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Vinav K. Ingle John G. Proakis

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A BC NOTE

Students learn in a number of ways and in a variety of settings. They learn through lectures, in informal study groups, or alone at their desks or in front of a computer terminal. Wherever the location, students learn most efficiently by solving problems, with frequent feedback from an instructor, following a worked-out problem as a model. Worked-out problems have a number of positive aspects. They can capture the essence of a key concept — often better than paragraphs of explanation. They provide methods for acquiring new knowledge and for evaluating its use. They provide a taste of real-life issues and demonstrate techniques for solving real problems. Most important, they encourage active participation in learning.

We created the BookWare Companion Series because we saw an unfulfilled need for computer-based learning tools that address the computational aspects of problem solving across the curriculum. The BC series concept was also shaped by other forces: a general agreement among instructors that students learn best when they are actively involved in their own learning, and the realization that textbooks have not kept up with or matched student learning needs. Educators and publishers are just beginning to understand that the amount of material crammed into most textbooks cannot be absorbed, let alone the knowledge to be mastered in four years of undergraduate study. Rather than attempting to teach students all the latest knowledge, colleges and universities are now striving to teach them to reason: to understand the relationships and connections between new information and existing knowledge; and to cultivate problem-solving skills, intuition, and critical thinking. The BookWare Companion Series was developed in response to this changing mission.

Specifically, the BookWare Companion Series was designed for educators who wish to integrate their curriculum with computer-based learning tools, and for students who find their current textbooks overwhelming. The former will find in the BookWare Companion Series the means by which to use powerful software tools to support their course activities, without having to customize the applications themselves. The latter will find relevant problems and examples quickly and easily and have instant electronic access to them.

We hope that the BC series will become a clearinghouse for the exchange of reliable teaching ideas and a baseline series for incorporating learning advances from emerging technologies. For example, we intend to reuse the kernel of each BC volume and add electronic scripts from other software programs as desired by customers. We are pursuing the addition of AI/Expert System technology to provide an intelligent tutoring capability for future iterations of BC volumes. We also anticipate a paperless environment in which BC content can flow freely over high-speed networks to support remote learning activities. In order for these and other goals to be realized, educators, students, software developers, network administrators, and publishers will need to communicate freely and actively with each other. We encourage you to participate in these exciting developments and become involved in the BC Series today. If you have an idea for improving the effectiveness of the BC concept, an example problem, a demonstration using software or multimedia, or an opportunity to explore, contact us.

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DIGITAL SIGNAL PROCESSING

USING MATLAB V.4®

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Vinay K. Ingle
John G. Proakis
Northeastern University

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About the Cover: The BookWare Companion Series cover illustration was created on a Macintosh Quadra 700, using Aldus FreeHand and Quark XPress. The surface plot on the cover, provided courtesy of The MathWorks, Inc., Natick, MA, was created with MATLAB® and was inserted on the cover mockup with an HP ScanJet IIP Scanner. It represents a surface created by assigning the values of different functions to specific matrix elements.

Editor: Bill Barter
Assistant Editor: Angie Mlinko
Manufacturing Coordinator: Wendy Kilborn
Cover Designer: Stuart Paterson, Image House, Inc.
Editorial Assistant: Monica Block

Printed and bound in the United States of America.
97 98 99—10 9 8 7 6 5 4 3

International Thomson Editores
Campos Eliseos 385, Piso 7
Col. Polanco
11560 Mexico D.F., Mexico

International Thomson Publishing GmbH
Königswinterer Strasse 418
53227 Bonn, Germany

International Thomson Publishing Asia
221 Henderson Road
#05-10 Henderson Building
Singapore 0315

International Thomson Publishing Japan
Hirakawacho Kyowa Building, 31
2-2-1 Hirakawacho
Chiyoda-ku, Tokyo 102
Japan

Marketing Manager: Nathan Wilbur
Production: Pamela Rockwell
Cover Printer: Henry N. Sawyer, Inc.
Text Printer and Binder: Quebecor/Martinsburg

ISBN: 0-534-93805-1



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PREFACE

From the beginning of the last decade we have witnessed a revolution in computer technology and an explosion in user-friendly applications. This revolution is still continuing today with low-cost personal computer systems that rival the performance of expensive workstations. This technological prowess should be brought to bear on the educational process and, in particular, on effective teaching that can result in enhanced learning. This companion book on digital signal processing (DSP) makes a small contribution toward that goal.

The teaching methods in signal processing have changed over the years from the simple "lecture-only" format to a more integrated "lecture-laboratory" environment in which practical hands-on issues are taught using DSP hardware. However, for effective teaching of DSP the lecture component must also make extensive use of computer-based explanations, examples, and exercises. For the last several years, the MATLAB software developed by *The MathWorks, Inc.* has established itself as the *de facto* standard for numerical computation in the signal-processing community and as a platform of choice for algorithm development. There are several reasons for this development, but one most important reason is that MATLAB is available on practically all computing platforms. For several years the expensive Professional Version of MATLAB was the only version available on the market. The advent of an inexpensive Student Edition has now made it possible to use it in classrooms. Recently, several textbooks in DSP have appeared which generally provide exercises that can be done using MATLAB. However, for students (and for practicing engineers interested in DSP) there are no "how-to" references for effective use of MATLAB in DSP. In this book we have made an attempt at integrating MATLAB with traditional topics in DSP so that it can be used to explore difficult topics and solve problems to gain insight. Many problems or design algorithms in DSP require considerable computation. It is for these that MATLAB provides a convenient tool so that many scenarios can be tried with ease. Such an approach can enhance the learning process.

This book is primarily intended for use as a supplement in junior- or senior-level undergraduate courses on DSP. We assume that the student (or user) is familiar with the fundamentals of MATLAB. Those topics are not covered since several tutorial books and manuals on MATLAB are available. Similarly, this book is not written as a textbook in DSP because of the availability of excellent textbooks. What we have tried to do is to provide enough depth to the material augmented by MATLAB functions and examples so that the presentation is consistent, logical, and enjoyable. Therefore this book can also be used as a self-study guide by anyone interested in DSP.

When this project got under way, version 3.5 of the Student Edition of MATLAB was available. Since the beginning of 1995 a more advanced GUI (graphical user interface) version 4.0 of the Student Edition is available. This book is compatible with the newer version.

ORGANIZATION OF THE BOOK

The first eight chapters of this book discuss traditional material covered in an introductory course on DSP. The last two chapters are presented as applications in DSP with emphasis on MATLAB-based projects. The following is a list of chapters and a brief description of their contents:

Chapter 1, Introduction: This chapter introduces readers to the discipline of signal processing and discusses the advantages of DSP over analog signal processing. A brief introduction to MATLAB is also provided.

Chapter 2, Discrete-time Signals and Systems: This chapter provides a brief review of discrete-time signals and systems in the time domain. Appropriate use of MATLAB functions is demonstrated.

Chapter 3, The Discrete-time Fourier Analysis: This chapter discusses discrete-time signal and system representation in the frequency domain. Sampling and reconstruction of analog signals are also presented.

Chapter 4, The z -Transform: This chapter provides signal and system description in the complex frequency domain. MATLAB techniques are introduced to analyze z -transforms and to compute inverse z -transforms. Solutions of difference equations using the z -transform and MATLAB are provided.

Chapter 5, The Discrete Fourier Transform: This chapter is devoted to the computation of the Fourier transform and to its efficient implementation. The discrete Fourier series is used to introduce the discrete Fourier transform, and several of its properties are demonstrated using

MATLAB. Topics such as fast convolution and fast Fourier transform are thoroughly discussed.

Chapter 6, Digital Filter Structures: This chapter discusses several structures for the implementation of digital filters. Several useful MATLAB functions are developed for the determination and implementation of these structures. Lattice and ladder filters are also introduced and discussed.

Chapter 7, FIR Filter Design: This chapter and the next introduce the important topic of digital filter design. Three important design techniques for FIR filters — namely, window design, frequency sampling design, and the equiripple filter design — are discussed. Several design examples are provided using MATLAB.

Chapter 8, IIR Filter Design: Included in this chapter are techniques in IIR filter design. It begins with analog filter design and introduces such topics as filter transformations and filter-band transformation. Once again several design examples using MATLAB are provided.

Chapter 9, Applications in Adaptive Filtering: This chapter is the first of two chapters on projects using MATLAB. Included is an introduction to the theory and implementation of adaptive FIR filters with projects in system identification, interference suppression, narrowband frequency enhancement, and adaptive equalization.

Chapter 10, Applications in Communications: This chapter focuses on several projects dealing with waveform representation and coding, and with digital communications. Included is a description of pulse-code modulation (PCM), differential PCM (DPCM) and adaptive DPCM (ADPCM), delta modulation (DM) and adaptive DM (ADM), linear predictive coding (LPC), generation and detection of dual-tone multifrequency (DTMF) signals, and a description of signal detection applications in binary communications and spread-spectrum communications.

SOFTWARE

The book is an outgrowth of our teaching of a MATLAB-based undergraduate DSP course over several years. Many MATLAB functions discussed in this book were developed in this course. These functions are available on the accompanying diskette as a `pwsk_dsp` toolbox. Create a separate directory for this toolbox and reference it in the `matlabpath` environment. The book also contains numerous MATLAB scripts in many examples. These scripts are also made available on the disk and are kept in individual directories created for each chapter. In addition, many figures were produced as MATLAB plots, and their scripts are available in the `figures` directory. Students should study these scripts to gain insight into the MATLAB procedures. We will appreciate any comments, corrections, or compact coding of these programs and scripts. Solutions to problems and

the associated script files will be made available to instructors in the near future.

Further information about MATLAB and related publications may be obtained from

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ACKNOWLEDGMENTS

We are indebted to our numerous students in our ECE-1456 course at Northeastern University who provided us a forum to test teaching ideas using MATLAB and who endured our constant emphasis on MATLAB. Some efficient MATLAB functions are due to these students. We are also indebted to our reviewers, whose constructive criticism resulted in a better presentation of the material: Abeer A. H. Alwan, University of California, Los Angeles; Steven Chin, Catholic University; and Joel Trussel, North Carolina State University.

We would like to thank Tom Robbins, former editor at PWS Publishing Company, for his initiative in creating the BookWare Companion Series and for his enthusiastic support of MATLAB in classroom teaching, especially in DSP. Thanks are also due to present editor Bill Barter for his support throughout the project. Finally, we would like to thank the staff at PWS Publishing Company for the final preparation of the manuscript.

Vinay K. Ingle
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Boston, Massachusetts

INTRODUCTION



Over the past several decades the field of digital signal processing (DSP) has grown to be important both theoretically and technologically. A major reason for its success in industry is due to the development and use of low-cost software and hardware. New technologies and applications in various fields are now poised to take advantage of DSP algorithms. This will lead to a greater demand for electrical engineers with background in DSP. Therefore it is necessary to make DSP an integral part of any electrical engineering curriculum.

Not long ago an introductory course on DSP was given mainly at the graduate level. It was supplemented by computer exercises on filter design, spectrum estimation, and related topics using mainframe (or mini) computers. However, considerable advances in personal computers and software over the past decade made it possible to introduce a DSP course to undergraduates. Since DSP applications are primarily algorithms that are implemented either on a DSP processor [11] or in software, a fair amount of programming is required. Using interactive software, such as MATLAB, it is now possible to place more emphasis on learning new and difficult concepts than on programming algorithms. Interesting practical examples can be discussed, and useful problems can be explored.

With this philosophy in mind, we have developed this book as a *companion book* (to traditional textbooks like [16, 19]) in which MATLAB is an integral part in the discussion of topics and concepts. We have chosen MATLAB as the programming tool primarily because of its wide availability on computing platforms in many universities across the country. Furthermore, a student edition of MATLAB has been available for several years, placing it among the least expensive software for educational purposes. We have treated MATLAB as a computational and programming toolbox containing several tools (sort of a super calculator with several keys) that can be used to explore and solve problems and, thereby, enhance the learning process.

This book is written at an introductory level in order to introduce undergraduate students to an exciting and practical field of DSP. We emphasize that this is not a textbook in the traditional sense but a

companion book in which more attention is given to problem solving and hands-on experience with MATLAB. Similarly, it is not a tutorial book in MATLAB. We assume that the student is familiar with MATLAB and is currently taking a course in DSP. The book provides basic analytical tools needed to process real-world signals (a.k.a. analog signals) using digital techniques. We deal mostly with discrete-time signals and systems, which are analyzed in both the time and the frequency domains. The analysis and design of processing structures called *filters* and *spectrum analyzers* is one of the most important aspects of DSP and is treated in great detail in this book. Many advanced topics in DSP (which are generally covered in a graduate course) are not treated in this book, but it is hoped that the experience gained in this book will allow students to tackle advanced topics with greater ease and understanding.

In this chapter we provide a brief overview of both DSP and MATLAB.

OVERVIEW OF DIGITAL SIGNAL PROCESSING

In this modern world we are surrounded by all kinds of signals in various forms. Some of the signals are natural, but most of the signals are manmade. Some signals are necessary (speech), some are pleasant (music), while many are unwanted or unnecessary in a given situation. In an engineering context, signals are carriers of information, both useful and unwanted. Therefore extracting or enhancing the useful information from a mix of conflicting information is a simplest form of signal processing. More generally, signal processing is an operation designed for extracting, enhancing, storing, and transmitting useful information. The distinction between useful and unwanted information is often subjective as well as objective. Hence signal processing tends to be application dependent.

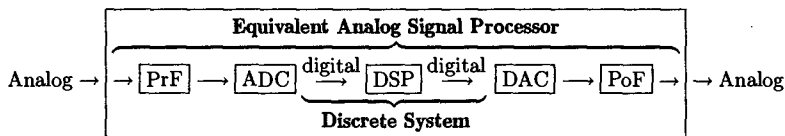
HOW ARE SIGNALS PROCESSED?

The signals that we encounter in practice are mostly analog signals. These signals, which vary continuously in time and amplitude, are processed using electrical networks containing active and passive circuit elements. This approach is known as analog signal processing (ASP)—for example, radio and television receivers.

Analog signal: $x_a(t)$ \longrightarrow Analog signal processor \longrightarrow $y_a(t)$:Analog signal

They can also be processed using digital hardware containing adders, multipliers, and logic elements or using special-purpose microprocessors. However, one needs to convert analog signals into a form suitable for digital hardware. This form of the signal is called a digital signal. It takes

one of the finite number of values at specific instances in time, and hence it can be represented by binary numbers, or bits. The processing of digital signals is called DSP; in block diagram form it is represented by



where the various block elements are discussed below.

PrF: This is a prefilter or an antialiasing filter, which conditions the analog signal to prevent aliasing.

ADC: This is called an analog-to-digital converter, which produces a stream of binary numbers from analog signals.

Digital signal processor: This is the heart of DSP and can represent a general-purpose computer or a special-purpose processor, or digital hardware, and so on.

DAC: This is the inverse operation to the ADC, called a digital-to-analog converter, which produces a staircase waveform from a sequence of binary numbers, a first step towards producing an analog signal.

PoF: This is a postfilter to smooth out staircase waveform into the desired analog signal.

It appears from the above two approaches to signal processing, analog and digital, that the DSP approach is the more complicated, containing more components than the “simpler looking” ASP. Therefore one might ask a question: Why process signals digitally? The answer lies in many advantages offered by DSP.

ADVANTAGES OF DSP OVER ASP

A major drawback of ASP is its limited scope for performing complicated signal processing applications. This translates into nonflexibility in processing and complexity in system designs. All of these generally lead to expensive products. On the other hand, using a DSP approach, it is possible to convert an inexpensive personal computer into a powerful signal processor. Some important advantages of DSP are these:

1. Systems using the DSP approach can be developed using software running on a general-purpose computer. Therefore DSP is relatively convenient to develop and test, and the software is portable.

2. DSP operations are based solely on additions and multiplications, leading to extremely stable processing capability—for example, stability independent of temperature.

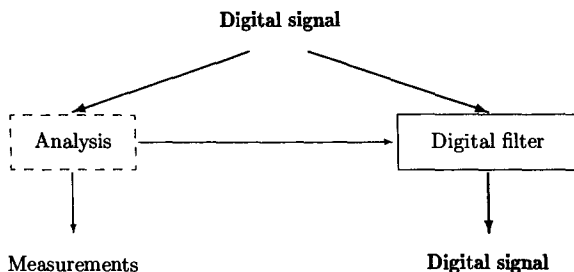
3. DSP operations can easily be modified in real time, often by simple programming changes, or by reloading of registers.

4. DSP has lower cost due to VLSI technology, which reduces costs of memories, gates, microprocessors, and so forth.

The principal disadvantage of DSP is the speed of operations, especially at very high frequencies. Primarily due to the above advantages, DSP is now becoming a first choice in many technologies and applications, such as consumer electronics, communications, wireless telephones, and medical imaging.

TWO IMPORTANT CATEGORIES OF DSP

Most DSP operations can be categorized as being either signal *analysis* tasks or signal *filtering* tasks as shown below.



Signal analysis This task deals with the measurement of signal properties. It is generally a frequency-domain operation. Some of its applications are

- spectrum (frequency and/or phase) analysis
- speech recognition
- speaker verification
- target detection

Signal filtering This task is characterized by the “signal in–signal out” situation. The systems that perform this task are generally called *filters*. It is usually (but not always) a time-domain operation. Some of the applications are

- removal of unwanted background noise
- removal of interference
- separation of frequency bands
- shaping of the signal spectrum

In some applications, such as voice synthesis, a signal is first analyzed to study its characteristics, which are then used in digital filtering to generate a synthetic voice.

In the first half of this book we will deal with the signal-analysis aspect of DSP. In Chapter 2 we will begin with basic descriptions of discrete-time signals and systems. These signals and systems are analyzed in the frequency domain in Chapter 3. A generalization of the frequency-domain description, called the z -transform, is introduced in Chapter 4. The practical algorithms for computing the Fourier transform are discussed in Chapter 5 in the form of the discrete Fourier transform and the fast Fourier transform.

The second half of this book is devoted to the signal-filtering aspect of DSP. In Chapter 6 we describe various implementations and structures of digital filters. In Chapter 7 we provide design techniques and algorithms for designing one type of digital filter called finite-duration impulse response (or FIR) filters, while in Chapter 8 we provide a similar treatment for another type of filter called infinite-duration impulse response (or IIR) filters. In both chapters we discuss only the simpler but practically useful techniques of filter design. More advanced techniques are not covered. Finally, the last two chapters provide some practical applications in the form of projects that can be done using material learned in the first eight chapters. In Chapter 9 concepts in adaptive filtering are introduced, and simple projects in system identification, interference suppression, adaptive line enhancement, and so forth are discussed. In Chapter 10 a brief introduction to digital communications is presented with projects in such topics as PCM, DPCM, and LPC being outlined.

In all these chapters the central theme is the generous use and adequate demonstration of MATLAB tools. Most of the existing MATLAB functions for DSP are described in detail, and their correct use is demonstrated in many examples. Furthermore, many new MATLAB functions are developed to provide insights into the working of many algorithms. We believe that this “hand-holding” approach will enable students to dispel fears about DSP and will provide an enriching learning experience.

A FEW WORDS ABOUT MATLAB®

MATLAB is an interactive, matrix-based system for scientific and engineering numeric computation and visualization. Its strength lies in the fact that complex numerical problems can be solved easily and in a fraction of the time required with a programming language such as Fortran or C. It is also powerful in the sense that by using its relatively simple programming capability, MATLAB can be easily extended to create new commands and functions.