# Preface

The field of digital signal processing (DSP) has seen explosive growth during the past five decades, as phenomenal advances both in research and application have been made. Fueling this growth have been the advances in digital computer technology and software development. Almost every electrical and computer engineering department in this country and abroad now offers one or more courses in digital signal processing, with the first course usually being offered at the senior level. This book is intended for a two-semester course on digital signal processing for seniors or first-year graduate students. It is also written at a level suitable for self-study by the practicing engineer or scientist.

The third edition of this book was published five years ago, and the user feedback we have received since then made it evident that a new edition was needed to incorporate the suggested changes. Three types of changes were made to the manuscript: inclusion of a number of new topics, elimination of some topics, and a major reorganization of the materials. We believe the materials in each chapter are now organized more logically. A few additional worked-out examples have been included to explain new and difficult concepts.

One major change occurring in the fourth edition is reorganizing the contents of Chapters 2, 3, and 4 into three new chapters: a chapter dealing with the time-domain representation of discrete-time signals, a chapter on the frequency-domain representation of discrete-time signals, and a chapter on the time-domain and frequency-domain representations of a class of discrete-time systems. The sections on design of analog lowpass filters, design of analog highpass, bandpass, and bandstop filters, analog anti-aliasing filter design, and analog reconstruction filter design in Chapter 4 of the third edition have been moved into two appendices in this edition. In addition, the discussion of the interface devices needed for the digital processing of continuous-time signals in practice have been eliminated. These devices are the sample-and-hold circuit, analog-to-digital converter, and digital-to-analog converter.

The second major change implemented in this edition is the removal of the chapter on applications and the inclusion of most of the materials of this chapter in the CD accompanying this book. The discussion on short-time Fourier transform from this chapter has also been moved to Chapter 5 on finite-length discrete transforms.

The new topics included in the fourth edition are the cyclic prefix (Section 5.10.2), digital integrators (Section 7.4.3), digital differentiators (Section 7.4.4), DC blockers (Section 7.4.5), a new method of the realization of a pair of FIR transfer functions in the form of a cascaded lattice structure (Section 8.9), expanded discussion of computer-aided design of IIR digital filters (Section 9.7), a method for the determination of the optimal value of the sparsity factor for the design of computationally efficient interpolated FIR filters (Section 10.6.2), and the development of fast DFT computation algorithm using the transpose operation (Section 11.3.3). The section on the design of digital sine-cosine generators has been removed from Chapter 8 and included as problems at the end of the chapter. The section on the design of tunable digital filters has been moved from Chapter 11 to the chapter on digital filter implementation (Section 8.7). Finally, the sections on arithmetic operations and function approximation have been removed from Chapter 11. A few problems on certain function approximations have been included as problems at the end of the chapter.

A key feature of this book is the extensive use of MATLAB® -based[1] examples that illustrate the program's powerful capability to solve signal processing problems. The book uses a three-stage pedagogical structure designed to take full advantage of MATLAB and to avoid the pitfalls of a "cookbook" approach to problem solving. First, each chapter begins by developing the essential theory and algorithms. Second, the material is illustrated with examples solved by hand calculation. And third, solutions are derived using MATLAB. From the beginning, MATLAB codes are provided with enough details to permit the students to repeat the examples on their computers. In addition to conventional theoretical problems requiring analytical solutions, each chapter also includes a large number of problems requiring solution via MATLAB. This book requires a minimal knowledge of MATLAB. We believe students learn the intricacies of problem solving with MATLAB faster by using tested, complete programs and then writing simple programs to solve specific problems that are included at the ends of Chapters 2 to 14.

Because computer verification enhances the understanding of the underlying theories, as in the first three editions, a large library of worked-out MATLAB programs are included in the fourth edition. The original MATLAB programs of the third edition have been updated to run on the newer versions of MATLAB and the *Signal Processing Toolbox*. In addition, new MATLAB programs and code fragments have been added in this edition. All MATLAB programs are included in the CD accompanying this text. The reader can run these programs to verify the results included in the book. All MATLAB programs and code fragments in the text have been tested under version 7.10.0.499 (R2010a) of MATLAB and version 6.13 (R2010a) of the *Signal Processing Toolbox*. Some of the programs listed in this book are not necessarily the fastest with regard to their execution speeds, nor are they the shortest. They have been written for maximum clarity without detailed explanations.

A second attractive feature of this book is the inclusion of extensive simple, but practical, examples that expose the reader to real-life signal processing problems, which has been made possible by the use of computers in solving practical design problems. This book also covers many topics of current interest not normally found in an upper-division text. Additional topics are also introduced to the reader through problems at the end of Chapters 2 through 14.

The CD accompanying the book includes several important, practical applications of digital signal processing. These applications are easy to follow and do not require knowledge of other advanced-level courses. It also contains several other useful materials, such as files of real signals, review materials, additional examples, frequently asked questions (FAQs), a large number of typical applications of digital signal processing, and a short tutorial on MATLAB. Where possible, pointers in the text with CD symbols have been used to direct the reader to relevant materials in the CD. From the reader's feedback, we hope to improve the contents in the CD for future editions.

The prerequisite for this book is a junior-level course in linear continuous-time and discrete-time systems, which is usually required in most universities. A minimal review of linear systems and transforms is provided in the text, and basic materials from linear system theory are included, with important materials summarized in tables. This approach permits the inclusion of more advanced materials without significantly increasing the length of the book.

The book is divided into 14 chapters and three appendices. Chapter 1 presents an introduction to the field of signal processing and provides an overview of signals and signal processing methods.

Chapter 2 discusses the time-domain representations of discrete-time signals as sequences of numbers. Several basic discrete-time signals that play important roles in the time-domain characterization of arbitrary discrete-time signals and discrete-time systems are introduced here. Next, a number of basic operations to generate other sequences from one or more sequences are described. A combination

[1] MATLAB is a registered trademark of The MathWorks, Inc., 3 Apple Hill Dr., Natick, MA 01760, Phone: 508-647-7000, **http://www.mathworks.com**.

of these operations is also used in developing a discrete-time system. The problem of representing a continuous-time signal by a discrete-time sequence is examined for a simple case.

Chapter 3 is devoted to the frequency-domain representation of discrete-time signals. It starts with a short review of the continuous-time Fourier transform (CTFT) representations of continuous-time signals. The discrete-time Fourier transform (DTFT) that is used to represent the discrete-time signal in the frequency domain is then introduced followed by the inverse discrete-time Fourier transform to recover the original discrete-time signal from its DTFT representation. As the DTFT representation involves an infinite sum, a discussion of the convergence of the DTFT is included. Properties of the DTFT are next reviewed, and the unwrapping of the phase function to remove certain discontinuities in the DTFT is discussed. The conditions for discrete-time representation of a band-limited continuous-time signal under ideal sampling and its exact recovery from the sampled version are next derived.

Chapter 4 begins with a review of the time-domain representations of a few simple discrete-time systems and their applications. This is followed by a discussion of various classes of discrete-time systems of which the class of causal, linear, and time-invariant (LTI) systems is of major interest in this book. It is shown here that the time-domain representation of a causal LTI discrete-time system is in terms of its impulse response which leads to the input-output relation of the system. Generation of more complicated LTI system by interconnecting simple LTI systems is then discussed. The frequency-domain representation of an LTI discrete-time system is given by its frequency response, which is the DTFT of its impulse response. The concept of the frequency response is then introduced, followed by a careful examination of the difference between phase and group delays associated with the frequency response.

The major part of Chapter 5 is concerned with the discrete Fourier transform (DFT), which plays an important role in some digital signal processing applications as it can be used to implement linear convolution efficiently using fast algorithm for its computation. The DFT and its inverse are introduced, along with a discussion of their properties. This chapter also includes a review of the discrete cosine transform (DCT) and the Haar transform. All three transforms discussed in this chapter are examples of orthogonal transforms of a finite-length sequence. The chapter also includes a brief review of the short-time Fourier transform, which is often used to provide a frequency-domain representation of nondeterministic discrete-time signals.

Chapter 6 is devoted to a discussion of the $z$-transform. The transform and its inverse are introduced, along with a discussion of their properties. The convergence condition of the $z$-transform is examined in detail. It also includes a discussion of the concept of the transfer function of an LTI discrete-time system and its relation to the frequency response of the system.

As mentioned earlier, this book concentrates almost exclusively on the LTI discrete-time systems, and Chapter 7 discusses their transform-domain representations. Specific properties of such transform-domain representations are investigated, and several simple applications are considered.

A structural representation using interconnected basic building blocks is the first step in the hardware or software implementation of an LTI digital filter. The structural representation provides the relations between some pertinent internal variables with the input and the output, which, in turn, provides the keys to the implementation. There are various forms of the structural representation of a digital filter, and two such representations are reviewed in Chapter 8, followed by a discussion of some popular schemes for the realization of real causal IIR and FIR digital filters.

Chapter 9 considers the IIR digital filter design problem. First, it discusses the issues associated with the filter design problem. Then, it describes the most popular approach to IIR filter design, based on the conversion of a prototype analog transfer function to a digital transfer function. The spectral transformation of one type of IIR transfer function into another type is discussed. The use of MATLAB in IIR digital filter design is illustrated.

Chapter 10 is concerned with the FIR digital filter design problem. A very simple approach to FIR filter design is described, followed by a discussion of a popular algorithm for the computer-aided design of equiripple linear-phase FIR digital filters. The use of MATLAB in FIR digital filter design is illustrated.

Chapter 11 is concerned with the implementation aspects of DSP algorithms. Two major issues concerning implementation are discussed first. The software implementations of digital filtering and DFT algorithms on a computer are reviewed to illustrate the main points. This is followed by a discussion of various schemes for the representation of number and signal variables on digital machines, which is basic to the development of methods for the analysis of finite wordlength effects considered in Chapter 12. A brief review of operations often used to handle overflow is included here.

Chapter 12 is devoted to analysis of the effects of the various sources of quantization errors; it describes structures that are less sensitive to these effects. Included here are discussions on the effect of coefficient quantization.

Chapters 13 and 14 discuss multirate discrete-time systems with unequal sampling rates at various parts. The chapter includes a review of the basic concepts and properties of sampling rate alteration, design of decimation and interpolation digital filters, and multirate filter bank design.

Appendix A provides a brief review of analog lowpass filter design methods along with the requirements for the design of analog anti-aliasing filter and analog reconstruction filter. Appendix B discusses the methods for the design of analog highpass, bandpass and bandstop filters. Appendix C reviews the important statistical properties of the random variable and the random process.

The materials in this book have been used in a two-quarter course sequence on digital signal processing at the University of California, Santa Barbara, and have been extensively tested in the classroom for over 20 years. Basically, Chapters 2 through 8 formed the basis of an upper-division course, while Chapters 8 through 14 along with a few examples of applications formed the basis of a graduate-level course. In addition, a major part of this book has been used in an upper-division course at the University of Southern California for the last several years.

This text contains 312 examples, 147 MATLAB programs and code fragments, 859 problems, and 161 MATLAB exercises.

Every attempt has been made to ensure the accuracy of all materials in this book, including the MATLAB programs. I would, however, appreciate readers bringing to my attention any errors that may appear in the printed version for reasons beyond my control and that of the publisher. These errors and any other comments can be communicated to me by e-mail addressed to **mitra@ece.ucsb.edu**.

The book's website, **www.mhhe.com/mitra**, contains additional resources for both instructors and students. Professors can benefit from McGraw-Hill's COSMOS electronic solutions manual. COSMOS enables instructors to generate a limitless supply of problem material for assignment, as well as transfer and integrate their own problems into the software. Please contact your McGraw-Hill sales representative for additional information.

Finally, I have been particularly fortunate to have had the opportunity to work with outstanding students who were in my research group during my teaching career, which spans over 40 years. I have benefited immensely, and continue to do so, both professionally and personally, from my friendship and association with them, and to them I dedicate this book.

Sanjit K. Mitra

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## Supplements

All MATLAB programs included in this book are in the CD accompanying this book and are also available from the Internet site **www.ece.ucsb.edu/Faculty/Mitra/Book4e**.

A solutions manual prepared by Hsin-Han Ho, Travis Smith, and Martin Gawecki and containing the solutions to all problems and MATLAB exercises is available to instructors from the publisher. PowerPoint slides of most materials of this book are available to instructors from the author.