

Complex Systems: Chaos and Beyond

Springer-Verlag Berlin Heidelberg GmbH

Physics and Astronomy  **ONLINE LIBRARY**

<http://www.springer.de/phys/>

Kunihiko Kaneko Ichiro Tsuda

Complex Systems: Chaos and Beyond

A Constructive Approach
with Applications in Life Sciences

With 111 Figures



Springer

Professor Kunihiko Kaneko
Department of Pure and Applied Sciences
University of Tokyo
Komaba, Meguro
Tokyo 153-8902
Japan

Professor Ichiro Tsuda
Department of Mathematics
Graduate School of Science
Hokkaido University
Kita-10 jo, Nishi-8 chome
Sapporo 060-0810
Japan

Title of the original Japanese edition:
Fukuzatsukei no kaosu-teki shinario
© 1996, Kunihiko Kaneko and Ichiro Tsuda
English translation © 2000, Kunihiko Kaneko and Ichiro Tsuda
All rights reserved.
The English edition rights are granted by Asakura Publishing Co., Ltd., Tokyo.

Library of Congress Cataloging-in-Publication Data.
Kaneko, Kunihiko. [Fukuzatsukei no kaosu-teki shinario. English] Complex systems : chaos and beyond :
a constructive approach with applications in life sciences / Kunihiko Kaneko, Ichiro Tsuda.
p.cm. Includes bibliographical references and index.
ISBN 978-3-642-63132-0 ISBN 978-3-642-56861-9 (eBook)
DOI 10.1007/978-3-642-56861-9
1. Chaotic behavior in systems. I. Tsuda, Ichiro. II. Title.
Q172.5.C45 K34 2000 003'.857-dc21 00-030752

ISBN 978-3-642-63132-0

Cover picture: Part of a schematic representation of chaotic itinerary. From: K. Kaneko, *Diversity Induced by Chaos*. © May 1994, 34, Nikkei-Science, (in Japanese)

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer-Verlag. Violations are liable for prosecution under the German Copyright Law.

© Springer-Verlag Berlin Heidelberg 2001
Originally published by Springer-Verlag Berlin Heidelberg New York in 2001
Softcover reprint of the hardcover 1st edition 2001

The use of general descriptive names, registered names, trademarks, 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.

Typesetting: Data conversion by LE-TeX/Jelonek, Schmidt & Vöckler GbR, Leipzig
Cover design: *design & production*, Heidelberg

Printed on acid-free paper SPIN: 10652079 55/3141/di 5 4 3 2 1 0

Preface

We first had the idea to write a joint book fourteen years ago. First we had intended to write a book on chaos, and then our vision expanded to include the significance of chaos in all fields of science, which exploded to a plan for a dozen-volume series. Since this was not realistic, it did not materialize. Then we made a reduced plan about a decade ago, with explicit outlines, but this did not work out either. In the meantime, our interest has shifted to the study of complex systems, based on, but beyond, chaos. Kaneko made a departure to a 'jungle tour' to search for universal structures in high-dimensional chaos, based on the study of coupled map lattices and globally coupled maps. With concepts and phenomenal he discovered, he started to study life from the viewpoint of a complex system, where life can be viewed as complementarity dynamics itself between the whole and parts. Tsuda proposed a hermeneutic study of the brain and also a dynamic aspect of the brain, taking the information structure of chaos into account. There, he started brain research in order to epistemologically understand chaos, whose essence is regarded as "descriptive instability" and some sort of undecidability.

After this long detour, we finally published the Japanese version of the present book in 1996 with Asakura Publ. Inc. This book is based on the Japanese version, but the contents are updated.

This is neither a textbook on chaos nor a textbook on complex systems. It is not intended to transfer established knowledge, either. Rather, we intend to provoke discussions on complex systems, by showing what we have achieved and what we aim at accomplishing in the field of 'complex systems'.

We take a standpoint that chaos is essential to a practical and philosophical study of complex systems, although the complex systems are such that we must postulate some other concepts beyond chaos. Here we reexamine what concepts in chaos are relevant to the study of complex systems. From this reconsideration, we take the following three standpoints for the study of complex systems: a constructive approach, a many-to-many relationship, and descriptive instability. The last issue is, in particular, based on the observation problem, where we intend to consider seriously what a description of a system means, how descriptions or observations impinge on a system, and then what condition is imposed on a system for stability against descriptions. A clear

answer to this issue has not yet been obtained, but we try to provide a basis for future studies.

As people from a variety of fields show interest in the studies of complex systems, there will be diverse ways in reading the present book. Hence we give some possible guidance for readers, so that they are not lost in the jungle of complex systems.

Those who are interested generally in complex systems are recommended to read Chap. 1, and then choose some chapters depending on their interests. Chapter 1 is written so that it can be read as an independent monograph, which we hope will be understandable to the general readership, including nonscientists.

It is recommended that all readers choose some chapters depending on their interests. For example, those who are interested in brain and cognition problems will probably read Chap. 6, but it is hoped that they will also read Chaps. 2–4; while Chap. 5 provides a bridge between these chapters and Chap. 6.

Those who work in the field of statistical physics, mathematical physics, and dynamical systems will find several research topics they should study in the future in Chaps. 2–6. Some topics in these chapters are not yet mathematically refined, but it is hoped that they will be formalized and established as a concrete concept or framework.

Physicists and chemists in general may find Chaps. 2–4 most interesting.

Those who try to understand dynamics in a biological system can find relevant parts in Chaps. 2 and 4 and in a part of Chap. 3, depending on their interests. After scanning these chapters, they will find Chaps. 5 and 6 interesting.

Those who are interested in the engineering applications of chaos and biology-oriented systems, and the search for novel basic ideas, can find some relevant concepts or phenomena throughout Chaps. 2–6.

It is our regret that the translation of this book from Japanese has taken so much longer than we had imagined. Indeed we first looked for a good translator, but in vain. Finally we decided to translate it ourselves. This was a painful decision for us, but there have been some merits, we believe. We have succeeded in updating the contents throughout the book. We revised some vague expressions in Chap. 1 to be more understandable. Chapters 2 and 3 in the Japanese version are joined to form a new Chap. 2, where excessive mathematical discussions have been eliminated. In Chap. 3, we have added some paragraphs on the significance of coupled map lattices, and recent examples of its applications are discussed at length. There are quite recent developments on the collective dynamics in globally coupled maps, which are also included in Chap. 4. Of course, the core of complex systems lies in a biological system, and our recent studies focus on this direction. In Sect. 5.6, we have outlined recent studies on theoretical (cell) biology along the lines of Chap. 1. In Chap. 6, we deleted some lengthy explanations that appeared in

the Japanese version, and instead added a concise description. Recent studies about a temporal coding were additionally introduced and their references were updated. Besides these major ones, minor revisions have been carried out throughout the book.

Although we do not list all the names as is usually done, we would, of course, like to give sincere thanks to all the collaborators and those who have shared interest in the topics of this book for their stimulating discussions. We heartily express our gratitude to Dr. Frederick Willeboordse who kindly took care of a critical reading of the manuscript and the correction of the English.

Tokyo and Sapporo
July 2000

Kunihiko Kaneko
Ichiro Tsuda

Contents

1. Necessity for a Science of Complex Systems	1
1.1 Introduction	1
1.2 Chaos	4
1.3 Chaos and Complexity	8
1.4 How Has Chaos Changed Our Way of Thinking?	11
1.4.1 Dialectic Method to Overcome the Antithesis Between Determinism and Nondeterminism or Between Programs and Errors	11
1.4.2 Dialectic Method to Overcome the Antithesis Between Order and Randomness	12
1.4.3 Beyond the Antithesis Between Reductionism and Holism	12
1.5 Dynamic Many-to-Many Relations and Bio-networks	13
1.5.1 The Necessity of Dynamic Many-to-Many Relations ..	13
1.5.2 Metabolic Systems, Differentiation, and Development .	15
1.5.3 Ecosystems	16
1.5.4 Immune Systems	17
1.5.5 The Brain	18
1.5.6 Rugged Landscapes and Their Problems	18
1.5.7 Conclusion	20
1.6 The Construction of an Artificial (Virtual) World	21
1.7 A Trigger to Emergence	24
1.8 Beyond Top-Down Versus Bottom-Up	26
1.9 Methodology of Study of Complex Systems	28
1.9.1 Constructive Way of Understanding	29
1.9.2 Plural Views	30
1.9.3 Mathematical Anatomy	31
1.9.4 The Problem of Internal Observers	31
2. Observation Problems from an Information-Theoretical Viewpoint	33
2.1 Observation Problems of Chaos	33
2.2 Undecidability and Entire Description	37

2.3	A Demon in Chaos	38
2.4	Chaos in the BZ Reaction	39
2.5	Noise-Induced Order	43
2.6	Could Structural Stability Lead to an Adequate Notion of a Model?	47
2.7	Information Theory of Chaos	50
3.	CMLs: Constructive Approach	
	to Spatiotemporal Chaos	57
3.1	From a Descriptive to a Constructive Approach of Nature	57
3.2	Coupled Map Lattice Approach to Spatiotemporal Chaos	59
3.2.1	Spatiotemporal Chaos	59
3.2.2	Introduction to Coupled Map Lattices	61
3.2.3	Comparison with Other Approaches	64
3.3	Phenomenology of Spatiotemporal Chaos in the Diffusively Coupled Logistic Lattice	65
3.3.1	Introduction	65
3.3.2	Frozen Random Patterns and Spatial Bifurcations	66
3.3.3	Pattern Selection with Suppression of Chaos	69
3.3.4	Brownian Motion of Chaotic Defects and Defect Turbulence	70
3.3.5	Spatiotemporal Intermittency (STI)	71
3.3.6	Stability of Fully Developed Spatiotemporal Chaos (FDSTC) Sustained by the Supertransients	75
3.3.7	Traveling Waves	77
3.3.8	Supertransients	81
3.4	CML Phenomenology as a Problem of Complex Systems	83
3.5	Phenomenology in Open-Flow Lattices	84
3.5.1	Introduction	84
3.5.2	Spatial Bifurcation to Down-Flow	85
3.5.3	Convective Instability and Spatial Amplification of Fluctuations	86
3.5.4	Phase Diagram	89
3.5.5	Spatial Chaos	91
3.5.6	Selective Amplification of Input	93
3.6	Universality	94
3.7	Theory for Spatiotemporal Chaos	97
3.8	Applications of Coupled Map Lattices	100
3.8.1	Pattern Formation (Spinodal Decomposition)	100
3.8.2	Crystal Growth and Boiling	101
3.8.3	Convection	101
3.8.4	Spiral and Traveling Waves in Excitable Media	103
3.8.5	Cloud Dynamics and Geophysics	104

3.8.6	Ecological Systems	104
3.8.7	Evolution	104
3.8.8	Closing Remarks	105
4.	Networks of Chaotic Elements	107
4.1	GCM Model	107
4.2	Clustering	111
4.3	Phase Transitions Between Clustering States	115
4.4	Ordered Phase and Cluster Bifurcation	117
4.5	Hierarchical Clustering and Chaotic Itinerancy	122
4.5.1	Partition Complexity	122
4.5.2	Hierarchical Clustering	125
4.5.3	Hierarchical Dynamics	128
4.5.4	Chaotic Itinerancy	132
4.6	Marginal Stability and Information Cascade	135
4.6.1	Marginal Stability	135
4.6.2	Information Cascade	139
4.7	Collective Dynamics	143
4.7.1	Remnant Mean-Field Fluctuation	143
4.7.2	Hidden Coherence	146
4.7.3	Instability of the Fixed Point of the Perron–Frobenius Operator	150
4.7.4	Destruction of Hidden Coherence by Noise and Anomalous Fluctuations	153
4.7.5	Heterogeneous Systems	155
4.7.6	Significance of Collective Dynamics	156
4.8	Universality and Nonuniversality	157
4.8.1	Universality of Clustering and Other Transitions	157
4.8.2	Globally Coupled Tent Map: Novelty Within Universality	159
5.	Significance of Coupled Chaotic Systems to Biological Networks	163
5.1	Relevance of Coupled Maps to Biological Information Processing	163
5.2	Application of Coupled Maps to Information Processing	164
5.2.1	Memory to Attractor Mapping and the Switching Process	164
5.2.2	Chaotic Itinerancy and Spontaneous Recall	168
5.2.3	Optimization and Search by Spatiotemporal Chaos as Spatiotemporally Structured Noise	170
5.2.4	Local–Global Transformation by Traveling Waves – Information Creation and Transmission by Chaotic Traveling Waves	170

5.2.5	Selective Amplification of Input Signals by the Unidirectionally Coupled Map Lattice	170
5.3	Information Dynamics of a CML with One-Way Coupling ...	171
5.4	Design of Coupled Maps and Plastic Dynamics	175
5.5	Construction of Dynamic Many-to-Many Logic and Information Processing	178
5.6	Implications to Biological Networks	179
5.6.1	Prototype of Hierarchical Structures	180
5.6.2	Prototype of Diversity and Differentiation	180
5.6.3	Formation and Collapse of Relationships	184
5.6.4	Clustering in Hypercubic Coupled Maps; Self-organizing Genetic Algorithms	184
5.6.5	Homeochaos	186
5.6.6	Summing Up	189
6.	Chaotic Information Processing in the Brain	191
6.1	Hermeneutics of the Brain	191
6.2	A Brief Comment on Hermeneutics (the Inside and the Outside)	194
6.3	A Method for Understanding the Brain and Mind – Internal Description	195
6.4	Evidence of Chaos in Nervous Systems	196
6.5	The Origin of Neurochaos	198
6.6	The Implications of Stochastic Renewal of Maps	203
6.6.1	Chaotic Game	203
6.6.2	Skew-Product Transformations	204
6.7	A Model for Dynamic Memory	205
6.8	A Model for Dynamically Linking Memories	206
6.9	Significance of Neurochaos	212
6.10	Temporal Coding	214
6.11	Capillary Chaos as a Complex Dynamics	219
6.11.1	Significance of Capillary Pulsation in the Brain Functions	219
6.11.2	Embedding Theorems	220
6.11.3	Experimental Systems	221
6.11.4	Reconstruction of the Dynamics	222
6.11.5	Calculations of Lyapunov Exponents	224
6.11.6	The Condition Dependence	226
6.11.7	Cardiac Chaos	230
6.11.8	Information Structure	231
6.11.9	Implications of Capillary Chaos	235

7. Conversations with Authors 237

 7.1 Concluding Discussions 237

 7.2 Questions and Answers 239

 7.2.1 The Significance of Models
 in Complex Systems Research 239

 7.2.2 Chaotic Itinerancy 243

 7.2.3 New Information Theory and Internal Observation ... 246

References 251

Index 267