国外电子与通信教材系列

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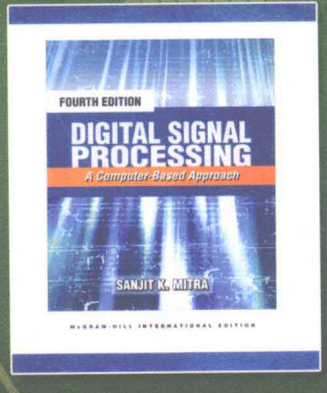
数字信号处理

——基于计算机的方法（第四版）

Digital Signal Processing

A Computer-Based Approach, Fourth Edition



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北京 · BEIJING

内容简介

本书是在数字信号领域的经典教材Digital Signal Processing: A Computer-Based Approach, Fourth Edition的基础上改编而成的，内容涵盖了信号与信号处理、时域中的离散时间信号、频域中的离散时间信号、离散时间系统、有限长离散变换、z变换、变换域中的LTI离散时间系统、数字滤波器结构、IIR数字滤波器设计、FIR数字滤波器设计、DSP算法实现等方面。本书的特点是，在讲解上述内容的同时，给出了大量简单而实用的例子，并用MATLAB程序进行了验证，同时提供了大量的高质量习题和仿真练习。

本书可作为高等院校电子信息类专业本科生或低年级研究生的教材，尤其适用于双语教学，也可供有关技术、科研管理人员使用，或作为继续教育的参考书。

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序

2001年7月间，电子工业出版社的领导同志邀请各高校十几位通信领域方面的老师，商量引进国外教材问题。与会同志对出版社提出的计划十分赞同，大家认为，这对我国通信事业、特别是对高等院校通信学科的教学工作会很有好处。

教材建设是高校教学建设的主要内容之一。编写、出版一本好的教材，意味着开设了一门好的课程，甚至可能预示着一个崭新学科的诞生。20世纪40年代MIT林肯实验室出版的一套28本雷达丛书，对近代电子学科、特别是对雷达技术的推动作用，就是一个很好的例子。

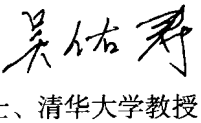
我国领导部门对教材建设一直非常重视。20世纪80年代，在原教委教材编审委员会的领导下，汇集了高等院校几百位富有教学经验的专家，编写、出版了一大批教材；很多院校还根据学校的特点和需要，陆续编写了大量的讲义和参考书。这些教材对高校的教学工作发挥了极好的作用。近年来，随着教学改革不断深入和科学技术的飞速进步，有的教材内容已比较陈旧、落后，难以适应教学的要求，特别是在电子学和通信技术发展神速、可以讲是日新月异的今天，如何适应这种情况，更是一个必须认真考虑的问题。解决这个问题，除了依靠高校的老师和专家撰写新的符合要求的教科书外，引进和出版一些国外优秀电子与通信教材，尤其是有选择地引进一批英文原版教材，是会有好处的。

一年多来，电子工业出版社为此做了很多工作。他们成立了一个“国外电子与通信教材系列”项目组，选派了富有经验的业务骨干负责有关工作，收集了230余种通信教材和参考书的详细资料，调来了100余种原版教材样书，依靠由20余位专家组成的出版委员会，从中精选了40多种，内容丰富，覆盖了电路理论与应用、信号与系统、数字信号处理、微电子、通信系统、电磁场与微波等方面，既可作为通信专业本科生和研究生的教学用书，也可作为有关专业人员的参考材料。此外，这批教材，有的翻译为中文，还有部分教材直接影印出版，以供教师用英语直接授课。希望这些教材的引进和出版对高校通信教学和教材改革能起一定作用。

在这里，我还要感谢参加工作的各位教授、专家、老师与参加翻译、编辑和出版的同志们。各位专家认真负责、严谨细致、不辞辛劳、不怕琐碎和精益求精的态度，充分体现了中国教育工作者和出版工作者的良好美德。

随着我国经济建设的发展和科学技术的不断进步，对高校教学工作会不断提出新的要求和希望。我想，无论如何，要做好引进国外教材的工作，一定要联系我国的实际。教材和学术专著不同，既要注意科学性、学术性，也要重视可读性，要深入浅出，便于读者自学；引进的教材要适应高校教学改革的需要，针对目前一些教材内容较为陈旧的问题，有目的地引进一些先进的和正在发展中的交叉学科的参考书；要与国内出版的教材相配套，安排好出版英文原版教材和翻译教材的比例。我们努力使这套教材能尽量满足上述要求，希望它们能放在学生们的课桌上，发挥一定的作用。

最后，预祝“国外电子与通信教材系列”项目取得成功，为我国电子与通信教学和通信产业的发展培土施肥。也恳切希望读者能对这些书籍的不足之处、特别是翻译中存在的问题，提出意见和建议，以便再版时更正。



中国工程院院士、清华大学教授

“国外电子与通信教材系列”出版委员会主任

出 版 说 明

进入21世纪以来，我国信息产业在生产和科研方面都大大加快了发展速度，并已成为国民经济发展的支柱产业之一。但是，与世界上其他信息产业发达的国家相比，我国在技术开发、教育培训等方面都还存在着较大的差距。特别是在加入WTO后的今天，我国信息产业面临着国外竞争对手的严峻挑战。

作为我国信息产业的专业科技出版社，我们始终关注着全球电子信息技术的发展方向，始终把引进国外优秀电子与通信信息技术教材和专业书籍放在我们工作的重要位置上。在2000年至2001年间，我社先后从世界著名出版公司引进出版了40余种教材，形成了一套“国外计算机科学教材系列”，在全国高校以及科研部门中受到了欢迎和好评，得到了计算机领域的广大教师与科研工作者的充分肯定。

引进和出版一些国外优秀电子与通信教材，尤其是有选择地引进一批英文原版教材，将有助于我国信息产业培养具有国际竞争能力的技术人才，也将有助于我国国内在电子与通信教学工作中掌握和跟踪国际发展水平。根据国内信息产业的现状、教育部《关于“十五”期间普通高等教育教材建设与改革的意见》的指示精神以及高等院校老师们反映的各种意见，我们决定引进“国外电子与通信教材系列”，并随后开展了大量准备工作。此次引进的国外电子与通信教材均来自国际著名出版商，其中影印教材约占一半。教材内容涉及的学科方向包括电路理论与应用、信号与系统、数字信号处理、微电子、通信系统、电磁场与微波等，其中既有本科专业课程教材，也有研究生课程教材，以适应不同院系、不同专业、不同层次的师生对教材的需求，广大师生可自由选择和自由组合使用。我们还将与国外出版商一起，陆续推出一些教材的教学支持资料，为授课教师提供帮助。

此外，“国外电子与通信教材系列”的引进和出版工作得到了教育部高等教育司的大力支持和帮助，其中的部分引进教材已通过“教育部高等学校电子信息科学与工程类专业教学指导委员会”的审核，并得到教育部高等教育司的批准，纳入了“教育部高等教育司推荐——国外优秀信息科学与技术系列教学用书”。

为做好该系列教材的翻译工作，我们聘请了清华大学、北京大学、北京邮电大学、南京邮电大学、东南大学、西安交通大学、天津大学、西安电子科技大学、电子科技大学、中山大学、哈尔滨工业大学、西南交通大学等著名高校的教授和骨干教师参与教材的翻译和审校工作。许多教授在国内电子与通信专业领域享有较高的声望，具有丰富的教学经验，他们的渊博学识从根本上保证了教材的翻译质量和专业学术方面的严格与准确。我们在此对他们的辛勤工作与贡献表示衷心的感谢。此外，对于编辑的选择，我们达到了专业对口；对于从英文原书中发现的错误，我们通过与作者联络、从网上下载勘误表等方式，逐一进行了修订；同时，我们对审校、排版、印制质量进行了严格把关。

今后，我们将进一步加强同各高校教师的密切关系，努力引进更多的国外优秀教材和教学参考书，为我国电子与通信教材达到世界先进水平而努力。由于我们对国内外电子与通信教育的发展仍存在一些认识上的不足，在选题、翻译、出版等方面的工作中还有许多需要改进的地方，恳请广大师生和读者提出批评及建议。

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改编者序

自教育部于2001年出台《关于加强高等学校本科教学工作提高教学质量的若干意见》以来，双语教学工作在许多高校开展起来，尽管对于双语教学的意义、效果的讨论一直没有中断过，但发展现状表明双语教学仍在较为迅速地发展。

不同院校开展双语教学的层次不同，最基本的要求是采用原版教材，主要是学习国外先进的教学思想，科学技术和语言文化；由于文化传统、教学体系的差异，原版教材与我国教学体系和教学习惯的矛盾是存在的。

“数字信号处理”是开展双语教学较早、较为普及的课程，很多学校都选择了Sanjit K. Mitra编写的本书第二版的影印版作为课本。Mitra博士是国际著名的信号处理专家、IEEE电路与系统学会的主席和多家国际著名学术刊物的编委，他的教材不仅详细介绍了数字信号处理的经典内容，也介绍了许多数字信号处理的最新发展及应用实例，是理论与实践结合的典范。书中有大量的例题、高质量的练习题和上机仿真作业，并用MATLAB来演示结果。该教材在美国加州大学、哥伦比亚大学、明尼苏达大学等著名大学使用，销量大。

原版教材的内容叙述非常详尽，实践性强，使得原版书通常很厚，容量是国内自编教材的几倍。国内的高校数字信号处理课程基本上是一个学期完成的，因此在实际的教学过程中，教材的1/3内容基本不涉及。由于国内双语教学的开展还没有系统化，学生的英文水平也有较大差异，造成了学生的学习负担加重。因此，对原版教材进行改编，以适应国内课程内容及教学改革的要求，都是一件有意义的工作。

该书第三版出版后，电子工业出版社委托我对本书进行了改编，取得了较好的效果。第四版与第三版相比，作者根据教师与学生的反馈意见，进行了较大的改动与修订；为此，电子工业出版社继续委托我对此书进行了改编。

在改编教材的过程中，主要考虑是在保证教学内容的前提下，压缩教材的篇幅，减轻学生的学习负担；同时兼顾到不同院校的具体教学大纲，尽可能使选择的内容覆盖中文数字信号处理课程的内容。与原版教材相比，改动如下：删除了1.4.1节、4.8.5节和4.8.6节、5.11节至5.14节、7.4.5节、7.5节、7.7节至7.9节、8.7节、8.9.2节、8.10节至8.12节、9.7节、10.6节、11.8节和11.9节、第12章至第14章及附录C。教材的编排仍沿用原版教材的体系，仅对删除相关内容后的全书进行了标题序号调整、相互引用调整等。

原书附带有光盘一张，为降低图书成本，改编后的本书，其光盘内容放在华信教育资源网上，请读者自www.hxedu.com.cn下载。

阚永红

2011-8-1

About the Author

Sanjit K. Mitra is the Stephen and Etta Varra Professor in the Ming Hsieh Department of Electrical Engineering, University of Southern California, Los Angeles and a Research Professor in the Department of Electrical & Computer Engineering, University of California, Santa Barbara, He received the M.S. and Ph.D. degrees in Electrical Engineering from the University of California, Berkeley, in 1960 and 1962, respectively. He has served IEEE in various capacities, including service as the President of the IEEE Circuits & Systems Society in 1986 and as a Member-at-Large of the Board of Governors of the IEEE Signal Processing Society from 1996 to 1999. He has published over 660 papers in the areas of analog and digital signal processing, and image processing, twelve books, and holds five patents. Dr. Mitra has received many distinguished industry and academic awards, including the 1973 F. E. Terman Award and the 1985 AT&T Foundation Award of the American Society of Engineering Education; the 1989 Education Award, the 1999 Mac Van Valkenburg Society Award and the CAS Golden Jubilee Medal of the IEEE Circuits & Systems Society; the 1989 Distinguished Senior U.S. Scientist Award from the Alexander von Humboldt Foundation of Germany; the 1995 Technical Achievement Award, the 2001 Society Award, and the 2006 Education Award of the IEEE Signal Processing Society; the Millennium Medal in 2000 and the 2006 James H. Mulligan, Jr. Education Medal of the IEEE; the 2002 Technical Achievement Award and the 2009 Athanasios Papoulis Award of the European Association for Signal Processing (EURASIP); the 2005 SPIE Technical Achievement Award of the International Society for Optical Engineering; and the University Medal of the Slovak Technical University, Bratislava, Slovakia in 2005. He is the co-recipient of the 2000 Blumlein-Browne-Willans Premium of the the Institution of Electrical Engineers (London) and the 2001 IEEE Transactions on Circuits & Systems for Video Technology Best Paper Award. He is a member of the U.S. National Academy of Engineering, an Academician of the Academy of Finland, a member of the Norwegian Academy of Technological Sciences, a foreign member of the Croatian Academy of Sciences and Arts, and a foreign member of the Academy of Engineering of Mexico, a Foreign Fellow of the Indian National Academy of Engineering and the National Academy of Sciences, India. He has been awarded Honorary Doctorate degrees from the Tampere University of Technology, Finland, the "Politehnica" University of Bucharest, Romania, and the Technical University of Iasi, Romania. Dr. Mitra is a Fellow of the IEEE, AAAS, and SPIE, and a member of EURASIP.

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), 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. 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 11.

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 11.

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 11 chapters and two 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.

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.

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 11 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.

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 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.

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