Cambridge University Press
978-0-521-58201-8 - Nonlinear Dynamics Chaotic and Complex Systems: Proceedings of an International Conference Held in Zakopane, Poland November 7–12, 1995: Plenary Invited Lectures
Edited by E. Infeld, R. Żelanzny and A. Gałkowski
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Nonlinear dynamics, chaotic and complex systems constitute some of the most fascinating developments of late twentieth century mathematics and physics. It transpires that chaotic behaviour can be understood, and sometimes even utilized, to a far greater degree than hitherto suspected. Surprisingly, universal constants have been discovered. The implications have changed our understanding of important phenomena in physics, biology, chemistry, economics, medicine and numerous other fields of human endeavor.

In this book, two dozen people largely responsible for the 'nonlinear revolution' cover most of the basic aspects of the field in 15–20 page articles. The book is subdivided into five parts: dynamical systems, bifurcation theory and chaos; spatially extended systems; dynamical chaos, quantum physics and foundations of statistical mechanics; evolutionary and cognitive systems; and complex systems as an interface between the sciences.

This book is expected to become a standard text on the subject. It grew out of an EC sponsored conference held in Zakopane, a Polish mountain resort, in November 1995. This conference was attended by many of the founders of the field and was considered to be one of the most important gatherings of 1995.

NONLINEAR DYNAMICS, CHAOTIC AND COMPLEX SYSTEMS

Nonlinear Dynamics Chaotic and Complex Systems

Proceedings of an International Conference
held in Zakopane, Poland
November 7–12, 1995
Plenary Invited Lectures

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University Printing House, Cambridge CB2 8BS, United Kingdom

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www.cambridge.org
Information on this title: www.cambridge.org/9780521582018

First published 1997
First paperback edition 2010

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data

Nonlinear dynamics, chaotic and complex systems: proceedings of an international conference held in Zakopane, Poland 7-12, 1995: plenary invited lectures/edited by E. Infeld, R. Żelazny, A. Ga łkowski.
p. cm.
ISBN 0 521 58201 6 (hardcover)
1. Differentiable dynamical systems – Congresses. 2. Chaotic behavior in systems – Congresses. 3. Nonlinear theories – Congresses. I. Infeld. E. (Eryk) II. Żelazny. Roman. III. Ga łkowki A. (Andr zej). 1951–
QA614.8 N66 1997
003'.85–dc21 97–4012 CIP

ISBN 978-0-521-58201-8 Hardback
ISBN 978-0-521-15294-5 Paperback

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Preface

The last thirty years have witnessed a powerful new development across the board of scientific research. The insight gained has changed our whole understanding of natural phenomena. It involves the complex behaviour in which many different states of a system occur. These states have wholly different stability properties and can exhibit abrupt transitions from one to the other. The seemingly erratic motion involved defies prediction and is extremely difficult to control. We usually refer to this phenomenon as *deterministic chaos*. It coexists with the classical, organized behaviour we learned about at school. It now seems that an understanding of both is required in a wide range of situations.

Chaotic behaviour is observed in most fields of science (e.g. subatomic to molecular physics, fluid dynamics, plasma physics, chemistry, molecular biology). It appears in environmental, social and economic phenomena, as well as in technological processes.

The important discovery is that there are universal mechanisms underlying the complex behaviours involved. Fortunately, these mechanisms can be studied by looking at simplified theoretical models. Once these two facts were grasped, people working in theory, experiments, and numerics inevitably came together to develop the field.

There is an interesting political aspect to all this. The human potential of people active in the field in Central and Eastern Europe is still immense (especially in theory). How can we avoid dispersion of these invaluable human resources? Does the EC wish to stand by while these scientists follow their colleagues working in other fields in fleeing our Continent? If not, what steps should be taken? With all this in mind, a group of scientists from EC countries joined forces with their colleagues in Central and Eastern Europe. They gained support from the Twelfth Directorate (DG XII) of the EC in Brussels. The idea was to convene a conference on nonlinear dynamics and complex systems. This conference would unite the two parts of Europe (EC and non-EC), but with strong North American participation. Largely due to personal contacts between the Brussels and Warsaw schools, the conference took place in Poland. The venue was Zakopane, a mountain resort south of Kraków. Forbidding weather notwithstanding, the turnout was excellent. Twenty three invited lectures were given. Mitchell Feigenbaum gave a fascinating banquet talk, a transcript of which is included in this volume under the heading 'Where will the future go?'. There were 212 contributed talks (to be published in the Journal of Technical Physics) and four very uneven panel discussions. The panels were on: Mathematics (coordinated by E. Ott and L. Bunimovich); Chemistry and Biology (G. Nicolis and M. Marek); Physics (R. Balescu, I. Białynicki-Birula, M. Feigenbaum, V. G. Makhankov and H. Woźniakowski); and on the future of nonlinear dynamics research (R. Żelazny). This last-mentioned panel might merit a comment here. The Local Organizing Committee put forward an idea for establishing a nonlinear dynamics center in Poland. At the time of writing, this idea is still being persued.

The invited talks

A short glance at the talks indicates just how diverse and dynamic the field is proving to be.

Professor Gundlach spoke about describing chaos in mechanical systems by using symbolic dynamics. His procedure allows us to describe quite general systems evolving under the influence of noise and exhibiting stochastic features. He is able to cope with fractal structures, at least formally.

Professor Shilnikov talked about the occurrence of homoclinic chaos. The main feature of the attractors involved here is the presence of homoclinic tangencies. He pointed out the possibility of the coexistence of infinitely many stable periodic orbits. There can also be infinitely many arbitrarily degenerate periodic orbits. It should be stressed that an infinity of non-periodic attractors can coexist in the systems concerned (with each other and with the periodic orbits).

Modern ergodic theory is the cornerstone of the formalism of classical chaos. However, in quantum systems, the energy and frequency spectra are discrete. To overcome the resulting difficulties, B. Chirikov introduced the concept of pseudochaos. However, examples of this phenomenon in classical systems were also given. As an aside, we were offered a warning. Computers can in fact exhibit pseudochaos, thus leading to a dynamic trajectory becoming a periodic one (an artefact).

Dr Dougherty gave a lecture on the foundations of non-equilibrium statistical mechanics. He shed some light on the otherwise difficult concept of subdynamics as introduced by Ilya Prigogine's school.

His talk was a rare example of a survey of the Brussels school's activity from the outside.

The Prigogine lecture was a survey of the Nobel Prize winner's results over his later period.† During the last hundred years, we have been faced with the fact that practically all interactive particle systems are nonintegrable. An important example of such a system is the Large Poincaré System having a continuous spectrum. This leads to the appearance of diffusive terms. It also leads to limitations on classical trajectory dynamics and wave functions. As a consequence, two important aspects appear in the fundamental dynamics description. They are probability and irreversibility. This is so because we must abandon the trajectory description and use the probabilistic, distribution function, approach. This in turn leads to the Liouville operator and its complex spectral decomposition. We are thus forced to go beyond the usual Hilbert space to a 'rigged' Hilbert space. In the case of chaotic maps, this procedure shows that the eigenvalues of an evolution operator are directly related to the Lyapunov exponents. Application of this idea to other Hamiltonian operators was presented.

Professor Woźniakowski spoke on the notion of computational complexity, which concerns the intrinsic difficulty of solving mathematically posed problems. Information based complexity is a branch of computational complexity that deals with continuous problems defined on spaces of multivariate functions. For such problems, only approximate solutions are possible. The complexity is defined as a minimal cost needed to compute an approximation with error at most ϵ.

Microscopic simulations along with applications in thermomechanical problems connected with heat transfer far from equilibrium were reported by Professor Hoover. The least action principle can be applied far from equilibrium, where it is necessary to control the temperature or internal energy or else other dynamical variables. The resulting equations of motion can be solved.

Professor Ott talked on the control of chaos by the selection and maintenance of an optimum or near optimum unstable periodic orbit from the point of view of a specified goal. Analogous considerations based on different models were discussed by Professor Vaněček. The point is that chaos can even be desirable. The control of chaos was also addressed by other contributors. Chaotic systems can often be managed. This is of immense importance in applications (medicine, industry, etc.).

Driven spatially extended systems, consisting of many almost identical elements, are quite frequent in nature. Some aspects of their complexity can be modelled with the help of sandpile-like cellular automata. Their dynamical properties are interesting from both

† Although the talk was given by Dr Antoniou, we were sent a version co-authored by a different collaborator.

a theoretical and a practical point of view. The question arises of whether scale invariant structures in nature are the consequences of the self-organized critical states that arise. The characteristic properties of these states have been studied both numerically and analytically. Analytical calculations of the characteristics of these states are done mainly for Abelian sandpile models on cubic and Bethe lattices. Abelian sandpile calculations were presented by M. Markošová.

Professor Procaccia spoke on scenarios for anomalous scaling in hydrodynamic turbulence. The scaling behaviour of turbulent hydrodynamic systems is often anomalous; the scaling exponents not being simply related to each other. Nevertheless, it was possible to formulate a theory yielding these exponents. Comparisons with experiments were given. Similar problems, in particular as related to transport in the von Karman sheet, were considered by Professor Tél.

Further important modelling devices are furnished by networks with learning capabilities.

Professor Van den Broeck presented problems connected with the understanding of the mechanism of learning. The learning process can be described as a competition between entropy (log of the number of configurations) and error (of a given configuration with respect to the target) and it is not surprising that a formalism, similar to that of equilibrium statistical mechanics, can be set up.

Professor Szu presented the concept of an Artificial Neuron Network defined to have fixed layers of neurons with threshold logic and capable of learning by the 'small perturbation' Hebb rules. Mathematical attempts to formulate such a self-organization architecture were given.

One way of studying evolutionary processes is by investigating sequences generated by evolution. The basic idea is that the evolution generates criticality structures which occur on the border between regular and chaotic regimes or between two different regular or chaotic critical structures. There is also an interesting class of systems showing 'self-organized criticality' or 'self-tuned criticalities'. Those criticality structures should exhibit very long memory effects, and thus long correlations. By using the methods of symbolic dynamics, any trajectory of a dynamic system may be mapped onto a string of letters in an alphabet.

Professor Ebeling presented studies on sequences generated by dynamic models of evolutionary processes, as in the Fibonacci model, the logistic map, and in strings carrying information such as a book, a piece of music, or DNA. The results show that, in particular, the low frequency spectra and the scaling of the mean square deviations are appropriate measures for long range correlations in symbolic sequences.

There is hope that the analysis of entropies, power spectra, and scaling exponents could be useful for studies of the large scale structures of series and information sequences.

Magnetic fields in plasma confining devices (e.g. tokamaks) or in astrophysics can have a broad range of behaviour ranging from integrable structures to erratic wandering in space. This is caused primarily by the nonlinearities of ideal magnetohydrodynamics. In addition, the presence of small dissipation (resistivity) induces reconnection of magnetic lines with the generation of magnetic islands. These are surrounded by regions where the field lines exhibit a high sensitivity to initial conditions. This means exponential instability, which is a signature of chaos. In confining devices, simplified configurations of the magnetic fields are being studied. These problems were examined by Dr Spineanu.

Excitability is a property shared by some chemical systems and a large number of biological systems. In an excitable medium, suprathreshold stimuli are propagated as a pulse or wave front by a mechanism combining local excitatory kinetics with transport. The Belousov–Zhabotinski reaction has often been used in studies of excitability. Typical examples of oscillatory and excitable phenomena in biology are Ca^{2+} oscillations and waves in cells. Intracellular Ca^{2+} release is connected with many receptor induced cell signals, controlling processes ranging from secretion and heart rate frequency control to transcription and cell division. The introduction of digital Ca^{2+} imaging techniques made it possible to visualize the spatiotemporal patterns of the ion. Ca^{2+} waves in biological systems are mostly treated within the framework of excitable media with ion transport. These waves can often be either provoked by electric stimulation or else influenced by an electric field. A talk on this was given by Professor Marek.

Interesting applications of stochastic differential geometry in financial studies were presented by Professor Makhankov. The idea was to develop a generalized pricing method for over the counter derivatives.

Analytical estimates and computer experiments reveal a variety of possible market developments:

(*a*) explosive instability of the solution which leads to unpredictability of the bond market,

(*b*) a number of stationary solutions: rising, falling and humped curves.

The form of the solution is completely determined by boundary conditions and hence is an exogenously defined feature of the system rather than an intrinsic one.

The difficulty in predicting the evolution of a nonlinear system varies with the state of the system. However, this variation is highly organized within the attractor. The point is to exploit this structure to improve predictions.

Panels

Four discussion panels augmented these talks and endeavoured to formulate some specific problems. All participants stressed the fact that research in the field is just emerging from its infancy and still has a wide range of problems to clarify. Further efforts are necessary to apply this knowledge to solve specific applicational problems. The tendency is to treat chaos in a more positive way (not just as a nuisance).

Formulating future lines of development can be risky. Science develops in an unpredictable and chaotic way resembling patterns and behaviours considered by the Conference. A surprise solution or idea that may emerge in one field is often used elsewhere. Nevertheless, we tried to look at where future development could go.

As for a **mathematical** way of looking at our problems, the following directions were formulated:

The development of new computer algorithms and software.

Consideration of, to what extent computer results reproduce the correct qualitative behaviour of the phenomena simulated ('artifacts', 'ghosts', etc.).

The development of new techniques for the analysis of experimental data (e.g. in the past the introduction of embedding techniques has had an enormous effect on experiments, and the prediction of chaotic system time evolutions promises wide applications).

The development of new bifurcation theory, software, etc., for higher dimensional dynamical systems.

The development of techniques for influencing chaotic systems.

The development of methods for the study of extended systems (e.g. cellular automata, lattice dynamical systems, fluids, reaction–diffusion systems, systems with nonlinear boundary conditions, self-organized criticality, etc.). It would be useful to create a collection of exactly solvable model problems.

The development of a theory for spatial patterns and spatial and temporal chaos.

Studies of chaos as an underpinning of statistical mechanics and transport properties.

Studies of quantum problems (e.g. quantum chaos and quantum dynamics in a Markovian background).

The views expressed on the future directions of research as seen from a **physical** angle were:

We need a well formulated statistical mechanics on three consecutive levels: microscopic, mesoscopic and macroscopic.

Due to the nonintegrability of their Hamilton or Liouville equations many-body problems must be described on a probabilistic level. The extension of Hilbert space to a 'rigged' one may open a new perspective here.

The many-body problem for open systems which can be described as systems with a Markovian background. Can noise be used for controlling chaos?

Measurements in quantum many-body systems. Preparation of the systems by measurements.

Simulation from the point of view of: describing multifractal objects; the understanding of ergodic strange attractors; developing smooth boundaries; excluding unwanted fluctuations; improving the description of turbulence; relating Nosé's mechanics to mechanical variational principles.

Further research on the development of chaos in fluids, the onset of turbulence and its perseverance, the control of turbulence.

The theory of nonlinear fluids and solids (stress tensors depending quadratically on strain and/or velocity gradient). Coefficients may exhibit additional dependence on dynamical variables.

Chaotic phenomena in plasmas, particularly in thermonuclear plasmas, understanding of anomalous and 'strange' transport processes in turbulent plasmas, the control and stabilization of plasma behaviour.

Improvement in the reliability of meteorological prognoses on the basis of experimental data and numerical simulations.

Capital markets are not well described by the traditional Efficient Market Hypothesis. By applying the theory of chaos to investments and economics, a new Fractal Market Hypothesis was recently presented by E. E. Peters. It gives an economic and mathematical structure to fractal market analysis. Through this approach, we can understand why self-similar statistical structures exist, as well as how risk is distributed among investors. All in all, results originally obtained for nonlinear and complex physical systems could be useful for an analysis of social and economic models.

The panel on **chemistry and biology** formulated the following recommendations on directions of nonlinear research:

The most common evidence of complex behaviour in chemistry and biology comes from phenomena on the macroscopic level. Here emphasis is on the origin of collective behaviour in multi-unit systems giving rise to new emergent properties.

There is increasing awareness that complexity also appears at the microscopic and mesoscopic levels, for example in the form of complex distributions of molecular spectra, anomalous transport and kinetics in dispersed media and fractal structures, or of supramolecular assemblies endowed with recognitional and other unusual properties, traditionally attributed exclusively to biomolecules. Bridging the gap between these three levels is one of the priorities. Potential implications are, among others, the control of chemical reactions by ultra-short light pulses and a better understanding of the structure and function of enzymes.

By and large, complex system studies were hitherto based on nonlinear dynamical systems of few degrees of freedom. The limitations of this approach are becoming evident. For instance, the behaviour of spatially extended systems described by partial differential equations is not amenable to conventional dynamic system analysis. In view of the above, a special research effort is required for developing a qualitative theory of spatially extended systems. Special emphasis should be put on the classification of the types of behaviour predicted by the normal form equations.

In the **application area**, the following recommendations were sketched by the panels:

• *Fusion.* Nonlinear problems appear to be crucial in almost all aspects of the physics of hot plasma confinement.

• *Chemical processing.* The manufacturing of both traditional and new materials relies to a large extent on the process of heterogeneous catalysis. It has recently been established that chemical transformations do not happen synchronously on the catalytic surface, but instead give rise to instabilities and complex spatiotemporal patterns. In a similar vein, chemical synthesis in dispersed media (films, micelles) can benefit from studying regimes in which traditional equilibrium-like states are unstable and replaced by self-organizing regimes.

• *Energy technology.* At the root of energy technology is the process of combustion, which gives rise to a variety of complex behaviours, from multistability to oscillations and the appearance of wave fronts. Problems involving flame stabilization are crucial for the efficiency and performance of heat engines. Their evolution could benefit from cross-fertilization with research on complex systems. Here microscopic simulation methods offer a promising tool.

• *Nonlinear dynamics in biology and medicine.* Chemical instabilities provide a natural prototype of a number of important biological phenomena from biological rhythms to morphogenesis and embryonic development. Evidence of wave-like behaviour in cardiac tissues and of spatiotemporal chaos in the brain is mounting. Nonlinear dynamics offers new ways of analyzing data which could culminate in the development of new diagnostic tools and mathematical models for certain types of disease.

• *Evolutionary and cognitive systems.* The emergent adaptive properties observed in biological evolution, animal interaction and cognition furnish striking examples of complex behaviour in nature. Insight gained from such biological phenomena can be applied to techniques for artificial self-organizing and computational devices. Decentralized interactions of simple autonomous units may lead to structures with properties complementary to those of conventional machines. Among some systems and issues currently studied and worthy of support in the future are:

- Evolutionary biotechnology;
- Genetic algorithms and evolutionary programming applied successfully to optimization problems;
- Neural networks, pattern recognition and information compression;
- Multiagent systems and robotics.

• *Ecosystem stability and biodiversity.* Hierarchic mixed populations which coexist and compete in various niches are ubiquitous in nature. Studies of the development of spatiotemporal patterns of such populations and of their stability in distributed systems are of primary importance. Such studies can benefit from the development of a common methodology as mentioned above. They should include a description of man-made chemical agents on populations and could be done in collaboration with biologists. Such investigations could also be of importance in improving the performance of bioreactors, or controlling the spreading of infections and diseases.

These remarks, however incoherent, do show impressive research and applicational potential of the field. Their possible impact on science, technology, and also industrial, environmental, socio-economical processes in the future are impressive. An integrated Europe should meet this challange. As mentioned above, something should be done to

Cambridge University Press
978-0-521-58201-8 - Nonlinear Dynamics Chaotic and Complex Systems: Proceedings of an International Conference Held in Zakopane, Poland November 7–12, 1995: Plenary Invited Lectures
Edited by E. Infeld, R. Żelanzny and A. Gałkowski
Frontmatter
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utilize resources in Central and Eastern Europe. This could perhaps be achieved through a centre for nonlinear dynamics, chaotic and complex systems as proposed by the Local Organizing Committee.

The Editors

Acknowledgements

The authors would like to thank the DG XII of the European Commission and Dr R. Gerold personally for making this conference possible. We would also like to thank the Polish State Agencies involved: Science Research Committee (KBN), Polish Academy of Sciences and Atomic Energy Agency. Dr A. A. Skorupski was extremely helpful in correcting the texts. If this book is now a uniform entity, it is largely thanks to him. Finally, Dr S. Capelin of CUP was most helpful and patient.