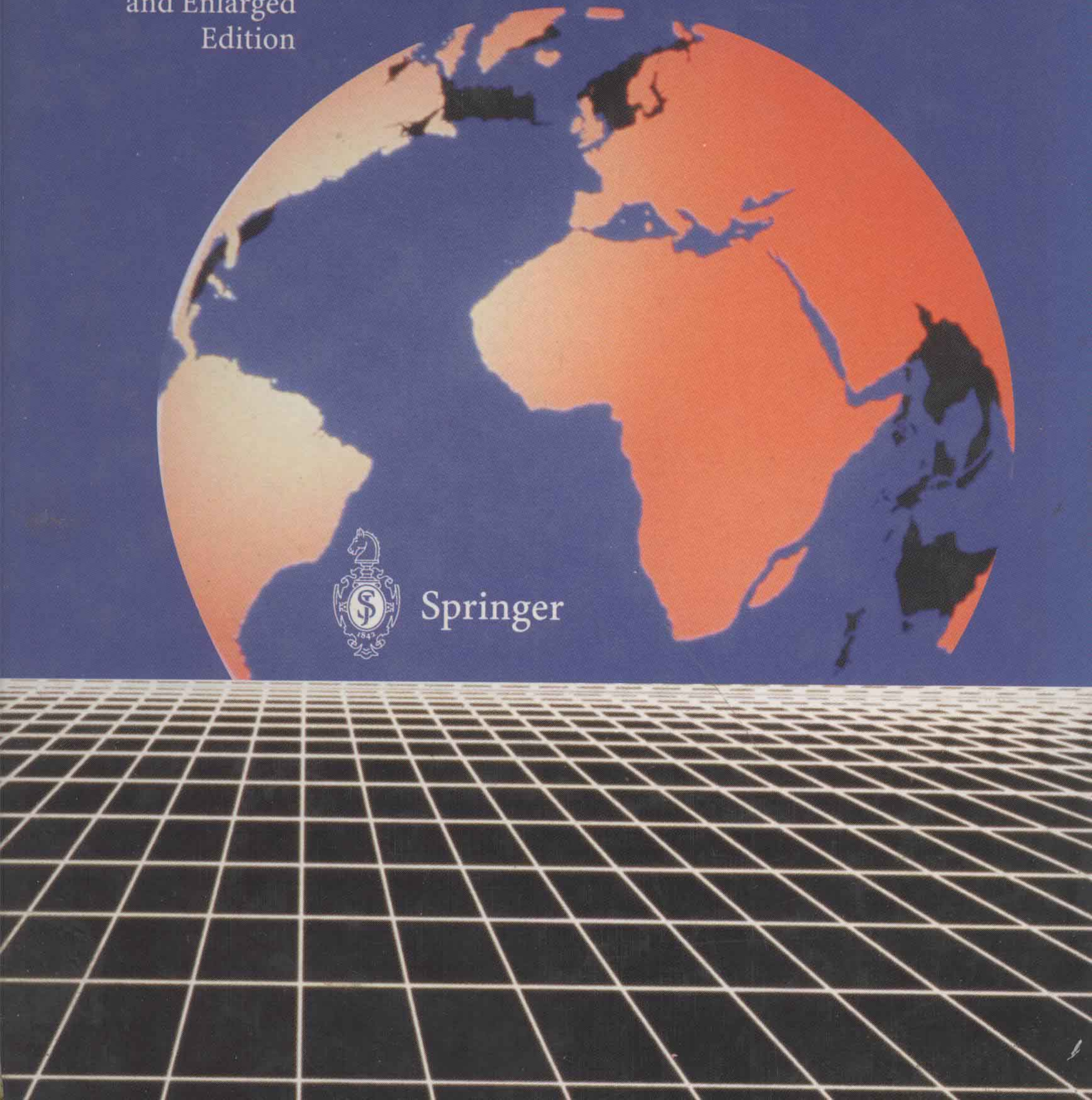
KLAUS MAINZER

Thinking in Complexity

The Complex Dynamics of Matter, Mind, and Mankind

Second Revised and Enlarged Edition



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The Complex Dynamics of Matter, Mind, and Mankind

Second Revised and Enlarged Edition
With 123 Figures

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Das Ganze aber ist nur das durch seine Entwicklung sich vollendende Wesen. *

G. W. F. Hegel: Phänomenologie des Geistes (1807)

* *The whole, however, is merely the essential nature reaching its completeness through the process of its own development.*

G. W. F. Hegel: The Phenomenology of Mind (1807)

Preface to the Second Edition

The first edition of "Thinking in Complexity" was sold out in less than one year. Obviously, complexity and nonlinearity are "hot" topics of interdisciplinary interest in the natural and social sciences. The situation is well summarized by a quotation of Ian Stewart (Mathematics Institute, University of Warwick) who wrote a nice review of my book under the title "Emerging new science" [Nature **374**, 834 (1995)]: "Nonlinearity is not a universal answer, but it is often a better way of thinking about the problem".

I have taken the opportunity provided by a second edition to revise and extend the text. In Sect. 2.4 a supplement is included on the recent importance of conservative self-organization in supramolecular chemistry and the material sciences. Some references are given to the recent discussion of self-organization in alternative cosmologies. Some remarks are made about new results on dissipative self-organization in living cells (Sect. 3.3). The success and limitations of adaptive neural prostheses in neurotechnology are analyzed in more detail (Sect. 5.4). The last chapter is extended into an "Epilogue on Future, Science, and Ethics": After a short introduction to traditional forecasting methods, their limitations and new procedures are discussed under the constraints of nonlinearity and complexity in the natural and social sciences. In particular, the possibilities of predicting and modeling scientific and technological growth are extremely interesting for the contemporary debates on human future and ethics.

General methods of nonlinear complex systems must be developed in cooperation with the natural and social sciences under their particular observational, experimental, and theoretical conditions. Thus, I want to thank some colleagues for their helpful advice: Rolf Eckmiller (Dept. of Neuroinformatics, University of Bonn), Hans-Jörg Fahr and Wolf Priester (Dept. of Astrophysics and Max-Planck Institute for Radioastronomy, Bonn), Hermann Haken (Institute of Theoretical Physics and Synergetics, Stuttgart), Benno Hess (Max-Planck Institute for Medical Research, Heidelberg), S. P. Kurdyumov (Keldysh Institute of Applied Mathematics, Moscow), Renate Mayntz (Max-Planck Institute for Social Sciences, Cologne), Achim Müller (Dept. of Inorganic Chemistry, University of Bielefeld). Last but not least, I would like to thank Wolf Beiglböck (Springer-Verlag) for initiating and supporting this new edition.

Augsburg, November 1995 *Klaus Mainzer*

Preface to the First Edition

Complexity and nonlinearity are prominent features in the evolution of matter, life, and human society. Even our mind seems to be governed by the nonlinear dynamics of the complex networks in our brain. This book considers complex systems in the physical and biological sciences, cognitive and computer sciences, social and economic sciences, and philosophy and history of science. An interdisciplinary methodology is introduced to explain the emergence of order in nature and mind and in the economy and society by common principles.

These methods are sometimes said to foreshadow the new sciences of complexity characterizing the scientific development of the 21st century. The book critically analyzes the successes and limits of this approach, its systematic foundations, and its historical and philosophical background. An epilogue discusses new standards of ethical behavior which are demanded by the complex problems of nature and mind, economy and society.

The "nucleus" of this book was a paper contributed to a conference on complex nonlinear systems which was organized by Hermann Haken and Alexander Mikhailov at the Center for Interdisciplinary Studies in Bielefeld, in October 1992. In December 1992, Dr. Angela M. Lahee (Springer-Verlag) suggested that I elaborate the topics of my paper into a book. Thus, I would like to express my gratitude to Dr. Lahee for her kind and efficient support and to Hermann Haken for his cooperation in several projects on complex systems and synergetics. I also wish to thank the German Research Foundation (DFG) for the support of my projects on "Computer, Chaos and Self-organization" (1990–1992: Ma 842/4-1)

and "Neuroinformatics" (1993–1994: Ma 842/6-1). I have received much inspiration from teaching in a mathematical graduate program on "Complex Systems" (supported by the DFG) and an economic program on "Nonlinearity in Economics and Management" at the University of Augsburg. In 1991 and 1993, the Scientific Center of Northrhine-Westphalia (Düsseldorf) invited me to two international conferences on the cultural effects of computer technology, neurobiology, and neurophilosophy.

Last but not least, I would especially like to thank J. Andrew Ross (Springer-Verlag) for carefully reading and correcting the book as a native speaker, and Katja E. Hüther and Jutta Janßen (University of Augsburg) for typing the text.

Augsburg, June 1994 *Klaus Mainzer*

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Contents

1. Introduction: From Linear to Nonlinear Thinking

The theory of nonlinear complex systems has become a successful problem solving approach in the natural sciences – from laser physics, quantum chaos, and metereology to molecular modeling in chemistry and computer-assisted simulations of cellular growth in biology. On the other hand, the social sciences are recognizing that the main problems of mankind are global, complex, and nonlinear, too. Local changes in the ecological, economic, or political system can cause a global crisis. Linear thinking and the belief that the whole is only the sum of its parts are evidently obsolete. One of the most exciting topics of present scientific and public interest is the idea that even our mind is governed by the nonlinear dynamics of complex systems. If this thesis of computational neuroscience is correct, then indeed we have a powerful mathematical strategy to handle interdisciplinary problems of natural sciences, social sciences, and humanities.

What is the reason behind these successful interdisciplinary applications? The book shows that the theory of nonlinear complex systems cannot be reduced to special natural laws of physics, although its mathematical principles were discovered and at first successfully applied in physics. Thus it is no kind of traditional "physicalism" to explain the dynamics of laser, ecological populations, or our brain by similar structural laws. It is an interdisciplinary methodology to explain the emergence of certain macroscopic phenomena via the nonlinear interactions of microscopic elements in complex systems. Macroscopic phenomena may be forms of light waves, fluids, clouds, chemical waves, plants, animals, populations, markets, and cerebral cell assemblies which are characterized by order parameters. They are not reduced to the microscopic level of atoms, molecules, cells, organisms, etc., of complex systems. Actually, they represent properties of real macroscopic phenomena, such as field potentials, social or economical power, feelings or even thoughts. Who will deny that feelings and thoughts can change the world?

In history the concepts of the social sciences and humanities have often been influenced by physical theories. In the age of mechanization Thomas Hobbes described the state as a machine ("Leviathan") with its citizens as cog wheels. For Lamettrie the human soul was reduced to the gear drive of an automaton. Adam Smith explained the mechanism of the market by an "invisible" force like Newton's gravitation. In classical mechanics causality is deterministic in the sense of the Newtonian or Hamiltonian equations of motion. A conservative system is characterized by its reversibility (i.e., symmetry or invariance) in time and the conservation of energy. Celestial mechanics and the pendulum without friction are prominent examples. Dissipative systems are irreversible, like Newton's force with a friction term, for instance.

But, in principle, nature was regarded as a huge conservative and deterministic system the causal events of which can be forecast and traced back for each point of time in the future and past if the initial state is well known ("Laplace's demon"). It was Henri Poincaré who recognized that celestial mechanics is no completely calculable clockwork even with the restrictions of conservation and determinism. The causal interactions of all planets, stars, and celestial bodies are nonlinear in the sense that their mutual effects can lead to chaotic trajectories (e.g., the 3-body problem). Nearly sixty years after Poincaré's discovery, A.N. Kolmogorov (1954), V.I. Arnold (1963), and J.K. Moser proved the so-called KAM theorem: Trajectories in the phase space of classical mechanics are neither completely regular nor completely irregular, but they depend very sensitively on the chosen initial states. Tiny fluctuations can cause chaotic developments (the "butterfly effect").

In this century quantum mechanics has become the fundamental theory of physics [1.1]. In Schrödinger's wave mechanics the quantum world is believed to be conservative and linear. In the first quantization classical systems described by a Hamiltonian function are replaced by quantum systems (for instance electrons or photons) described by a Hamiltonian operator. These systems are assumed to be conservative, i.e., non-dissipative and invariant with respect to time reversal and thus satisfy the conservation law of energy. States of a quantum system are described by vectors (wave functions) of a Hilbert space spanned by the eigenvectors of its Hamiltonian operator. The causal dynamics of quantum states is determined by a deterministic differential equation (the Schrödinger equation) which is linear in the sense of the superposition principle, i.e., solutions of this equation (wave functions or state vectors) can be superposed like in classical optics. The superposition or linearity principle of quantum mechanics delivers correlated ("entangled") states of combined systems which are highly confirmed by the EPR experiments (A. Aspect 1981). In an entangled pure quantum state of superposition an observable can only have indefinite eigenvalues. It follows that the entangled state of a quantum system and a measuring apparatus can only have indefinite eigenvalues. But in the laboratory the measuring apparatus shows definite measurement values. Thus, linear quantum dynamics cannot explain the measurement process.

In the Copenhagen interpretation of Bohr, Heisenberg, et al., the measurement process is explained by the so-called "collapse of the wave-packet", i.e., splitting up of the superposition state into two separated states of measurement apparatus and measured quantum system with definite eigenvalues. Obviously, we must distinguish the linear dynamics of quantum systems from the nonlinear act of measurement. This nonlinearity in the world is sometimes explained by the emergence of human consciousness. Eugene Wigner (1961) suggested that the linearity of Schrödinger's equation might fail for conscious observers, and be replaced by some nonlinear procedure according to which either one or the other alternative would be resolved out. But Wigner's interpretation forces us to believe that the linear quantum superpositions would be resolved into separated parts only in those corners of the universe where human or human-like consciousness emerges. In the history of science anthropic or teleological arguments often showed that there were weaknesses and failures of explanation in science. Thus, some scientists, like Roger Penrose, suppose that the linear dynamics of quantum mechanics is not appropriate to explain cosmic evolution with the emergence of consciousness. He argues that a unified theory of linear quantum mechanics and nonlinear general relativity could at least explain the separated states of macroscopic systems in the world. A measuring apparatus is a macroscopic system, and the measurement process is irreversible far from thermal equilibrium. Thus, an explanation could only succeed in a unified nonlinear theory. Even the generalization of Schrödinger's wave mechanics to quantum field theory is already nonlinear. In quantum field theory, field functions are replaced by field operators in the so-called second quantization. The quantum field equation with a two-particle potential, for instance, contains a nonlinear term corresponding to pair creation of elementary particles. In general the reactions of elementary particles in quantum field theory are essentially nonlinear phenomena. The interactions of an elementary particle cause its quantum states to have only a finite duration and thereby to violate the reversibility of time. Thus even the quantum world itself is neither conservative nor linear in general. In system theory, complexity means not only nonlinearity but a huge number of elements with many degrees of freedom [1.2]. All macroscopic systems like stones or planets, clouds or fluids, plants or animals, animal populations or human societies consist of component elements like atoms, molecules, cells or organisms. The behaviour of single elements in complex systems with huge numbers of degrees of freedom can neither be forecast nor traced back. The deterministic description of single elements must be replaced by the evolution of probabilistic distributions.

The second chapter analyzes *Complex Systems and the Evolution of Matter*. Since the presocratics it has been a fundamental problem of natural philosophy to discover how order arises from complex, irregular, and chaotic states of matter. Heraclitus believed in an ordering force of energy (*logos*) harmonizing irregular interactions and creating order states of matter. Modern thermodynamics describes the emergence of order by the mathematical concepts of statistical mechanics. We distinguish two kinds of phase transition (self-organization) for order states: conservative self-organization means the phase transition of reversible structures in thermal equilibrium. Typical examples are the growth of snow crystals or the emergence of magnetisation in a ferromagnet by annealing the system to a critical value of temperature. Conservative self-organization mainly creates order structures with low energy at low temperatures, which are described by a Boltzmann distribution. Dissipative self-organization is the phase transition of irreversible structures far from thermal equilibrium [1.3]. Macroscopic patterns arise from the complex nonlinear cooperation of microscopic elements when the energetic interaction of the dissipative ("open") system with its environment reaches some critical value. Philosophically speaking, the stability of the emergent structures is guaranteed by some balance of nonlinearity and dissipation. Too much nonlinear interaction or dissipation would destroy the structure.

As the conditions of dissipative phase transition are very general, there is a broad variety of interdisciplinary applications. A typical physical example is the laser. In chemistry, the concentric rings or moving spirals in the Belousov-Zhabotinski (BZ) reaction arise when specific chemicals are poured together with a critical value. The competition of the separated ring waves show the nonlinearity of these phenomena very clearly, because in the case of a superposition principle the ring waves would penetrate each other like optical waves.

The phase transitions of nonlinear dissipative complex systems are explained by synergetics. In a more qualitative way we may say that old structures become unstable and break down by changing control parameters. On the microscopic level the stable modes of the old states are dominated by unstable modes (Haken's "slaving principle") [1.4]. They determine order parameters which describe the macroscopic structure and patterns of systems. There are different final patterns of phase transitions corresponding to different attractors. Different attractors may be pictured as a stream, the velocity of which is accelerated step by step. At the first level a homogeneous state of equilibrium is shown ("fixed point"). At a higher level of velocity the bifurcation of two or more vortices can be observed corresponding to periodic and quasi-periodic attractors. Finally the order decays into deterministic chaos as a fractal attractor of complex systems. Philosophically, I want to underline that in synergetics the microscopic description of matter is distinguished from the macroscopic order states. Thus the synergetic concept of order reminds me of Heraclitus" "logos" or Aristotle's "form" which produces the order states of nature in a transformative process of matter. But, of course, in antiquity a mathematical description was excluded.

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