NONLINEAR ANALYSIS *for* HUMAN MOVEMENT VARIABILITY

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Preface

> The entire creation is synthesized by essence and attributes, and has the need of Divine Providence, because it is not free of variability.
>
> **Maximus the Confessor (580–662)**

Human movement variability can be defined as the typical variations that are present in motor performance and are observed across multiple repetitions of a task. This variability is inherent within all biological systems. It can also be observed quite easily as it is almost impossible for an individual, even an elite performer, to perform two identical actions of the same task. This has been described quite effectively as "repetition without repetition" since the repetition of an action involves unique and nonrepetitive neuromotor patterns. For example, when we play a game of throwing darts, we are unable to always hit the center. When we walk, if we observe our footprints on sand or in the snow, we will see that they never repeat themselves in the exact same fashion. When we stand quietly, especially if we close our eyes, we will observe that we continuously sway and are unable to remain completely still. The role of movement variability has attracted significant attention recently due to its relationship to pathology and performance.

Previous theoretical frameworks consider variability as an indicator of noise in the control system, and it has been quantified using traditional linear statistical measures (e.g., standard deviation). Such measures contain very limited information about how the motor control system responds to change either within or between individuals. Practically, linear measures are measures of centrality and, thus, provide a description of the amount or magnitude of the variability around a central point. This is accomplished by quantifying the magnitude of variation in a set of values independent of their order in the distribution. From this perspective, clinicians and scientists have believed that the mean is the "gold standard" of healthy behavior and that any deviation from this gold standard is error, or undesirable behavior, or the result of instability.

Recent literature from several disciplines and medical areas, including brain function and disease dynamics, however, has shown that many apparently "noisy" phenomena are the result of nonlinear interactions and have deterministic origins. As such, the measured signal, including its "noisy" component, may provide important information regarding the system that produced it. Therefore, new innovative clinical methods that use nonlinear mathematical analysis and investigate the temporal structure of variability have been proposed. These nonlinear methods are being used increasingly to describe complex conditions in which linear techniques for the analysis of variability have been inadequate, hence confounding scientific study and the development of meaningful therapeutic options. For example, nonlinear analysis of the temporal structure of the variability present has recently been used in research on heart rate irregularities, sudden cardiac death syndrome, blood pressure control, brain ischemia, epileptic seizures, and several other conditions. Such research allowed for better understanding of the complexity of these pathologies and eventually led to the development of better prognostic and diagnostic tools. Similarly, nonlinear analysis of the variability present in movement patterns generated as a result of motor-related disability provides a window into the neuromuscular status of the patient and insight into the complex strategies used to control movement and posture.

Our research team at the University of Nebraska, Omaha, have been pioneers in the investigation of human movement variability with nonlinear analysis and its investigative ability to develop critical prognostic and diagnostic tools for motor-related disabilities. Our annual workshop on movement variability is well attended by scientists and clinicians that come to Nebraska from all over the world. In addition, many scientists come to us for sabbaticals or to receive more extensive training. The editor and members of his scientific staff are routinely invited to conduct workshops and tutorials in conferences around the globe (i.e., Australia, Spain, Ireland, Germany, Portugal, Brazil, and many others). Through these experiences, we received countless requests for a comprehensive book on nonlinear analysis to study human movement variability.

We have finally decided to grant these requests and develop such a book. The organization of our book is as follows. After introductory chapters on dynamical systems and time series, we present a wide variety of nonlinear tools such as the Lyapunov exponent, surrogation, entropy, fractal analysis, and several others. Whenever possible, we include exercises with data analysis problems. Their solutions can be found in the complementary solutions manual. In addition, each chapter provides numerous examples from the literature and our research on how nonlinear analysis can be used to understand real-world applications. We believe that this will enhance the readers' understanding of the material presented in each section of the book. Finally, the book concludes with a chapter that presents numerous case studies in postural control, gait, motor control, motor development, and others to enhance comprehension. PowerPoint slides in each chapter are also provided for the same reason and also for assisting in a possible adaptation of this book as a course textbook. All the software used in this book is available to be downloaded freely from our website: http://www.unomaha.edu/college-of-education/biomechanics-core-facility/research/computer-codes.php.

We believe that our approach will allow engineers, movement scientists, clinicians, and many others to develop the foundation necessary to utilize nonlinear analysis in their practices. Our book will offer the know-how that, along with the research capabilities provided, could leverage novel departures in the field of human movement variability research. The future may hold new advancements of our understanding of human performance, biomechanics, motor control, and motor learning, and, most importantly, of a variety of diseases and conditions that affect our nation's health.

This book is a result of the marvelous contributions of a select group of exceptional authors. They all worked extremely hard and with diligence, providing drafts on time and addressing all comments and revisions asked from them. On a personal note, they are all my students (either graduate students or postdocs), my academic children, and have worked with me for many years investigating the concepts presented in this book. Therefore, I am extremely proud about their progress and development demonstrated by their excellent chapters written for this book. However, at the same time I do not want to forget the contributions of numerous other graduate students and postdocs who have worked with me over the years on nonlinear analysis for human movement variability. Students such as Max Kurz, Joan Deffeyes, Naomi Kochi, Jessie Huisinga, Joshua Haworth, Dimitrios Katsavelis, Fabien Cignetti, Joseph Siu, Mukul Mukherjee, James Cavanaugh, Regina Harbourne, Srikant Vallabhajosula, and many others, who must forgive me for not mentioning their names here, have been instrumental in the development of the material presented in this book. I am blessed that I have worked with every single one of them. I am also blessed that I have been able to pass along to these students the knowledge that I acquired from my mentors at the University of Oregon where the ideas for this book were originally molded.

Our team has received significant financial support for the research on which this book is based. The NIH, NASA, U.S. Department of Education (NIDRR), NSF, VA, Nebraska Research Initiative, and many others, have consistently provided funds for our work and allowed us to progress with financial stability over the years. I am particularly grateful to the NIH and NIGMS for a COBRE P20GM109090 grant that supported the writing of this book.

Ramon Y. Cajal, the father of modern neurobiology, almost a hundred years ago wrote: “more than once I was hopelessly discouraged about my ability to pursue science.” Such times have been aplenty in my career and in the development not only of this book but also in the investigation of a novel area of research that is different from traditional approaches. In these times, there is one certainty: that solace is needed around you to overcome even the highest of obstacles. This is why I am eternally grateful for my cornerstone, my wife Ann, my parents Jesus and Vaya, and my brother Dimitris, for their love, support, and constant encouragement.

Editor

Dr. Nick Stergiou is the distinguished community research chair in biomechanics and professor and director of the Biomechanics Research Building at the University of Nebraska at Omaha. He is also a faculty member in the Department of Environmental, Agricultural, and Occupational Health of the College of Public Health at the University of Nebraska Medical Center. His research focuses on understanding variability inherent in human movement, and he recently founded the first ever Center for Research in Human Movement Variability through a $10 million grant from the NIH/NIGMS. He is an international authority in the study of nonlinear dynamics and has published more than 200 peer-reviewed articles. Dr. Stergiou's research spans from infant development to older adult fallers and has impacted training techniques of surgeons and treatment and rehabilitation techniques of pathologies, such as peripheral arterial disease. He has received more than $20 million in personal funding from NIH, NASA, NSF, the NIDRR/U.S. Department of Education, and many other agencies and foundations. He also holds several patents and procured a private donation of $6 million to build the 23,000 sq. ft. Biomechanics Research Building that opened in August 2013. This is the first building on his campus exclusively dedicated to research.

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1 Introduction

John McCamley and Steven J. Harrison

CONTENTS

Mathematics is the language with which God has written the universe.

Galileo Galilei (1564–1642)

The studies of the dynamical properties of systems have generally been restricted to reducing these systems to a linear approximation. The limitations that exist in such analysis have long been considered. In 1976 Robert May stated that many different situations from a variety of disciplines can be modeled and approximated by simple first-order difference equations. Then the investigation of the dynamical characteristics of these models entails the identification of constant equilibrium solutions and a linearized analysis to describe how stable they are when exposed to small perturbations. Unfortunately, the nonlinear dynamical features that are present have not been considered (May 1976).

The aim of this book is to consider the nonlinear dynamical features to be found in complex biological and physical systems, especially those characteristic to human movement. In this introductory chapter, we will set the stage for appreciating the relevance of nonlinear methods to the scientific study of complex systems. We will introduce key concepts that have motivated the development and application of nonlinear methods, including the notion of a dynamical system, and concepts such as chaos, nonlinear dynamics, self-organization, and complexity.

DYNAMICAL SYSTEMS

Early scientists believed that if it was possible to know all the possible aspects of a system, and through the laws of nature describe it and hence understand it, then it would be possible to know its future path (de Laplace 1902). Others, including James Maxwell (1831–1879), observed that systems exist with "sensitive dependence to initial data" (Hunt and Yorke 1993). In 1899, French mathematician Henri Poincaré (1854–1912) recognized that the laws of physics could not provide a complete understanding of the motion of celestial bodies (*three-body problem*); however, it was many years before people began to realize the importance of chaos, and how it applies to dynamical systems.

> A *dynamical* system is one which changes in time; what changes is the state of the system. The capitalist system is dynamical (according to Marx), while the decimal system is (we hope) not dynamical. A mathematical dynamical system consists of the space of states of the system together with a rule called the dynamic for determining the state which corresponds at a given future time to a given present state. Determining such rules for various natural systems is a central problem of science. Once the dynamic is given, it is the task of mathematical dynamical systems theory to investigate the patterns of how states change in the long run.
>
> **Hirsch (1984)**

The terms "dynamic" and "dynamical" are generally used to describe systems that evolve or change over time (Hirsch 1984; Thelen and Smith 1994; Crutchfield et al. 2010). Thelen and Smith (2006) are more specific. They apply the term "dynamic systems" to the systems of elements that change over time. "Dynamical system" is the more technical name they give to the mathematical equations that describe the time evolution of such systems with particular properties. The technical description is also favored by others. Hilborn (2000) attributes the term "dynamical systems theory" to the mathematical theory of dynamical systems, which have "a state space and a rule for the evolution of trajectories starting at various initial conditions." Crutchfield et al. (2010) also divide the definition of a dynamical system into a "state" and a "dynamic" part. Examples of dynamical systems exist all around (and within) us. They include astrological systems; chemical reactions; pendula; the economy (stock market); ecological systems (including plant and animal populations, cancer growth, and the spread of disease); and the human body (heart, brain, lungs). Studies of dynamical systems have led to the understanding of important concepts for biologists (Mpitsos and Soinila 1993). The way the variables of a dynamical system change over time can be described by a set of functions. These functions may be defined in continuous time by differential equations, or discrete time by difference equations. Within the realm of dynamical systems, there are many that will exhibit nonlinear characteristics. Among those nonlinear systems exists a subset of *chaotic*

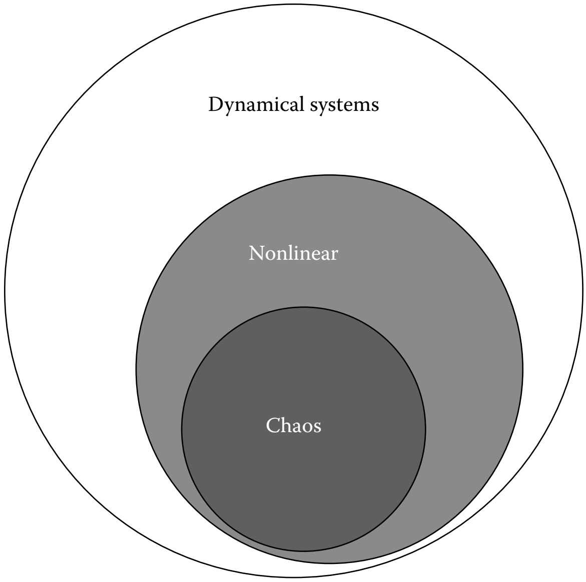


FIGURE 1.1 Not all nonlinear systems are chaotic, but all chaotic systems are nonlinear. Nonlinear systems are in turn a particular form of dynamical systems.

systems (Figure 1.1). Chaotic behavior exists in many seemingly simple systems such as the movement of a ferromagnetic beam buckled between two magnets under the effect of sinusoidal oscillations (Moon and Holmes 1979), a double pendulum (Richter and Scholz 1984), or a dripping tap (Shaw 1984). Chaos is often thought of in terms of noise within a system that is unpredictable in nature; however, its technical meaning is quite different. Not all nonlinear dynamical systems are chaotic, but all chaotic systems are nonlinear (Hilborn 2000). Chaos, and the important role it plays in understanding the dynamics of nonlinear systems, is discussed in more detail in a later section.

To understand the underlying properties of a dynamical system, it is necessary to understand the space that it occupies. The behavior of a dynamical system is ideally represented in a phase space, that is, in a space that contains dimensions sufficient to specify the state of the system. In subsequent chapters, methods for reconstructing phase spaces and quantifying the phase-space dynamics in terms of Lyapunov exponents and dimensions (Kantz and Schreiber 2004) will be introduced. The phase-space geometry of attractors can provide useful information about the dynamics of a system, and further understanding can be discovered through bifurcation analysis.

Deterministic versus Stochastic

Dynamical systems can be either deterministic or stochastic. A *deterministic* system is one that, given a current state, can only have one unique future state. A deterministic system is one in which the equations of the system, and the parameters describing the system, along with the initial conditions, describe the subsequent behavior of the system (Hilborn 2000). There is a one-to-one relationship, which is governed by a rule for the system. On the other hand a *stochastic* system can have more than one, perhaps many, future states for a given current state. These outcomes can occur according to some probabilistic process.

Continuous versus Discrete

A continuous measure is one that evolves continuously over time. The outcome is, thus, a function of time, for example, $x = f(t)$. Consider the children's story character Pinocchio, whose nose grows when he tells lies. We can create a function to describe the length of Pinocchio's nose over time. Let us say that his nose grows at 0.1 cm, multiplied by time in minutes, raised to the third power:

$$L = 0.1 \times t^3$$

When plotted this will appear as shown in Figure 1.2a. If the length of Pinocchio's nose is calculated (and grows) at discrete intervals, say at the end of each minute, then the length will grow as shown in Figure 1.2b. A discrete variable is measured at a particular point in time (as distinct from continuously) or it is something that is counted. The time intervals between drips from a tap can be considered discrete measurements. Discrete measures may often result from questionnaires. The difference between continuous and discrete measurements needs to be taken into account for many statistical analyses. It should be remembered that most measurements (especially digital ones) can only be taken at discrete intervals even if the system being measured is continuous.

Another discrete process is the way a bank pays interest on a savings account. The amount paid each period is based on the value at a discrete point in time, usually at the end of the period. This new value (unless a withdrawal is made)

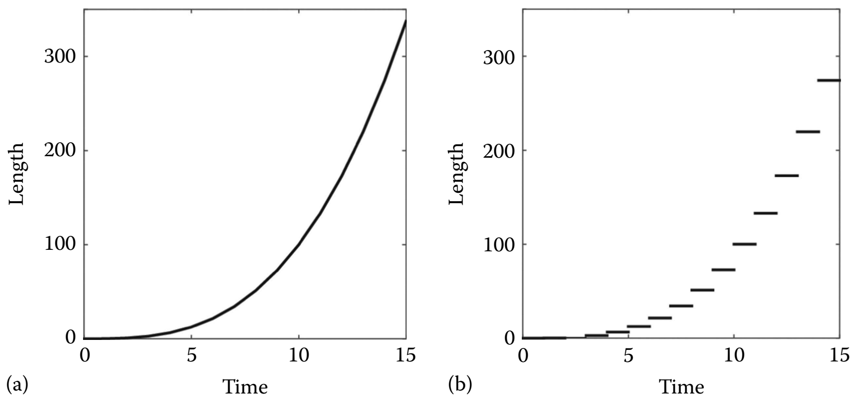


FIGURE 1.2 The length of Pinocchio's nose: (a) continuous growth and (b) growth using discrete measurements.

becomes the value on which the next payment is calculated. Populations may also grow in a discrete manner and are generally based on the annual changes in seasons.

The difference between continuous and discrete systems is important when conducting numerical analysis of chaotic processes (Mpitsos and Soinila 1993) with different nonlinear tools having a more suitable application to one or the other type of measure.

Linear versus Nonlinear

A *linear* function is one in which the outcome changes in direct proportion to the change in the input. A simple linear function can appear as:

$$Y = b + mX$$

where
 b is the intercept
 m is the slope
 X is raised to the first power.

A plot of this function will be a straight line (Figure 1.3a). A linear system is governed by the paradigm that small changes to inputs lead to small changes in outcome. Not all functions appear as straight lines (Figure 1.3b). Functions of the form

$$Y = aX_n^2$$

are *nonlinear* since the right-hand side of the equation is not the equation of a straight line. Statistical tools for use with linear data are not meaningful when applied to nonlinear data. A new set of measures is necessary and these will be discussed in detail later in the text.

Growth Model and Its Limitations

Let us consider an initial bank deposit of $100 into a savings account. If the interest is 0.1 (10%) for a given period, at the end of the first period $10 will be added to the account. For the next period the deposit will be $110 (1.1*100) and at the end of this period $11 will be added and the total deposit will become $121 (1.1*1.1*100). This is an example of a growth model described by

$$X_n = r^n X_0$$

where
 X_0 represents the initial deposit ($100)
 r is the compounded interest rate (1.1)
 n is the number of periods

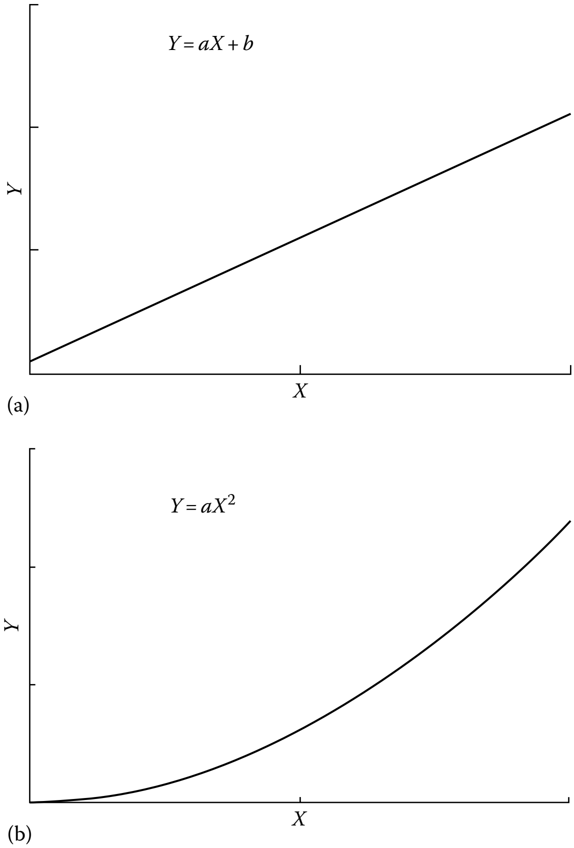


FIGURE 1.3 (a) Plot of a linear function and (b) plot of a nonlinear function.

An alternative way to write this function is

$$X_{n+1} = rX_n$$

For values of $r < 1$ the population will decay to zero over time (Figure 1.4a). For values of $r > 1$ such a system would soon grow to infinity (Figure 1.4b). This model is deterministic and linear, which can be seen if X_{n+1} is graphed against X_n (Figure 1.4c). A growth model of this form may not be realistic. Systems may be constrained whereby growth becomes limited at some point, such as when populations are limited by food sources or space, or when chemical reactions are limited by supply of reagents. In biological systems predators can provide further restriction on growth.

Logistic Map

To understand how a population is related to the population at a previous point in time, it must be able to grow, but this growth must also be limited. In 1976 biologist

R. May published a paper (May 1976) in which he introduced the "logistic" difference equation to describe the growth of populations:

$$N_{t+1} = N_t(a - bN_t)$$

In this function if $b = 0$ it becomes the previously described growth function, which will grow exponentially when $a > 1$. For $b \neq 0$ it produces a growth curve with a hump the shape of which can be changed by the parameter a. If the function is scaled such that $X = bN/a$, the resulting equation becomes

$$X_{t+1} = aX_t(1 - X_t)$$

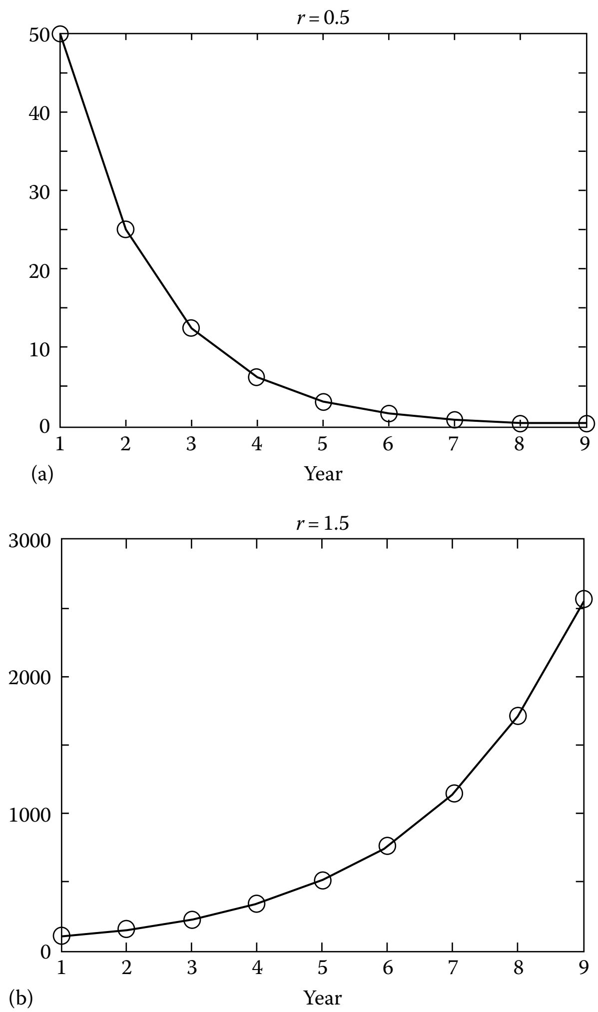


FIGURE 1.4 (a) For $r < 1$ the population decays to zero. (b) For $r > 1$ the population grows to infinity.
(*Continued*)

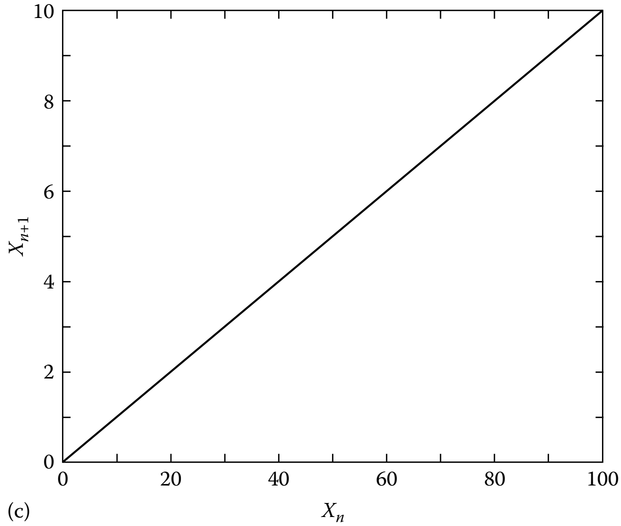


FIGURE 1.4 (*Continued*) (c) The growth model is linear.

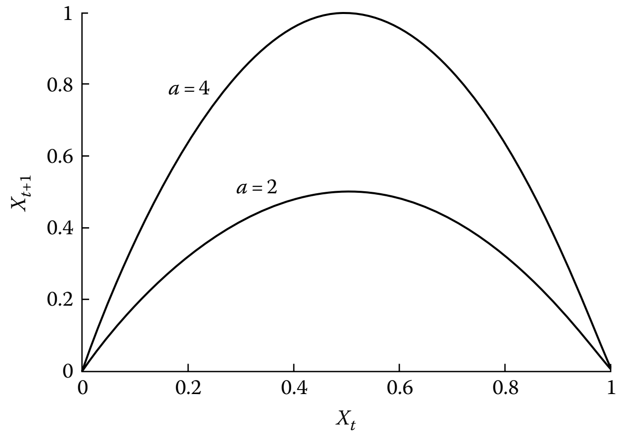


FIGURE 1.5 Quadratic curve of the equation $X_{t+1} = aX_t(1 - X_t)$ for $a = 2$ and 4.

A graphical representation of the equation, depicting the effect of different values of the parameter a, is shown in Figure 1.5.

While this equation may appear simple, it is not always possible to find a simple mathematical answer due to the character of the solutions. Solutions can, however, be found using numerical iteration, or the cobweb method. The cobweb method (Figure 1.6a through d) is a graphical plot to iterate the equation that requires a sketch of the function. Starting with a value X_0 and drawing a vertical line (Figure 1.6a: line 1), the corresponding value X_1 is found. The value X_1 can then be transferred to the horizontal axis of the graph by using a horizontal line (Figure 1.6a: line 2) and the diagonal line ($X_{t+1} = X_t$). Another vertical line (Figure 1.6a: line 3) will find the value of X_3. This process can be continued to show the growth of the population over time. May (1976) noted that as the value of a is increased, the outcome changes from a single value (Figure 1.6a) to oscillating between two values (Figure 1.6b). A further increase leads to a four-period oscillation (Figure 1.6c) and finally chaos (Figure 1.6d). Plots of these solutions are shown in Figure 1.7a through d, respectively.

In the one-dimensional form presented here the logistic equation has limited direct application to biological populations that generally involve interaction with other species and overlapping generations. The behavior of the logistic equation,

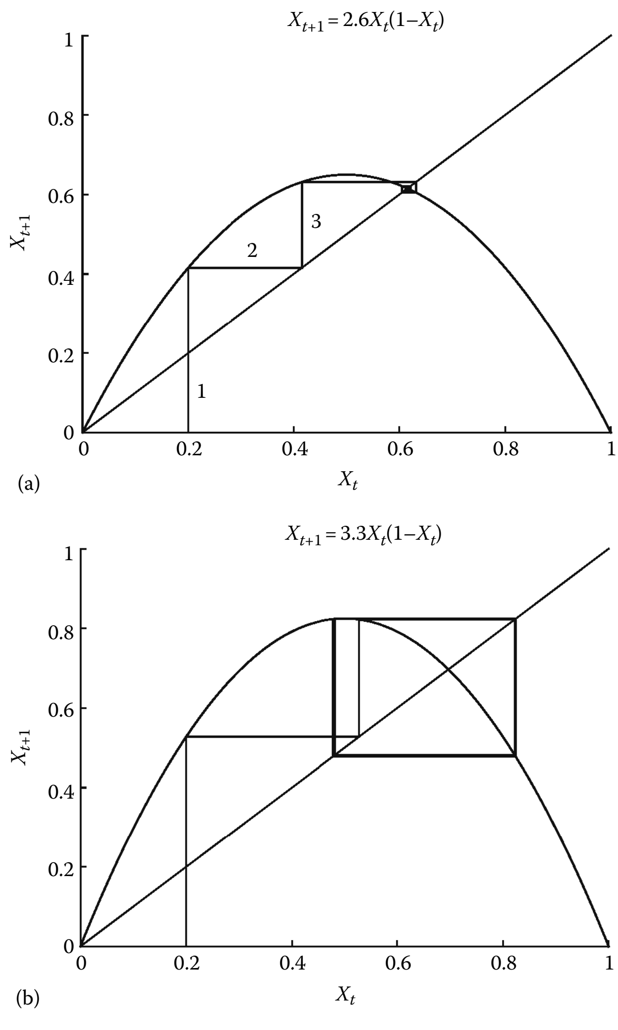
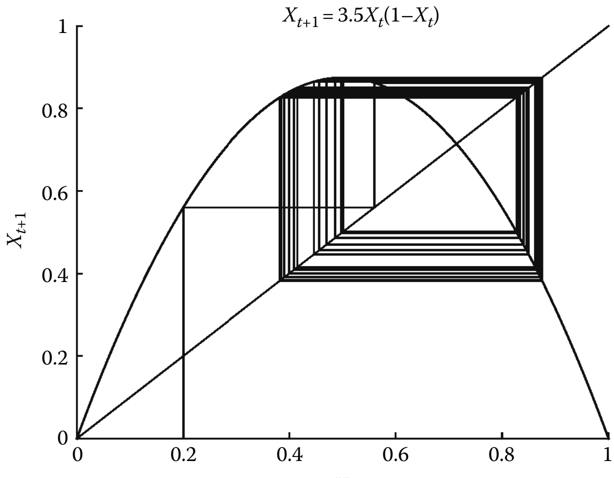
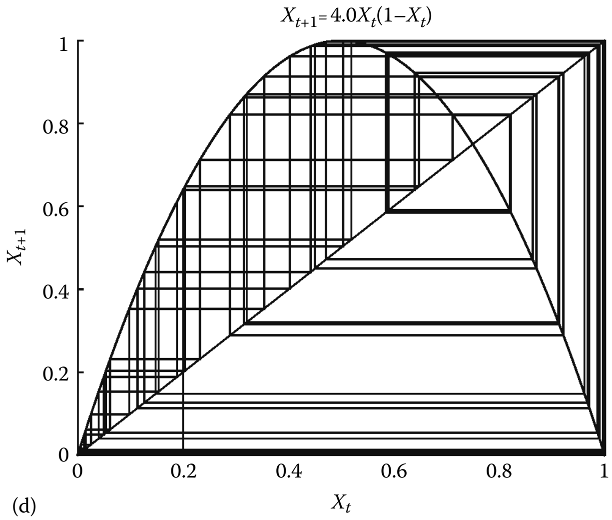


FIGURE 1.6 Cobweb plots showing (a) a single steady state; (b) the solution oscillates between two values. (*Continued*)



(c)



(d)

FIGURE 1.6 (*Continued*) Cobweb plots showing (c) the solution oscillations between four values; and (d) the solution is chaotic.

and other apparently simple nonlinear difference equations, can however account for many observations of apparently erratic fluctuations in animal populations as well as in other dynamical systems (May and Oster 1976).

Bifurcation Diagram

The transition from steady state to two- and four-period oscillations and to chaos is termed "bifurcations," and the point at which the number states or stability of the system changes is called a bifurcation point.

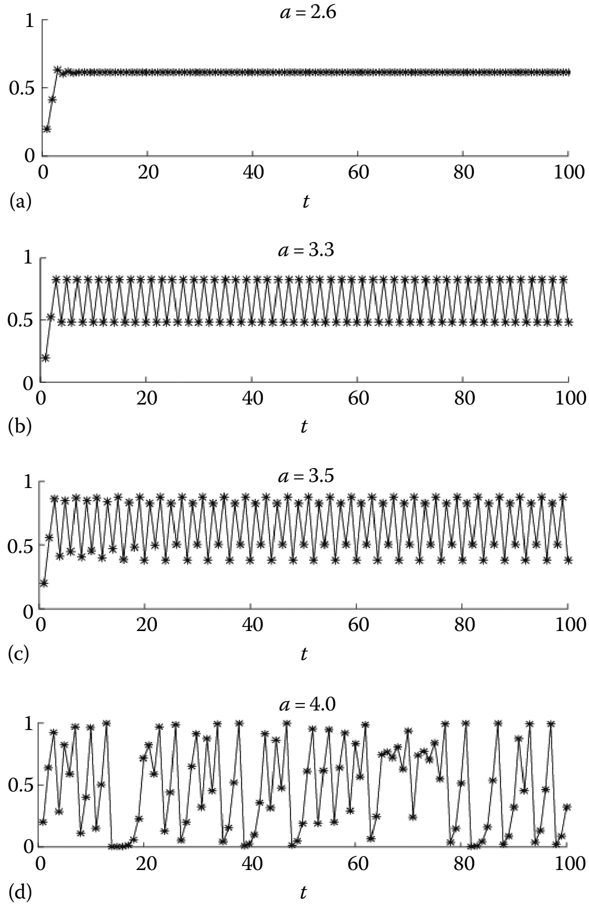


FIGURE 1.7 Plots showing solutions to the logistic equation: (a) steady-state; (b) period two oscillation; (c) period four oscillation; (d) chaos.

If the equation

$$X_{t+1} = aX_t(1 - X_t)$$

is numerically iterated and the values of X plotted after the transients have died out for successive values of a, and these values shown as a plot of X vs. a, then a *bifurcation diagram* (Figure 1.8) is generated. This diagram provides much useful information about the behavior of the system. The bifurcation diagram depicts the values of a when a period doubling (bifurcation) will occur and the broad areas of chaos interspersed with periodic windows. While not all nonlinear functions follow a period doubling route to chaos, those that do follow this pattern have been observed to follow mathematical rules (Feigenbaum 1978). Feigenbaum realized that the "rate of convergence" toward chaos is the same for different functions that exhibit bifurcations. If a_n is the value of a where period 2^n is "born" then: $\delta = (a_n - a_{n-1})/(a_{n+1} - a_n)$. Feigenbaum found

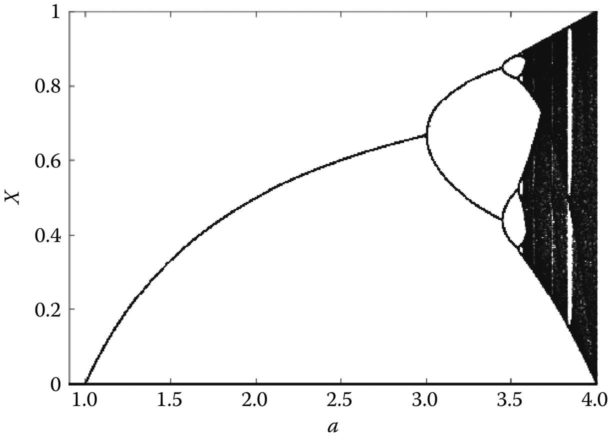


FIGURE 1.8 Bifurcation diagram for the function: $X_{t+1} = aX_t(1 - X_t)$.

that the value of δ is approximately the same for all values of *n* and for large value of *n* the value of δ approaches the same number for different functions. The value δ = 4.6692… has become known as the *Feigenbaum's number.*

Chaos

In truth at first Chaos came to be, but next wide-bosomed Earth.

(From Hesiod, 750–650 BC, The Homeric Hymns and Homerica with English Translation by Hugh G. Evelyn-White (1914))

In violent order is disorder; and a great disorder is an order. These two things are one.

Wallace Stevens (1879–1955, "Connoisseur of Chaos")

One of the most well-known sets of equations to describe a chaotic system was developed by Edward Lorenz (1917–2008). He was trying to model particular weather patterns and, after simplifying equations for fluid dynamics, produced the following three coupled, differential equations (Lorenz 1963)

$$\frac{dX}{dt} = p(Y - X)$$

$$\frac{dY}{dt} = -XZ + rX - Y$$

$$\frac{dZ}{dt} = XY - bZ$$

with *p*, *r*, and *b* representing adjustable parameters.

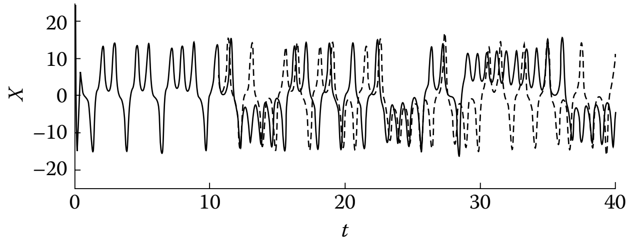


FIGURE 1.9 Solution to the Lorenz equations showing the effect of a small change in initial conditions: $p = 10$, $r = 24.5$, $b = 8/3$. Solid line: $X_0 = 10$, $Y_0 = 70$, $Z_0 = 19$. Dashed line: $X_0 = 10$, $Y_0 = 70$, $Z_0 = 19.001$.

Lorenz found (apparently almost by accident, and perhaps due to the computational limitations of the time) that the outcome of this set of equations is extremely sensitive to the initial conditions. Figure 1.9 shows how, when chaos exists, a small change in the initial value of Z (from 19 to 19.001) leads to large changes in the outcome after a short period of time. This sensitivity to initial conditions has become known as the butterfly effect (Lorenz 1972) and is a characteristic that exemplifies chaos.

Chaos theory has been applied to many fields of biological and nonbiological analysis. It has been used in systems ranging from psychology (Ayers 1997) to hydrology (Sivakumar 2000) and as a means to analyze the financial markets (Peters 1994). When a dynamical system displays sensitivity to its initial conditions, which lead to irregularity, it can be termed *chaotic* (Çambel 1993; Kaplan and Glass 1995; Williams 1997; Wiggins 2010). Such a system while appearing irregular is actually deterministic (Kaplan and Glass 1995); however, it is impossible to make long-term predictions for such a system. Kaplan and Glass (1995) add further to the definition of chaos, noting the same state is never repeated and that it is bounded. Often the equations that describe such behavior are deceptively simple as was shown in the previous section. Representation of system behavior in phase space provides a powerful basis for both visualizing and quantifying the dynamics of both nonlinear and chaotic systems (Figure 1.10). The concept of a phase space representation rather than a time or frequency domain approach is the hallmark of nonlinear dynamical time series analysis (Kantz and Schreiber 2004). In order to be bounded and unstable at the same time, a trajectory of a dissipative dynamical system has to live on a set of unusual geometric properties. Understanding if a system is chaotic, it may not provide the underlying laws that govern the system, but it will provide important information concerning whether the system is deterministic and the feasibility of making longer term prediction about future states of the system.

SELF-ORGANIZATION

> One of the principal objects of theoretical research in any department of knowledge is to find the point of view from which the subject appears in its greatest simplicity.
>
> **J. Willard Gibbs (1839–1903) from Winfree (2001)**

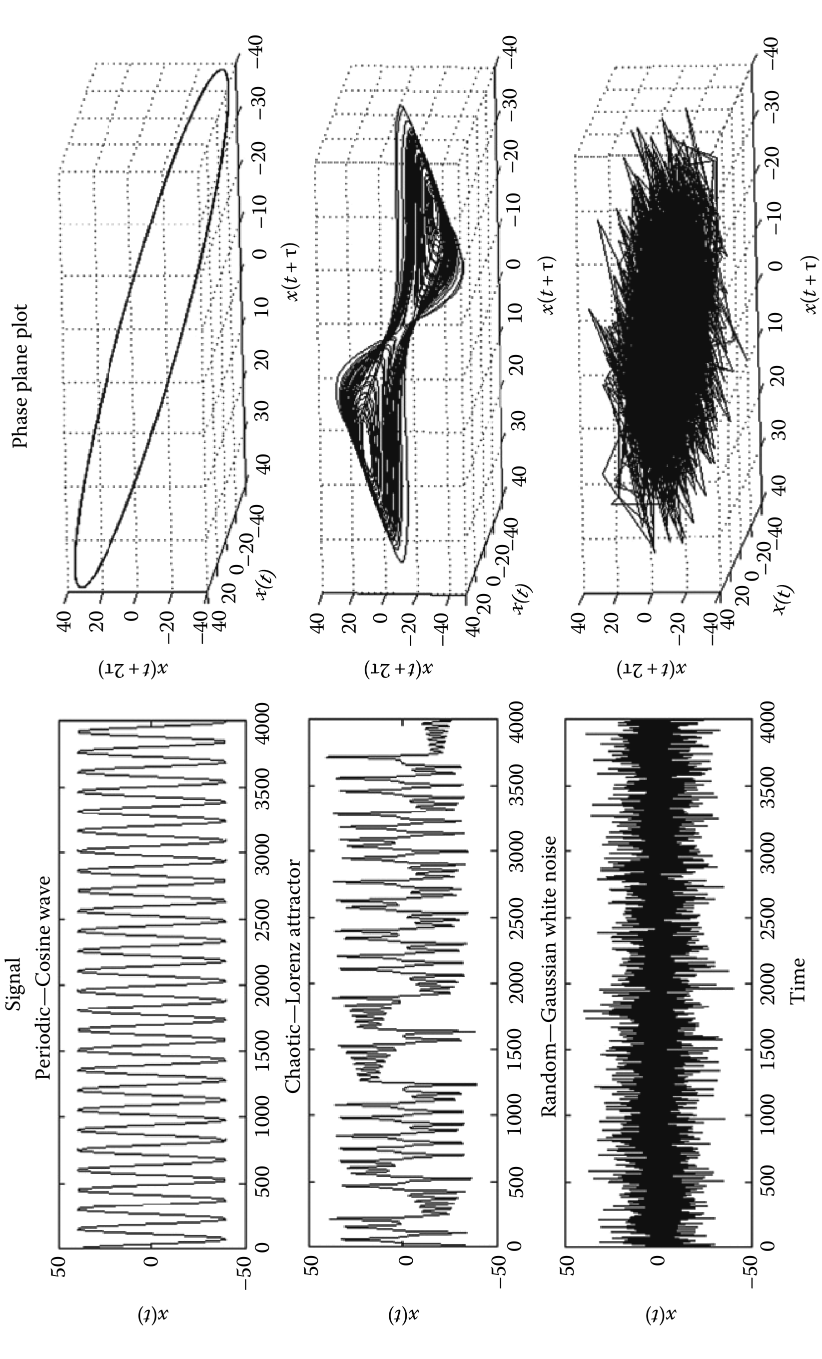


FIGURE 1.10 Phase space plots provide a means to geometrically show chaotic behavior which may not be readily apparent within a time series.

Organization in a system implicates the following property: the relationship between two components of the system is dependent upon the state of a third component (Ashby 1947). Self-organization can lead the system to change from an unorganized to an organized state. In other words, self-organization changes a system from having bad organization to having good organization (Ashby 1947). When a system establishes a state only because of the dynamical interactions among individual elements within the system, the state is self-organized (Bak 1997). This can only happen in natural systems when they are both complex and open to flux with the environment (Kugler and Turvey 1987; Thelen and Smith 1994; Kelso 1995). External processes do not cause self-organization, rather it is generated by components within the system (Haken 1977; Camazine et al. 2001; Thelen and Smith 2006). These systems are dynamical in nature (Bolender 2010), with many components interacting in nonlinear ways to produce highly complex, ordered behavior (Thelen and Smith 1994). The patterns that emerge are different from the elements that make up the system, and cannot be predicted solely from the characteristics of the individual elements (Thelen and Smith 1994).

The laws of physics cannot always describe the interactions that take place and lead to the observed patterns for biological systems (Camazine et al. 2001). When the nature of the connections, couplings, or interactions between components of a system changes and it results in a change, self-organization occurs, which enables the system dynamics to occupy a much smaller state space (Kauffman 1995). Self-organization results in increased complexity, which is “the amount of information the process stores in its causal states” (Crutchfield 2011).

Simple Examples of Self-Organization

> … and the thousands of fishes moved as a huge beast, piercing the water. They appeared united, inexorably bound to a common fate. How comes this unity?
>
> **Anonymous, seventeenth century from Shaw (1975)**

A quick Internet search of “bird flocking” results in amazing videos of great undulating masses of thousands of birds with global behavioral coordination. Where does this global coordination come from? Is there a leader or a group of leaders that are giving orders and communicating their plans to the group? No, there is no leader. The answer to the source of global coordination is that the flock self-organizes. In a school of fish, each individual bases its behavior not on the movement of the whole school of fish but rather on the movements of its neighbors. This simple rule for coupling individuals locally to the dynamic environment in a way that constrains the direction of animal motion has provided the basis for computer generated animations that reproduce many of the complex features evident in the flocking, swarming, and schooling behaviors found in nature (Reynolds 1987).

Perhaps the most well-known model of complex flocking behavior is the boids model. The behavior is based on only three simple (but nonlinear) rules that each boid follows locally. Each boid has interactions with the boids in its immediate vicinity, but they are not directly affected by the global behavior of the flock. The first rule is that the boid will change its heading in order to avoid collisions with the nearby boids. The second rule is that the boid will try to match the velocity with nearby boids. The third rule is that the boids will try to stay near to the center of mass of their nearby boids.

The advent of this model was a major breakthrough in the development of group behavior for flocking, herding, or schooling animals in air, on land, or in water, respectively (Lett and Mirabet 2008). It then becomes possible to generate complex flocking behavior without directly prescribing the path of each individual bird. This is akin to a dynamical systems theory of movement, wherein you do not store patterns but rather you store a simpler generative architecture that creates complex movements. Again, this model is an example of the organization of complexity from simplicity.

The potential of simple rules to produce self-organized complex dynamic patterns has been investigated through the systematic development of a class of models collectively referred to as cellular automata models (Wolfram 1984, 2002). Imagine a piece of graph paper on which the vertical axis is time. At the top of the graph paper the time is equal to 0 and increases as you go down the graph paper. For this top row at time equal 0 we have our initial condition. Each square in that row is a different cell and can have a state of either 0 or 1 (Figure 1.11).

The update rules define how the second step in time is dependent on the first. In this example of a simple one dimensional cellular automata, each cell at time $t + 1$ has a state that is dependent upon its value at time t and the states of its two nearest neighbors at time t. Again, this is a local interaction that, as we will see, leads to global emergent coordination patterns. Let's define how this update rule works.

We have already stated that the time evolution of each cell depends only on the previous state of itself and its two neighbors. This means the state of the cell is dependent upon the state of three cells at the previous time step. For these three cells there are eight combinations of what those states could have been (Figure 1.12):

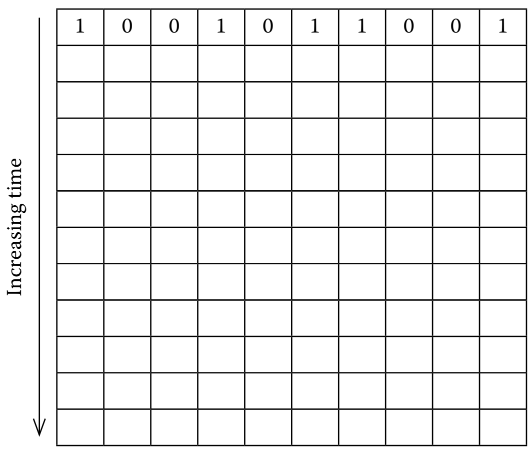


FIGURE 1.11 Cellular automata showing initial condition (top row).

1	2	3	4	5	6	7	8
1 1 1	1 1 0	1 0 1	1 0 0	0 1 1	0 1 0	0 0 1	0 0 0

FIGURE 1.12 The eight possible combinations of states.

1	2	3	4	5	6	7	8
1 1 1	1 1 0	1 0 1	1 0 0	0 1 1	0 1 0	0 0 1	0 0 0
?	?	?	?	?	?	?	?

FIGURE 1.13 For each state an update rule must be defined.

And, for each of these eight combinations of what those states could have been in the previous time step, an update rule must define what the current state of the cell will be in the next time step (Figure 1.13):

For each one of these eight combinations we can define a rule by specifying what the next state of the cell will be depending on the previous cell and its two neighbors. Let us pick a specific instantiation of a rule by filling in a value of 0 or 1 for each question mark (Figure 1.14):

This rule can be stated by the outputs for each of the eight combinations—“01101110.” Each rule is by convention stated in the base 10 version (decimal) of this binary format. This example (01101110) is 110 after we convert it from binary to decimal. With the base 10 convention, the update rules go from 0 (“00000000” in binary) to 255 (“11111111” in binary). If we take this rule and the initial conditions, we can begin to iterate the dynamics and see what global patterns emerge from this rule. The next five time steps are shown in the following. The three instances are highlighted. For example, “100” gives a “0” from combination number 4, “111” gives “0” from combination number 1, and “101” gives “1” from combination number 3. Notice that in this model of cellular automata the edges wrap around so that the cell to the right of the cell on the right edge is the cell on the left edge. Feel free to write in this page and finish the dynamics of the cellular automata shown (Figure 1.15).

The patterns become more apparent when you use more than 10 cells and when you use black cells for “1” and white cells for “0.” Of course that would be a bit more cumbersome to do by hand. You can explore the different patterns that emerge from different update rules with the MATLAB® code included at the end of this chapter in the exercises. Here is a screenshot of the rule 110, the rule we iterated earlier (Figure 1.16).

1	2	3	4	5	6	7	8
1 1 1	1 1 0	1 0 1	1 0 0	0 1 1	0 1 0	0 0 1	0 0 0
0	1	1	0	1	1	1	0

FIGURE 1.14 Definition of the rule for the next state.

Increasing time

1	0	0	1	0	1	1	0	0	1
1	0	1	1	1	1	1	0	1	1
1	1	1	0	0	0	1	1	1	0
1	0	1	0	0	1	1	0	1	1
1	1	1	0	1	1	1	1	1	0
1	0	1	1	1	0	0	0	1	1

FIGURE 1.15 First five steps of cellular automata model.

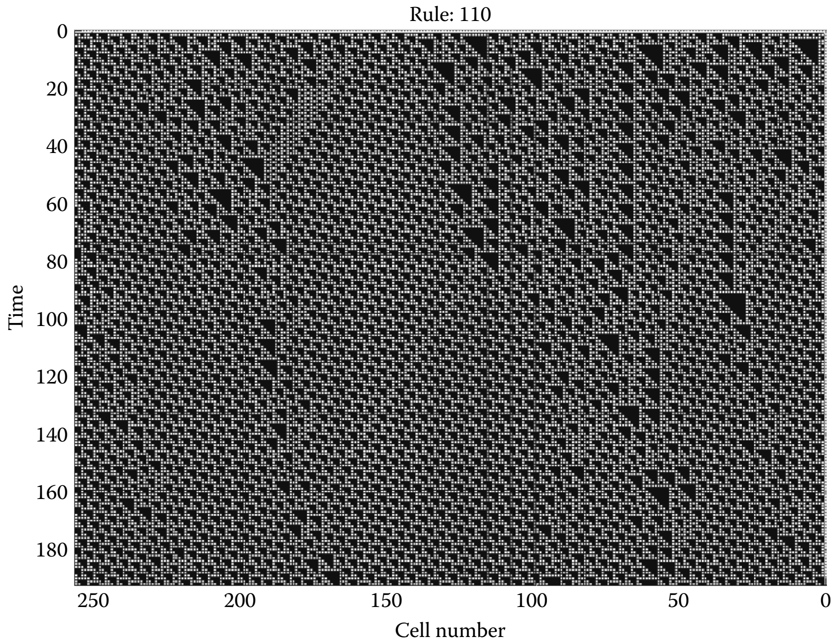


FIGURE 1.16 Screenshot of MATLAB® output for cellular automata rule 110.

Self-Organization in Human Movement

There are many examples of self-organization in nature (Camazine et al. 2001), both biological and nonbiological. In movement science, self-organization has been used to explain phenomena ranging from coordinated movements of limbs, body segments, and people, to the power law distributions of movement variability (Harrison and

Stergiou 2015). Perhaps the most well-known example of self-organization (as well as of the application of a dynamical systems approach) applied to an understanding of human movement is the Haken–Kelso–Bunz (HKB) model. The HKB model is a dynamical model of motor coordination. It was developed initially to describe the pattern of behavior observable in the simple task of rhythmically coordinating two fingers (Kelso 1981) but has since been applied to a wide range of motor coordination phenomena. The task involves simply oscillating your fingers in an antiphase pattern, such that one finger moves medially while the contralateral finger moves laterally and vice versa (see Figure 1.17a). If the required frequency of coordinated oscillation is increased, and you now slowly try to perform the task at a faster and faster rate, a curious phenomenon is observed. At a critical frequency you will observe your fingers

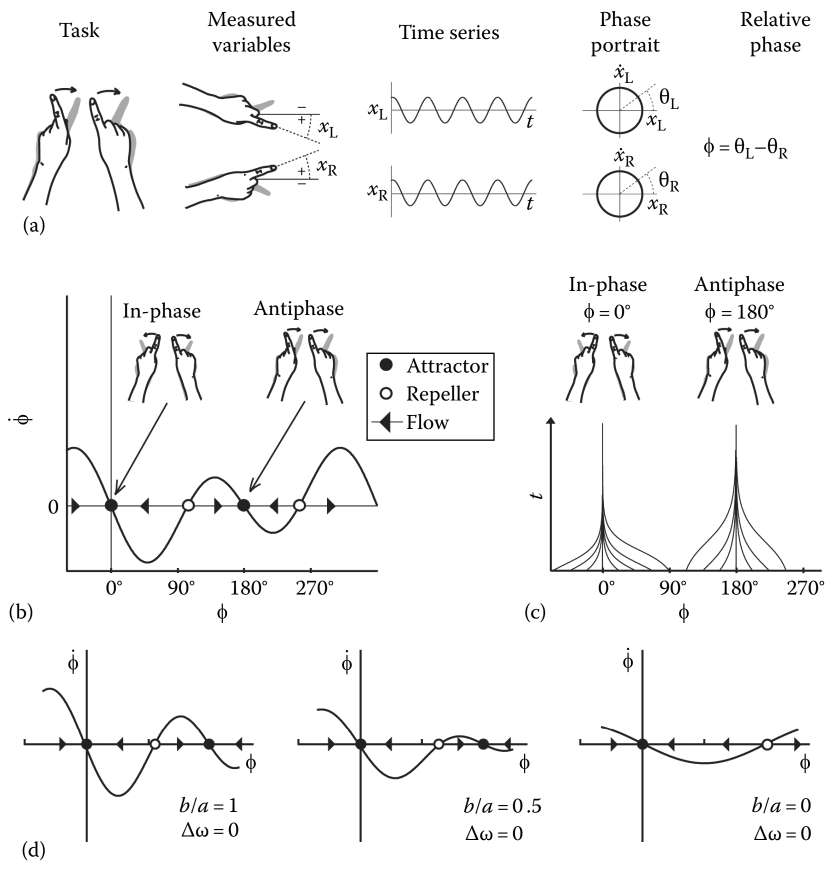


FIGURE 1.17 The dynamics of rhythmically coordinated finger movements. (Adapted from Harrison, S.J. and Stergiou, N., *Nonlinear Dyn. Psychol. Life Sci.*, 2015.) (a) Calculation of the collective variable relative phase. (b) The relative phase dynamics of the HKB equation. (c) From initial various initial conditions relative phase values are found to converge upon one of two stable states. (d) The relative phase dynamics of the HKB equation shown as a function of changes in the control parameter *b/a*.

spontaneously switch to an in-phase coordination pattern, such that both fingers are moving in the medial and lateral directions at the same time. In-phase refers to the fact that homologous (i.e., the same) muscles are involved at the same time. Antiphase (or alternatively out-of-phase) refers to the fact that nonhomologous muscles are involved at the same time in order to coordinate finger movements.

To model this phenomenon, Haken et al. (1985) developed the HKB model to capture the collective variable dynamics of this phenomenon. A collective variable is a variable that captures collective ordering or collective organization or a behavior. The collective variable identified for coordinated finger wiggling is relative phase (ϕ). As shown in Figure 1.17a relative phase is calculated by starting with the time series of the angle of oscillation of the component oscillators (i.e., fingers), and then calculating the phase of these oscillators. Here phase is simply defined in a space with dimensions of angle, and rate or change of angle (i.e., angular velocity). This phase space can be represented as a phase portrait in which we can calculate a phase angle (θ) for each oscillator. Relative phase is calculated as the difference in phase angle between the two phase angles. This collective variable captures in-phase coordination with a relative phase of 0° and antiphase coordination with a relative phase of 180°.

The relative phase dynamics (i.e., how relative phase is constrained to change over time in this system) is captured by the following equation:

$$\dot{\phi} = \Delta\omega - a\sin(\phi) - 2b\sin(2\phi)$$

Here, $\dot{\phi}$ signifies differentiation with respect to time. The first term $\Delta\omega$ is used to denote the difference in intrinsic frequencies of the two oscillators in the model. For our present purposes $\Delta\omega$ is always 0. The parameters a and b are of key significance in the model. The ratio b/a acts as a control parameter in the model, such that changes in b/a are used to model changes in the collective frequency of oscillator movements. An increase in collective frequency is represented as a decrease in the ratio b/a. The relative phase dynamics for the equation, with $\Delta\omega = 0$ and $b/a = 1$, is shown in Figure 1.17b. Remembering that we are plotting relative phase against change in relative phase here, we can use this plot to graphically understand how the system will change over time given a particular initial value for relative phase. With reference for Figure 1.17b, if we start with a relative phase value of 45° we see that the rate of change of relative phase is negative, and as such the model predicts that the relative phase will change until it reaches 0° (i.e., in-phase coordination). Both 0° and 180° are referred to as stable fixed points or attractors. They represent states of coordination to which the system is organized to converge upon. This convergence can be seen in Figure 1.17c in which various initial relative phase values are seen to converge on either in-phase or antiphase coordination patterns. Note in Figure 1.17c that relative phase converges on the stable state at 0° faster than it does for the stable state at 180°. The in-phase attractor at 0° is consequently said to have greater attractor strength. In Figure 1.17b both attractors and repellers are represented, capturing states the system is organized toward and away from respectively. This is captured by a vector field, with arrows shown to be pointing toward attractors, and away from repellers (Strogatz 1994). Here then we have graphically represented the two patterns that our fingers are drawn to when we coordinate them.

In Figure 1.17d we see the HKB equation plotted for three different values of the control parameter *b/a*. As we move from left to right across the plots, *b/a* decreases, and as such the frequency of finger coordination is modeled to decrease. As we decrease *b/a* (and increase finger oscillation frequency), a qualitative change in the relative phase dynamics is observed. At a critical frequency, one of the stable fixed points disappears. The antiphase attractor at 180° no longer exists. As this critical point is passed, a phase transition is said to have occurred, with the fingers transitioning from an antiphase to an in-phase coordination pattern. This particular phase transition represents a specific example of a bifurcation. We can now come to appreciate bifurcations as changes in number or type of fixed points in the dynamics of a system. You can see an animation of this by running the MATLAB program of the HKB model visualization found at the end of the chapter in the exercises.

The significance of the HKB equation, and of the dynamical systems approach more generally, is the discovered potential of simple models to capture multiple dimensions of biological phenomena and to produce nonobvious testable predictions. One such prediction in the case of the HKB model is hysteresis. We can see hysteresis in the case of coordinated finger movements if, after we transition from antiphase to in-phase coordination, we begin to decrease the frequency of coordination. If we do this we do not observe a transition back to antiphase as we move below the critical frequency. Rather the systems stays attracted to the continually stable in-phase mode of coordination.

What Is the Cause of Self-Organization?

Although the phenomenon of self-organization has been well characterized across myriad physical and biological systems, there are no widely agreed upon causes of self-organization. A general principle that does appear to apply across many of the identified instances of self-organization states that self-organization arises from a balance of competing processes. In the case of the HKB model the self-organized dynamics of coordinated finger movements are taken to arise from a balance of tendencies for competition and cooperation at the level of component oscillators. In the case of the simple growth model described earlier in this chapter, self-organization appears to arise from the interplay between positive and negative feedback. It will quickly become unsustainable in a natural system and require some form of limitation to keep the population in check. A graphical representation of a model with both positive and negative feedback is demonstrated with cellular automata. The iteration rules, in the context of density of ones and zeroes, have positive feedback (as the density of ones leads to more ones) and negative feedback (all ones may lead to zero). Positive and negative feedback loops are not readily apparent in the flocking behavior of birds. Positive feedback may be in the form of social interaction and protection from predation, whereas negative feedback may be as simple as getting too close so as to interrupt stable flight. In all cases, self-organization appears to be dependent upon the presence of nonlinear interactions between components of the system.

Tell-Tale Signs of Self-Organization

There are multiple signatures you can look for in data to help identify if the system you are examining is self-organizing. The first sign is the existence of a control parameter and an order parameter, although they may not be a typically measured quantity. The control parameter should be something available for the experimenter to manipulate continuously. The order parameter should be a measured parameter that changes according to the control parameter. More specifically, continuous changes in the control parameter should move the system through critical points (also referred to as bifurcations, or phase transitions) in which the order parameter changes discontinuously. A classic example of a system with a control parameter and an order parameter is the logistic map that was described earlier. Let's revisit the logistic map to help us with these newer concepts we introduced.

The logistic map is defined by the following equation:

$$x_{t+1} = rx_t(1 - x_t)$$

If you start this system with x between 0 and 1 and iterate it with the map, it can do many different things. The Figure 1.18 shows the behavior of the map after it has been iterated many times with r being held constant at various values. For smaller values of r, x will converge to a fixed point. For larger values of r, x will oscillate between 2, 4, 8, 16,… different values. At a certain value of r the logistic map displays chaotic dynamics. You can see in Figure 1.18 (and in Figure 1.8) that as the control parameter r is increased continuously, there are discontinuous changes in the order parameter (the periodicity of the system in this case).

While the logistic map only has a single variable and may not meet a strict definition of self-organization, coupled nonlinear iterative maps have been used to model cortical networks (Pashaie and Farhat 2009). These authors first developed mathematical models of each individual processing unit, and then coupled the resulting

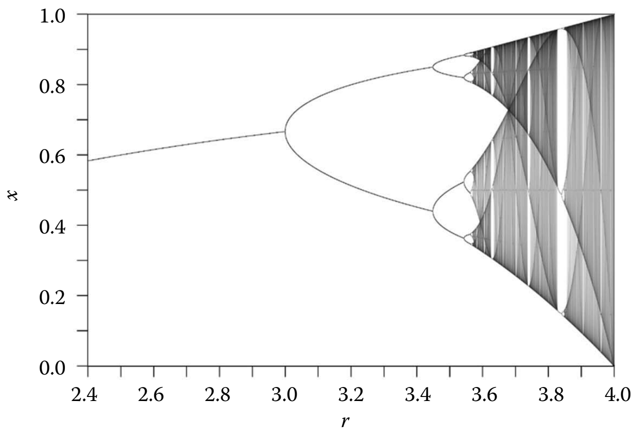


FIGURE 1.18 Bifurcation diagram for the logistic map.

complex elements using nonlinear couplings indirectly applied through the bifurcation parameters. They used the entropy of the activity of each element and the joint entropy between surrounding elements to quantify patterns of activity.

Another signature of a self-organizing system is the presence of multistability and hysteresis. A multistable system is one in which, for a single control parameter, there are multiple stable order parameters. Furthermore, multistability implies that noise in the system is sufficient to cause the system to switch between its multistable order parameters without any change in the control parameter. A similar situation is one of hysteresis. Hysteresis occurs when the value of the critical point (the point at which manipulation of a control parameter causes a bifurcation in the order parameter) depends upon the direction of change of the control parameter. A designed system that exhibits hysteresis is a thermostat that controls the temperature in one's house. If you set your thermostat to 72°F, it will cool the house if it detects temperatures above 72 and heat the house if it detects temperatures below 72. You do not want the heating and cooling to kick on often due to slight variations in the temperature so thermostats are built with hysteresis. Maybe the heat does not start until the temperature drops to 70 and the cooling does not start until the room temperature reaches 74. Interestingly, this is made possible by the addition of positive feedback. The simultaneous presence of positive and negative feedback in a system may not only produce self-organization and hysteresis, but is also the mechanism for chaos.

SELF-ORGANIZATION AND COMPLEXITY

> The laws of physics can explain how an apple falls but not why Newton, a part of a complex world, was watching the apple.
>
> **Bak (1997)**

Self-organization has been defined in many different ways by different people.

1. Self-organization is a process in which internal interactions of a system lead to the formation of patterns without any intervention by external processes (Haken 1977).
2. Self-organization is the spontaneous formation of patterns (Kelso 1995).
3. Self-organization is a process that leads to emergent patterns in a system of components (Camazine et al. 2001).
4. Self-organization is an "internally caused rise in complexity" (Shalizi et al. 2004).

We can see differences between these definitions but many commonalities as well. One interesting point to note here is that in the last definition—self-organization is a movement from lower complexity to higher complexity. In systems that have period doubling bifurcation cascades that lead to chaos, it has been demonstrated that complexity, by this definition, is maximized at the onset of chaos (Crutchfield 2011). Complexity is maximized in between complete order and disorder (Stergiou et al. 2006) (Figure 1.19). Thus, in systems that may exhibit chaos,

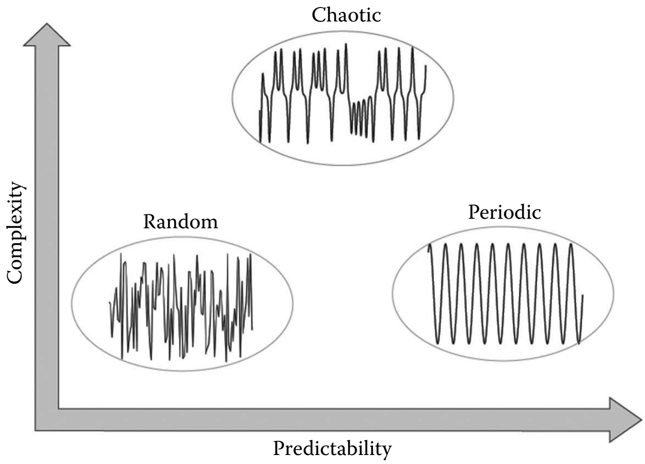


FIGURE 1.19 Chaotic systems lie between random and periodic systems in terms of predictability but are more complex than each of them.

self-organization is the movement, from order or disorder, toward the maximum complexity at the onset of chaos.

Self-Organized Criticality Hypothesis of Movement Variability

Another phenomenon that may be a product of self-organization is the presence of $1/f$ fractal scaling phenomenon movement variability. This fractal scaling (or power law, or $1/f$ noise) phenomenon arises in the variability of repeated performances of a task. It has been found in many phenomena that exist across many different time scales: heartbeat (Peng et al. 1993), finger tapping (Gilden et al. 1995), stride to stride fluctuations (Hausdorff et al. 1995), reaction times (Van Orden et al. 2003), self-esteem (Delignières et al. 2004), and more. The $1/f$ fractal scaling is where the spectral density as a function of the frequency obeys the following power law:

$$S(f) \approx \frac{1}{f^{\beta}}$$

In accordance with the definition, the value β can be found as the slope of a linear regression of the spectral density plotted against the frequency on a log–log plot, although more sophisticated methods have been developed as well (Peng et al. 1994; Wagenmakers et al. 2005).

One model for explaining this phenomenon is called self-organized criticality (Bak et al. 1987). In this model, the system requires no external manipulation of parameters but self-organizes to a critical point. An example of this behavior is found in a model of a sand pile. At each point in time, a grain of sand is dropped randomly on the sand pile. If the slope at that point is below a critical threshold, then the sand pile does not move and the slope at that point increases slightly. If the slope of the sand pile at that point goes beyond a certain threshold, then an avalanche is triggered, and sand is transferred down the slope. If the adjacent point down the slope is now above the threshold, then the avalanche continues. This system is attracted to have sand pile slopes exactly at the critical threshold (lower slopes build up and higher slopes decrease via avalanches). Thus, this system has a critical point as an attractor.

The sand pile model is a single instance of a class of self-organized criticality models. It leads to avalanche sizes and intervals between avalanches that obey a fractal power law. It has been proposed that this phenomenon is a source of natural complexity in nature (Bak et al. 1987), and that living systems will self-organize to this fractal scaling in order to be both creative and constrained in their behaviors (Van Orden et al. 2003).

SUMMARY

Dynamical systems theory, and complexity science more generally, has developed useful tools for analyzing and understanding the complex patterns to be found in measurements of biological and other systems. It has grown from the advances in understanding complex and nonlinear systems in physics and mathematics. In the case of movement patterns, this approach provides tools and techniques for investigating the dynamics of motor behavior that result from interactions between nervous system, body, and the surrounding environment in the performance of a particular task.

> When applied to human movement analysis "DST (dynamic systems theory) embraces the idea that the generation of movement patterns is multifactorial and that movement involves the coupling of the multiple degrees of freedom present in the human body."
>
> **Kurz and Stergiou (2004)**

This chapter has introduced the reader to important aspects of nonlinear analysis including dynamical systems, chaos, nonlinear dynamics, and complexity. It discussed the nonlinear dynamics of systems within and around us and how these can lead to chaos. The presence of chaos can be explained and understood though not always measured. Not all nonlinear systems are chaotic but all chaotic systems are nonlinear. Such systems transition from periodic to chaotic behavior and are highly sensitive to initial conditions.

The tools that exist to provide an understanding of the phase space geometry of nonlinear dynamical systems and for identifying and the presence of chaos will be discussed in detail in the succeeding chapters. Given the generality of the challenge of studying complex systems, new tools are continually being developed, and applied across a wide range of disciplines of scientific study. In some cases the nonlinear tools employed by movement scientists have originally been developed to meet the challenges of understanding and quantifying the dynamics of complex physical, chemical, neural, social, geologic, or economic systems. The methods introduced in this text are designed to account for (as opposed to average over) the complexity of the system under study. As such it is a reasonable expectation that when applied appropriately such measures may be more sensitive than their linear counterparts.

While the application and efficacy of the measures presented in this text do not require any particular theoretical commitments on the part of the scientist or clinician utilizing them, an understanding of dynamic systems theory provides a valuable perspective for interpreting them (see Harrison and Stergiou 2015). Dynamic systems theory also provides a starting point for investigating the hypothesis that observed behavior can be interpreted to be self-organized (Harrison and Stergiou 2015; Warren 2006). Biological and nonbiological systems often appear to create patterns in an apparently spontaneous manner without any external direction. It has been shown that the process of self-organization is a change from lower complexity to higher complexity, which in systems with period doubling bifurcation, is maximized at the onset of chaos. Self-organization is movement from order or disorder toward maximum complexity at the onset of chaos. For the movement scientist, the significance of the tools and techniques presented in this text is principally related to the hypothesis that the functionality of human movement (i.e., its stability and adaptability) is supported by both the complexity of the system, and principles of self-organization (Harrison and Stergiou 2015).

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6 Chapter 6 - Entropy

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TABLE 6.2

Approximate Entropy and Sample Entropy Values for the Sample Time Series

in Table 6.1 Approximate Entropy Sample Entropy r = 0.25 r = 0.30 r = 0.25 r = 0.30

Young 1.217 1.217 1.701 1.701

Older 0.552 1.185 2.504 1.395

Parameters used were N = 200, m = 2, and r = 0.25 and 0.3 times the standard deviation of the entire

time series. TABLE 6.1 (Continued) Sample Step Width (mm) Time Series, One from a Healthy Young Adult (Column 1) and One from a Healthy Older Adult (Column 2) while Walking on a Treadmill Young Older 75 86 73 87 76 88 73 88 75 87

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8 Chapter 8 - Autocorrelation Function, Mutual Information, and Correlation Dimension

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9 Chapter 9 - Case Studies

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