国外电子与通信教材系列

CMOS模拟电路设计

（第二版）

CMOS Analog Circuit Design

Second Edition

英文版

[美] Phillip E. Allen
Douglas R. Holberg 著

電子工業出版社
Publishing House of Electronics Industry
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内 容 简 介

本书是模拟集成电路设计课的一本经典教材。全书共分5个部分。主要介绍了模拟集成电路设计的背景知识、基本MOS半导体制造工艺、CMOS技术、CMOS器件建模，MOS开关、MOS二极管、有源电阻、电流阱和电流源等模拟CMOS分支电路，以及反相器、差分放大器、共源共栅放大器、电流放大器、输出放大器等CMOS放大器的原理、特性、分析方法和设计，CMOS运算放大器、高性能CMOS运算放大器、比较器，开关电容电路、D/A和A/D变换器等CMOS模拟系统的分析方法、设计和模拟等内容。

该书可作为高等学校电子工程、微电子学、计算机科学、电机工程与应用电子技术等专业的的教科书，以及有关专业的选修课教材或研究生教材、教学参考书；也可作为在职的模拟集成电路设计工程师或与模拟集成电路设计有关的工程师的进修教材或工程设计参考书。

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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。

吴佑寿

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、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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PREFACE

The objective of the second edition of this book continues to be to teach the design of CMOS analog circuits. The teaching of design reaches far beyond giving examples of circuits and showing analysis methods. It includes the necessary fundamentals and background but must apply them in a hierarchical manner that the novice can understand. Probably of most importance is to teach the concepts of designing analog integrated circuits in the context of CMOS technology. These concepts enable the reader to understand the operation of an analog CMOS circuit and to know how to change its performance. With today's computer-oriented thinking, it is vital to maintain personal control of a design, to know what to expect, and to discern when simulation results may be misleading. As integrated circuits become more complex, it is crucial to know "how the circuit works." Simulating a circuit without the understanding of how it works can lead to disastrous results.

How does the reader acquire the knowledge of how a circuit works? The answer to this question has been the driving motivation of the second edition of this text. There are several important steps in this process. The first is to learn to analyze the circuit. This analysis should produce simple results that can be understood and reapplied in different circumstances. The second is to view analog integrated circuit design from a hierarchical viewpoint. This means that the designer is able to visualize how subcircuits are used to form circuits, how simple circuits are used to build complex circuits, and so forth. The third step is to set forth procedures that will help the new designer come up with working designs. This has resulted in the inclusion of many "design recipes," which became popular with the first edition and have been expanded in the second edition. It is important that the designer realize that there are simply three outputs of the electrical design of CMOS analog circuits. They are (1) a schematic of the circuit, (2) dc currents, and (3) W/L ratios. Most design flows or "recipes" can be organized around these three outputs very easily.

Fifteen years ago, it was not clear what importance CMOS technology would have on analog circuits. However, it has become very clear that CMOS technology has become the technology of choice for analog circuit design in a mixed-signal environment. This "choice" is not necessarily that of the designer but of industry trends that want to use standard technologies to implement analog circuits along with digital circuits. As a result, the first edition of *CMOS Analog Circuit Design* fulfilled a need for a text in this area before there were any other texts on this subject. It has found extensive use in industry and has been used in classrooms all over the world. Like the first edition, the second edition has also chosen not to include BJT technology. The wisdom of this choice will be seen as the years progress. The second edition has been developed with the goal of extending the strengths of the first edition, namely in the area of analog circuit design insight and concepts.

The second edition has been a long time in coming but has resulted in a unique blending of industry and academia. This blending has occurred over the past 15 years in short courses taught by the first author. Over 50 short courses have been taught from the first edition to over 1500 engineers all over the world. In these short courses, the engineers demanded to understand the concepts and insight to designing analog CMOS circuits, and much of the response to these demands has been included in the second edition. In addition to the industrial input to the second edition, the authors have taught this material at Georgia Institute of Technology and the University of Texas at Austin over the past 10–15 years. This experience has provided insight that has been included in the second edition from the viewpoint of students and their questions. Also, the academic application of this material has resulted in a large body of problems that have been given as tests and have now been included in the second edition. The first edition had 335 problems. The second edition has over 500 problems, and most of those are new to the second edition.

The audience for the second edition is essentially the same as for the first edition. The first edition was very useful to those beginning a career in CMOS analog design—many of whom have communicated to the authors that the text has been a ready reference in their daily work. The second edition should continue to be of value to both new and experienced engineers in industry. The principles and concepts discussed should never become outdated even though technology changes.

The second audience is the classroom. The output of qualified students to enter the field of analog CMOS design has not met the demand from industry. Our hope is that the second edition will provide both instructors and students with a tool that will help fulfill this demand. In order to help facilitate this objective, both authors maintain websites that permit the downloading of short course lecture slides, short course schedules and dates, class notes, and problems and solutions in pdf format. More information can be found at www.aicdesign.org (P.E. Allen) and www.holberg.org (D.R. Holberg). These sites are continually updated, and the reader or instructor is invited to make use of the information and teaching aides contained on these sites.

The second edition has received extensive changes. These changes include the moving of Chapter 4 of the first edition to Appendix B of the second edition. The comparator chapter of the first edition was before the op amp chapters and has been moved to after the op amp chapters. In the 15 years since the first edition, the comparator has become more like a sense amplifier and less like an op amp without compensation. A major change has been the incorporation of Chapter 9 on switched capacitor circuits. There are two reasons for this. Switched capacitors are very important in analog circuits and systems design, and this information is needed for many of the analog–digital and digital–analog converters of Chapter 10. Chapter 11 of the first edition has been dropped. There were plans to replace it with a chapter on analog systems including phase-locked loops and VCOs, but time did not allow this to be realized. The problems of the second edition are organized into sections and have been designed to reinforce and extend the concepts and principles associated with a particular topic.

The hierachical organization of the second edition is illustrated in Table 1.1-2. Chapter 1 presents the material necessary to introduce CMOS analog circuit design. This chapter gives an overview of the subject of CMOS analog circuit design, defines notation and convention, makes a brief survey of analog signal processing, and gives an example of analog CMOS design with emphasis on the hierarchial aspect of the design. Chapters 2 and 3 form the basis for analog CMOS design by covering the subjects of CMOS technology and modeling. Chapter 2 reviews CMOS technology as applied to MOS devices, pn junctions, passive components compatible with CMOS technology, and other components such as the lateral and substrate

BJT and latchup. This chapter also includes a section on the impact of integrated circuit layout. This portion of the text shows that the physical design of the integrated circuit is as important as the electrical design, and many good electrical designs can be ruined by poor physical design or layout. Chapter 3 introduces the key subject of modeling, which is used throughout the remainder of the text to predict the performance of CMOS circuits. The focus of this chapter is to introduce a model that is good enough to predict the performance of a CMOS circuit to within $\pm 10\%$ to $\pm 20\%$ and will allow the designer insight and understanding. Computer simulation can be used to more exactly model the circuits but will not give any direct insight or understanding of the circuit. The models in this chapter include the MOSFET large-signal and small-signal models, including frequency dependence. In addition, how to model the noise and temperature dependence of MOSFETs and compatible passive elements is shown. This chapter also discusses computer simulation models. This topic is far too complex for the scope of this book, but some of the basic ideas are presented so that the reader can appreciate computer simulation models. Other models for the subthreshold operation are presented along with how to use SPICE for computer simulation of MOSFET circuits.

Chapters 4 and 5 represent the topics of subcircuits and amplifiers that will be used to design more complex analog circuits, such as an op amp. Chapter 4 covers the use of the MOSFET as a switch followed by the MOS diode or active resistor. The key subcircuits of current sinks/sources and current mirrors are presented next. These subcircuits permit the illustration of important design concepts such as negative feedback, design tradeoffs, and matching principles. Finally, this chapter presents independent voltage and current references and the bandgap voltage reference. These references attempt to provide a voltage or current that is independent of power supply and temperature. Chapter 5 develops various types of amplifiers. These amplifiers are characterized from their large-signal and small-signal performance, including noise and bandwidth where appropriate. The categories of amplifiers include the inverter, differential, cascode, current, and output amplifiers. The last section discusses how high-gain amplifiers could be implemented from the amplifier blocks of this chapter.

Chapters 6, 7, and 8 represent examples of complex analog circuits. Chapter 6 introduces the design of a simple two-stage op amp. This op amp is used to develop the principles of compensation necessary for the op amp to be useful. The two-stage op amp is used to formally present methods of designing this type of analog circuit. This chapter also examines the design of the cascode op amps, particularly the folded-cascode op amp. This chapter concludes with a discussion of techniques to measure and/or simulate op amps and macromodels. Macromodels can be used to more efficiently simulate op amps at higher levels of abstraction. Chapter 7 presents the subject of high-performance op amps. In this chapter various performances of the simple op amp are optimized, quite often at the expense of other performance aspects. The topics include buffered output op amps, high-frequency op amps, differential-output op amps, low-power op amps, low-noise op amps, and low-voltage op amps. Chapter 8 presents the open-loop comparator, which is an op amp without compensation. This is followed by methods of designing this type of comparator for linear or slewing responses. Methods of improving the performance of open-loop comparators, including autozeroing and hysteresis, are presented. Finally, this chapter describes regenerative comparators and how they can be combined with low-gain, high-speed amplifiers to achieve comparators with a very short propagation time delay.

Chapters 9 and 10 focus on analog systems. Chapter 9 is completely new and presents the topic of switched capacitor circuits. The concepts of a switched capacitor are presented along with such circuits as the switched capacitor amplifier and integrator. Methods of analyzing and simulating switched capacitor circuits are given, and first-order and second-order switched capacitor circuits are used to design various filters using cascade and ladder approaches. Chapter 9 concludes with anti-aliasing filters, which are required by all switched capacitor circuits. Chapter 10 covers the topics of CMOS digital–analog and analog–digital converters. Digital–analog converters are presented according to their means of scaling the reference and include voltage, current, and charge digital–analog converters. Next, methods of extending the resolution of digital–analog converters are given. The analog–digital converters are divided into Nyquist and oversampling converters. The Nyquist converters are presented according to their speed of operation—slow, medium and fast. Finally, the subject of oversampled analog–digital and digital–analog converters is presented. These converters allow high resolution and are very compatible with CMOS technology.

Three appendices cover the topics of circuit analysis methods for CMOS analog circuits, CMOS device characterization (this is essentially chapter 4 of the first edition), and time and frequency domain relationships for second-order systems.

The material of the second edition is more than sufficient for a 15-week course. Depending upon the background of the students, a 3-hour-per-week, 15-week-semester course could include parts of Chapters 2 and 3, Chapters 4 through 6, parts of Chapter 7, and Chapter 8. Chapter 9 and 10 could be used as part of the material for a course on analog systems. At Georgia Tech, this text is used along with the fourth edition of *Analysis and Design of Analog Integrated Circuits* in a two-semester course that covers both BJT and CMOS analog IC design. Chapters 9 and 10 are used for about 70% of a semester course on analog IC systems design.

The background necessary for this text is a good understanding of basic electronics. Topics of importance include large-signal models, biasing, small-signal models, frequency response, feedback, and op amps. It would also be helpful to have a good background in semiconductor devices and how they operate, integrated circuit processing, simulation using SPICE, and modeling of MOSFETs. With this background, the reader could start at Chapter 4 with little problem.

The authors would like to express their appreciation and gratitude to the many individuals who have contributed to the development of the second edition. These include both undergraduate and graduate students who have used the first edition and offered comments, suggestions, and corrections. It also includes the over 1500 industrial participants who, over the last 15 years, have attended a one-week course on this topic. We thank them for their encouragement, patience, and suggestions. We also appreciate the feedback and corrections from many individuals in industry and academia worldwide. The input from those who have read and used the preliminary edition is greatly appreciated. In particular, the authors would like to thank Tom DiGiacomo, Babak Amini, and Michael Hackner for providing useful feedback on the new edition. The authors gratefully acknowledge the patience and encouragement of Peter Gordon, Executive Editor of Engineering, Science and Computer Science of Oxford University Press during the development of the second edition and the firm but gentle shepherding of the second edition through the production phase by the project editor, Justin Collins. Lastly, the assistance of Marge Boehme in helping with detail work associated with the preparation and teaching of the second edition is greatly appreciated.

Phillip E. Allen
Atlanta, GA

Douglas R. Holberg
Austin, TX

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Chapter 1

Introduction and Background

The evolution of *very large-scale integration* (VLSI) technology has developed to the point where millions of transistors can be integrated on a single die or "chip." Where integrated circuits once filled the role of subsystem components, partitioned at analog–digital boundaries, they now integrate complete systems on a chip by combining both analog and digital functions [1]. *Complementary metal-oxide semiconductor* (CMOS) technology has been the mainstay in mixed-signal* implementations because it provides density and power savings on the digital side, and a good mix of components for analog design. By reason of its widespread use, CMOS technology is the subject of this text.

Due in part to the regularity and granularity of digital circuits, computer-aided design (CAD) methodologies have been very successful in automating the design of digital systems given a behavioral description of the function desired. Such is not the case for analog circuit design. Analog design still requires a "hands on" design approach in general. Moreover, many of the design techniques used for discrete analog circuits are not applicable to the design of analog/mixed-signal VLSI circuits. It is necessary to examine closely the design process of analog circuits and to identify those principles that will increase design productivity and the designer's chances for success. Thus, this book provides a hierarchical organization of the subject of analog integrated-circuit design and identification of its general principles.

The objective of this chapter is to introduce the subject of analog integrated-circuit design and to lay the groundwork for the material that follows. It deals with the general subject of analog integrated-circuit design followed by a description of the notation, symbology, and terminology used in this book. The next section covers the general considerations for an analog signal-processing system, and the last section gives an example of analog CMOS circuit design. The reader may wish to review other topics pertinent to this study before continuing to Chapter 2. Such topics include modeling of electronic components, computer simulation techniques, Laplace and z-transform theory, and semiconductor device theory.

1.1 ANALOG INTEGRATED-CIRCUIT DESIGN

Integrated-circuit design is separated into two major categories: analog and digital. To characterize these two design methods we must first define analog and digital signals. A *signal* will be considered to be any detectable value of voltage, current, or charge. A signal should

*The term "mixed-signal" is a widely accepted term describing circuits with both analog and digital circuitry on the same silicon substrate.

convey information about the state or behavior of a physical system. An *analog signal* is a signal that is defined over a continuous range of time and a continuous range of amplitudes. An analog signal is illustrated in Fig. 1.1-1(a). A *digital signal* is a signal that is defined only at discrete values of amplitude, or said another way, a digital signal is quantized to discrete values. Typically, the digital signal is a binary-weighted sum of signals having only two defined values of amplitude as illustrated in Fig. 1.1-1(b) and shown in Eq. (1.1-1). Figure 1.1-1(b) is a three-bit representation of the analog signal shown in Fig. 1.1-1(a).

$$D = b_{N-1}\,2^{-1} + b_{N-2}\,2^{-2} + b_{N-3}\,2^{-3} + \cdots + b_0\,2^{-N} = \sum_{i=1}^{N} b_{N-i}\,2^{-i} \tag{1.1-1}$$

The individual binary numbers, b_i, have a value of either zero or one. Consequently, it is possible to implement digital circuits using components that operate with only two stable states. This leads to a great deal of regularity and to an algebra that can be used to describe the function of the circuit. As a result, digital circuit designers have been able to adapt readily to the design of more complex integrated circuits.

Another type of signal encountered in analog integrated-circuit design is an analog *sampled-data* signal. An analog sampled-data signal is a signal that is defined over a continuous range of amplitudes but only at discrete points in time. Often the sampled analog signal is held at the value present at the end of the sample period, resulting in a sampled-and-held signal. An analog sampled-and-held signal is illustrated in Fig. 1.1-1(c).

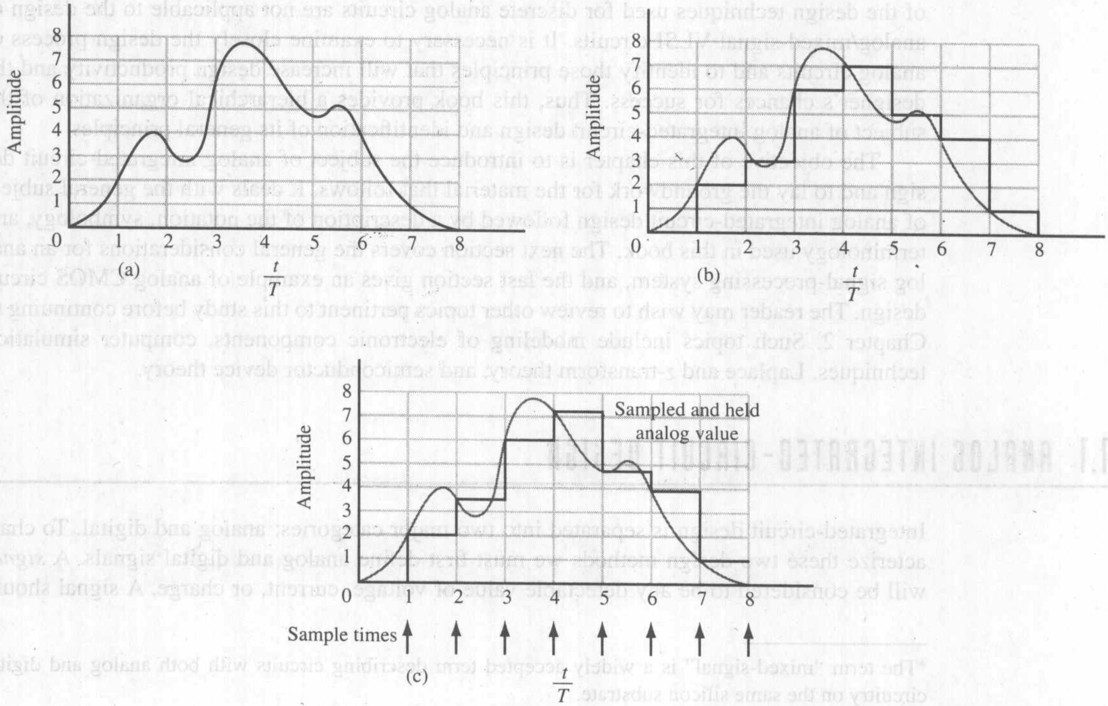

Figure 1.1-1 Signals. (a) Analog or continuous time. (b) Digital. (c) Analog sampled data or discrete time. *T* is the period of the digital or sampled signals.