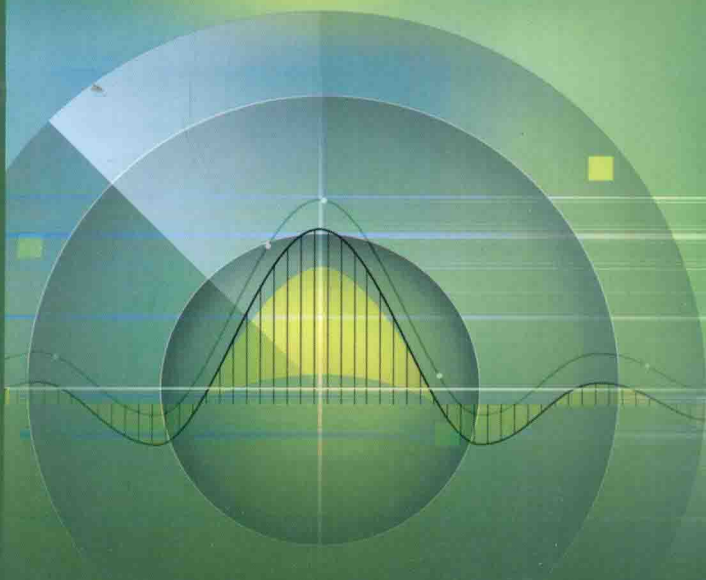


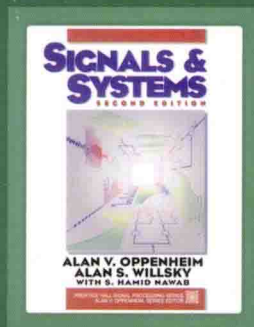
国外电子与通信教材系列

PEARSON



奥本海姆

*Signals and Systems*  
*Second Edition*



# 信号与系统

(第二版)(英文版)

Alan V. Oppenheim  
[美] Alan S. Willsky 著  
S. Hamid Nawab



中国工信出版集团



电子工业出版社  
PUBLISHING HOUSE OF ELECTRONICS INDUSTRY  
<http://www.phei.com.cn>

国外电子与通信教材系列

# 信号与系统

(第二版)

(英文版)

Signals and Systems

Second Edition

Alan V. Oppenheim

[美] Alan S. Willsky 著

S. Hamid Nawab

电子工业出版社

Publishing House of Electronics Industry

北京·BEIJING

## 内 容 简 介

本书是美国麻省理工学院(MIT)的经典教材之一,讨论了信号与系统分析的基本理论、基本分析方法及其应用。本书共分11章,主要讲述了线性系统的基本理论、信号与系统的基本概念、线性时不变系统、连续与离散信号的傅里叶表示、傅里叶变换以及时域和频域系统的分析方法等内容。本书作者使用了大量在滤波、抽样、通信和反馈系统中的实例,并行讨论了连续系统、离散系统、时域系统和频域系统的分析方法,使读者能透彻地理解各种信号系统的分析方法并比较其异同。

本书可作为通信与电子系统类、自动化类以及全部电类专业信号与系统课程的双语教材,也可以供所有从事信息获取、转换、传输及处理工作的其他专业研究生、教师和广大科技工作者参考。

Original edition, entitled Signal and Systems, Second Edition 9780138147570 by Alan V. Oppenheim, Alan S. Willsky, S. Hamid Nawab, published by Pearson Education, Inc., published as Pearson Hall, Copyright © 1997 Alan V. Oppenheim, Alan S. Willsky.

All rights reserved. No part of this book may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording or by any information storage retrieval system, without permission from Pearson Education, Inc.

China edition published by Pearson Education Asia Ltd., and Publishing House of Electronics Industry, Copyright © 2015.

This edition is manufactured in the People's Republic of China, and is authorized for sale only in the mainland of China exclusively (except Taiwan, Hong Kong SAR and Macau SAR).

本书英文影印版专有出版权由 Pearson Education 培生教育出版亚洲有限公司授予电子工业出版社。未经出版者预先书面许可,不得以任何方式复制或抄袭本书的任何部分。

此版本仅限在中国大陆发行。

本书贴有 Pearson Education 培生教育出版集团激光防伪标签,无标签者不得销售。

版权贸易合同登记号 图字:01-2002-2679

### 图书在版编目(CIP)数据

信号与系统:第2版=Signals and Systems, Second Edition:英文/(美)奥本海姆(Oppenheim, A. V.), (美)威尔斯基(Willsky, A. S.), (美)纳瓦卜(Nawab, S. H.)著. —北京:电子工业出版社,2015.4

(国外电子与通信教材系列)

ISBN 978-7-121-25727-8

I. ①信… II. ①奥… ②威… ③纳… III. ①信号系统—高等学校—教材—英文 IV. ①TN911.6

中国版本图书馆 CIP 数据核字(2015)第 054140 号

策划编辑:马 岚

责任编辑:李秦华

印 刷:三河市双峰印刷装订有限公司

装 订:三河市双峰印刷装订有限公司

出版发行:电子工业出版社

北京市海淀区万寿路173信箱 邮编 100036

开 本:787×980 1/16 印张:61.75 字数:2055千字

版 次:2015年4月第1版(原著第2版)

印 次:2015年4月第1次印刷

定 价:89.00元

凡所购买电子工业出版社图书有缺损问题,请向购买书店调换。若书店售缺,请与本社发行部联系,联系及邮购电话:(010)88254888。

质量投诉请发邮件至 zlts@phei.com.cn, 盗版侵权举报请发邮件至 dbqq@phei.com.cn。

服务热线:(010)88258888。

# 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 and 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 and 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。

电子工业出版社

# 教材出版委员会

主任	吴佑寿	中国工程院院士、清华大学教授
副主任	林金桐	北京邮电大学校长、教授、博士生导师
	杨千里	总参通信部副部长, 中国电子学会会士、副理事长 中国通信学会常务理事、博士生导师
委员	林孝康	清华大学教授、博士生导师、电子工程系副主任、通信与微波研究所所长 教育部电子信息科学与工程类专业教学指导分委员会委员
	徐安士	北京大学教授、博士生导师、电子学系主任
	樊昌信	西安电子科技大学教授、博士生导师 中国通信学会理事、IEEE 会士
	程时昕	东南大学教授、博士生导师
	郁道银	天津大学副校长、教授、博士生导师 教育部电子信息科学与工程类专业教学指导分委员会委员
	阮秋琦	北京交通大学教授、博士生导师 计算机与信息技术学院院长、信息科学研究所所长 国务院学位委员会学科评议组成员
	张晓林	北京航空航天大学教授、博士生导师、电子信息工程学院院长 教育部电子信息科学与电气信息类基础课程教学指导分委员会副主任委员 中国电子学会常务理事
	郑宝玉	南京邮电大学副校长、教授、博士生导师 教育部电子信息与电气学科教学指导委员会委员
	朱世华	西安交通大学副校长、教授、博士生导师 教育部电子信息科学与工程类专业教学指导分委员会副主任委员
	彭启琮	电子科技大学教授、博士生导师、通信与信息工程学院院长 教育部电子信息科学与电气信息类基础课程教学指导分委员会委员
	毛军发	上海交通大学教授、博士生导师、电子信息与电气工程学院副院长 教育部电子信息与电气学科教学指导委员会委员
	赵尔沅	北京邮电大学教授、《中国邮电高校学报(英文版)》编委会主任
	钟允若	原邮电科学研究院副院长、总工程师
	刘彩	中国通信学会副理事长兼秘书长, 教授级高工 信息产业部通信科技委副主任
	杜振民	电子工业出版社原副社长
	王志功	东南大学教授、博士生导师、射频与光电集成电路研究所所长 教育部高等学校电子电气基础课程教学指导分委员会主任委员
	张中兆	哈尔滨工业大学教授、博士生导师、电子与信息技术研究院院长
	范平志	西南交通大学教授、博士生导师、信息科学与技术学院院长



# PREFACE

This book is the second edition of a text designed for undergraduate courses in signals and systems. While such courses are frequently found in electrical engineering curricula, the concepts and techniques that form the core of the subject are of fundamental importance in all engineering disciplines. In fact, the scope of potential and actual applications of the methods of signal and system analysis continues to expand as engineers are confronted with new challenges involving the synthesis or analysis of complex processes. For these reasons we feel that a course in signals and systems not only is an essential element in an engineering program but also can be one of the most rewarding, exciting, and useful courses that engineering students take during their undergraduate education.

Our treatment of the subject of signals and systems in this second edition maintains the same general philosophy as in the first edition but with significant rewriting, restructuring, and additions. These changes are designed to help both the instructor in presenting the subject material and the student in mastering it. In the preface to the first edition we stated that our overall approach to signals and systems had been guided by the continuing developments in technologies for signal and system design and implementation, which made it increasingly important for a student to have equal familiarity with techniques suitable for analyzing and synthesizing both continuous-time and discrete-time systems. As we write the preface to this second edition, that observation and guiding principle are even more true than before. Thus, while students studying signals and systems should certainly have a solid foundation in disciplines based on the laws of physics, they must also have a firm grounding in the use of computers for the analysis of phenomena and the implementation of systems and algorithms. As a consequence, engineering curricula now reflect a blend of subjects, some involving continuous-time models and others focusing on the use of computers and discrete representations. For these reasons, signals and systems courses that bring discrete-time and continuous-time concepts together in a unified way play an increasingly important role in the education of engineering students and in their preparation for current and future developments in their chosen fields.

It is with these goals in mind that we have structured this book to develop in parallel the methods of analysis for continuous-time and discrete-time signals and systems. This approach also offers a distinct and extremely important pedagogical advantage. Specifically, we are able to draw on the similarities between continuous- and discrete-time methods in order to share insights and intuition developed in each domain. Similarly, we can exploit the differences between them to sharpen an understanding of the distinct properties of each.

In organizing the material both originally and now in the second edition, we have also considered it essential to introduce the student to some of the important uses of the basic methods that are developed in the book. Not only does this provide the student with an appreciation for the range of applications of the techniques being learned and for directions for further study, but it also helps to deepen understanding of the subject. To achieve this goal we include introductory treatments on the subjects of filtering, commu-

nications, sampling, discrete-time processing of continuous-time signals, and feedback. In fact, in one of the major changes in this second edition, we have introduced the concept of frequency-domain filtering very early in our treatment of Fourier analysis in order to provide both motivation for and insight into this very important topic. In addition, we have again included an up-to-date bibliography at the end of the book in order to assist the student who is interested in pursuing additional and more advanced studies of the methods and applications of signal and system analysis.

The organization of the book reflects our conviction that full mastery of a subject of this nature cannot be accomplished without a significant amount of practice in using and applying the tools that are developed. Consequently, in the second edition we have significantly increased the number of worked examples within each chapter. We have also enhanced one of the key assets of the first edition, namely the end-of-chapter homework problems. As in the first edition, we have included a substantial number of problems, totaling more than 600 in number. A majority of the problems included here are new and thus provide additional flexibility for the instructor in preparing homework assignments. In addition, in order to enhance the utility of the problems for both the student and the instructor we have made a number of other changes to the organization and presentation of the problems. In particular, we have organized the problems in each chapter under several specific headings, each of which spans the material in the entire chapter but with a different objective. The first two sections of problems in each chapter emphasize the mechanics of using the basic concepts and methods presented in the chapter. For the first of these two sections, which has the heading Basic Problems with Answers, we have also provided answers (but not solutions) at the end of the book. These answers provide a simple and immediate way for the student to check his or her understanding of the material. The problems in this first section are generally appropriate for inclusion in homework sets. Also, in order to give the instructor additional flexibility in assigning homework problems, we have provided a second section of Basic Problems for which answers have not been included.

A third section of problems in each chapter, organized under the heading of Advanced Problems, is oriented toward exploring and elaborating upon the foundations and practical implications of the material in the text. These problems often involve mathematical derivations and more sophisticated use of the concepts and methods presented in the chapter. Some chapters also include a section of Extension Problems which involve extensions of material presented in the chapter and/or involve the use of knowledge from applications that are outside the scope of the main text (such as advanced circuits or mechanical systems). The overall variety and quantity of problems in each chapter will hopefully provide students with the means to develop their understanding of the material and instructors with considerable flexibility in putting together homework sets that are tailored to the specific needs of their students. A solutions manual is also available to instructors through the publisher.

Another significant additional enhancement to this second edition is the availability of the companion book *Explorations in Signals and Systems Using MATLAB* by Buck, Daniel, and Singer. This book contains MATLAB<sup>®</sup>-based computer exercises for each topic in the text, and should be of great assistance to both instructor and student.

Students using this book are assumed to have a basic background in calculus as well as some experience in manipulating complex numbers and some exposure to differential



equations. With this background, the book is self-contained. In particular, no prior experience with system analysis, convolution, Fourier analysis, or Laplace and  $z$ -transforms is assumed. Prior to learning the subject of signals and systems most students will have had a course such as basic circuit theory for electrical engineers or fundamentals of dynamics for mechanical engineers. Such subjects touch on some of the basic ideas that are developed more fully in this text. This background can clearly be of great value to students in providing additional perspective as they proceed through the book.

The Foreword, which follows this preface, is written to offer the reader motivation and perspective for the subject of signals and systems in general and our treatment of it in particular. We begin Chapter 1 by introducing some of the elementary ideas related to the mathematical representation of signals and systems. In particular we discuss transformations (such as time shifts and scaling) of the independent variable of a signal. We also introduce some of the most important and basic continuous-time and discrete-time signals, namely real and complex exponentials and the continuous-time and discrete-time unit step and unit impulse. Chapter 1 also introduces block diagram representations of interconnections of systems and discusses several basic system properties such as causality, linearity and time-invariance. In Chapter 2 we build on these last two properties, together with the sifting property of unit impulses to develop the convolution-sum representation for discrete-time linear, time-invariant (LTI) systems and the convolution integral representation for continuous-time LTI systems. In this treatment we use the intuition gained from our development of the discrete-time case as an aid in deriving and understanding its continuous-time counterpart. We then turn to a discussion of causal, LTI systems characterized by linear constant-coefficient differential and difference equations. In this introductory discussion we review the basic ideas involved in solving linear differential equations (to which most students will have had some previous exposure) and we also provide a discussion of analogous methods for linear difference equations. However, the primary focus of our development in Chapter 2 is not on methods of solution, since more convenient approaches are developed later using transform methods. Instead, in this first look, our intent is to provide the student with some appreciation for these extremely important classes of systems, which will be encountered often in subsequent chapters. Finally, Chapter 2 concludes with a brief discussion of singularity functions—steps, impulses, doublets, and so forth—in the context of their role in the description and analysis of continuous-time LTI systems. In particular, we stress the interpretation of these signals in terms of how they are defined under convolution—that is, in terms of the responses of LTI systems to these idealized signals.

Chapters 3 through 6 present a thorough and self-contained development of the methods of Fourier analysis in both continuous and discrete time and together represent the most significant reorganization and revision in the second edition. In particular, as we indicated previously, we have introduced the concept of frequency-domain filtering at a much earlier point in the development in order to provide motivation for and a concrete application of the Fourier methods being developed. As in the first edition, we begin the discussions in Chapter 3 by emphasizing and illustrating the two fundamental reasons for the important role Fourier analysis plays in the study of signals and systems in both continuous and discrete time: (1) extremely broad classes of signals can be represented as weighted sums or integrals of complex exponentials; and (2) the response of an LTI system to a complex exponential input is the same exponential multiplied by a complex-

number characteristic of the system. However, in contrast to the first edition, the focus of attention in Chapter 3 is on Fourier series representations for periodic signals in both continuous time and discrete time. In this way we not only introduce and examine many of the properties of Fourier representations without the additional mathematical generalization required to obtain the Fourier transform for aperiodic signals, but we also can introduce the application to filtering at a very early stage in the development. In particular, taking advantage of the fact that complex exponentials are eigenfunctions of LTI systems, we introduce the frequency response of an LTI system and use it to discuss the concept of frequency-selective filtering, to introduce ideal filters, and to give several examples of nonideal filters described by differential and difference equations. In this way, with a minimum of mathematical preliminaries, we provide the student with a deeper appreciation for what a Fourier representation means and why it is such a useful construct.

Chapters 4 and 5 then build on the foundation provided by Chapter 3 as we develop first the continuous-time Fourier transform in Chapter 4 and, in a parallel fashion, the discrete-time Fourier transform in Chapter 5. In both chapters we derive the Fourier transform representation of an aperiodic signal as the limit of the Fourier series for a signal whose period becomes arbitrarily large. This perspective emphasizes the close relationship between Fourier series and transforms, which we develop further in subsequent sections and which allows us to transfer the intuition developed for Fourier series in Chapter 3 to the more general context of Fourier transforms. In both chapters we have included a discussion of the many important properties of Fourier transforms, with special emphasis placed on the convolution and multiplication properties. In particular, the convolution property allows us to take a second look at the topic of frequency-selective filtering, while the multiplication property serves as the starting point for our treatment of sampling and modulation in later chapters. Finally, in the last sections in Chapters 4 and 5 we use transform methods to determine the frequency responses of LTI systems described by differential and difference equations and to provide several examples illustrating how Fourier transforms can be used to compute the responses for such systems. To supplement these discussions (and later treatments of Laplace and  $z$ -transforms) we have again included an Appendix at the end of the book that contains a description of the method of partial fraction expansion.

Our treatment of Fourier analysis in these two chapters is characteristic of the parallel treatment we have developed. Specifically, in our discussion in Chapter 5, we are able to build on much of the insight developed in Chapter 4 for the continuous-time case, and toward the end of Chapter 5 we emphasize the complete duality in continuous-time and discrete-time Fourier representations. In addition, we bring the special nature of each domain into sharper focus by contrasting the differences between continuous- and discrete-time Fourier analysis.

As those familiar with the first edition will note, the lengths and scopes of Chapters 4 and 5 in the second edition are considerably smaller than their first edition counterparts. This is due not only to the fact that Fourier series are now dealt with in a separate chapter but also to our moving several topics into Chapter 6. The result, we believe, has several significant benefits. First, the presentation in three shorter chapters of the basic concepts and results of Fourier analysis, together with the introduction of the concept of frequency-selective filtering, should help the student in organizing his or her understanding of this material and in developing some intuition about the frequency domain and appreciation for its potential applications. Then, with Chapters 3-5 as a foundation, we can engage in

a more detailed look at a number of important topics and applications. In Chapter 6 we take a deeper look at both the time- and frequency-domain characteristics of LTI systems. For example, we introduce magnitude-phase and Bode plot representations for frequency responses and discuss the effect of frequency response phase on the time domain characteristics of the output of an LTI system. In addition, we examine the time- and frequency-domain behavior of ideal and nonideal filters and the tradeoffs between these that must be addressed in practice. We also take a careful look at first- and second-order systems and their roles as basic building blocks for more complex system synthesis and analysis in both continuous and discrete time. Finally, we discuss several other more complex examples of filters in both continuous and discrete time. These examples together with the numerous other aspects of filtering explored in the problems at the end of the chapter provide the student with some appreciation for the richness and flavor of this important subject. While each of the topics in Chapter 6 was present in the first edition, we believe that by reorganizing and collecting them in a separate chapter following the basic development of Fourier analysis, we have both simplified the introduction of this important topic in Chapters 3-5 and presented in Chapter 6 a considerably more cohesive picture of time- and frequency-domain issues.

In response to suggestions and preferences expressed by many users of the first edition we have modified notation in the discussion of Fourier transforms to be more consistent with notation most typically used for continuous-time and discrete-time Fourier transforms. Specifically, beginning with Chapter 3 we now denote the continuous-time Fourier transform as  $X(j\omega)$  and the discrete-time Fourier transform as  $X(e^{j\omega})$ . As with all options with notation, there is not a unique best choice for the notation for Fourier transforms. However, it is our feeling, and that of many of our colleagues, that the notation used in this edition represents the preferable choice.

Our treatment of sampling in Chapter 7 is concerned primarily with the sampling theorem and its implications. However, to place this subject in perspective we begin by discussing the general concepts of representing a continuous-time signal in terms of its samples and the reconstruction of signals using interpolation. After using frequency-domain methods to derive the sampling theorem, we consider both the frequency and time domains to provide intuition concerning the phenomenon of aliasing resulting from under-sampling. One of the very important uses of sampling is in the discrete-time processing of continuous-time signals, a topic that we explore at some length in this chapter. Following this, we turn to the sampling of discrete-time signals. The basic result underlying discrete-time sampling is developed in a manner that parallels that used in continuous time, and the applications of this result to problems of decimation and interpolation are described. Again a variety of other applications, in both continuous and discrete time, are addressed in the problems.

Once again the reader acquainted with our first edition will note a change, in this case involving the reversal in the order of the presentation of sampling and communications. We have chosen to place sampling before communications in the second edition both because we can call on simple intuition to motivate and describe the processes of sampling and reconstruction from samples and also because this order of presentation then allows us in Chapter 8 to talk more easily about forms of communication systems that are closely related to sampling or rely fundamentally on using a sampled version of the signal to be transmitted.

Our treatment of communications in Chapter 8 includes an in-depth discussion of continuous-time sinusoidal amplitude modulation (AM), which begins with the straightforward application of the multiplication property to describe the effect of sinusoidal AM in the frequency domain and to suggest how the original modulating signal can be recovered. Following this, we develop a number of additional issues and applications related to sinusoidal modulation, including frequency-division multiplexing and single-sideband modulation. Many other examples and applications are described in the problems. Several additional topics are covered in Chapter 8. The first of these is amplitude modulation of a pulse train and time-division multiplexing, which has a close connection to the topic of sampling in Chapter 7. Indeed we make this tie even more explicit and provide a look into the important field of digital communications by introducing and briefly describing the topics of pulse-amplitude modulation (PAM) and intersymbol interference. Finally, our discussion of frequency modulation (FM) provides the reader with a look at a nonlinear modulation problem. Although the analysis of FM systems is not as straightforward as for the AM case, our introductory treatment indicates how frequency-domain methods can be used to gain a significant amount of insight into the characteristics of FM signals and systems. Through these discussions and the many other aspects of modulation and communications explored in the problems in this chapter we believe that the student can gain an appreciation both for the richness of the field of communications and for the central role that the tools of signals and systems analysis play in it.

Chapters 9 and 10 treat the Laplace and  $z$ -transforms, respectively. For the most part, we focus on the bilateral versions of these transforms, although in the last section of each chapter we discuss unilateral transforms and their use in solving differential and difference equations with nonzero initial conditions. Both chapters include discussions on: the close relationship between these transforms and Fourier transforms; the class of rational transforms and their representation in terms of poles and zeros; the region of convergence of a Laplace or  $z$ -transform and its relationship to properties of the signal with which it is associated; inverse transforms using partial fraction expansion; the geometric evaluation of system functions and frequency responses from pole-zero plots; and basic transform properties. In addition, in each chapter we examine the properties and uses of system functions for LTI systems. Included in these discussions are the determination of system functions for systems characterized by differential and difference equations; the use of system function algebra for interconnections of LTI systems; and the construction of cascade, parallel- and direct-form block-diagram representations for systems with rational system functions.

The tools of Laplace and  $z$ -transforms form the basis for our examination of linear feedback systems in Chapter 11. We begin this chapter by describing a number of the important uses and properties of feedback systems, including stabilizing unstable systems, designing tracking systems, and reducing system sensitivity. In subsequent sections we use the tools that we have developed in previous chapters to examine three topics that are of importance for both continuous-time and discrete-time feedback systems. These are root locus analysis, Nyquist plots and the Nyquist criterion, and log-magnitude/phase plots and the concepts of phase and gain margins for stable feedback systems.

The subject of signals and systems is an extraordinarily rich one, and a variety of approaches can be taken in designing an introductory course. It was our intention with the first edition and again with this second edition to provide instructors with a great deal of

flexibility in structuring their presentations of the subject. To obtain this flexibility and to maximize the usefulness of this book for instructors, we have chosen to present thorough, in-depth treatments of a cohesive set of topics that forms the core of most introductory courses on signals and systems. In achieving this depth we have of necessity omitted introductions to topics such as descriptions of random signals and state space models that are sometimes included in first courses on signals and systems. Traditionally, at many schools, such topics are not included in introductory courses but rather are developed in more depth in follow-on undergraduate courses or in courses explicitly devoted to their investigation. Although we have not included an introduction to state space in the book, instructors of introductory courses can easily incorporate it into the treatments of differential and difference equations that can be found throughout the book. In particular, the discussions in Chapters 9 and 10 on block diagram representations for systems with rational system functions and on unilateral transforms and their use in solving differential and difference equations with initial conditions form natural points of departure for the discussions of state-space representations.

A typical one-semester course at the sophomore-junior level using this book would cover Chapters 1-5 in reasonable depth (although various topics in each chapter are easily omitted at the discretion of the instructor) with selected topics chosen from the remaining chapters. For example, one possibility is to present several of the basic topics in Chapters 6-8 together with a treatment of Laplace and  $z$ -transforms and perhaps a brief introduction to the use of system function concepts to analyze feedback systems. A variety of alternate formats are possible, including one that incorporates an introduction to state space or one in which more focus is placed on continuous-time systems by de-emphasizing Chapters 5 and 10 and the discrete-time topics in Chapters 3, 7, 8, and 11.

In addition to these course formats this book can be used as the basic text for a thorough, two-semester sequence on linear systems. Alternatively, the portions of the book not used in a first course on signals and systems can, together with other sources, form the basis for a subsequent course. For example, much of the material in this book forms a direct bridge to subjects such as state space analysis, control systems, digital signal processing, communications and statistical signal processing. Consequently, a follow-on course can be constructed that uses some of the topics in this book together with supplementary material in order to provide an introduction to one or more of these advanced subjects. In fact, a new course following this model has been developed at MIT and has proven not only to be a popular course among our students but also a crucial component of our signals and systems curriculum.

As it was with the first edition, in the process of writing this book we have been fortunate to have received assistance, suggestions, and support from numerous colleagues, students and friends. The ideas and perspectives that form the heart of this book have continued to evolve as a result of our own experiences in teaching signals and systems and the influences of the many colleagues and students with whom we have worked. We would like to thank Professor Ian T. Young for his contributions to the first edition of this book and to thank and welcome Professor Hamid Nawab for the significant role he played in the development and complete restructuring of the examples and problems for this second edition. We also express our appreciation to John Buck, Michael Daniel and Andrew Singer for writing the MATLAB companion to the text. In addition, we would like to thank Jason Oppenheim for the use of one of his original photographs and Vivian Berman for her ideas and help in arriving at a cover design. Also, as indicated on the acknowledg-

ment page that follows, we are deeply grateful to the many students and colleagues who devoted a significant number of hours to a variety of aspects of the preparation of this second edition.

We would also like to express our sincere thanks to Mr. Ray Stata and Analog Devices, Inc. for their generous and continued support of signal processing and this text through funding of the Distinguished Professor Chair in Electrical Engineering. We also thank M.I.T. for providing support and an invigorating environment in which to develop our ideas.

The encouragement, patience, technical support, and enthusiasm provided by Prentice-Hall, and in particular by Marcia Horton, Tom Robbins, Don Fowley, and their predecessors and by Ralph Pescatore of TKM Productions and the production staff at Prentice-Hall, have been crucial in making this second edition a reality.

Alan V. Oppenheim  
Alan S. Willsky

Cambridge, Massachusetts



# ACKNOWLEDGMENTS

In producing this second edition we were fortunate to receive the assistance of many colleagues, students, and friends who were extremely generous with their time. We express our deep appreciation to:

**Jon Maiara** and **Ashok Papat** for their help in generating many of the figures and images. **Babak Ayazifar** and **Austin Frakt** for their help in updating and assembling the bibliography.

**Ramamurthy Mani** for preparing the solutions manual for the text and for his help in generating many of the figures.

**Michael Daniel** for coordinating and managing the LaTeX files as the various drafts of the second edition were being produced and modified.

**John Buck** for his thorough reading of the entire draft of this second edition.

**Robert Becker, Sally Bemus, Maggie Beucler, Ben Halpern, Jon Maira, Chirag Patel,** and **Jerry Weinstein** for their efforts in producing the various LaTeX drafts of the book.

And to all who helped in careful reviewing of the page proofs:

<b>Babak Ayazifar</b>	<b>Christina Lamarre</b>
<b>Richard Barron</b>	<b>Nicholas Laneman</b>
<b>Rebecca Bates</b>	<b>Li Lee</b>
<b>George Bevis</b>	<b>Sean Lindsay</b>
<b>Sarit Birzon</b>	<b>Jeffrey T. Ludwig</b>
<b>Nabil Bitar</b>	<b>Seth Pappas</b>
<b>Nirav Dagi</b>	<b>Adrienne Prahler</b>
<b>Anne Findlay</b>	<b>Ryan Riddolls</b>
<b>Austin Frakt</b>	<b>Alan Seefeldt</b>
<b>Siddhartha Gupta</b>	<b>Sekhar Tatikonda</b>
<b>Christoforos Hadjicostis</b>	<b>Shawn Verbout</b>
<b>Terrence Ho</b>	<b>Kathleen Wage</b>
<b>Mark Ibanez</b>	<b>Alex Wang</b>
<b>Seema Jaggi</b>	<b>Joseph Winograd</b>
<b>Patrick Kreidl</b>	

# FOREWORD

The concepts of signals and systems arise in a wide variety of fields, and the ideas and techniques associated with these concepts play an important role in such diverse areas of science and technology as communications, aeronautics and astronautics, circuit design, acoustics, seismology, biomedical engineering, energy generation and distribution systems, chemical process control, and speech processing. Although the physical nature of the signals and systems that arise in these various disciplines may be drastically different, they all have two very basic features in common. The signals, which are functions of one or more independent variables, contain information about the behavior or nature of some phenomenon, whereas the systems respond to particular signals by producing other signals or some desired behavior. Voltages and currents as a function of time in an electrical circuit are examples of signals, and a circuit is itself an example of a system, which in this case responds to applied voltages and currents. As another example, when an automobile driver depresses the accelerator pedal, the automobile responds by increasing the speed of the vehicle. In this case, the system is the automobile, the pressure on the accelerator pedal the input to the system, and the automobile speed the response. A computer program for the automated diagnosis of electrocardiograms can be viewed as a system which has as its input a digitized electrocardiogram and which produces estimates of parameters such as heart rate as outputs. A camera is a system that receives light from different sources and reflected from objects and produces a photograph. A robot arm is a system whose movements are the response to control inputs.

In the many contexts in which signals and systems arise, there are a variety of problems and questions that are of importance. In some cases, we are presented with a specific system and are interested in characterizing it in detail to understand how it will respond to various inputs. Examples include the analysis of a circuit in order to quantify its response to different voltage and current sources and the determination of an aircraft's response characteristics both to pilot commands and to wind gusts.

In other problems of signal and system analysis, rather than analyzing existing systems, our interest may be focused on designing systems to process signals in particular ways. One very common context in which such problems arise is in the design of systems to enhance or restore signals that have been degraded in some way. For example, when a pilot is communicating with an air traffic control tower, the communication can be degraded by the high level of background noise in the cockpit. In this and many similar cases, it is possible to design systems that will retain the desired signal, in this case the pilot's voice, and reject (at least approximately) the unwanted signal, i.e., the noise. A similar set of objectives can also be found in the general area of image restoration and image enhancement. For example, images from deep space probes or earth-observing satellites typically represent degraded versions of the scenes being imaged because of limitations of the imaging equipment, atmospheric effects, and errors in signal transmission in returning the images to earth. Consequently, images returned from space are routinely processed by systems to compensate for some of these degradations. In addition, such images are usu-

ally processed to enhance certain features, such as lines (corresponding, for example, to river beds or faults) or regional boundaries in which there are sharp contrasts in color or darkness.

In addition to enhancement and restoration, in many applications there is a need to design systems to extract specific pieces of information from signals. The estimation of heart rate from an electrocardiogram is one example. Another arises in economic forecasting. We may, for example, wish to analyze the history of an economic time series, such as a set of stock market averages, in order to estimate trends and other characteristics such as seasonal variations that may be of use in making predictions about future behavior. In other applications, the focus may be on the design of signals with particular properties. Specifically, in communications applications considerable attention is paid to designing signals to meet the constraints and requirements for successful transmission. For example, long distance communication through the atmosphere requires the use of signals with frequencies in a particular part of the electromagnetic spectrum. The design of communication signals must also take into account the need for reliable reception in the presence of both distortion due to transmission through the atmosphere and interference from other signals being transmitted simultaneously by other users.

Another very important class of applications in which the concepts and techniques of signal and system analysis arise are those in which we wish to modify or control the characteristics of a given system, perhaps through the choice of specific input signals or by combining the system with other systems. Illustrative of this kind of application is the design of control systems to regulate chemical processing plants. Plants of this type are equipped with a variety of sensors that measure physical signals such as temperature, humidity, and chemical composition. The control system in such a plant responds to these sensor signals by adjusting quantities such as flow rates and temperature in order to regulate the ongoing chemical process. The design of aircraft autopilots and computer control systems represents another example. In this case, signals measuring aircraft speed, altitude, and heading are used by the aircraft's control system in order to adjust variables such as throttle setting and the position of the rudder and ailerons. These adjustments are made to ensure that the aircraft follows a specified course, to smooth out the aircraft's ride, and to enhance its responsiveness to pilot commands. In both this case and in the previous example of chemical process control, an important concept, referred to as feedback, plays a major role, as measured signals are fed back and used to adjust the response characteristics of a system.

The examples in the preceding paragraphs represent only a few of an extraordinarily wide variety of applications for the concepts of signals and systems. The importance of these concepts stems not only from the diversity of phenomena and processes in which they arise, but also from the collection of ideas, analytical techniques, and methodologies that have been and are being developed and used to solve problems involving signals and systems. The history of this development extends back over many centuries, and although most of this work was motivated by specific applications, many of these ideas have proven to be of central importance to problems in a far larger variety of contexts than those for which they were originally intended. For example, the tools of Fourier analysis, which form the basis for the frequency-domain analysis of signals and systems, and which we will develop in some detail in this book, can be traced from problems of astronomy studied by the ancient Babylonians to the development of mathematical physics in the eighteenth and nineteenth centuries.