Preface

This textbook is intended for college sophomores and juniors students whose electrical engineering programs include linear systems and signals courses. It can be also used by other engineering students interested in linear dynamic systems and signals—especially biomedical, aerospace, mechanical, and industrial engineering students. The text is based on the author's sixteen years of teaching linear systems and signals to undergraduate and graduate students in the Rutgers University Department of Electrical and Computer Engineering.

In the electrical engineering curriculum, a course in linear dynamic systems and signals is a prerequisite for courses in control systems, communication systems, and digital signal processing courses. In addition, many problems in wireless communications, networking, signal processing, electronics, photonics, and robotics are now studied from the dynamic system point of view. The book presents both continuous- and discrete-time linear systems and signals. Historically, teachers and students have first studied continuous-time phenomena, and then applied the results to the discrete-time domain. However, with the development of modern computers, discrete-time analysis is increasingly dominant, especially from the application and computation points of view. Furthermore, some phenomena are much easier to explain and understand in the discrete-time domain than in the continuous-time domain, since discrete-time linear systems are represented by simple recursive formulas.

It should be emphasized that this textbook reflects the most recent changes in electrical and computer engineering curricula at U.S. universities. Due to the increased number of computer engineering courses over the last fifteen years, and due to newly introduced senior level courses in wireless communications, networking, photonics, and signal processing, some courses in classical electrical engineering areas have had to be modified, condensed, combined, or even eliminated. These changes primarily affected courses in the principles of electrical engineering, electrical circuits, systems and signals, control systems, electromagnetic fields, communication systems, electronics, power systems, and related courses. The modification of linear systems and signals courses has gone in two directions: (a) teaching it at the sophomore level, as the course on signals and time-frequency transforms, with little emphasis on system dynamics (in general sophomore students do not have sufficient knowledge of differential equations); (b) teaching it as a junior (or even senior) level course with emphasis on system dynamics, and including some topics from electrical circuits, feedback systems, communications, and signal processing. This textbook has taken a twofold approach: Chapters 2–6 and 9–10 have been written in the direction of (a), and Chapters 1, 7–8 and 11–12 have been written in the direction of (b).

The book is divided into three major parts: 1) the frequency domain approach to linear dynamic systems; 2) the time domain approach to linear dynamic systems; and 3) the linear system approach to electrical engineering. An introduction to continuous- and

discrete-time signals is presented in Chapter 2. Signal transforms (Fourier, Laplace, and $\mathcal{Z}$-transform) are presented in Chapters 3–5. The Fourier series and Fourier transform are presented in Chapters 3 is done in the continuous-time domain. Chapter 9 gives a full coverage of the discrete-time Fourier transform and its variants. The time domain approach to linear systems presents continuous- and discrete-time convolution (Chapter 6), methods for solving differential and difference equations (Chapter 7), and continuous- and discrete-time state space approaches (Chapter 8). Additional topics on signals in digital signal processing and communication systems are presented in Chapters 9 and 10. Instructors intending to teach a linear *dynamic* systems course should be able to cover most of Chapters 1–8 in one semester (see Table 1). Instructors more interested in signals than in systems should cover in detail Chapters 2–6 and 9 and selected parts of Chapter 10 (see Table 2).

The complete book can be thoroughly covered in a two-semester course. Chapters from the third part of the book (Chapters 9–12) explain how to approach other linear system areas of electrical engineering. Since many systems in electrical engineering are linear, the reader will find these chapters extremely useful in combination with other advanced undergraduate courses in electrical engineering (such as control systems, robotics, signal processing, communications, neural networks, computer/communication networks, power systems, and electronics). In that case, the reader will conclude that the linear system course (area) is not just another electrical engineering course, but the *core course around which several courses (areas) of electrical engineering evolve*.

A one-semester junior-level course with emphasis on *linear dynamic systems* can cover the topics presented in Table 1. At Rutgers University, we also cover the introductory topics from Chapter 12 on linear feedback systems, since an undergraduate control course is not required in our curriculum.

One semester course with emphasis on dynamic systems
Chapter 1: Section 1.3 may be skipped
Chapter 2:
Chapter 3: Fourier series and transform may be less emphasized
Chapter 4:
Chapter 5:
Chapter 6: Convolution (can be taught after Chapter 2)
Chapter 7: Selected topics
Chapter 8: State space (Section 8.6 may be omitted)

Table 1: Suggested Topics for a One-Semester Course with Emphasis on Linear Dynamic Systems

A one-semester sophomore/junior-level course *with emphasis on signals* can be taught according to Table 2.

One semester course with emphasis on signals
Chapter 1: Introduction and Section 1.1.1 only
Chapter 2:
Chapter 3:
Chapter 4:
Chapter 5:
Chapter 6: Convolution (can be taught after Chapter 2)
Chapter 9: DFDT, DFT, FFT, and DFS
Chapter 10: Sections 10.1-4

Table 2: Suggested Topics for a One-Semester Course with Emphasis on Signals

A two-semester sophomore/junior-level course with a distinction between continuous- and discrete-time signals/systems (with the first semester on continuous-time signals and systems, and the second semester on discrete-time signals and systems) can be taught by organizing material according to Table 3.

First-semester course on continuous-time signals and systems	*Second-semester course on discrete-time signals and systems*
Chapter 1: Continuous part	Chapter 1: Discrete part
Chapter 2: Continuous part	Chapter 2: Discrete part
Chapter 3:	Chapter 5:
Chapter 4:	Chapter 6: Discrete part
Chapter 6: Continuous part	Chapter 7: Discrete part
Chapter 7: Continuous part	Chapter 8: Discrete part
Chapter 8: Continuous part	Chapter 9:
Chapters 10-12: Selected topics	Chapter 10: Section 10.6

Table 3: Suggested Topics for a Two-Semester Course Independently Covering Continuous- and Discrete-Time Signals and Systems

The main goal in linear dynamic system analysis is to find the system response due to any excitation (input). It is that the most systematic way to achieve that goal

is to first find the system impulse response. Finding the system impulse response directly in the continuous-time domain is a very tedious task. From the author's teaching experience, students are able to find the system impulse response in the frequency domain rather easily, but they have difficulty in the time domain. To avoid this problem, *all important system concepts (including the system impulse response) are introduced first in the frequency domain.* It is very simple to define the system transfer function in the frequency domain. Having defined (and obtained) the transfer function, it is very simple to define (and obtain) the system impulse response in an inverse procedure, in which signals are mapped from the frequency domain to the time domain. In this book, the continuous-time system impulse response is obtained as the inverse Laplace transform of the system transfer function. From the impulse response, we derive the most important result of linear dynamic systems theory, which states that for a system at rest (with no initial energy stored in the system), *the system response to an arbitrary input is the convolution of the system impulse response and the given input signal*. The convolution operation is studied thoroughly in Chapter 6.

After all of the important linear system concepts are introduced in the frequency domain, we interpret these concepts in the time domain and develop the time domain techniques for finding the response of continuous- and discrete-time linear systems. This leads to the state space technique as a highlight of the time domain approach for studying linear systems. Due to the rapid development of electrical engineering and other engineering disciplines in the last two decades and the frequent use of modern computer packages (such as MATLAB) for system analysis, it is imperative that modern courses in linear system analysis give extensive coverage of the state space technique. This book achieves that goal by requiring only elementary knowledge of linear algebra and differential equations. Using this mathematical background, the main state space concepts are slowly and thoroughly developed, and new notions are fully explained. In general, it is well known and accepted that the frequency domain gives a better understanding of considered physical phenomena, but the time domain is more efficient from the computational point of view. In the last part of this book, we demonstrate how to use linear system theory concepts to solve problems in other fields of electrical engineering: signal processing, control systems, communication systems, and electrical circuits.

The material presented in this book has been class-tested for several years in the required junior-level course on linear systems and signals at Rutgers University. The book includes many examples and problems. Most are of analytical nature; some especially those referring to higher-order systems, are performed (or ought to be performed) using the MATLAB package. The real-world linear system examples are given in terms of differential/difference equations or in the state space form (system, input, and output matrices), without explaining the physics of linear systems and the development of corresponding mathematical models. The author believes that most sophomore/junior students will have difficulty grasping all of the modeling issues from diverse linear system dis-

ciplines (electrical, mechanical, chemical, and biomedical engineering). Consequently, real physical systems are represented by the numerical entries in corresponding differential/difference equations and matrices (for the state space description). At some points to show the relationship between mathematical models, state space forms, and system transfer functions, mathematical modeling is fully explained.

The undergraduate linear systems and signals course at Rutgers University is associated with the linear systems and signals laboratory, which over the years has been slowly evolving from a hardware oriented laboratory to a fully software oriented laboratory based on MATLAB. This computer aided system design package is used quite often in this book for solving problems and designing laboratory experiments. MATLAB is a good learning tool, which helps students to get a better understanding of main linear systems and signal concepts. It is especially useful for studying higher-order linear dynamic systems.

The book provides concurrently a laboratory manual for linear systems and signals. Since undergraduate laboratories at major United States universities and abroad, are more and more software oriented, we use the MATLAB package to design corresponding laboratory experiments. After each important topic, a laboratory experiment is presented. However, the inclusion of MATLAB only helps to get deepen understanding and practical working knowledge of main linear system theory concepts. *By no means is MATLAB essential for the material presented in this textbook.*

The book is supplemented with a teacher's solution manual for problems and laboratory experiments, available only to instructors who have adopted the text for classroom use. The MATLAB programs and numerical data used in this book may be obtained at the homepage of the book, `http://www.ece.rutgers.edu/~gajic/systems.html`. *The same web site also contains additional problems and their complete or partial solutions, laboratory experiments, sample exams, and list of corrections (if any). The author is in the process of developing the transparencies to help instructors teach the corresponding course(s) on linear systems and signals.*

The author approached the writing of this book with the desire to present linear systems theory essentials in sufficient detail, yet explain these essentials in a such way that every student in electrical engineering will be able to use it as a self-study guide. After taking this course, engineering students should be well equipped to cope with all types of linear *dynamic* system problems, especially those encountered in related courses (such as communications, signal processing, controls, networking, robotics, power systems, electrical circuits, and electronics). Hence, the main purpose of this course is to develop unified techniques for recognizing and solving linear *dynamic* system problems regardless of their origin.

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