic tasks so reliably? Can we export their self-formation capabilities to engineered systems? What would be the principles and best practices to create such morphogenetic systems?

To meet these challenges, ***Morphogenetic Engineering***: ***Toward Programmable Complex Systems*** establishes a new field of research that explores the artificial design and implementation of autonomous systems capable of developing complex, heterogeneous morphologies and functions without central planning or external drive. Particular emphasis is set on the mutual relationship between programmability/controllability and self-organization. Its many potential applications in artificial systems (or hybrid "techno-natural" systems) include self-assembling robots, self-coding software, self-constructing buildings, self-reconfiguring production lines, or self-managing energy grids, all based on a multitude of components, modules, software agents, and/or human users creating their own network solely on the basis of local rules and peer-to-peer interactions. Decentralized automation relying on emergent architectures promises to be the new paradigm for a future science of "complex systems engineering".

This volume should play an influential role in setting the scopes and directions of this emerging field of research. The intended audience consists of researchers and graduate students who are working on, or have interest in programmable self-organizing systems across a broad range of scientific and technological fields, including computer science, robotics, bio(-inspired) engineering, control theory, networks, theoretical biology, physics, and many others.

René Doursat
Complex Systems Institute, Paris
CNRS and Ecole Polytechnique
http://www.iscpif.fr/~doursat

Hiroki Sayama
Department of Bioengineering
Binghamton University, SUNY
http://bingweb.binghamton.edu/~sayama

Olivier Michel
Department of Computer Science
Université Paris-Est Créteil
http://www.lacl.fr/~michel

Contents

Part I Constructing

Part II Coalescing

Part III Developing

Part IV Generating