Nonlinear Time Series Analysis

非线性时间序列分析

Holger Kantz
Thomas Schreiber 著

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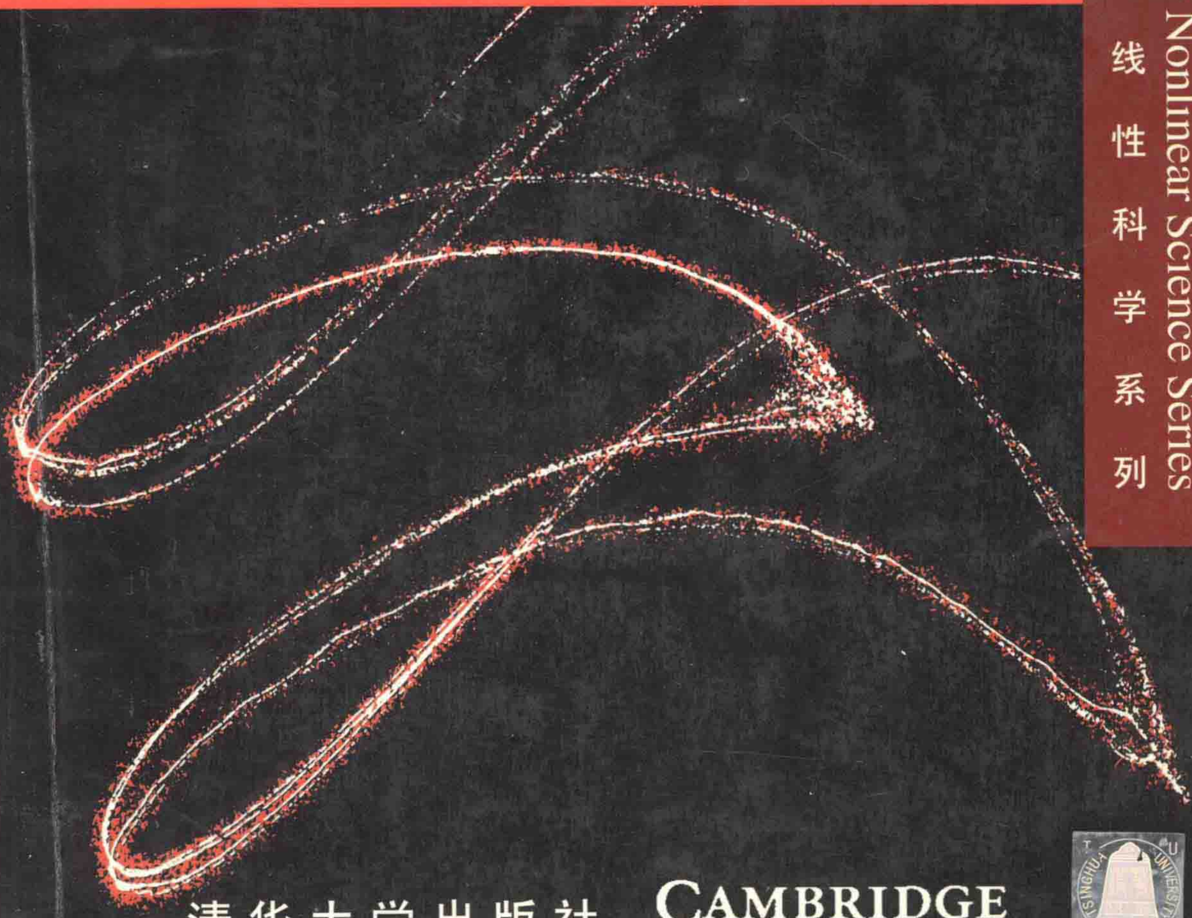

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Deterministic chaos offers a striking explanation for irregular behaviour and anomalies in systems which do not seem to be inherently stochastic. The most direct link between chaos theory and the real world is the analysis of time series from real systems in terms of nonlinear dynamics. This book provides experimentalists with methods for processing, enhancing, and analysing measured signals using these methods; and for theorists it demonstrates the practical applicability of mathematical results.

The framework of deterministic chaos constitutes a new approach to the analysis of irregular time series. Traditionally, nonperiodic signals have been modelled by linear stochastic processes. But even very simple chaotic dynamical systems can exhibit strongly irregular time evolution without random inputs. Chaos theory offers completely new concepts and algorithms for time series analysis which can lead to a thorough understanding of the signals. The book introduces a broad choice of such concepts and methods, including phase space embeddings, nonlinear prediction and noise reduction, Lyapunov exponents, dimensions and entropies, as well as statistical tests for nonlinearity. Related topics such as chaos control, wavelet analysis, and pattern dynamics are also discussed. Applications range from high-quality, strictly deterministic laboratory data to short, noisy sequences which typically occur in medicine, biology, geophysics, and the social sciences. All the material discussed is illustrated using real experimental data.

This book will be of value to any graduate student and researcher who needs to be able to analyse time series data, especially in the fields of physics, chemistry, biology, geophysics, medicine, economics, and the social sciences.

Preface

The paradigm of deterministic chaos has influenced thinking in many fields of science. As mathematical objects, chaotic systems show rich and surprising structures. Most appealing for researchers in the applied sciences is the fact that deterministic chaos provides a striking explanation for irregular behaviour and anomalies in systems which do not seem to be inherently stochastic.

The most direct link between chaos theory and the real world is the analysis of time series from real systems in terms of nonlinear dynamics. On the one hand, experimental technique and data analysis have seen such dramatic progress that, by now, most fundamental properties of nonlinear dynamical systems have been observed in the laboratory. On the other hand, great efforts are being made to exploit ideas from chaos theory in cases where the system is not necessarily deterministic but the data displays more structure than can be captured by traditional methods. Problems of this kind are typical in biology and physiology but also in geophysics, economics, and many other sciences.

In all these fields, even simple models, be they microscopic or phenomenological, can create extremely complicated dynamics. How can one verify that one's model is a good counterpart to the equally complicated signal that one receives from nature? Very often, good models are lacking and one has to study the system just from the observations made in a single time series, which is the case for most nonlaboratory systems in particular. The theory of nonlinear dynamical systems provides new tools and quantities for the characterisation of irregular time series data. The scope of these methods ranges from invariants such as Lyapunov exponents and dimensions which yield an accurate description of the structure of a system (provided the data are of high quality) to statistical techniques which allow for classification and diagnosis even in situations where determinism is almost lacking.

This book provides the experimental researcher in nonlinear dynamics with methods for processing, enhancing, and analysing the measured signals. The theorist will be offered discussions about the practical applicability of mathematical results. The time series analyst in economics, meteorology, and other fields will find inspiration for the development of new prediction algorithms. Some of the techniques presented here have also been considered as possible diagnostic tools in clinical research. We will adopt a critical but constructive point of view, pointing out ways of obtaining more meaningful results with limited data. We hope that everybody who has a time series problem which cannot be solved by traditional, linear methods will find inspiring material in this book.

Dresden and Wuppertal
November 1996

Acknowledgements

If there is any feature of this book that we are proud of, it is the fact that almost all the methods are illustrated with real, experimental data. However, this is anything but our own achievement – we exploited other people's work. Thus we are deeply indebted to the experimental groups who supplied data sets and granted permission to use them in this book. The production of every one of these data sets required skills, experience, and equipment that we ourselves do not have, not forgetting the hours and hours of work spent in the laboratory. We appreciate the generosity of the following experimental groups:

NMR laser. Our contact persons at the Institute for Physics at Zürich University were Leci Flepp and Joe Simonet; the head of the experimental group is E. Brun. (See Appendix C.2.)

Vibrating string. Data were provided by Tim Molteno and Nick Tufillaro, Otago University, Dunedin, New Zealand. (See Appendix C.3.)

Taylor–Couette flow. The experiment was carried out at the Institute for Applied Physics at Kiel University by Thorsten Buzug and Gerd Pfister. (See Appendix C.4.)

Atrial fibrillation. This data set is taken from the MIT-BIH Arrhythmia Database, collected by G. B. Moody and R. Mark at Beth Israel Hospital in Boston. (See Appendix C.6.)

Human ECG. The ECG recordings we used were taken by Petr Saparin at Saratov State University. (See Appendix C.7.)

Foetal ECG. We used noninvasively recorded (human) foetal ECGs taken by John F. Hofmeister at the Department of Obstetrics and Gynecology, University of Colorado, Denver CO. (See Appendix C.7.)

Phonation data. This data set was made available by Hanspeter Herzel at the Technical University in Berlin. (See Appendix C.8.)

Autonomous CO_2 laser with feedback. The data were taken by Riccardo Meucci and Marco Ciofini at the INO in Firenze, Italy. (See Appendix C.10.)

Human posture data. The time series was provided by Steven Boker and Bennett Bertenthal at the Department of Psychology, University of Virginia, Charlottesville VA. (See Appendix C.9.)

We used the following data sets published for the Santa Fe Institute Time Series Contest, which was organised by Neil Gershenfeld and Andreas Weigend in 1991:

Human breath rate. The data we used is part of data set B of the contest. It was submitted by Ari Goldberger and coworkers. (See Appendix C.5.)

NH_3 laser. We used data set A and its continuation, which was published after the contest was closed. The data was supplied by U. Hübner, N. B. Abraham, and C. O. Weiss. (See Appendix C.1.)

During the composition of the text we asked various people to read all or part of the manuscript. The responses ranged from general encouragement to detailed technical comments. In particular we thank Peter Grassberger, James Theiler, Daniel Kaplan, Ulrich Parlitz, and Martin Wiesenfeld for their helpful remarks. Members of our research groups who volunteered to comment on some of the computer programs are Rainer Hegger, Andreas Schmitz, Marcus Richter, and Frank Schmüser.

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Part 1

Basic topics