Preface

Since the first printing of this book in 2004, MATLAB® has evolved from MATLAB version 6 to MATLAB version R2014b, where presently, the package is updated twice a year. Accordingly, the second edition has been thoroughly updated and new material has been added. In this edition, there are many more applications, examples, and exercises, all with solutions, and new sections on series solutions of ordinary differential equations, perturbation methods, normal forms, Gröbner bases, and chaos synchronization have been added. There are also new chapters on image processing and binary oscillator computing.

This book provides an introduction to the theory of dynamical systems with the aid of MATLAB, the Symbolic Math Toolbox™, the Image Processing Toolbox™, and Simulink™. It is written for both senior undergraduates and graduate students. Chapter 1 provides a tutorial introduction to MATLAB—new users should go through this chapter carefully whilst those moderately familiar and experienced users will find this chapter a useful source of reference. Chapters 2–7 deal with discrete systems, Chaps. 8–17 are devoted to the study of continuous systems using ordinary differential equations and Chaps. 18–21 deal with both continuous and discrete systems. Chapter 22 lists three MATLAB-based examinations to be sat in a computer laboratory with access to MATLAB and Chap. 23 lists answers to all of the exercises given in the book. It should be pointed out that dynamical systems theory is not limited to these topics but also encompasses partial differential equations, integral and integro-differential equations, stochastic systems, and time-delay systems, for instance. References [1–5] given at the end of the Preface provide more information for the interested reader. The author has gone for breadth of coverage rather than fine detail and theorems with proofs are kept at a minimum. The material is not clouded by functional analytic and group theoretical definitions and so is intelligible to readers with a general mathematical background. Some of the topics covered are scarcely covered elsewhere. Most of the material in Chaps. 7, 10, 11, 15–19, and 21 is at postgraduate level and has been influenced by the author's own research interests. There is more theory in these chapters than in the rest of the book since it is not easily accessed anywhere else. It has been found that these chapters are especially useful as reference material for senior undergraduate project work. The theory in other chapters of the book is dealt with more comprehensively in other texts, some of which may be found in the references section of the corresponding chapter. The book has a very hands-on approach and takes the reader from the basic theory right through to recently published research material.

MATLAB is extremely popular with a wide range of researchers from all sorts of disciplines, it has a very user-friendly interface and has extensive visualization and numerical computation capabilities. It is an ideal package to adopt for the study of nonlinear dynamical systems; the numerical algorithms work very quickly, and complex pictures can be plotted within seconds. The Simulink accessory to MATLAB is used for simulating dynamical processes. It is as close as one can get to building apparatus and investigating the output for a given input without the need for an actual physical model. For this reason, Simulink is very popular in the field of engineering. Note that the latest student version of MATLAB comes with a generous additional ten toolboxes including the Symbolic Math Toolbox, the Image Processing Toolbox, and Simulink.

The first chapter provides an efficient tutorial introduction to MATLAB. New users will find the tutorials will enable them to become familiar with MATLAB within a few hours. Both engineering and mathematics students appreciate this method of teaching and I have found that it generally works well with one staff member to about twenty students in a computer laboratory. In most cases, I have chosen to list the MATLAB program files at the end of each chapter, this avoids unnecessary cluttering in the text. The MATLAB programs have been kept as simple as possible and should run under later versions of the package. The MATLAB program files and Simulink model files (including updates) can even be downloaded from the Web at

http://www.mathworks.com/matlabcentral/fileexchange/authors/6536.

Readers will find that they can reproduce the figures given in the text, and then it is not too difficult to change parameters or equations to investigate other systems. Readers may be interested to hear that the MATLAB and Simulink model files have been downloaded over 30,000 times since they were uploaded in 2002 and that these files were selected as the MATLAB Central Pick of the Week in July 2013.

Chapters 2–7 deal with discrete dynamical systems. Chapter 2 starts with a general introduction to iteration and linear recurrence (or difference) equations. The bulk of the chapter is concerned with the Leslie model used to investigate the population of a single species split into different age classes. Harvesting and culling policies are then investigated and optimal solutions are sought. Nonlinear discrete dynamical systems are dealt with in Chap. 3. Bifurcation diagrams, chaos, intermittency, Lyapunov exponents, periodicity, quasiperiodicity, and universality are some of the topics introduced. The theory is then applied to real-world problems from a broad range of disciplines including population dynamics, biology, economics, nonlinear optics, and neural networks. Chapter 4 is concerned with complex iterative maps; Julia sets and the now-famous Mandelbrot set are plotted. Basins of attraction are investigated for these complex systems. As a simple introduction to optics, electromagnetic waves and Maxwell's equations are studied at the beginning of Chap. 5. Complex iterative equations are used to model the propagation of light waves through nonlinear optical fibers. A brief history of nonlinear bistable optical resonators is discussed and the simple fiber ring resonator is analyzed in particular. Chapter 5 is devoted to the study of these optical resonators and phenomena such as bistability, chaotic attractors, feedback, hysteresis, instability, linear stability analysis, multistability, nonlinearity, and steady states are discussed. The first and second iterative methods are defined in this chapter. Some simple fractals may be constructed using pencil and paper in Chap. 6, and the concept of fractal dimension is introduced. Fractals may be thought of as identical motifs repeated on ever-reduced scales. Unfortunately, most of the fractals appearing in nature are not homogeneous but are more heterogeneous, hence the need for the multifractal theory given later in the chapter. It has been found that the distribution of stars and galaxies in our universe is multifractal, and there is even evidence of multifractals in rainfall, stock markets, and heartbeat rhythms. Applications in materials science, geoscience, and image processing are briefly discussed. Chapter 7 provides a brief introduction to the Image Processing Toolbox™ which is being used more and more by a diverse range of scientific disciplines, especially medical imaging. The fast Fourier transform is introduced and has a wide range of applications throughout the realms of science.

Chapters 8–17 deal with continuous dynamical systems. Chapters 8 and 9 cover some theory of ordinary differential equations and applications to models in the real world are given. The theory of differential equations applied to chemical kinetics and electric circuits is introduced in some detail. The memristor is introduced and one of the most remarkable stories in the history of mathematics is relayed. Chapter 8 ends with the existence and uniqueness theorem for the solutions of certain types of differential equations. A variety of numerical procedures are available in MATLAB when solving stiff and nonstiff systems when an analytic solution does not exist or is extremely difficult to find. The theory behind the construction of phase plane portraits for two-dimensional systems is dealt with in Chap. 9. Applications are taken from chemical kinetics, economics, electronics, epidemiology, mechanics, and population dynamics. The modeling of the populations of interacting species is discussed in some detail in Chap. 10 and domains of stability are discussed for the first time. Limit cycles, or isolated periodic solutions, are introduced in Chap. 11. Since we live in a periodic world, these are the most common type of solution found when modeling nonlinear dynamical systems. They appear extensively when modeling both the technological and natural sciences. Hamiltonian, or conservative, systems and stability are discussed in Chaps. 12, and 13 is concerned with how planar systems vary depending upon a parameter. Bifurcation, bistability, multistability, and normal forms are discussed.

The reader is first introduced to the concept of chaos in continuous systems in Chaps. 14 and 15, where three-dimensional systems and Poincaré maps are investigated. These higher-dimensional systems can exhibit strange attractors and chaotic dynamics. One can rotate the three-dimensional objects in MATLAB and plot time series plots to get a better understanding of the dynamics involved. Once again, the theory can be applied to chemical kinetics (including stiff systems), electric circuits, and epidemiology; a simplified model for the weather is also briefly discussed. Chapter 15 deals with Poincaré first return maps that can be used to untangle complicated interlacing trajectories in higher-dimensional spaces. A periodically driven nonlinear pendulum is also investigated by means of a nonautonomous differential equation. Both local and global bifurcations are investigated in Chap. 16. The main results and statement of the famous second part of David Hilbert's sixteenth problem are listed in Chap. 17. In order to understand these results, Poincaré compactification is introduced. The study of continuous systems ends with one of the author's specialities—limit cycles of Liénard systems. There is some detail on Liénard systems, in particular, in this part of the book, but they do have a ubiquity for systems in the plane.

A brief introduction to the enticing field of neural networks is presented in Chap. 18. Imagine trying to make a computer mimic the human brain. One could ask the question: In the future will it be possible for computers to think and even be conscious? The human brain will always be more powerful than traditional, sequential, logic-based digital computers and scientists are trying to incorporate some features of the brain into modern computing. Neural networks perform through learning and no underlying equations are required. Mathematicians and computer scientists are attempting to mimic the way neurons work together via synapses; indeed, a neural network can be thought of as a crude multidimensional model of the human brain. The expectations are high for future applications in a broad range of disciplines. Neural networks are already being used in machine learning and pattern recognition (computer vision, credit card fraud, prediction and forecasting, disease recognition, facial and speech recognition), the consumer home entertainment market, psychological profiling, predicting wave over-topping events, and control problems, for example. They also provide a parallel architecture allowing for very fast computational and response times. In recent years, the disciplines of neural networks and nonlinear dynamics have increasingly coalesced and a new branch of science called neurodynamics is emerging. Lyapunov functions can be used to determine the stability of certain types of neural network. There is also evidence of chaos, feedback, nonlinearity, periodicity, and chaos synchronization in the brain.

Chapter 19 is devoted to the new and exciting theory behind chaos control and synchronization. For most systems, the maxim used by engineers in the past has been "stability good, chaos bad," but more and more nowadays this is being replaced with "stability good, chaos better." There are exciting and novel applications in cardiology, communications, engineering, laser technology, and space research, for example.

Chapter 20 focuses on binary oscillator computing, the subject of UK, International and Taiwanese patents. The author and his coinventor, Jon Borresen, came up with the idea when modeling connected biological neurons. Binary oscillator technology can be applied to the design of arithmetic logic units (ALUs), memory, and other basic computing components. It has the potential to provide revolutionary computational speedup, energy saving, and novel applications and may be applicable to a variety of technological paradigms including biological neurons, complementary metal–oxide–semiconductor (CMOS), memristors, optical oscillators, and superconducting materials. The research has the potential for MMU and industrial partners to develop super fast, low-power computers and may provide an assay for neuronal degradation for brain malfunctions such as Alzheimer's, epilepsy, and Parkinson's disease!

Examples of Simulink models, referred to in earlier chapters of the book, are presented in Chap. 21. It is possible to change the type of input into the system, or parameter values, and investigate the output very quickly. This is as close as one can get to experimentation without the need for expensive equipment.

Three examination-type papers are listed in Chap. 22 and a complete set of solutions is listed in Chap. 23.

Both textbooks and research papers are presented in the list of references. The textbooks can be used to gain more background material, and the research papers have been given to encourage further reading and independent study.

This book is informed by the research interests of the author which are currently nonlinear ordinary differential equations, nonlinear optics, multifractals, neural networks, and binary oscillator computing. Some references include recently published research articles by the author along with an international patent.

The prerequisites for studying dynamical systems using this book are undergraduate courses in linear algebra, real and complex analysis, calculus, and ordinary differential equations; a knowledge of a computer language such as C or Fortran would be beneficial but not essential.

Recommended Textbooks

1. M.P. Coleman, *An Introduction to Partial Differential Equations with MATLAB*, 2nd edn. Chapman and Hall/CRC Applied Mathematics and Nonlinear Science (Chapman and Hall/CRC, New York, 2013)
2. B. Bhattacharya, M. Majumdar, *Random Dynamical Systems: Theory and Applications* (Cambridge University Press, Cambridge, 2007)
3. R. Sipahi, T. Vyhlídal, S. Niculescu, P. Pepe (eds.), *Time Delay Systems: Methods, Applications and New Trends*. Lecture Notes in Control and Information Sciences (Springer, New York, 2012)
4. V. Volterra, *Theory of Functionals and of Integral and Integro-Differential Equations* (Dover Publications, New York, 2005)
5. J. Mallet-Paret, J. Wu, H. Zhu, Y. Yi, *Infinite Dimensional Dynamical Systems (Fields Institute Communications)* (Springer, New York, 2013)

Instructors may be interested in two new features in MATLAB, namely, Cody Coursework™ and MATLAB apps. Instructors can automate grading of MATLAB coursework assignments using Cody Coursework; this is a free resource available to use for faculty who have an active site licence. MATLAB apps enable the user to perform computational tasks interactively and many of the toolboxes come with apps. More details can be found on the relevant MathWorks web pages.

I would like to express my sincere thanks to MathWorks for supplying me with the latest versions of MATLAB and its toolboxes. Thanks also go to all of the reviewers from the editions of the Maple and Mathematica books. Special thanks go to Birkhäuser and Springer publishers. Finally, thanks to my family, especially my wife, Gaynor, and our children, Sebastian and Thalia, for their continuing love, inspiration, and support.

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