Predictability of Complex Dynamical Systems

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Predictability of Complex Dynamical Systems

With 55 Figures

Springer

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Springer Series in Synergetics

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An ever increasing number of scientific disciplines deal with complex systems. These are systems that are composed of many parts which interact with one another in a more or less complicated manner. One of the most striking features of many such systems is their ability to spontaneously form spatial or temporal structures. A great variety of these structures are found, in both the inanimate and the living world. In the inanimate world of physics and chemistry, examples include the growth of crystals, coherent oscillations of laser light, and the spiral structures formed in fluids and chemical reactions. In biology we encounter the growth of plants and animals (morphogenesis) and the evolution of species. In medicine we observe, for instance, the electromagnetic activity of the brain with its pronounced spatio-temporal structures. Psychology deals with characteristic features of human behavior ranging from simple pattern recognition tasks to complex patterns of social behavior. Examples from sociology include the formation of public opinion and cooperation or competition between social groups.

In recent decades, it has become increasingly evident that all these seemingly quite different kinds of structure formation have a number of important features in common. The task of studying analogies as well as differences between structure formation in these different fields has proved to be an ambitious but highly rewarding endeavor. The Springer Series in Synergetics provides a forum for interdisciplinary research and discussions on this fascinating new scientific challenge. It deals with both experimental and theoretical aspects. The scientific community and the interested layman are becoming ever more conscious of concepts such as self-organization, instabilities, deterministic chaos, nonlinearity, dynamical systems, stochastic processes, and complexity. All of these concepts are facets of a field that tackles complex systems, namely synergetics. Students, research workers, university teachers, and interested laymen can find the details and latest developments in the Springer Series in Synergetics, which publishes textbooks, monographs and, occasionally, proceedings. As witnessed by the previously published volumes, this series has always been at the forefront of modern research in the above mentioned fields. It includes textbooks on all aspects of this rapidly growing field, books which provide a sound basis for the study of complex systems.

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Dedicated to the Kadtke and Kravtsov families,
who have always proven quite *un-predictable*...

Preface

This book was originally conceived as a continuation in theme of the collective monograph Limits of Predictability (Yu.A. Kravtsov, Ed., Springer Series in Synergetics, Vol. 60, Springer-Verlag, Heidelberg, 1993). The main thrust of that book was to examine the various effects and factors (system nonstationarity, measurement noise, predictive model accuracy, and so on) that may limit, in a fundamental fashion, our ability to mathematically predict physical and man-made phenomena and events. Particularly interesting was the diversity of fields from which the papers and examples were drawn, including climatology, physics, biophysics, cybernetics, synergetics, sociology, and ethnogenesis. Twelve prominant Russian scientists, and one American (Prof. A.J. Lichtman) discussed their philosophical and scientific standpoints on the problem of the limits of predictability in their various fields. During the preparation of that book, the editor (Yu.A.K) had the great pleasure of interacting with world-renowned Russian scientists such as oceanologist A.S. Monin, geophysicist V.I. Keilis-Borok, sociologist I.V. Bestuzhev-Lada, historian L.N. Gumilev, to name a few. Dr. Angela M. Lahee, managing editor of the Synergetics Series at Springer, was enormously helpful in the publishing of that book.

In 1992, Prof. H. Haken along with Dr. Lahee kindly supported the idea of publishing a second volume on the theme of nonlinear system predictability, this time with a more international flavor. It was then that the present editors (Yu.A.K. and J.B.K.) agreed to produce all the materials. During the ensuing period of preparation, Dr. Lahee happily gave birth to a baby (an event which could hardly have been predicted by either of the editors before the project began; we only wish for Angela that her child will prove a little more predictable than any of ours), and Prof. W. Beiglböck subsequently took over management of the project. Prof. Beiglböck wisely advised us to change the emphasis of the second volume, to provide a more practical and technical approach to the theme. Hence, this second volume provides the reader with a more applied framework, which is oriented towards the analysis of experimental data or artificial signals, often providing explicit numerical algorithms. The resulting book is both interesting and unique, in that the papers provide philosophical, intuitive, analytical, and numerical aspects of these state-of-the-art methods of analysis, which are drawn from experts in a wide variety of fields. The intent is, of course, cross-fertilization between these diverse disciplines, and we hope the reader will find them just as highly interesting and instructive as we have.

We would like to express our great appreciation to all the authors of this monograph for the timely submission of their papers and for their patience during the rather extended period of preparation. We are especially thankful to Dr. M. Kremliovsky for his heroic efforts in the TEX formatting of the camera-ready copy of the manuscript. We are also indebted to Ms. E.B. Grigor'eva for the superb translation of three Russian papers into English. It is our sincere wish that the joint efforts of all the participants of this project has resulted in an interesting, readable, and technically useful book.

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Part 1

Introduction

Introduction

James B. Kadtke and Yurii A. Kravtsov

1 A Changing Paradigm

As recently as 50 years ago, there was a firm conviction among many scientists that the universe was fundamentally mechanistic, and that at some level mathematical prediction of physical events could be exact. This view was of course rooted in the "romantic" period of the history of science (the 19th and beginning of the 20th centuries) when the overwhelming advances in science and technology often obscured the possibility that fundamental limitations to the power of science could exist. The situation has changed rather dramatically in recent decades. Most scientists will agree now (as did the most acute minds long ago) that long-term mathematical prediction of complicated physical systems is in practice unachievable. What is remarkable is that this realization has evolved from the "precise" science of classical mechanics, which has long upheld the principles of Laplacian determinism. This is due, ironically, to the development in the last twenty years of a consistent framework for "chaotic" dynamical systems, often generalized now to "nonlinear dynamics". These ideas have required an essential revision of the concepts of dynamical behavior and classical predictability.

Because of these advances, there is now an enormously renewed interest in classical dynamical systems and modeling, and in particular time series analysis and prediction. Much of this work attempts to take advantage of the rather unusual properties of systems exhibiting chaotic behavior. Typically, such a system exhibits so much local instability that any small inaccuracy in the specification of the state variables is rapidly magnified (sometimes referred to as the "butterfly effect"), typically making long-term predictions impossible. Since this type of generic instability is typically produced by nonlinear terms in the evolution equations of a continuous physical system, the study of this field has taken on the term nonlinear dynamics; as the classes of systems (and types of behavior) studied have become more general, we now speak in terms of the field of complex systems. Another important property is that, in many instances, the existence of chaos in a dynamical system can mean that a far simpler model of any complicated time evolution can be developed to explain its behaviour (due to the existence of a low-dimensional "attractor"), and this latter possibility has resulted in an explosion of numerical algorithms being developed to take advantage of this possibility. To evaluate and understand the performance of these methods, new and objective criteria need to be developed that are tailored to the dynamical modeling framework. For example, a useful concept introduced by Lighthill [Lighthill, 1986] is the "horizon of predictability", which is the farthest future time beyond which no prediction based on dynamical models can make sense. Not only does chaos present a new understanding of where this horizon may lie, but in many instances can point out the difference between an objective scientific prediction, and a subjective one based on dubious means. At present, the "new dynamicists", in many fields, are busily struggling with these problems, and it was the original intention of this monograph to examine some of these issues.

The theme of this current monograph may at first seem somewhat obscure, and indeed required a good deal of thinking to organize in an easily digestible form. One must realize, though, that modeling is a fundamental aspect of science (and other fields), where the practitioner builds a mathematical framework premised on some fundamental hypotheses, and then uses this to compare a model-based prediction to reality. The fact that our conceptualization of what constitutes modeling and prediction is changing within the framework of complex systems means that some fundamental aspect of modern science may also change. It is not the purpose of this book to delineate what these changes may be, since these sciences are currently evolving rapidly, and we are certainly not expert enough to tell. However, we here do attempt to bring together a variety of new ideas from some of the most important experts in their respective fields, to present technical examples and methods which examine some aspect of the predictability issues which may not be readily available in the literature. More importantly, we have attempted to collect such papers from a wide range of fields, with the intention of making available to the interested professional some of the common problems and solutions which are faced in disparate disciplines. It is the intent of the book to promote such "cross-fertilization" between these disciplines, which often face fundamentally identical technical problems, yet develop fundamentally different solutions.

A second hopefully interesting aspect of this book is that the editors have tried to encourage an intuitive, even speculative flavor in the contributions, and not simply technical discussions. This is in major part because a hallmark of the new area of complex systems is a fundamentally changed view of how computers can be used for research purposes. In the last two decades, the vastly increased power of computers, and new languages and visualization methods, have been coupled with the many new theories and modeling procedures to allow the researcher to explore qualitative aspects of the system of interest. In this sense, the researcher has become an "experimenter" in the virtual laboratory of his computer, and intuition and imagination have become key aspects. Consequently, modeling and prediction have taken on considerably more importance, even in the physical sciences, as researchers now search for global properties, rather than simply examining strings of numbers. Such strategies are perhaps not as foreign in, e.g., the social and political sciences, where modeling has often been the primary means of analysis. For example, model-based prediction may be used to explore the physically feasible behaviors existing in the universe of all possible behaviors, or for simple contingency planning. The central point here is that such intuitive analysis is becoming a key part of the research process even in the physical sciences, and will likely become more so in the future. We have therefore viewed it to be vital that the contributions in this volume contained at least some discussion of the qualitative or speculative aspects of each individual problem, and we feel that largely this has proven much more enlightening. It is this intuitive aspect that has provided the development of whole new paradigms for understanding many natural phenomena in recent years, and will no doubt continue to do so.

Perhaps a bit more should be said about the importance of prediction and predictability in the understanding of complicated physical systems. As hinted at above, the new sciences developing in complexity theory utilize at least two fundamentally new realizations: first, that a system whose time evolution may seem exceedingly complex (even to the extent that standard mathematical measures may declare it to be "random") may in actuality have simple nonlinear, deterministic models which can generate its behavior. This first concept has led in recent years to the development of whole new paradigms in some fields (e.g. cellular automata, or "artificial life"), as scientists attempt to re-interpret old, "random" data in light of new deterministic models. The second concept is that even simple deterministic systems can exhibit such local instability (i.e., chaos) that any mathematical prediction loses validity after some short average time scale. Although the implications are less well understood at this stage, this second point may have profound consequences for many fields of study which are model-oriented, especially in the social, military, and political arenas. Understanding when systems are predictable, and especially when they are fundamentally not, can lead us away from erroneous questions and lines of reason, and toward more relevant understanding. For example, in simulating a socio-military-political conflict, generals or politicians can move towards the physical parameters of the system which result in regular, predictable behavior, in order to avoid dynamical regimes which can generate catastrophic "flashpoints" which cannot be foreseen or controlled. As such, nonlinear modeling may have profound consequences for many aspects of society, and new ways of quantifying and understanding the predictability of given systems will be a vital aspect. It is hoped that many of the papers of this volume have at least touched on the issues involved in this aspect, and provide some examples of the technical framework available to researchers. We should also point out that many of these philosophical issues are also discussed in the excellent collective monograph *Long-Term Predictability* (Shebehely and Taply, Eds., 1976, Dordrecht: Reidel) and also in the discussion stimulated by J.Lighthill in "Proceedings of Royal Society", **A407** (1832), 1986.