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Foundations and Applications

Edited by
L. Douglas Kiel and Euel Elliott

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To Our Parents

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Introduction

Euel Elliott and L. Douglas Kiel

The social sciences, historically, have emulated both the intellectual and methodological paradigms of the natural sciences. From the behavioral revolution, to applications such as cybernetics, to a predominant reliance on the certainty and stability of the Newtonian paradigm, the social sciences have followed the lead of the natural sciences. This trend continues as new discoveries in the natural sciences have led to a reconsideration of the relevance of the Newtonian paradigm to all natural phenomena. One of these new discoveries, represented by the emerging field of chaos theory, raises questions about the apparent certainty, linearity, and predictability that were previously seen as essential elements of a Newtonian universe. The increasing recognition by natural scientists of the uncertainty, nonlinearity, and unpredictability in the natural realm has piqued the interest of social scientists in these new discoveries. Chaos theory represents the most recent effort by social scientists to incorporate theory and method from the natural sciences. Most importantly, chaos theory appears to provide a means for understanding and examining many of the uncertainties, nonlinearities, and unpredictable aspects of social systems behavior (Krasner 1990).

Chaos theory is the result of natural scientists' discoveries in the field of nonlinear dynamics. Nonlinear dynamics is the study of the temporal evolution of nonlinear systems. Nonlinear systems reveal dynamical behavior such that the relationships between variables are unstable. Furthermore, changes in these relationships are subject to positive feedback in which changes are amplified, breaking up existing structures and behavior and creating unexpected outcomes in the generation of new structure and behavior. These changes may result in new forms of equilibrium; novel forms of increasing complexity; or even temporal behavior that appears random and devoid of order, the state of "chaos" in which uncertainty dominates and predictability breaks down. Chaotic systems are often described as exhibiting *low-dimensional* or *high-dimensional* chaos. The former exhibit properties that may allow for some short-term prediction, while the latter may exhibit such variation as to preclude any prediction. In all nonlinear systems, however, the relationship between cause and effect does not appear proportional and determinate but rather vague and, at best, difficult to discern.

These discoveries have given rise to a new mathematics that belies previous scientific commitment to prediction and certainty. Natural scientists have now applied this mathematics to numerous fields of inquiry. A brief and partial listing of the fields includes meteorology (Lorenz 1963), population biology (May 1976), and human anatomy (West and Goldberger 1987). These studies consistently show that nonlinearity, instability, and the resulting uncertainty are essential components in the evolutionary processes of natural systems. Moreover, these inquiries have given precedence to a greater concern for the extent of and challenges of understanding the inherent complexity of natural systems.

The emerging paradigm of chaos thus has profound implications for the previously dominant Newtonian view of a mechanistic and predictable universe. While a Newtonian universe was founded on stability and order, chaos theory teaches that instability and disorder are not only widespread in nature, but essential to the evolution of complexity in the universe. Thus, chaos theory, as relativity theory and quantum theory before it, presents another strike against a singular commitment to the determinism of a Newtonian view of the natural realm.

This understanding also suggests that the relative successes in knowledge acquisition by the natural sciences are the result of a focus on "simple" systems that function in an orderly and consistent manner. As natural scientists have shifted their investigative focus to more complex systems, the previous quest for certainty has given way to a greater appreciation of uncertainty and the enormity of potential generated by the uncertainty of disorder and disequilibrium.

With the focus of chaos theory on nonlinearity, instability, and uncertainty, the application of this theory to the social sciences was perhaps a predictable eventuality. As Jay W. Forrester (1987, 104) has noted, "We live in a highly nonlinear world." The social realm is clearly nonlinear, where instability and unpredictability are inherent, and where cause and effect are often a puzzling maze. The obvious fact that social systems are historical and temporal systems also stresses the potential value of chaos theory to the social sciences. Social systems are typified by the changing relationships between variables.

The obvious metaphorical value of applying a theory of chaos to the social realm has served as an impetus for the emergence of the application of this theory to social phenomena. Yet chaos theory is founded on the mathematics of nonlinear systems. Thus, social scientists, in their efforts to match the mathematical rigor of the natural sciences, are increasingly applying this mathematics to a variety of social phenomena. Time-series analysis is essential to these efforts, as researchers strive to examine how nonlinear and chaotic behavior occurs and changes over time.

Clearly, the fundamental gap between the clear success of knowledge acquisition in the natural sciences versus the rather minimal successes in understanding the dynamics of the social realm is the inherent nonlinearity, instability, and uncertainty of social systems behavior. The seeming "chaos" of social phenomena has always been a stumbling block to knowledge acquisition in the social sciences. Social scientists have long argued that this relative knowledge gap was due to the relative complexity of the phenomena examined by the two scientific cultures. Yet chaos theory teaches that the "gap" between the two sciences may have largely been artificial. As natural scientists more intensively investigate complex natural phenomena, they too must contend with the challenges that have long served to keep the social sciences in the position of a scientific stepchild. Chaos theory seems to represent a promising means for a convergence of the sciences that will serve to enhance understanding of both natural and social phenomena.

Chaos theory has now been applied to a wide variety of social phenomena ranging across the subject matter of the traditional social science disciplines of economics (Grandmont 1985; Baumol and Benhabib 1989; Arthur 1990) and political science (Saperstein and Mayer-Kress 1989; Huckfeldt 1990; Kiel and Elliott 1992). Economists and political scientists have applied chaos theory with considerable methodological rigor and success to the temporal dynamics of a variety of phenomena in their fields. Chaos theory has also been applied to sociology. In this field, however, more than in economics and political science, such efforts have tended toward metaphorical and postmodernist or poststructuralist usages (Young 1991, 1992). Thus, while this volume does not include rigorous mathematical assessments of chaotic dynamics in the subject matter of sociology, the applications in political science and economics should serve as foundations for the development of such research in sociology. While no specific chapter contends solely with these postmodernist and poststructuralist issues, David Harvey and Michael Reed's concluding chapter examines the relevance of these elements to chaos research and social science inquiry.

The increasingly evident value of chaos theory in the social sciences is thus its promise as an emerging means for enhancing both the methodological and theoretical foundations for exploring the complexity of social phenomena. Exploring this emergent and potential value is the purpose of this book. By examining applications of chaos theory to a range of social phenomena and by providing means for exploring chaotic dynamics, the chapters in this book afford the reader a comprehensive vision of the promise and pitfalls of chaos theory in the social sciences.

This book seeks to provide knowledge to both social scientists new to this area of study and the well-informed chaos researcher. Chapters range from the mathematically and methodologically sophisticated to chapters with a strictly theoretical emphasis. The book is organized by both disciplinary area and general methodology. The disciplinary sections examine chaos theory in political science and economics. The first section of the book examines methods for exploring and examining the existence of chaotic dynamics in time-series data, which cut across the disciplines. First, though, an initial primer on chaos and nonlinear behavior is necessary to provide the basics of this theory and an introduction to the unique vocabulary it utilizes.

The Mathematics and Behavior of Chaos

A brief examination of the mathematics and behavior of chaotic systems provides a means for understanding the relevance of this theory to the complexity of social phenomena. Distinguishing between linear and nonlinear equations also reveals both the relevance and the challenge of contending with the nonlinear mathematics of nonlinear systems. Linear equations are typified by the superposition principle. This principle, simply stated, means that two solutions of a linear equation can be combined, or added together, to generate a new solution. This means that linear equations allow problems to be broken down into smaller pieces that may generate several separate solutions. In such linear mathematics, the individual solutions can be added back together to form a complete solution to the entire problem.

The superposition principle, however, does not hold for nonlinear equations. A nonlinear equation cannot be broken down into bits and then reformulated to obtain a solution. Nonlinear differential equations, and the phenomena or problems they describe, must be seen as a totality, that is, as nondecomposable. This further means that nonlinear equations are particularly intractable for the analyst. The inherent nonlinearity of many social phenomena and the intractability of the relevant mathematics thus must explain, in part, the challenges social scientists face when attempting to understand the complexity of social dynamics.

Another element of the mathematics of nonlinear equations is the fact that a simple deterministic equation can generate seemingly random or chaotic behavior over time. One nonlinear differential equation, the logistic map, is such an example. The logistic map is described in detail in the chapters in this edition by Kiel and Elliott (chap. 1), Diana Richards (chap. 5), and Alvin Saperstein (chap. 7). These examples of the logistic map also detail an essential element of chaotic behavior. Chaotic behavior occurs within defined parameters. The logistic map shows that a simple system can create very complex and chaotic behavior. This realization has obvious impact for the social sciences. Social systems of initial relative simplicity may result over time in very complex behavior.

The varying mathematics of linear and nonlinear systems also result in divergent temporal behavior for these types of systems. Linear systems, characterized by stable relationships between variables, respond to changes in their parameters, or to external "shocks," in a smooth and proportionate manner. Consequently, linear systems will exhibit smooth, regular, and well-behaved motion. Even large waves or pulses in a linear system will be dispersed over time, generally resulting in a move back to the typical behavior of the system.

Nonlinear systems may be characterized by periods of both linear and nonlinear interactions. During some time periods behavior may reveal linear continuity. However, during other time periods relationships between variables may change, resulting in dramatic structural or behavioral change. Such dramatic change from one qualitative behavior to another is referred to as a "bifurcation." Nonlinear systems are consequently capable of generating very complex behavior over time. Studies of nonlinear systems evidence three types of temporal behavior. Nonlinear systems may evidence behavior that (1) is stable (a mathematical equilibrium or fixed point); (2) oscillates between mathematical points in a stable, smooth, and periodic manner; or (3) is chaotic and seemingly random, devoid of pattern (nonperiodic behavior). Chapter one presents graphical images of these three temporal regimes. These behaviors may occur intermittently throughout the "life" of a nonlinear system. One regime may dominate for some time periods while other regimes dominate at other times. It is the potential for a variety of behaviors that represents the dynamics of nonlinear systems.

Chaotic behavior is the behavioral regime in nonlinear systems of greatest interest. Chaotic behavior, while occurring within defined mathematical parameters, appears random and without pattern over time. Chaotic behavior does not retrace previous points during its temporal evolution. This creates the appearance of randomness. Chaotic behavior, however, is not random behavior, since it can be generated with a completely deterministic equation. This understanding is an essential foundation of knowledge for chaos researchers. Even deterministic systems can generate very erratic behavior over time. Moreover, as noted above, a chaotic system may appear more or less random depending on its complexity. A system mapped by the logistic equation may allow for some predictability and is an example of a low-dimensional chaotic system.

This point raises another distinctive point regarding nonlinear systems. Nonlinear systems are historical systems in that they are determined by the interactions between the deterministic elements in a system's history and "chance" factors that may alter its evolution. In systems operating in a chaotic

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regime, this fact is referred to as *sensitive dependence on initial conditions*. In short, the combination of factors that defines the initial condition of the phenomenon and the insertion of chance elements during its "life" may generate very divergent outcomes from systems that initially appeared quite similar. This distinguishes chaotic behavior from truly random behavior. In a genuinely random system, such a system is insensitive to its initial condition.

Uncertainty is also an important element of nonlinear systems since the outcomes of changing variable interactions cannot be known. Thus, the complexities of both internal dynamics and environmental "disturbances" generate considerable uncertainty during change processes in nonlinear systems. Furthermore, a wide and complex array of possible outcomes is available to nonlinear systems. This is particularly true during chaotic regimes. As a result, any effort at long-term prediction in nonlinear systems is highly suspect (Baumol and Quandt 1985).

Graphical Analysis in Chaos Research

The intractability of nonlinear equations and the inherent difficulties in understanding the dynamics of complex time series have led chaos researchers to formulate new methods for analyzing data from nonlinear phenomena. This point is well stated by Hasslacher (1992, 60), who notes in reference to complex nonlinear systems:

> In these systems complexity is usually both emergent and Byzantine. This means that organized and extended structures evolve and dominate a system, and the structures themselves are so complex that, when first seen, they produce a sense of beauty followed by a deep feeling of unease. One instinctively realizes that the analytic tools that worked so well in the past are going to be of little use.

Many of these new analytical methods are graphical in nature and are based on researchers' efforts to examine the dynamical motion of time series generated by social science data. Chaos researchers have thus focused on examining the morphology (Abraham and Shaw 1982) of the graphics generated by these time series. For example, the chapter in this volume by Brian J. L. Berry and Heja Kim, on the dynamics of the economic long wave, relies solely on this graphical approach to data analysis.

These graphical representations are lagged mapping of data at adjacent time periods that result in an amazing array of geometric structures, resulting in what Abraham and Shaw (1982) label the "geometry of behavior." These mappings reveal that nonlinear systems possess an underlying order known as an *attractor*, where the mathematical points describing the systems' behavior create pattern and structure. These geometric formulations are used throughout the chapters in the text as a means of examining the underlying structure of longitudinal social science data.

Studies of the attractors of nonlinear time series reveal that each of the three behavioral regimes emanating from nonlinear differential equations creates a uniquely shaped attractor. A stable equilibrium generates a *point attractor*, in which the data are attracted to a single point on the mapping. A stable periodic oscillation generates a circular mapping, or *limit cycle*, as the data revolve back and forth between consistent mathematical points. The chaotic attractor is represented by a variety of unique shapes resulting in the labeling of such attractors as *strange attractors*. These attractors are typified by the creation of form without retracing previous mappings.

It is an examination of these attractors that serves as a graphical foundation for the notion of "order in chaos." Even though the numerical data describing a chaotic regime appear disorderly, their geometric representation creates unique shapes of order. And since chaotic regimes function within defined parameters, a stability also exists in chaos. We then begin to see that chaotic behavior is globally stable, but locally unstable.

Organization of the Book

This volume represents research spanning a range of disciplines, methodologies, and perspectives. We have incorporated many different substantive areas in order to provide the reader with as balanced a perspective as possible of the kind of social science research and writing that is currently being done. Moreover, while the book is organized into four separate sections, (1) exploration and method, (2) political science, (3) economics, and (4) implications for social systems management and social science, we would emphasize that chaos theory is really about not only the interdisciplinary but also the multidisciplinary character of the social sciences. Thus, the reader will occasionally note references and allusions in one section to chaos research being conducted in other areas of the social or even natural sciences.

In addition to the desire on our part to incorporate a diverse array of substantive areas in this volume, a number of other considerations were critical to our thinking about this work. First, we were very concerned that the subject matter be treated in a fashion that would make the arguments and concepts as accessible and "user friendly" as possible to the professional social scientist, as well as to graduate students with an interest in nonlinear dynamics. While we recognize that some of the chapters deal with rather complex arguments and formulations, the authors of these chapters have done an admirable job in presenting the material in such a way as to allow anyone reasonably comfortable with undergraduate mathematics to capture the gist of the arguments. More sophisticated readers, however, are not shortchanged. While accessible, we have insisted that the integrity of the material not be jeopardized. At the same time, it will be readily apparent that there is substantial variation among the chapters in terms of methodological rigor.

We were also concerned that the contributions represent both macro- and micro-level phenomena. Readers will observe that this is particularly the case in our economics and political science sections. It is crucial, in our view, to demonstrate that chaotic processes can occur at the level of individuals and small groups, as well as at highly aggregated levels of analysis. Indeed, Thad A. Brown, in his overview chapter for political science (chap. 6), argues that an important next step in the research agenda is to attempt a linkage of the two perspectives using theoretical approaches drawn from chaos theory.

Finally, we did not want to fall into the trap of seeing an emerging intellectual and methodological paradigm as a singular solution to the challenges of understanding the complexities of social systems behavior. As with all efforts to understand the complexity that constitutes the human and social realms, a mature and reasoned skepticism is appropriate. The final chapter of this book, by David L. Harvey and Michael Reed, attempts to make sense of the evolution of chaos theory in the social sciences and its prospects for enhancing knowledge in the social sciences.

Chaotic Dynamics in the Social Sciences: Exploration and Method

The first section of this volume examines the dynamics of nonlinear and chaotic systems and focuses on methodological approaches to testing for the presence of chaos in a time series. Testing for actual "chaos" in time-series data is a particularly important issue, due not only to the technical challenge involved, but also to ensuring that chaotic time series in social science data emulate chaotic time series discovered in data from the natural sciences. While a variety of techniques exist to test for chaos, we have concentrated our attention on those approaches that appear to be most often used by chaos researchers. While each chapter has been written in what we consider a highly accessible fashion, many readers may well prefer to start with the substantive chapters in sections two and three and then return later to this section. For those researchers who are either beginning to apply chaos theory to empirical work or otherwise interested in some of the more technical methodological facets of empirical work in the area, this section should be an invaluable resource.

The editors of this volume lead off this first section with a brief exploration of the time series of nonlinear and chaotic systems. This chapter is highly recommended as a starting point for researchers new to chaos theory. It shows how an elcctronic spreadsheet can be used to generate nonlinear and chaotic time series. These series can be used to create graphs and phase diagrams essential to investigating nonlinear time series. This chapter is intended to reveal for social scientists how the dynamics of a nonlinear differential equation emulate much of the temporal dynamics of social system behavior.

The remaining chapters in this section are mathematically rigorous approaches to the statistical analysis of chaotic dynamics in social science data. Michael McBurnett's chapter examines the use of spectral analysis in investigating the dynamics of a time series. McBurnett begins with a necessary but tractable mathematical introduction to spectral density and spectral distribution functions. He then examines the different types of time series—periodic, random, and chaotic—and demonstrates with regard to the first two types the problems in resolving the nature of a series when "noise" is introduced into the analysis. He concludes by examining known chaotic time series as well as an "unknown" series. McBurnett's study is an excellent introduction to both the advantages and the limitations of spectral analysis in testing for chaotic dynamics.

A second approach for examining chaotic dynamics relies on the use of Lyapunov exponents. The Lyapunov exponent measures the extent to which "small" changes in initial conditions produce divergence in a system over time. Thad A. Brown's chapter explores in detail both the advantages and disadvantages of such an approach. The Lyapunov is shown to be linked to the information gained and lost during chaotic episodes, and hence is linked to the amount of information available for prediction. This chapter guides the reader through the formal nature of unfolding subspaces and the state space reconstruction needed to estimate the Lyapunov exponent. The mathematics here are downplayed, in favor of words and even some humor.

Ted Jaditz's chapter is concerned with the development of empirical techniques for predicting a time series exhibiting deterministic chaos. As Jaditz notes in the introduction to chapter 4, "The Prediction Test for Nonlinear Determinism," standard linear statistical models provide good fits with data that are taken "in sample," but out-of-sample predictions do much worse. For this reason, economic forecasters have been attracted to the possibility of nonlinear determinism in economic data. Jaditz discusses the problems inherent in determining whether or not a series truly manifests chaos and demonstrates some analytical tools for improving forecasting models. Specifically, by using "near neighbor techniques," Jaditz shows how this new approach provides dramatic improvements over conventional linear prediction models typically used by economists, at least with data that are known to be chaotic.

Diana Richards's contribution, "From Individuals to Groups: The Aggregation of Votes and Chaotic Dynamics," presents another method for testing for chaotic dynamics. Richards applies Devaney's (1989) three-part test for chaotic dynamics. Although the application of chaos theory to the social choice problem leads to several research questions specific to social choice, the intent is to introduce chaotic dynamics to a broader social science audience using the case of the generic social choice problem. The social choice problem is only one of potentially many examples of interaction among individuals or groups that is nonlinear, and therefore a potential candidate for the domain of chaotic dynamics. Richards's chapter provides a rich understanding of the translation of individual preferences into group outcomes and the classic problem of intransitivities. The application of chaos theory is a relatively small modeling step; it is only a small extension of existing frameworks into the nonequilibrium realm. However, chaos theory has major implications, in terms of complex outcomes from simple relationships, in terms of instability and structural constraints, and in terms of prospects for prediction for all of the social sciences.

This chapter demonstrates that chaotic dynamics are present in many social choice settings, including some cases of Arrow-type social choice and in nearly all cases where two or more issues are considered simultaneously. Since the aggregation of individual preferences into outcomes is inherently nonlinear, it is natural to expect chaos theory—the theory of nonequilibrium nonlinear dynamics—to apply to social choice. It also therefore becomes impossible to make long-term predictions concerning group interactions. However, Richards emphasizes as well the underlying order of chaotic processes. Specifically, she suggests that a complex "fractal structure" exists, indicating, at a fundamental level, structured stability in the system.

Chaos Theory and Political Science

The use of chaos and related theoretical and methodological constructs in political science is still in its infancy. Many of the features that have attracted economists to chaos theory also exist among political scientists. Like economics, much of political science is concerned with analyzing change and exploring the evolution of some phenomenon over time. Studies of changes in aggregate-level electoral fortunes and trends in public opinion such as presidential approval or attitudes toward particular issues all fit this genre. Accordingly, such data raise the question of whether underlying deterministic, and thus potentially chaotic, processes exist. The methodological advances in statistical analysis that have been made in recent years, advances that to a great extent have been borrowed from economics, have made some political scientists more willing, and able, to explore the existence of complex nonlinear processes. The highly formal game-theoretic and social choice work has required the application of mathematical tools that are invaluable in chaos research.

The lead chapter in the political science section is Thad A. Brown's "Nonlinear Politics." Brown introduces the reader to the role of chaos in understanding political phenomena. Brown points out that politics at every level results from the interactions of individuals. The difficulty is that, "Formally treating interactive political behavior within massively diverse collectives is tricky. Interactive behavior is peculiar in that it can neither be predicted nor analyzed by observing sets of individuals cross-sectionally or even the time series from a given individual or group." Brown suggests that this characteristic, together with the likely existence of spatial and temporal phase transitions, calls into serious question traditional methodologies for investigating chaotic phenomena. Brown goes on to explain that cellular automata simulations provide an innovative means of investigating complex dynamical systems. He also discusses specific applications of such an approach including game theory, electoral behavior, and social choice theory, all of which are represented in this volume.

Physicist Alvin M. Saperstein was among the first natural scientists to rigorously apply chaos theory to social phenomena. His chapter, "The Prediction of Unpredictability: Applications of the New Paradigm of Chaos in Dynamical Systems to the Old Problem of the Stability of a System of Hostile Nations," is in much the same spirit as other chapters in this section. Like Richards and McBurnett, Saperstein is concerned with the fundamental problem of prediction. Saperstein points out that while the international system shows considerable stability and hence predictability in an overall sense, crises represent episodes of fundamental instability, ergo unpredictability. Saperstein then points out that an important political "technology" would be to know when given national security policies will produce instability. In other words, the aim should be to "predict the unpredictable." Saperstein models several facets of international interactions, asking fascinating (and long-standing) questions such as whether bipolar or multipolar international systems are more likely to produce conflict, and whether democratic or nondemocratic states are more likely to go to war. The conclusions illuminate with great clarity some of the most fundamental questions of the nuclear age. Saperstein's study has the added advantage of providing simple algorithms that can be used by anyone with a desktop computer to generate an evolution of national sanity behavior on the part of nations.

The chapter "Complexity in the Evolution of Public Opinion" by Michael McBurnett explores the dynamics of public opinion in presidential nomination campaigns. Using data from the 1984 National Election Study's "rolling thunder" survey, McBurnett demonstrates the series to have properties characteristic of chaotic behavior. Utilizing techniques discussed in the methodology section, McBurnett shows how different analytic techniques reveal a complex nonlinear deterministic chaos pattern to public support for Democratic presidential candidates during the 1984 primary season. McBurnett's analyses and findings should be of profound interest to all serious students of public opinion. If, indeed, the solution of public opinion can be described as exhibiting deterministic chaos, then the question is raised how one can deduce governing or predictive equations from this time series. Certainly, McBurnett's study suggests how and why drastic shifts in public opinion may occur, and the consequences for predicting the evolution of public opinion.

Chaos Theory and Economics

The third section of the book examines chaos applications in economics. Among all the disciplines we cover, chaotic and, more generally, nonlinear dynamical approaches are most developed in this field. This may be at least partly explained by the mathematical rigor and statistical sophistication that have typified economics for the past several decades. However, the interest in chaos may also have resulted from an increasing dissatisfaction with orthodox equilibrium-based models of both micro- and macro-level economics phenomena. Relatedly, the obvious difficulties that economists have encountered in developing adequate predictive models of behavior almost certainly have helped explain the developing interest by many economists in applications of chaos theory.

J. Barkley Rosser, Jr.'s "Chaos Theory and Rationality in Economics" provides an illuminating theoretical overview of the implications chaos theory has for orthodox microeconomic theory. Rosser points out that standard neoclassical theory makes a number of information assumptions and that economic agents, more generally, are in possession of some basic model of reality. The existence of nonlinearities that are characteristic of chaotic systems, however, calls into serious question such assumptions of neoclassical economic theory. The "sensitive dependence on initial conditions," especially, means that the most seemingly trivial initial errors in economic judgment can produce totally unexpected outcomes. Rosser employs these basic characteristics of chaotic systems to show how they can produce a variety of economic phenomena. Most important, he concludes with a discussion of the kind of decision-making rule that can be employed where chaos exists.

Brian J. L. Berry and Heja Kim's chapter is entitled "Long Waves 1790–1990: Intermittency, Chaos, and Control." Berry, whose earlier research focused on economic and urban geography, has in recent years devoted his considerable abilities to demonstrating the existence of economic long waves, their origins and impact. This macroeconomic study addresses two questions. First, the annual fluctuations as well as longer-run fluctuations in prices in the United States over the 1790–1990 time period, and second, the fluctuations and swings in the rate of economic growth over the same period. Using graphical analysis, Berry and Kim demonstrate that the inflationary and stagflation cycles of the last 200 years are characterized by a chaotic limit cycle. Their work shows how chaotic processes can be contained within a larger and more extensive stable series. Berry and Kim also draw some very important policy conclusions from their analyses of the post–World War II period relating to Keynesian macroeconomic management techniques.

The forms of human settlement in physical space are the subject of Dimitrios Dendrinos's "Cities as Spatial Chaotic Attractors." Using an iterative process that places a time series of human activity in this space, Dendrinos shows how human settlements such as cities can take the form of periodic, quasi-periodic, or nonperiodic (or chaotic) attractors. Dendrinos indicates, for example, that chaotic patterns are the result of laissez-faire-type market processes. This analysis distinguishes two distinct forces in locational choice: (1) those that determine the current location of a population at particular points in time within a given space, and that are associated with the attributes of location at a distance from where populations are currently formed, and (2) those locational forces that determine current location of populations and are associated with the location of prior settlement activity.

Chaos Theory Implications for Social Systems Management and Social Science

The two chapters in this section serve the purpose of examining what chaos theory means for social systems management and public policy and for research and knowledge generation in the social sciences. These chapters attempt to provide insights to both the practical potentialities and the methodological limitations of chaos theory as a tool for both altering and understanding the dynamics of social systems. These chapters raise the philosophical issues of the relevance of chaos theory to social systems and social science investigation that must be considered if this research paradigm is to remain robust.

Kenyon B. De Greene's "Field-Theoretic Framework for the Interpretation of the Evolution, Instability, Structural Change, and Management of Complex Systems" begins by pointing out that theories relating to the management of complex systems have tended to lag behind changes in technology and society. He goes on to point out that an increasing gap exists between management capabilities and reality. De Greene develops a model for understanding organizational dynamics and change by employing a field-theoretic framework. The author demonstrates the history of field theory in the natural sciences and employs similar approaches to understanding organizational management. Like many other authors, De Greene demonstrates the linkages between macro-level phenomena, in this case the "field," which is produced by micro-level events and resulting feedback loops. De Greene's major theoretical contribution is to apply this particular theoretical approach to Kondratiev long wave behavior, showing how such waves encompass much more than just economic waves, but also institutions, technologies, and the like.

David L. Harvey and Michael Reed's chapter, "Social Science as the Study of Complex Systems," provides a capstone for this volume. The authors begin with a discussion of some important epistemological issues. Among them is the question of the relationship between the natural and social sciences, and the role of chaos theory as a bridge between two scientific and intellectual traditions. Specifically, the authors "explore the circumstances under which research strategies employing the deterministic chaos paradigm can and cannot be deployed in the human sciences." As such, Harvey and Reed provide a useful antidote to those who would uncritically apply nonlinear and mathematical methods and paradigms originally developed for the natural sciences. Taking what they consider a "middle course," the work of the British philosopher Roy Bhaskar and his modified naturalist epistemology becomes critical for understanding the form a future science of society might take. In elaborating upon this science, Harvey and Reed present a rigorous demonstration of how chaos theory fits into various modeling strategies employed in the social sciences. These authors also provide a vision of both the prospects for and limitations of chaos theory as a means for enhancing our understanding of the behavior of complex social systems.

Finally, this volume brings together a comprehensive bibliography of both the chaos literature from the natural sciences and the relevant chaos literature from the social sciences. This definitive bibliography should serve as a valuable resource for all chaos researchers, regardless of the level of their mathematical or scientific sophistication and whether or not they are new to the field or experienced chaos researchers.

Conclusion

The process of knowledge acquisition in the sciences traditionally follows a logical flow of hypothesis development, quantification, testing, and validation or falsification. Validation and replication then generally lead to theory development. Such theory aims at explaining the behavior of systems and expedites prediction of the future state or behavior of the system. Such an approach to theory development is founded on assumptions of global stability and, implicitly, of linearity in the relationships between variables. Stability in such relationships allows prediction. Thus, the behavior of nonlinear systems challenges traditional notions of theory development. By inhibiting prediction, a fundamental element of theory building is restricted. Thus, chaos researchers face the compound problem of dealing with highly intractable data that are not easily amenable to traditional empirical analysis, as well as which, by their nature, may preclude or limit traditional hypothetic-deductive means of theory generation.

The dynamics in the relationships between variables over time in nonlinear systems may generate complexities that defy generalization. This difficulty in developing such generalizations underscores the challenge of building theories that are relevant to complex social phenomena such as government budgeting. The fundamental dynamics of social phenomena clearly exacerbate theory building in the social realm. At the same time, however, chaos theory suggests a much richer and interesting world for the social scientist to explore. For, as Heinz Pagels (1987, 73) has noted, "Life is nonlinear, and so is just about everything else of interest." Indeed, as the following chapters convey, it is this richness and complexity that readers will find most fascinating.