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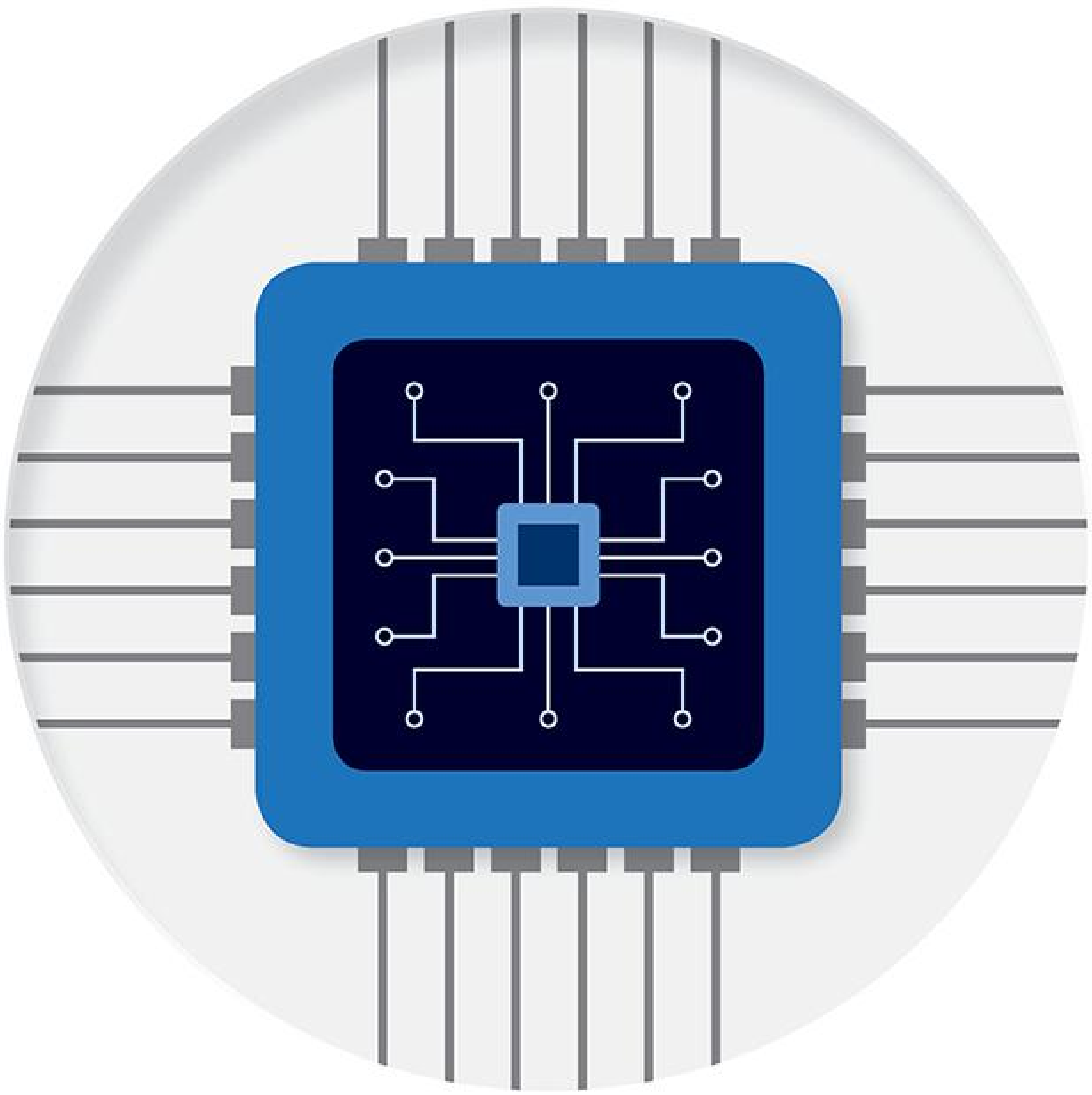
Microelectronic Circuits

EIGHTH EDITION

ADEL S. SEDRA | KENNETH C. SMITH | TONY CHAN CARUSONE | VINCENT GAUDET



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Microelectronic Circuits

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CONTENTS

* Available online at www.oup.com/he/sedra-smith8e.

TABLES

FOR REFERENCE AND STUDY

For ease of reference, many of these tables are presented in the Summary Tables (ST) supplement found online at www.oup.com/he/sedra-smith8e.

HISTORICAL NOTES

PREFACE

Microelectronic Circuits, Eighth Edition, is intended as a text for the core courses in electronic circuits taught to majors in electrical and computer engineering. It should also prove useful to engineers and other professionals wishing to update their knowledge through self-study.

As was the case with the first seven editions, the objective of this book is to develop in the reader the ability to analyze and design electronic circuits, both analog and digital, discrete and integrated. While the application of integrated circuits is covered, emphasis is placed on transistor circuit design. This is done because of our belief that even if the majority of those studying this book were not to pursue a career in IC design, knowledge of what is inside the IC package would enable intelligent and innovative application of such chips. Furthermore, with the advances in VLSI technology and design methodology, IC design itself has become accessible to an increasing number of engineers.

Prerequisites

The prerequisite for studying the material in this book is a first course in circuit analysis. As a review, some linear circuits material is included here in the appendices: specifically, two-port network parameters in Appendix C; some useful network theorems in Appendix D; single-time-constant circuits in Appendix E; and s-domain analysis in Appendix F. In addition, a number of relevant circuit analysis problems are included at the beginning of the end-of-chapter problems section of Chapter 1. No prior knowledge of physical electronics is assumed. All required semiconductor device physics is included, and Appendix A provides a brief description of IC fabrication. All these appendices can be found on the book's website.

Emphasis on Design

It has been our philosophy that circuit design is best taught by pointing out the various tradeoffs available in selecting a circuit configuration and in selecting component values for a given configuration. The emphasis on design has been retained in this edition. In addition to design examples, and design-oriented exercises and end-of-chapter problems (indicated with a D), the book includes on its website an extensive appendix (Appendix B) where a large number of simulation and design examples are presented. These emphasize the use of SPICE, the most valuable circuit-design aid.

New to the Eighth Edition

The most important change in the eighth edition is that two new coauthors have joined our team: Tony Chan Carusone of the University of Toronto and Vincent Gaudet of the University of Waterloo.

While maintaining the philosophy and pedagogical approach of the first seven editions, several changes have been made to both organization and coverage. Our goal in making structural changes has been to increase modularity and thus flexibility for the instructor, without causing disturbance to courses currently using the seventh edition. Changes in coverage are necessitated by the continuing advances in technology which make some topics of greater relevance and others of less interest. As well, advances in IC process technology require that the numbers used in the examples, exercises, and end-of-chapter problems be updated to reflect the parameters of newer generations of IC technologies (e.g., some problems utilize the parameters of the 28-nm CMOS process). This ensures that students are acquiring a real-world perspective on technology.

The guiding principle in this revision has been *to make the book easier to teach and learn from*. In pursuit of this goal, the following specific and noteworthy changes have been made:

1. **New End-of-Chapter Problems.** About half of the approximately 1400 end-of-chapter problems are new or revised. To aid the instructor in deciding which of this large number of problems to assign, we have carefully selected a subset that we have designated **essential problems**. This should also be helpful to students using the book for self-study. The Instructor's Solutions Manual (ISM) has been thoroughly revised by the authors. It includes complete solutions for all exercises and end-of-chapter problems.
2. **Video Examples.** For the first time, we are including forty video examples. For each, the problem statement is provided and the student is directed to a video on the website to watch the authors solve the problem. Also, a directly related end-of-chapter problem is highlighted for the student to solve after watching the video.
3. **Summary Tables.** New and existing summary tables have been combined together and made available on the website. This collection of tables is an important resource for the student in studying and as a reference while doing homework problems.
4. **Improved Organization.** While maintaining the very successful modular organization of the seventh edition, we have reduced the number of parts of the eighth edition to three. Specifically, the filters and oscillators chapters are now in Part II: Analog Integrated Circuits.
5. **Streamlined Coverage and Book Size.** Almost every chapter has been revised and streamlined with emphasis on the essentials. This has resulted in a substantial reduction in the size of the book (by almost 200 pages). However, removed material has been made available on the website for those who want to continue to use it. Particular chapters that have been reduced are: Chapter 12 (Output Stages and Power Amplifiers); Chapter 13 (Op Amp Circuits); Chapter 14 (Filters); Chapter 15 (Oscillators); and Part III: Digital Integrated Circuits.
6. **Early Coverage of Technology Scaling and Moore's Law.** The discussion of technology scaling and Moore's law is now started in Chapter 5 (MOSFETs). It is then referenced throughout the book, and resumed in Chapter 17 (Digital Design) where the effects of scaling on the trinity of digital design—speed, power, and area—are considered.
7. **Modernizing the Study of Diodes.** Chapter 4 has been reorganized to highlight the different levels of abstraction and accuracy in diode modeling. While the coverage of standard material has been streamlined and reduced somewhat, newer topics have been expanded and/or included such as photodiodes, light-emitting diodes, application of diodes in electronic discharge (ESD) protection, etc.
8. **Clearer Derivations and Better Explanations.** Three chapters in Part II: Analog Integrated Circuits, have been thoroughly revised to simplify and clarify the presentation and to provide better derivations. These are Chapter 8 (Building Blocks of IC Amplifiers), specifically the treatment of the CG and CB amplifiers and the study of advanced current mirrors; Chapter 9 (Differential and Multistage Amplifiers), specifically the treatment of common-mode gain

and CMRR, DC offsets, and the current-mirror-loaded differential amplifier; and Chapter 10 (Frequency Response), which has been reorganized to deemphasize the study of the low-frequency response of discrete-circuit amplifiers (now placed at the end of the chapter).

9. **Clearer, Improved, and Simplified Study of Feedback.** Substantial improvements have been made to Chapter 11 (Feedback) to make the subject easier to understand and use.
10. **Streamlined and Better Organized Coverage of the Digital Topics.** Part III: Digital Integrated Circuits has undergone a thorough re-organization making it easier to integrate its topics into the first and/or the second electronics course. Its first chapter, now Chapter 16, emphasizes the basics of digital CMOS design, culminating in an in-depth study of the CMOS inverter's static characteristic. Then, Chapter 17 covers the three main metrics that are commonly used in digital circuit design and optimization, namely speed, power, and area. We then complete the discussion of technology scaling, first started in Chapter 5, by looking at how scaling impacts these three metrics. Finally, Chapter 18 focuses on transistor-level memory circuits and clocking circuits. Many of the examples, exercises, and problems in Part III have been redesigned to use newer technologies.

The Book's Website

The companion website for the book (www.oup.com/he/sedra-smith8e) contains important materials that will change frequently to reflect new developments. Here is a list of some of the materials available on the website:

1. Summary tables useful for studying and practice problems.
2. Resources to support the use of Spice with problems and examples including
   - Links to circuit simulation tools.
   - The input files needed to perform simulations of problems from the book identified with a SIM icon.
   - Additional Spice examples and the associated files.
   - Step-by-step guidance to help performing the Spice simulations.
3. Bonus text material of specialized topics that are either not covered or covered briefly in the current edition of the textbook. These include:
   - Precision Rectifier Circuits
   - Junction Field-Effect Transistors (JFETs)
   - Gallium Arsenide (GaAs) Devices and Circuits
   - Specialty Diode Topics: Diode Logic Gates, Temperature Effects in Zener Diodes, and the Schottky-Barrier Diode (SBD)
   - Useful Transistor Pairings
   - Selected Topics in BJT Ouput Stages: Class B Power Dissipation and Improvements, and Protection Circuitry
   - The Classical CMOS Class AB Configuration
   - IC Power Amplifiers
   - Power Transistor Thermal Considerations
   - The 741 Op-Amp Circuit
   - Selected Analog Filter Topics
     - First- and Second-Order Filter Functions
     - Single-Amplifier Biquadratic Active Filters
     - Sensitivity
     - Transconductance-C Filters
     - Tuned Amplifiers
   - Waveform Generators: The Monostable Multivibrator, IC Timers, and Waveform-Shaping Circuits

- MOS Velocity Saturation and Subthreshold Leakage
- Alternative Digital Logic Families
  - Pseudo-NMOS Logic Circuits
  - Dynamic MOS Logic Circuits
  - Transistor-Transistor Logic (TTL) Circuits
  - Emitter-Coupled Logic (ECL) Circuits
  - Bipolar and BiCMOS Digital Circuits
- Memory Architectures and Read-Only Memory (ROM)
- CMOS Image Sensors

4. Data sheets for hundreds of useful devices to help in laboratory experiments as well as in design projects.
5. Appendices for the Book:
   - Appendix A: VLSI Fabrication Technology
   - Appendix B: Spice Design and Simulation Examples
   - Appendix C: Two-Port Network Parameters
   - Appendix D: Some Useful Network Theorems
   - Appendix E: Single-Time-Constant Circuits
   - Appendix F: *s*-Domain Analysis: Poles, Zeros and Bode Plots
   - Appendix G: Comparison of the MOSFET and the BJT
   - Appendix H: Filter Design Tools
   - Appendix I: Bibliography
   - Appendix L: Answers to Selected Problems

Exercises and End-of-Chapter Problems

Over 450 Exercises are integrated throughout the text. The answer to each exercise is given below the exercise so students can check their understanding of the material as they read. Solving these exercises should enable the reader to gauge his or her grasp of the preceding material. In addition, more than 1400 end-of-chapter problems, half of which are new or revised in this edition, are provided. The problems are keyed to the individual chapter sections and their degree of difficulty is indicated by a rating system: difficult problems are marked with an asterisk (*); more difficult problems with two asterisks (**); and very difficult (and/or time consuming) problems with three asterisks (***). We must admit, however, that this classification is by no means exact. Our rating no doubt depended to some degree on our thinking (and mood!) at the time a particular problem was created. Answers to sample problems are given in Appendix L (on the website), so students have a checkpoint to tell if they are working out the problems correctly. Complete solutions for all exercises and problems are included in the *Instructor's Solutions Manual*, which is available from the publisher to those instructors who adopt the book.

As an aid to the instructor on deciding which to assign of this large number of problems, we have carefully selected a subset and designated it essential problems. (These are the problems with blue numbers). This should also be helpful to students using the book for self-study.

As in the previous seven editions, many examples are included. The examples, and indeed most of the problems and exercises, are based on real circuits and anticipate the applications encountered in designing real-life circuits. This edition continues the use of numbered solution steps in the figures for many examples, as an attempt to recreate the dynamics of the classroom.

Summary Tables

New and existing summary tables are presented together on the website. This collection of tables is an important resource for the student studying for exams or doing homework problems.

Video Examples

Today's students learn by watching, and they appreciate video for the ability to control the pace of presentation. For this edition, we have introduced video as a way to help students connect the text's examples to the homework problems they are assigned to solve. In 40 professionally produced videos, we walk students step by step through the procedures required to solve some of the most common, and complex, circuits they will have to master. We then provide related problems so that they can apply the strategies they have just learned to comparable circuits. We believe these videos will help students close the gap between learning and application. These videos are included in the enhanced ebook and are available to purchasers of the print book using the access code packaged with new print copies. Students with rented or used print copies can gain access to the videos by purchasing access to the ARC Premium site for *Microelectronic Circuits* at www.oup.com/he/sedra-smith8e. Videos are also available on the ARC site for instructors using *Microelectronic Circuits*.

Course Organization

The book contains sufficient material for a sequence of two single-semester courses, each of 40–50 lecture hours. The modular organization of the book provides considerable flexibility for course design. In the following, we suggest content for a sequence of two classical or standard courses. We also describe some variations on the content of these two courses and specify supplemental material for a possible third course.

The First Course

The first course is based on Part I of the book, that is, Chapters 1–7. It can be taught, most simply by starting at the beginning of Chapter 1 and concluding with the end of Chapter 7. However, as guidance to instructors who wish to follow a different order of presentation or a somewhat modified coverage, or to deal with situations where time might be constrained, we offer the following remarks:

The core of the first course is the study of the two transistor types, Chapters 5 and 6, in whatever order the instructor wishes, and transistor amplifiers in Chapter 7. These three chapters must be covered in full.

Another important part of the first course is the study of diodes (Chapter 4). Here, however, if time does not permit, some of the applications in the later part of the chapter can be skipped.

We have found it highly motivational to cover op amps (Chapter 2) near the beginning of the course. This provides the students with the opportunity to work with a practical integrated circuit and to experiment with nontrivial circuits.

Coverage of Chapter 1, at least of the amplifier sections, should prove helpful. Here the sections on signals can be either covered in class or assigned as reading material. Section 1.6 on frequency response is needed if the frequency-response of op-amp circuits is to be studied; otherwise this section can be delayed to the second course.

Finally, if the students have not taken a course on physical electronics, Chapter 3 needs to be covered. Otherwise, it can be used as review material or skipped altogether.

The Second Course

The main subject of the second course is integrated-circuit amplifiers and is based on Part II of the book, that is, Chapters 8–15. These eight chapters, however, contain more material than can be taught in one course. Thus, a judicious selection of topics to cover is called for. We hope that the following remarks can be helpful in making these choices:

The core material of Part II is presented in Chapters 8–11 and these four chapters must be covered, though not necessarily in their entirety. For instance, some of the sections near the end of a chapter and identified by the "advanced material" icon can be skipped, usually with no loss of continuity.

Beyond the required chapters (8–11), the instructor has many possibilities for the remainder of the course. These include a selection of topics from the remaining four chapters of Part II (12–15). Another possibility, is to include an introduction to digital integrated circuits by covering Chapter 16, and if time permits, selected topics of Chapters 17 and 18.

A Digitally Oriented First Course

A digitally-oriented first course can include the following: Chapter 1 (without Section 1.6), Chapter 2, Chapter 3 (if the students have not had any exposure to physical electronics), Chapter 4 (perhaps without some of the later applications sections), Chapter 5, selected topics from Chapter 7 emphasizing the basics of the application of the MOSFET as an amplifier, Chapter 16, and selected topics from Chapters 17 and 18. Such a course would be particularly suited for Computer Engineering students.

Supplemental Material/Third Course

Depending on the selection of topics for the first and second courses, some material will remain and can be used for part of a third course or as supplemental material to support student design projects. These can include Chapter 12 (Output Stages and Power Amplifiers), Chapter 13 (Op-Amp Circuits), Chapter 14 (Filters), and Chapter 15 (Oscillators), which can be used together with the advanced topics of Chapters 8–11 to support a third course on analog circuits. These can also include Chapters 16, 17, and 18 which can be used for a portion of a senior-level course on digital IC design.

The Accompanying Laboratory

Courses in electronic circuits are usually accompanied by laboratory experiments. To support the laboratory component for courses using this book, Vincent Gaudet has, in collaboration with K.C. Smith, authored a laboratory manual. *Laboratory Explorations*, together with an Instructor's Manual, is available from Oxford University Press.

An alternative approach for laboratory experimentation involves the use of pre-wired circuit boards with the experiments digitally controlled. Products that support this approach include AELabs, by Illuster Technologies, and Analog Electronic Board, by Texas Instruments; both work on the NI Elvis platform. More information can be found on the companion website (www.oup.com/he/sedra-smith8e).

An Outline for the Reader

Part I, *Devices and Basic Circuits*, includes the most fundamental and essential topics for the study of electronic circuits. At the same time, it constitutes a complete package for a first course on the subject.

Chapter 1. The book starts with an introduction to the basic concepts of electronics in Chapter 1. Signals, their frequency spectra, and their analog and digital forms are presented. Amplifiers are introduced as circuit building blocks and their various types and models are studied. This chapter also establishes some of the terminology and conventions used throughout the text.

Chapter 2. Chapter 2 deals with operational amplifiers, their terminal characteristics, simple applications, and practical limitations. We chose to discuss the op amp as a circuit building block at this early stage simply because it is easy to deal with and because the student can experiment with op-amp circuits that perform nontrivial tasks with relative ease and with a sense of accomplishment. We have found this approach to be highly motivating to the student. We should point out, however, that part or all of this chapter can be skipped and studied at a later stage (for instance, in conjunction with Chapter 9, Chapter 11, and/or Chapter 13) with no loss of continuity.

Chapter 3. Chapter 3 provides an overview of semiconductor concepts at a level sufficient for understanding the operation of diodes and transistors in later chapters. Coverage of this material is useful in particular for students who have had no prior exposure to device physics. Even those with such a background would find a review of Chapter 3 beneficial as a refresher. The instructor can choose to cover this material in class or assign it for outside reading.

Chapter 4. The first electronic device, the diode, is studied in Chapter 4. The diode terminal characteristics, the circuit models that are used to represent it, and its circuit applications are presented. Depending on the time available in the course, some of the diode applications and special diode types (Section 4.7) can be skipped or left for the student to read.

Chapters 5 and 6. The foundation of electronic circuits is established by the study of the two transistor types in use today: the MOS transistor in Chapter 5 and the bipolar transistor in Chapter 6. ***These two chapters have been written to be completely independent of one another and thus can be studied in either order, as desired.*** Furthermore, the two chapters have the same structure, making it easier and faster to study the second device, as well as to draw comparisons between the two device types.

Each of Chapters 5 and 6 begins with a study of the device structure and its physical operation, leading to a description of its terminal characteristics. Then, to allow the student to become very familiar with the operation of the transistor as a circuit element, a large number of examples are presented of dc circuits utilizing the device. The last section of each of Chapters 5 and 6 deals with second-order effects that are included for completeness, but that can be skipped if time does not permit detailed coverage. Nevertheless, we strongly recommend coverage of the newly introduced section on Moore's law and tehnology scaling in Chapter 5.

Chapter 7. The heart of a first course in electronics is the study of transistor amplifiers. Chapter 7 presents a unified treatment of the subject. It begins with the basic principles that underlie the operation of a transistor, of either type, as an amplifier, and proceeds to present the important concepts of small-signal operation and modeling. This is followed by a study of the basic configurations of single-transistor amplifiers. After a presentation of dc biasing methods, the chapter concludes with practical examples of discrete-circuit amplifiers. The combined presentation emphasizes the unity of the basic principles while allowing for separate treatment of the two device types where this is warranted. Very importantly, we are able to compare the two devices and to draw conclusions about their unique areas of application.

After the study of Part I, the reader will be fully prepared to study either analog integrated-circuits in Part II, or digital integrated circuits in Part III.

Part II, *Analog Integrated Circuits*, is devoted to the study of practical amplifier circuits that can be fabricated in the integrated-circuit (IC) form and their application in the design of filters and oscillators. Its eight chapters constitute a coherent treatment of IC amplifier design and applications and can thus serve as a second course in electronic circuits.

MOS and Bipolar. Throughout Part II, both MOS and bipolar circuits are presented side-by-side. Because the MOSFET is by far the dominant device, its circuits are presented first. Bipolar circuits are discussed to the same depth but occasionally more briefly.

Chapter 8. Beginning with a brief introduction to the philosophy of IC design, Chapter 8 presents the basic circuit building blocks that are used in the design of IC amplifiers. These include current mirrors, current sources, gain cells, and cascode amplifiers.

Chapter 9. The most important IC building block, the differential pair, is the main topic of Chapter 9. The last section of Chapter 9 is devoted to the study of multistage amplifiers.

Chapter 10. Chapter 10 presents a comprehensive treatment of the important subject of amplifier frequency response. Here, Sections 10.1 and 10.2 contain essential material; Section 10.3 provides a very useful analysis method; Sections 10.4 to 10.7 present the frequency response analysis of a variety of amplifier configurations; and Section 10.8 presents the low-frequency response of discrete-circuit amplifiers. A selection of the later sections can be made depending on the time available and the instructor's preference.

Chapter 11. The fourth of the essential topics of Part II, feedback, is the subject of Chapter 11. Both the theory of negative feedback and its application in the design of practical feedback amplifiers are presented. We also discuss the stability problem in feedback amplifiers and treat frequency compensation in some detail.

Chapter 12. In Chapter 12 we switch gears from dealing with small-signal amplifiers to those that are required to handle large signals and large amounts of power. Here we study the different amplifier classes—A, B, and AB—and their realization in bipolar and CMOS technologies. We also briefly consider power BJTs and power MOSFETs, and introduce the increasingly popular Class D amplifier. Depending on the availability of time, some of the later sections can be skipped in a first reading.

Chapter 13. Chapter 13 brings together the topics of Part II in an important application; namely, the design of operational amplifier circuits. We study both CMOS and bipolar op amps. We focus on the most fundamental circuits: the two-stage and the folded cascode op amps. We also present biasing circuits and techniques for low-voltage operation.

The last portion of Part III, Chapters 14 and 15, deals with *Filters and Oscillators*, and is intentionally oriented toward applications and systems. The two topics illustrate powerfully and dramatically the application of both negative and positive feedback.

Chapter 14. Chapter 14 deals with the design of filters, which are important building blocks of communication and instrumentation systems. A comprehensive, design-oriented treatment of the subject is presented. The material provided, together with the supplemental material in Appendix H, should allow the reader to perform a complete filter design, starting from specification and ending with a complete circuit realization. A wealth of design material is included.

Chapter 15. Chapter 15 deals with circuits for the generation of sinusoidal signals. It also includes a section on nonlinear oscillators or function generators.

Part III, *Digital Integrated Circuits*, provides a brief but nonetheless comprehensive and sufficiently detailed study of digital IC design. Our treatment is almost self-contained, requiring for the most part only a thorough understanding of the MOSFET material presented in Chapter 5. Thus Part III can be studied right after Chapter 5. The only exception to this is that knowledge of the internal capacitances of a MOSFET (Section 10.1) will be needed before taking on Chapter 17.

Chapter 16. Chapter 16 is the foundation of Part III. It begins with the motivating topic of CMOS logic-gate circuits, with a focus on switch-level implementaion of logic functions and gates. Then, following a detailed study of digital logic inverters, we concentrate on the CMOS inverter, its static characteristics, and its design. This chapter is the minimum needed to learn something meaningful about ditigal circuits.

Chapter 17. Chapter 17 presents a comprehensive overview of the so-called trinity of digital design metrics: speed, area, and power. The chapter starts by thoroughly analyzing the dynamic characteristics of a CMOS inverter. Then, transistor sizing is discussed, including the impact of sizing on speed and circuit area. Afterwards, sources of power dissipation in digital circuits are introduced. The chapter concludes by investigating the impact of semiconductor scaling—first introduced in Chapter 5—on digital circuit performance metrics.

Chapter 18. Digital circuits can be broadly divided into logic and memory circuits. The latter is the subject of Chapter 18, which first looks at the design of latches and flip-flops, and then goes into static and dynamic cell designs for memory arrays. Finally, the chapter also introduces several useful peripheral circuits used in synchronous systems.

Appendices. The twelve appendices contain much useful background and supplementary material. We wish to draw the reader's attention in particular to the first two: Appendix A provides a concise introduction to the important topic of IC fabrication technology including IC layout. Appendix B provides SPICE device models as well as a large number of design and simulation examples in PSpice® and Multisim™. The examples are keyed to the book chapters. These Appendices and a great deal more material on these simulation examples can be found on the Companion Website.

Ancillaries

A complete set of ancillary materials is available with this text to support your course.

For the Instructor

The Ancillary Resource Center (ARC) at www.oup.com/he/sedra-smith8e is a convenient destination for all the instructor resources that accompany *Microelectronic Circuits*. Accessed online through individual user accounts, the ARC provides instructors with access to up-to-date ancillaries at any time while guaranteeing the security of grade-significant resources. On the ARC, you will find:

- **An electronic version of the Instructor's Solutions Manual.**
- **Video examples** that take students step by step through the procedures required to solve 40 problems presented in the text.
- **PowerPoint-based figure slides** that feature all the images and summary tables from the text, with their captions, so they can easily be displayed and explained in class.
- Detailed **instructor's support** for the SPICE circuit simulations.
- A set of 65 exam questions, grouped by chapter, with complete solutions, suggested time allocations, and a recommended breakdown of points per question.

The **Instructor's Solutions Manual** (ISBN 9780190853488), written by Adel Sedra, contains detailed solutions to all chapter exercises and end-of-chapter problems found in *Microelectronic Circuits*. The Instructor's Solutions Manual for ***Laboratory Explorations to Accompany Microelectronic Circuits*** (ISBN 9780197508589) contains detailed solutions to all the exercises and problems found in this student's laboratory guide; these solutions are also available online on the ARC instructor site for *Microelectronic Circuits* (www.oup.com/he/sedra-smith8e).

For the Student and Instructor

The **ARC Premium site,** available at www.oup.com/he/sedra-smith8e, features 40 professionally produced videos in which we walk students step by step through the procedures required to solve some of the most common, and complex, circuits they will have to master. ***Solved Problems*** is a set of 150 additional homework problems with complete solutions, covering concepts from the nine most used chapters in the book. This self-study aid will help students master core concepts and prepare for homework assignments and exams. Premium ARC content is included in the enhanced ebook. It is also available to purchasers of the print book using the access code packaged with new print copies. Students with rented or used print copies can purchase access codes to the ARC premium site for *Microelectronic Circuits* at www.oup.com/he/sedra-smith8e.

A Companion Website at www.oup.com/he/sedra-smith8e features permanently cached versions of device datasheets, so students can design their own circuits in class. The website also contains

SPICE circuit simulation examples and lessons. Bonus text topics and the Appendices are also featured on the website. Another very important item on the website is the Summary Tables (ST) supplement. This compilation of reference tables will benefit students completing homework assignments and studying for exams.

The ***Laboratory Explorations to Accompany Microelectronic Circuits*** (ISBN 9780197508572) invites students to explore the realm of real-world engineering through practical, hands-on experiments. Keyed to sections in the text and taking a "learn-by-doing" approach, it presents labs that focus on the development of practical engineering skills and design practices.

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Finally, we wish to thank our families for their support and understanding, and to thank all the students and instructors who have valued this book thoroughout its history.

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Microelectronic Circuits

PART I

Devices and Basic Circuits

Part I, *Devices and Basic Circuits*, includes the most fundamental and essential topics for the study of electronic circuits. At the same time, it constitutes a complete package for a first course on the subject.

The heart of Part I is the study of the three basic semiconductor devices: the diode (Chapter 4), the MOS transistor (Chapter 5), and the bipolar transistor (Chapter 6). In each case, we study the device operation, its characterization, and its basic circuit applications. Chapter 7 then follows with a study of the most fundamental application of the two transistor types; namely, their use in amplifier design. This side-by-side study of MOSFET and BJT amplifiers allows us to see similarities between these amplifiers and to compare them, which in turn highlights the distinct areas of applicability of each, as well as showing the unity of the basic principles that underlie the use of transistors as amplifiers.

For those who have not had a prior course on device physics, Chapter 3 provides an overview of semiconductor concepts at a level sufficient for the study of electronic circuits. A review of Chapter 3 should prove useful even for those with prior knowledge of semiconductors.

Since the purpose of electronic circuits is the processing of signals, it is essential to understand signals, their characterization in the time and frequency domains, and their analog and digital representations. The basis for such understanding is provided in Chapter 1, which also introduces the most common signal-processing function, *amplification*, and the characterization and types of *amplifiers*.

Besides diodes and transistors, the basic electronic devices, the op amp is studied in Part I. Although not an electronic device in the most fundamental sense, the op amp is commercially available as an integrated circuit (IC) package and has well-defined terminal characteristics. Thus, even though the op amp's internal circuit is complex, typically incorporating 20 or more transistors, its almost-ideal terminal behavior makes it possible to treat the op amp as a circuit element and to use it in the design of powerful circuits, as we do in Chapter 2, without any knowledge of its internal construction. We should mention, however, that the study of op amps can be delayed until a later point, and Chapter 2 can be skipped with no loss of continuity.

The foundation of this book, and of any electronics course, is the study of the two transistor types in use today: the MOS transistor in Chapter 5 and the bipolar transistor in Chapter 6. These two chapters have been written to be completely independent of each other and thus can be studied in either order, as desired.

After the study of Part I, the reader will be fully prepared to undertake the study of either integrated-circuit amplifiers in Part II or digital integrated circuits in Part III.

CHAPTER 1

Signals and Amplifiers

IN THIS CHAPTER YOU WILL LEARN

- That electronic circuits process signals, and thus understanding electrical signals is essential to appreciating the material in this book.
- The Thévenin and Norton representations of signal sources.
- The representation of a signal as the sum of sine waves.
- The analog and digital representations of a signal.
- The most basic and pervasive signal-processing function: signal amplification, and correspondingly, the signal amplifier.
- How amplifiers are characterized (modeled) as circuit building blocks independent of their internal circuitry.
- How the frequency response of an amplifier is measured, and how it is calculated, especially in the simple but common case of a single-time-constant (STC) type response.

Introduction

The subject of this book is modern electronics, a field that has come to be known as **microelectronics**. **Microelectronics** refers to the integrated-circuit (IC) technology that at the time of this writing is capable of producing circuits that contain billions of components in a small piece of silicon (known as a **silicon chip**) whose area is roughly 100 mm^2. One such microelectronic circuit is a complete digital computer, which is known, appropriately, as a **microcomputer** or, more generally, a **microprocessor**. The microelectronic circuits you will learn to design in this book are used in almost every device we encounter in our daily lives: in the appliances we use in our homes; in the vehicles and transportation systems we use to travel; in the cellphones we use to communicate; in the medical equipment we need to care for our health; in the computers we use to do our work; and in the audio and video systems, the gaming consoles and televisions, and the multitude of other digital devices we use to entertain ourselves. Indeed, it is difficult to conceive of modern life without microelectronic circuits.

In this book we will study electronic devices that can be used singly (in the design of **discrete circuits**) or as components of an **integrated-circuit (IC)** chip. We will study the design and analysis of interconnections of these devices, which form discrete and integrated circuits of varying complexity and perform a wide variety of functions. We will also learn about available IC chips and their application in the design of electronic systems.

The purpose of this first chapter is to introduce some basic concepts and terminology. In particular, we will learn about signals and about one of the most important signal-processing functions electronic circuits are designed to perform: signal amplification. We will then look at circuit representations or models for linear amplifiers. These models will be used in subsequent chapters in the design and analysis of actual amplifier circuits.

In addition to motivating the study of electronics, this chapter serves as a bridge between the study of linear circuits and that of the subject of this book: the design and analysis of electronic circuits. Thus, we presume a familiarity with linear circuit analysis, as in the following example.

Video Example VE 1.1

For the circuit shown in Fig. VE1.1, find the current in each of the three resistors and the voltage (with respect to ground) at their common node using two methods:

(a) Loop Equations: Define branch currents I_1 and I_2 in R_1 and R_2, respectively; write two equations and solve them.

(b) Node Equation: Define the node voltage V at the common node; write a single equation and solve it.

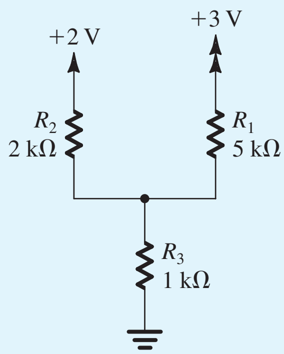


Figure VE1.1 The circuit for Video Example 1.1.

VE 1.1

Solution: Go to www.oup.com/he/sedra-smith8e to watch the authors solve this problem.

Related end-of-chapter problem: 1.17

1.1 Signals

Signals contain information about a variety of things and activities in our physical world. Examples abound: Information about the weather is contained in signals that represent the air temperature, pressure, wind speed, etc. The voice of a radio announcer reading the news into a microphone provides an acoustic signal that contains information about world affairs. To monitor the status of a nuclear reactor, instruments are used to measure a multitude of relevant parameters, each instrument producing a signal.

To extract required information from a set of signals, the observer (be it a human or a machine) invariably needs to **process** the signals in some predetermined manner. This **signal processing** is usually most conveniently performed by electronic systems. For this to be possible, however, the signal must first be converted into an electrical signal, that is, a voltage or a current. This process is accomplished by devices known as **transducers**. A variety of transducers exist, each suitable for one of the various forms of physical signals. For instance, the sound waves generated by a human can be converted into electrical signals using a microphone, which is in effect a pressure transducer. It is not our purpose here to study transducers; rather, we shall assume that the signals of interest already exist in the electrical domain and represent them by one of the two equivalent forms shown in Fig. 1.1.

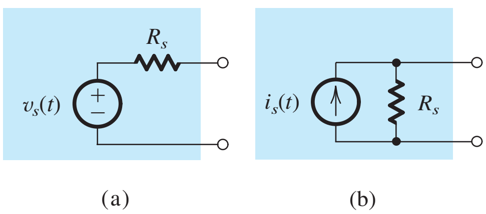


Figure 1.1 Two alternative representations of a signal source: **(a)** the Thévenin form; **(b)** the Norton form.

In Fig. 1.1(a) the signal is represented by a voltage source $v_s(t)$ with a source resistance R_s. In the alternate representation of Fig. 1.1(b) the signal is represented by a current source $i_s(t)$ with a source resistance R_s. Although the two representations are equivalent, the one in Fig. 1.1(a) (known as the Thévenin form) is preferred when R_s is low. The representation of Fig. 1.1(b) (known as the Norton form) is preferred when R_s is high. You will come to appreciate this point later in this chapter when we study the different types of amplifiers. For the time being, it is important to be familiar with Thévenin's and Norton's theorems (for a brief review, see Appendix D) and to note that for the two representations in Fig. 1.1 to be equivalent, their parameters are related by

$$v_s(t) = R_s i_s(t)$$

Example 1.1

The output resistance of a signal source, although inevitable, is an imperfection that limits the ability of the source to deliver its full signal strength to a **load**. To see this point more clearly, consider the signal source when connected to a load resistance R_L as shown in Fig. 1.2. For the case in which the source is represented by its Thévenin equivalent form, find the voltage v_o that appears across R_L, and hence the condition that R_s must satisfy for v_o to be close to the value of v_s. Repeat for the Norton-represented source, in this case finding the current i_o that flows through R_L and hence the condition that R_s must satisfy for i_o to be close to the value of i_s.

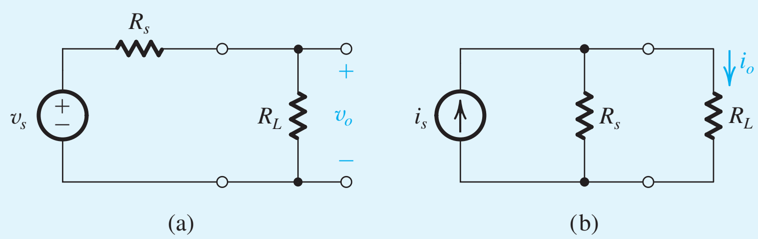


Figure 1.2 Circuits for Example 1.1.

Solution

For the Thévenin-represented signal source shown in Fig. 1.2(a), the output voltage v_o that appears across the load resistance R_L can be found from the ratio of the voltage divider formed by R_s and R_L,

$$v_o = v_s \frac{R_L}{R_L + R_s}$$

From this equation we see that as long as $R_s \ll R_L$,

$$v_o \simeq v_s$$

insensitive to small changes in R_s and R_L. Thus, for a source represented by its Thévenin equivalent, ideally $R_s = 0$, and as R_s is increased, relative to the load resistance R_L, the voltage v_o that appears across the load becomes smaller, not a desirable outcome.

Example 1.1 *continued*

Next, we consider the Norton-represented signal source in Fig. 1.2(b). To obtain the current i_o that flows through the load resistance R_L, we use the ratio of the current divider formed by R_s and R_L,

$$i_o = i_s \frac{R_s}{R_s + R_L}$$

From this relationship we see that as long as $R_s \gg R_L$,

$$i_o \simeq i_s$$

insensitive to the precise values of R_s and R_L. Thus for a signal source represented by its Norton equivalent, ideally $R_s = \infty$, and as R_s is reduced, relative to the load resistance R_L, the current i_o that flows through the load becomes smaller, not a desirable outcome.

Finally, we note that although circuit designers cannot usually do much about the value of R_s, they may have to devise a circuit solution that minimizes or eliminates the loss of signal strength that results when the source is connected to the load.

Video Example VE 1.2

Consider the voltage source in Fig. 1.2(a) connected to loads with the values shown below. In each case, find the percentage change in the voltage and current across R_L, v_o and o_o, in response to a 10% increase in the value of R_L. In which cases is it more appropriate to use a Norton equivalent source? In those cases, find the Norton equivalent for $V_s = 1$ V.

(a) $R_s = 2$ kΩ; $R_L = 100$ kΩ
(b) $R_s = 100$ Ω; $R_L = 8$ Ω
(c) $R_s = 5$ kΩ; $R_L = 50$ kΩ
(d) $R_s = 1$ kΩ; $R_L = 50$ Ω

VE 1.2

Solution: Go to www.oup.com/he/sedra-smith8e to watch the authors solve this problem.

Related end-of-chapter problem: **1.30**

EXERCISES

1.1 For the signal-source representations shown in Figs. 1.1(a) and 1.1(b), what are the open-circuit output voltages that would be observed? If, for each, the output terminals are short-circuited (i.e., wired together), what current would flow? For the representations to be equivalent, what must the relationship be between v_s, i_s, and R_s?

Ans. For (a), $v_{oc} = v_s(t)$; for (b), $v_{oc} = R_s i_s(t)$; for (a), $i_{sc} = v_s(t)/R_s$; for (b), $i_{sc} = i_s(t)$; for equivalency, $v_s(t) = R_s i_s(t)$

1.2 A signal source has an open-circuit voltage of 10 mV and a short-circuit current of 10 μA. What is the source resistance?
Ans. 1 kΩ

1.3 A signal source that is most conveniently represented by its Thévenin equivalent has $v_s = 10$ mV and $R_s = 1$ kΩ. If the source feeds a load resistance R_L, find the voltage v_o that appears across the load for $R_L = 100$ kΩ, 10 kΩ, 1 kΩ, and 100 Ω. Also, find the lowest permissible value of R_L for which the output voltage is at least 80% of the source voltage.
Ans. 9.9 mV; 9.1 mV; 5 mV; 0.9 mV; 4 kΩ

1.4 A signal source that is most conveniently represented by its Norton equivalent form has $i_s = 10$ μA and $R_s = 100$ kΩ. If the source feeds a load resistance R_L, find the current i_o that flows through the load for $R_L = 1$ kΩ, 10 kΩ, 100 kΩ, and 1 MΩ. Also, find the largest permissible value of R_L for which the load current is at least 80% of the source current.
Ans. 9.9 μA; 9.1 μA; 5 μA; 0.9 μA; 25 kΩ

From the discussion above, it should be apparent that a signal is a time-varying quantity that can be represented by a graph such as that shown in Fig. 1.3. In fact, the information content of the signal is represented by the changes in its magnitude as time progresses; that is, the information is contained in the "wiggles" in the signal waveform. In general, such waveforms are difficult to characterize mathematically. In other words, it is not easy to describe succinctly an arbitrary-looking waveform such as that of Fig. 1.3. Of course, such a description is of great importance for the purpose of designing appropriate signal-processing circuits that perform desired functions on the given signal. An effective approach to signal characterization is studied in the next section.

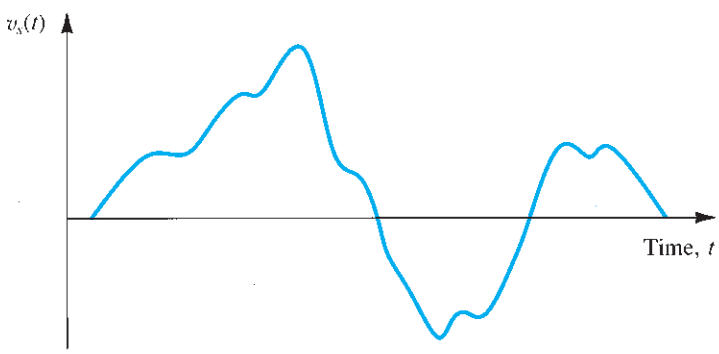


Figure 1.3 An arbitrary voltage signal $v_s(t)$.

1.2 Frequency Spectrum of Signals

It can be extremely useful to characterize a signal, and for that matter any arbitrary function of time, in terms of its **frequency spectrum**. We can obtain such a description of signals through the mathematical tools of **Fourier series** and **Fourier transform**.[1] We are not interested here in the details of these transformations; suffice it to say that they provide the means for representing a voltage signal $v_s(t)$ or a current signal $i_s(t)$ as the sum of sine-wave signals of different frequencies and amplitudes. This makes the sine wave a very important signal in the analysis, design, and testing of electronic circuits. Therefore, we shall briefly review the properties of the sinusoid.

Figure 1.4 shows a sine-wave voltage signal $v_a(t)$,

$$v_a(t) = V_a \sin \omega t \tag{1.1}$$

where V_a denotes the peak value or amplitude in volts and ω denotes the angular frequency in radians per second; that is, $\omega = 2\pi f$ rad/s, where f is the frequency in hertz, $f = 1/T$ Hz, and T is the period in seconds.

The sine-wave signal is completely characterized by its peak value V_a, its frequency ω, and its phase with respect to an arbitrary reference time. In the case depicted in Fig. 1.4, the time origin has been chosen so that the phase angle is 0. It is common to express the amplitude of a sine-wave signal in terms of its root-mean-square (rms) value, which is equal to the peak value divided by $\sqrt{2}$. Thus the rms value of the sinusoid $v_a(t)$ of Fig. 1.4 is $V_a/\sqrt{2}$. For instance, when we speak of the wall power supply in our homes as being 120 V, we mean that it has a sine waveform of $120\sqrt{2}$ volts peak value.

Returning now to the representation of signals as the sum of sinusoids, we note that the Fourier series is utilized to accomplish this task for the special case of a signal that is a periodic function of time. On the other hand, the Fourier transform is more general and can be used to obtain the frequency spectrum of a signal whose waveform is an arbitrary function of time.

The Fourier series allows us to express a given periodic function of time as the sum of an infinite number of sinusoids whose frequencies are harmonically related. For instance, the symmetrical square-wave signal in Fig. 1.5 can be expressed as

$$v(t) = \frac{4V}{\pi}\left(\sin \omega_0 t + \frac{1}{3}\sin 3\omega_0 t + \frac{1}{5}\sin 5\omega_0 t + \cdots\right) \tag{1.2}$$

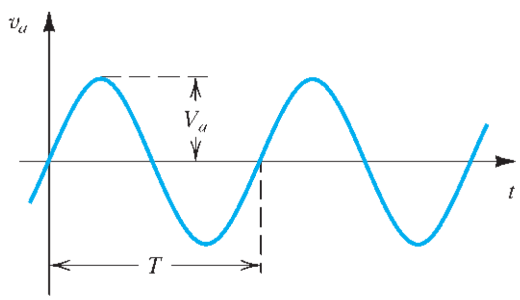


Figure 1.4 Sine-wave voltage signal of amplitude V_a and frequency $f = 1/T$ Hz. The angular frequency $\omega = 2\pi f$ rad/s.

[1]The reader who has not yet studied these topics should not be alarmed. No detailed application of this material will be made until Chapter 10. Nevertheless, a general understanding of Section 1.2 should be very helpful in studying early parts of this book.

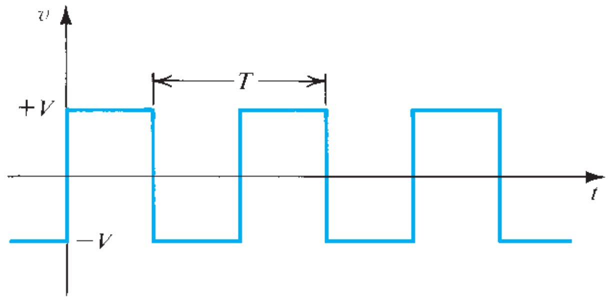


Figure 1.5 A symmetrical square-wave signal of amplitude V.

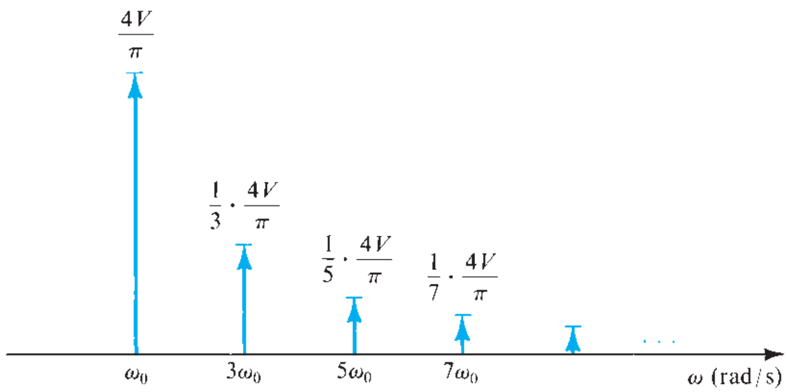


Figure 1.6 The frequency spectrum (also known as the **line spectrum**) of the periodic square wave of Fig. 1.5.

where V is the amplitude of the square wave and $\omega_0 = 2\pi/T$ (T is the period of the square wave) is called the **fundamental frequency**. Note that because the amplitudes of the harmonics progressively decrease, the infinite series can be truncated, with the truncated series providing an approximation to the square waveform.

The sinusoidal components in the series of Eq. (1.2) constitute the frequency spectrum of the square-wave signal. Such a spectrum can be graphically represented as in Fig. 1.6, where the horizontal axis represents the angular frequency ω in radians per second.

The Fourier transform can be applied to a nonperiodic function of time, such as that depicted in Fig. 1.3, and provides its frequency spectrum as a continuous function of frequency, as indicated in Fig. 1.7. Unlike the case of periodic signals, where the spectrum consists of discrete frequencies (at ω_0 and its harmonics), the spectrum of a nonperiodic signal contains in general all possible frequencies. Nevertheless, the essential parts of the spectra of practical signals are usually confined to relatively short segments of the frequency (ω) axis—an observation that is very useful in the processing of such signals. For instance, the spectrum of audible sounds such as speech and music extends from about 20 Hz to about 20 kHz—a frequency range known as the **audio band**. Note that although some musical tones have frequencies above 20 kHz, the human ear is incapable of hearing frequencies that are much above 20 kHz. Analog video signals have their spectra in the range of 0 MHz to 4.5 MHz.

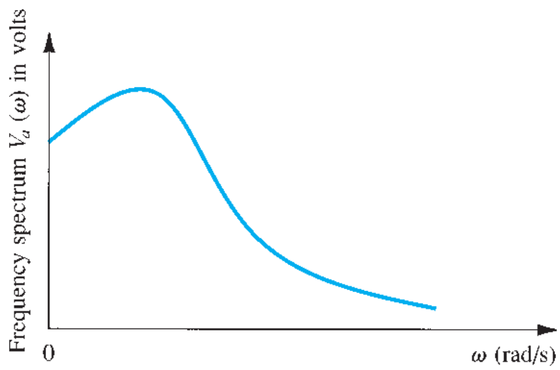


Figure 1.7 The frequency spectrum of an arbitrary waveform such as that in Fig. 1.3.

We conclude this section by noting that a signal can be represented either by the manner in which its waveform varies with time, as for the voltage signal $v_a(t)$ shown in Fig. 1.3, or in terms of its frequency spectrum, as in Fig. 1.7. The two alternative representations are known as the time-domain representation and the frequency-domain representation, respectively. The frequency-domain representation of $v_a(t)$ will be denoted by the symbol $V_a(\omega)$.

EXERCISES

1.5 Find the frequencies f and ω of a sine-wave signal with a period of 1 ms.
Ans. $f = 1000$ Hz; $\omega = 2\pi \times 10^3$ rad/s

1.6 What is the period T of sine waveforms characterized by frequencies of (a) $f = 60$ Hz? (b) $f = 10^{-3}$ Hz? (c) $f = 1$ MHz?
Ans. 16.7 ms; 1000 s; 1 μs

1.7 The UHF (ultra high frequency) television broadcast band begins with channel 14 and extends from 470 MHz to 608 MHz. If 6 MHz is allocated for each channel, how many channels can this band accommodate?
Ans. 23; channels 14 to 36

1.8 When the square-wave signal of Fig. 1.5, whose Fourier series is given in Eq. (1.2), is applied to a resistor, the total power dissipated may be calculated directly using the relationship $P = 1/T \int_0^T (v^2/R)\,dt$ or indirectly by summing the contribution of each of the harmonic components, that is, $P = P_1 + P_3 + P_5 + \ldots$, which may be found directly from rms values. Verify that the two approaches are equivalent. What fraction of the energy of a square wave is in its fundamental? In its first five harmonics? In its first seven? First nine? In what number of harmonics is 90% of the energy? (Note that in counting harmonics, the fundamental at ω_0 is the first, the one at $2\omega_0$ is the second, etc.)
Ans. 0.81; 0.93; 0.95; 0.96; 3

1.3 Analog and Digital Signals

The voltage signal depicted in Fig. 1.3 is called an **analog signal**. The name derives from the fact that such a signal is *analogous* to the physical signal that it represents. The magnitude of an analog signal can take on any value; that is, the amplitude of an analog signal exhibits a continuous variation over its range of activity. The vast majority of signals in the world around us are analog. Electronic circuits that process such signals are known as **analog circuits**. A variety of analog circuits will be studied in this book.

An alternative form of signal representation is that of a sequence of numbers, each number representing the signal magnitude at an instant of time. The resulting signal is called a **digital signal**. To see how a signal can be represented in this form—that is, how signals can be converted from analog to digital form—consider Fig. 1.8(a). Here the curve represents a voltage signal, identical to that in Fig. 1.3. At equal intervals along the time axis, we have marked the time instants t_0, t_1, t_2, and so on. At each of these time instants, the magnitude of the signal is measured, a process known as **sampling**. Figure 1.8(b) shows a representation of the signal of Fig. 1.8(a) in terms of its samples. The signal of Fig. 1.8(b) is defined only at the sampling instants; it no longer is a continuous function of time; rather, it is a **discrete-time signal**. However, since the magnitude of each sample can take any value in a continuous range, the signal in Fig. 1.8(b) is still an analog signal.

Now if we represent the magnitude of each of the signal samples in Fig. 1.8(b) by a number having a finite number of digits, then the signal amplitude will no longer be continuous; rather, it is said to be **quantized**, **discretized**, or **digitized**. The resulting digital signal then is simply a sequence of numbers that represent the magnitudes of the successive signal samples.

The choice of number system to represent the signal samples affects the type of digital signal produced and has a profound effect on the complexity of the digital circuits required to process the signals. It turns out that the **binary** number system results in the simplest possible digital signals and circuits. In a binary system, each digit in the number takes on one of only two possible values, denoted 0 and 1. Correspondingly, the digital signals in binary systems need have only two voltage levels, which can be labeled low and high. As an example, in some of the digital circuits studied in this book, the levels may be 0 V and +1.8 V. Figure 1.9 shows the time variation of such a digital signal. Observe that the waveform is a pulse train with 0 V representing a 0 signal, or logic 0, and +1.8 V representing logic 1. Unlike the original analog signal, which can take on any real value and therefore can be corrupted by noise, the digital waveform can withstand some noise while still being able to distinguish between logic levels without any loss of information.

If we use N *b*inary dig*its* (bits) to represent each sample of the analog signal, then the digitized sample value can be expressed as

$$D = b_0 2^0 + b_1 2^1 + b_2 2^2 + \cdots + b_{N-1} 2^{N-1} \tag{1.3}$$

where $b_0, b_1, \ldots, b_{N-1}$, denote the N bits and have values of 0 or 1. Here bit b_0 is the **least significant bit** (**LSB**), and bit b_{N-1} is the **most significant bit** (**MSB**). Conventionally, this binary number is written as $b_{N-1}\, b_{N-2} \ldots b_0$. We observe that such a representation quantizes the analog sample into one of 2^N levels. Obviously the greater the number of bits (i.e., the larger the N), the closer the digital word D approximates the magnitude of the analog sample. That is, increasing the number of bits reduces the *quantization error* and increases the resolution of the analog-to-digital conversion. This improvement is, however, usually obtained at the expense of more complex and hence more costly circuit implementations. It

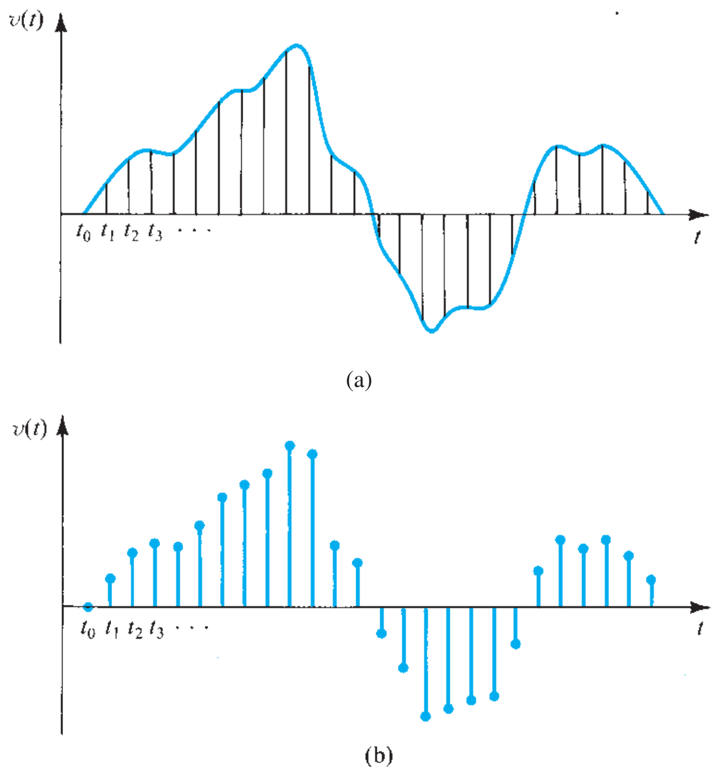


Figure 1.8 Sampling the continuous-time analog signal in **(a)** results in the discrete-time signal in **(b)**.

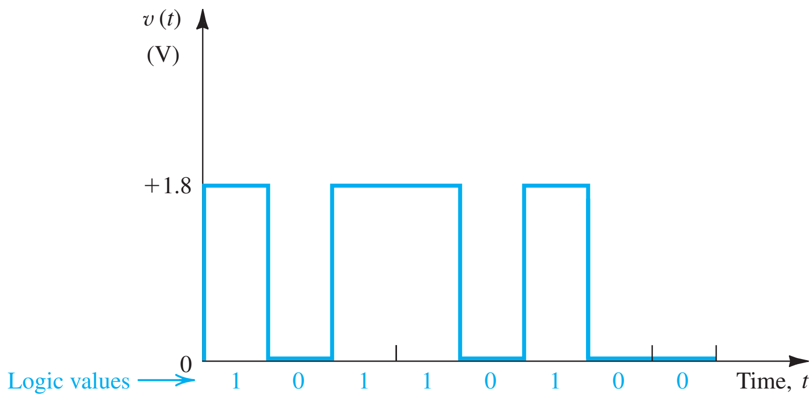


Figure 1.9 Variation of a particular binary digital signal with time.

is not our purpose here to delve into this topic any deeper; we merely want the reader to appreciate the nature of analog and digital signals. Nevertheless, it is an opportune time to introduce a very important circuit building block of modern electronic systems: the **analog-to-digital converter** (**A/D** or **ADC**) shown in block form in Fig. 1.10. The ADC accepts at its input the samples of an analog signal and provides for each input sample the corresponding N-bit digital representation (according to Eq. 1.3) at its N output terminals.

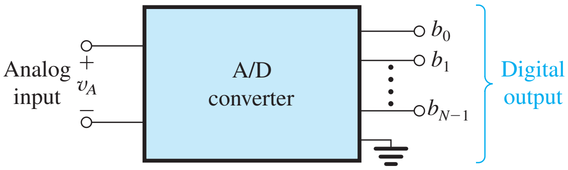


Figure 1.10 Block-diagram representation of the analog-to-digital converter (ADC).

Thus although the voltage at the input might be, say, 1.51 V, at each of the output terminals (say, at the *i*th terminal), the voltage will be either low (0 V) or high (1.8 V) if b_i is supposed to be 0 or 1, respectively. The dual circuit of the ADC is the **digital-to-analog converter** (**D/A** or **DAC**). It converts an *N*-bit digital input to an analog output voltage.

Once the signal is in digital form, it can be processed using **digital circuits**. Of course digital circuits can deal also with signals that do not have an analog origin, such as the signals that represent the various instructions of a digital computer.

Since digital circuits deal exclusively with binary signals, their design is simpler than that of analog circuits. Furthermore, digital systems can be designed using a relatively few different kinds of digital circuit blocks. However, a large number (e.g., hundreds of thousands or even millions) of each of these blocks are usually needed. Thus the design of digital circuits poses its own set of challenges to the designer but provides reliable and economic implementations of a great variety of signal-processing functions, many of which are not possible with analog circuits. Many signal-processing functions that relied upon analog circuits in the past are now being performed digitally. Examples around us abound, from the digital watch and calculator to digital audio systems and telephony. Modern computers and smartphones are enabled by very-large-scale digital circuits. Image and video recording, storage, and transmission are all predominantly performed by digital circuits. Digital circuits have a particularly special role to play in communication because digital information is inherently more robust to noise than an analog signal.

The basic building blocks of digital systems are logic circuits and memory circuits. We will study both in this book, beginning in Chapter 16.

One final remark: Although the digital processing of signals may appear to be all-pervasive, in fact many electronic systems include both analog and digital parts. It follows that a good electronics engineer must be proficient in the design of both analog and digital circuits, or **mixed-signal** or **mixed-mode** design as it is currently known. Such is the aim of this book.

EXERCISE

1.9 Consider a 4-bit digital word $D = b_3b_2b_1b_0$ (see Eq. 1.3) used to represent an analog signal v_A that varies between 0 V and +3.75 V.

(a) Give *D* corresponding to $v_A = 0$ V, 0.25 V, 1 V, and 3.75 V.

(b) What change in v_A causes a change from 0 to 1 in (i) b_0, (ii) b_1, (iii) b_2, and (iv) b_3?

(c) If $v_A = 1.3$ V, what do you expect *D* to be? What is the resulting error in representation?

Ans. (a) 0000, 0001, 0100, 1111; (b) +0.25 V, +0.50 V, +1 V, +2 V; (c) 0101, –4%

ANALOG VS. DIGITAL CIRCUIT ENGINEERS

As digital became the preferred implementation of more and more signal-processing functions, the need arose for greater numbers of digital circuit design engineers. Yet despite predictions made periodically that the demand for analog circuit design engineers would lessen, this has not been the case. Rather, the demand for analog engineers has, if anything, increased. What is true, however, is that the skill level required of analog engineers has risen. Not only are they asked to design circuits of greater sophistication and tighter specifications, but they also have to do this using technologies that are optimized for digital (and not analog) circuits. This is dictated by economics, as digital usually constitutes the larger part of most systems.

1.4 Amplifiers

In this section, we shall introduce the most fundamental signal-processing function, one that is employed in some form in almost every electronic system, namely, signal amplification. We shall study the amplifier as a circuit building block; that is, we shall consider its external characteristics and leave the design of its internal circuit to later chapters.

1.4.1 Signal Amplification

From a conceptual standpoint, the simplest signal-processing task is **signal amplification**. The need for amplification arises because transducers provide signals that are said to be "weak," that is, in the microvolt (μV) or millivolt (mV) range and possessing little energy. Such signals are too small for reliable processing, which becomes much easier if the signal magnitude is made larger. The functional block that accomplishes this task is the **signal amplifier**.

It is appropriate at this point to discuss the need for **linearity** in amplifiers. Care must be exercised in the amplification of a signal, so that the information contained in the signal is not changed and no new information is introduced. Thus when we feed the signal shown in Fig. 1.3 to an amplifier, we want the output signal of the amplifier to be an exact replica of that at the input, except of course for having larger magnitude. In other words, the "wiggles" in the output waveform must be identical to those in the input waveform. Any change in waveform is considered to be **distortion** and is obviously undesirable.

An amplifier that preserves the details of the signal waveform is characterized by the relationship

$$v_o(t) = Av_i(t) \tag{1.4}$$

where v_i and v_o are the input and output signals, respectively, and A is a constant representing the magnitude of amplification, known as **amplifier gain**. Equation (1.4) is a linear relationship; hence the amplifier it describes is a **linear amplifier**. It should be easy to see that if the relationship between v_o and v_i contains higher powers of v_i, then the waveform of v_o will no longer be identical to that of v_i. The amplifier is then said to exhibit **nonlinear distortion**.

The amplifiers discussed so far are primarily intended to operate on very small input voltage signals. Their purpose is to make the signal magnitude larger, and therefore they are

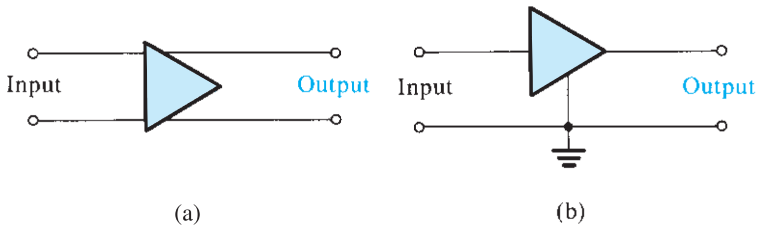


Figure 1.11 **(a)** Circuit symbol for amplifier. **(b)** An amplifier with a common terminal (ground) between the input and output ports.

thought of as **voltage amplifiers**. The **preamplifier** in the home stereo system is an example of a voltage amplifier.

At this time we wish to mention another type of amplifier, namely, the **power amplifier**. Such an amplifier may provide only a modest amount of voltage gain but substantial current gain. Thus while absorbing little power from the input signal source to which it is connected, often a preamplifier, it delivers large amounts of power to its load. An example is found in the power amplifier of the home stereo system, whose purpose is to provide sufficient power to drive the loudspeaker, which is the amplifier load. Here we should note that the loudspeaker is the output transducer of the stereo system; it converts the electric output signal of the system into an acoustic signal. A further appreciation of the need for linearity can be acquired by reflecting on the power amplifier. A linear power amplifier causes both soft and loud music passages to be reproduced without distortion.

1.4.2 Amplifier Circuit Symbol

The signal amplifier is obviously a two-port circuit. Its function is conveniently represented by the circuit symbol of Fig. 1.11(a). This symbol clearly distinguishes the input and output ports and indicates the direction of signal flow. Thus, in subsequent diagrams it will not be necessary to label the two ports "input" and "output." For generality we have shown the amplifier to have two input terminals that are distinct from the two output terminals. A more common situation is illustrated in Fig. 1.11(b), where a common terminal exists between the input and output ports of the amplifier. This common terminal is used as a reference point and is called the **circuit ground**.

1.4.3 Voltage Gain

A linear amplifier accepts an input signal $v_I(t)$ and provides at the output, across a load resistance R_L (see Fig. 1.12(a)), an output signal $v_O(t)$ that is a magnified replica of $v_I(t)$. The **voltage gain** of the amplifier is defined by

$$\text{Voltage gain } (A_v) = \frac{v_O}{v_I} \tag{1.5}$$

Fig. 1.12(b) shows the **transfer characteristic** of a linear amplifier. If we apply to the input of this amplifier a sinusoidal voltage of amplitude $\hat{V}$, we obtain at the output a sinusoid of amplitude $A_v\hat{V}$.

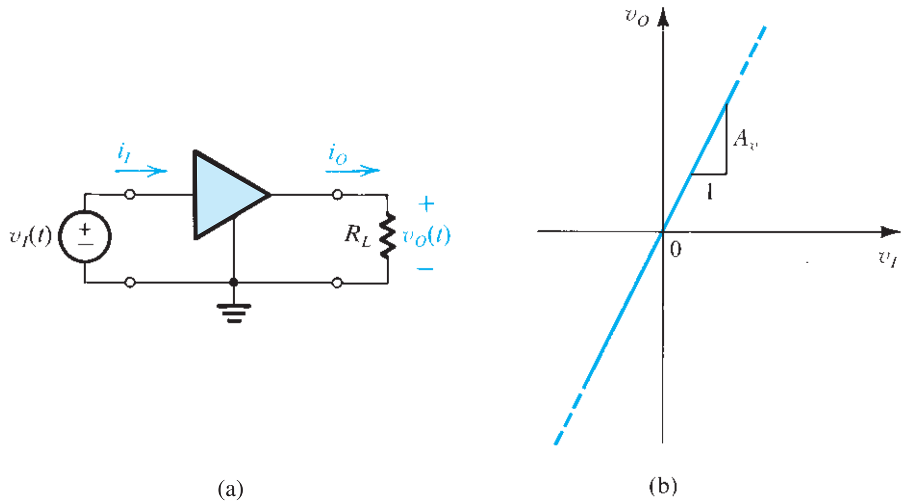


Figure 1.12 **(a)** A voltage amplifier fed with a signal $v_I(t)$ and connected to a load resistance R_L. **(b)** Transfer characteristic of a linear voltage amplifier with voltage gain A_v.

1.4.4 Power Gain and Current Gain

An amplifier increases the signal power, an important feature that distinguishes an amplifier from a transformer. In the case of a transformer, although the voltage delivered to the load could be greater than the voltage feeding the input side (the primary), the power delivered to the load (from the secondary side of the transformer) is less than or at most equal to the power supplied by the signal source. On the other hand, an amplifier provides the load with power greater than that obtained from the signal source. That is, amplifiers have power gain. The **power gain** of the amplifier in Fig. 1.12(a) is defined as

$$\text{Power gain } (A_p) \equiv \frac{\text{load power } (P_L)}{\text{input power} (P_I)} \tag{1.6}$$

$$= \frac{v_O i_O}{v_I i_I} \tag{1.7}$$

where i_O is the current that the amplifier delivers to the load $(R_L), i_O = v_O/R_L$, and i_I is the current the amplifier draws from the signal source. The **current gain** of the amplifier is defined as

$$\text{Current gain } (A_i) \equiv \frac{i_O}{i_I} \tag{1.8}$$

From Eqs. (1.5) to (1.8) we note that

$$A_p = A_v A_i \tag{1.9}$$

1.4.5 Expressing Gain in Decibels

The amplifier gains defined above are ratios of similarly dimensioned quantities. Thus they will be expressed either as dimensionless numbers or, for emphasis, as V/V for the voltage gain, A/A for the current gain, and W/W for the power gain. Alternatively, for a number of reasons, some of them historic, electronics engineers express amplifier gain with a logarithmic measure. Specifically the voltage gain A_v can be expressed as

$$\text{Voltage gain in decibels} = 20 \log |A_v| \quad \text{dB}$$

and the current gain A_i can be expressed as

$$\text{Current gain in decibels} = 20 \log |A_i| \quad \text{dB}$$

Since power is related to voltage (or current) squared, the power gain A_p can be expressed in decibels as

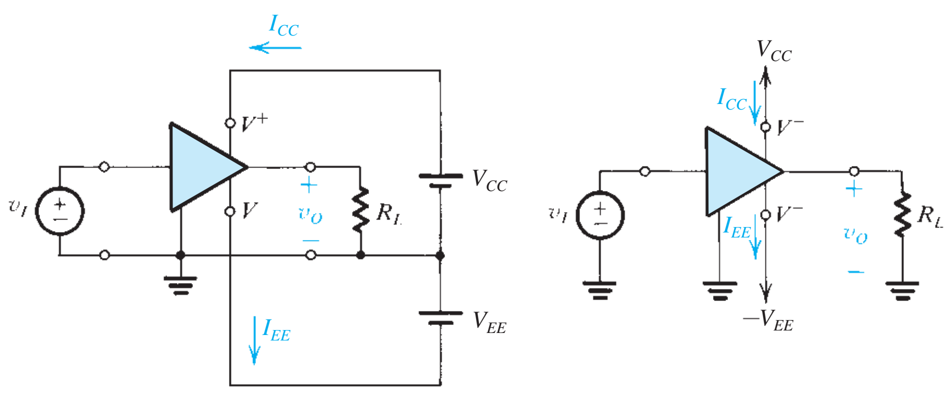
$$\text{Power gain in decibels} = 10 \log A_p \quad \text{dB}$$

The absolute values of the voltage and current gains are used because in some cases A_v or A_i will be a negative number. A negative gain A_v simply means that there is a 180° phase difference between input and output signals; it does not imply that the amplifier is **attenuating** the signal. On the other hand, an amplifier whose voltage gain is, say, −20 dB is in fact attenuating the input signal by a factor of 10 (i.e., $A_v = 0.1$ V/V).

1.4.6 The Amplifier Power Supplies

Since the power delivered to the load is greater than the power drawn from the signal source, you may wonder where this additional power comes from. The answer is found by observing that amplifiers need dc power supplies for their operation. These dc sources supply the extra power delivered to the load as well as any power that might be dissipated in the internal circuit of the amplifier (such power is converted to heat). In Fig. 1.12(a) we have not explicitly shown these dc sources.

Figure 1.13(a) shows an amplifier that requires two dc sources: one positive of value V_{CC} and one negative of value V_{EE}. The amplifier has two terminals, labeled V^+ and V^-, for connection to the dc supplies. For the amplifier to operate, the terminal labeled V^+ has to be connected to the positive side of a dc source whose voltage is V_{CC} and whose negative side is connected to the circuit ground. Also, the terminal labeled V^- has to be connected to the



(a) (b)

Figure 1.13 An amplifier that requires two dc supplies (shown as batteries) for operation.

negative side of a dc source whose voltage is V_{EE} and whose positive side is connected to the circuit ground. Now, if the current drawn from the positive supply is denoted I_{CC} and that from the negative supply is I_{EE} (see Fig. 1.13a), then the dc power delivered to the amplifier is

$$P_{\mathrm{dc}} = V_{CC}I_{CC} + V_{EE}I_{EE}$$

If the power dissipated in the amplifier circuit is denoted $P_{\mathrm{dissipated}}$, the power-balance equation for the amplifier can be written as

$$P_{\mathrm{dc}} + P_I = P_L + P_{\mathrm{dissipated}}$$

where P_I is the power drawn from the signal source and P_L is the power delivered to the load. Since the power drawn from the signal source is usually small, the amplifier power **efficiency** is defined as

$$\eta \equiv \frac{P_L}{P_{\mathrm{dc}}} \times 100 \tag{1.10}$$

The power efficiency is an important performance parameter for amplifiers that handle large amounts of power. Such amplifiers, called power amplifiers, are used, for example, as output amplifiers of stereo systems.

In order to simplify circuit diagrams, we shall adopt the convention illustrated in Fig. 1.13(b). Here the V^+ terminal is shown connected to an arrowhead pointing upward and the V^- terminal to an arrowhead pointing downward. The corresponding voltage is indicated next to each arrowhead. Note that in many cases we will not explicitly show the connections of the amplifier to the dc power sources. Finally, we note that some amplifiers require only one power supply.

Example 1.2

Consider a microphone producing a sinusoidal signal that is 400-mV peak. It delivers 10-μA peak sinusoidal current to an amplifier that operates from ±1-V power supplies. The amplifier delivers a 0.8-V peak sinusoid to a speaker load with 32-Ω resistance. The amplifier draws a current of 30 mA from each of its two power supplies. Find the voltage gain, the current gain, the power gain, the power drawn from the dc supplies, the power dissipated in the amplifier, and the amplifier efficiency.

Solution

$$A_v = \frac{0.8\ \mathrm{V}}{0.4\ \mathrm{V}} = 2\ \mathrm{V/V},\ \text{or}\ A_v = 20\log 2 = 6\ \mathrm{dB}$$

$$\hat{I}_o = \frac{0.8\ \mathrm{V}}{32\ \Omega} = 25\ \mathrm{mA}$$

$$A_i = \frac{\hat{I}_o}{\hat{I}_i} = \frac{25\text{ mA}}{0.01\text{ mA}} = 2500\text{ A/A, or } A_i = 20\log 2500 = 68\text{ dB}$$

$$P_L = V_{o\text{rms}}\, I_{o\text{rms}} = \frac{0.8\text{ V}}{\sqrt{2}}\,\frac{25\text{ mA}}{\sqrt{2}} = 10\text{ mW}$$

$$P_I = V_{i\text{rms}}\, I_{i\text{rms}} = \frac{0.4\text{ V}}{\sqrt{2}}\,\frac{0.01\text{ mA}}{\sqrt{2}} = 2\ \mu\text{W}$$

$$A_p = \frac{P_L}{P_I} = \frac{10\text{ mW}}{2\ \mu\text{W}} = 5000\text{ W/W, or } A_p = 10\log 5000 = 37\text{ dB}$$

$$P_{\text{dc}} = 1\text{ V} \times 30\text{ mA} + 1\text{ V} \times 30\text{ mA} = 60\text{ mW}$$

$$P_{\text{dissipated}} = P_{\text{dc}} + P_I - P_L$$
$$= 60\text{ mW} + 0.002\text{ mW} - 10\text{ mW} \simeq 50\text{ mW}$$

$$\eta = \frac{P_L}{P_{\text{dc}}} \times 100 = 16.7\%$$

From the above example we observe that the amplifier converts some of the dc power it draws from the power supplies to signal power that it delivers to the load.

1.4.7 Amplifier Saturation

Practically speaking, the amplifier transfer characteristic remains linear over only a limited range of input and output voltages. For an amplifier operated from two power supplies the output voltage cannot exceed a specified positive limit and cannot decrease below a specified negative limit. The resulting transfer characteristic is shown in Fig. 1.14, with the positive and negative saturation levels denoted L_+ and L_-, respectively. Each of the two saturation levels is usually within a fraction of a volt of the voltage of the corresponding power supply.

Obviously, in order to avoid distorting the output signal waveform, the input signal swing must be kept within the linear range of operation,

$$\frac{L_-}{A_v} \le v_I \le \frac{L_+}{A_v}$$

In Fig. 1.14, which shows two input waveforms and the corresponding output waveforms, the peaks of the larger waveform have been clipped off because of amplifier saturation.

1.4.8 Symbol Convention

At this point, we draw your attention to the terminology we will use throughout the book. To illustrate, Fig. 1.15 shows the waveform of a current $i_C(t)$ that is flowing through a branch in a particular circuit. The current $i_C(t)$ consists of a dc component I_C on which is superimposed a sinusoidal component $i_c(t)$ whose peak amplitude is I_c. Observe that at a time t, the **total**

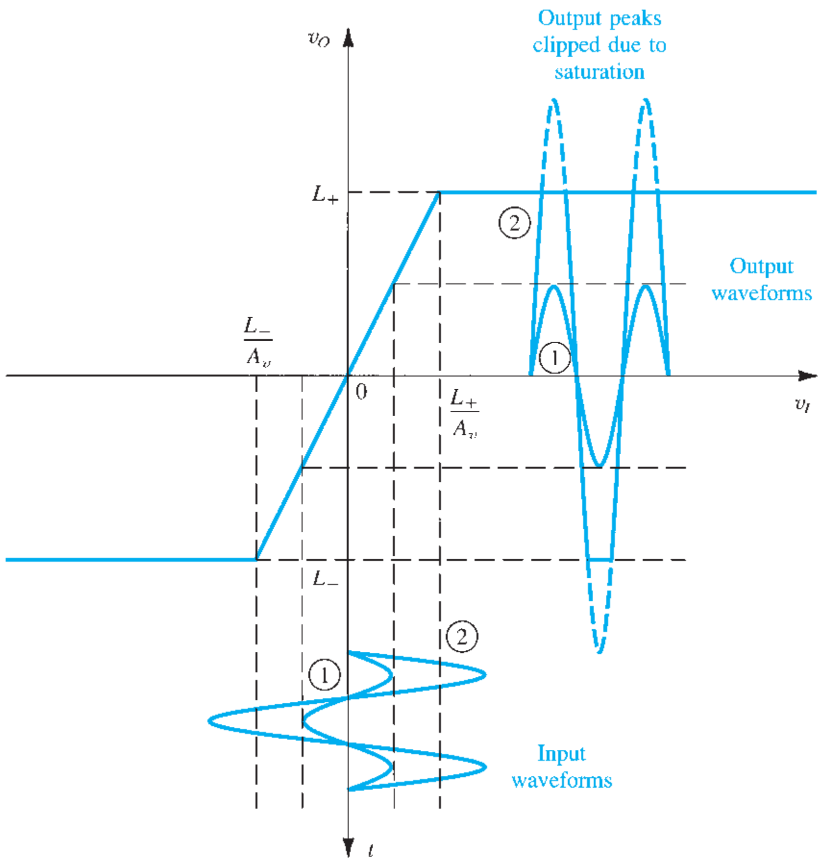


Figure 1.14 An amplifier transfer characteristic that is linear except for output saturation.

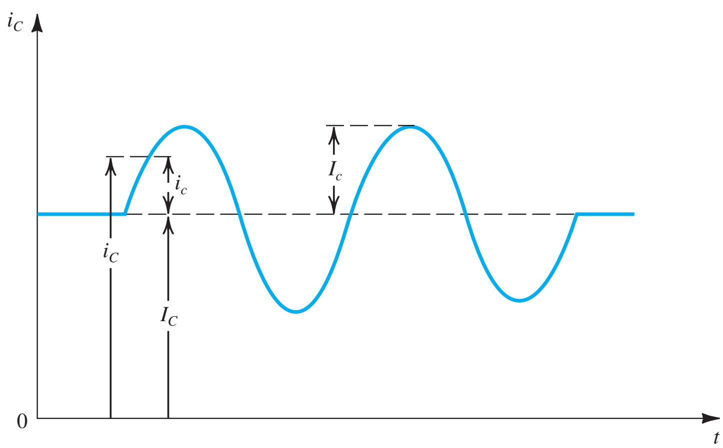


Figure 1.15 Symbol convention employed throughout the book.

instantaneous current $i_C(t)$ is the sum of the dc current I_C and the signal current $i_c(t)$,

$$i_C(t) = I_C + i_c(t) \tag{1.11}$$

where the signal current is given by

$$i_c(t) = I_c \sin \omega t$$

Thus, we state some conventions: Total instantaneous quantities are denoted by a lowercase symbol with uppercase subscript(s), for example, $i_C(t), v_{DS}(t)$. Direct-current (dc) quantities are denoted by an uppercase symbol with uppercase subscript(s), for example, I_C, V_{DS}. Incremental signal quantities are denoted by a lowercase symbol with lowercase subscript(s), for example, $i_c(t), v_{gs}(t)$. If the signal is a sine wave, then its amplitude is denoted by an uppercase symbol with lowercase subscript(s), for example, I_c, V_{gs}. Finally, although not shown in Fig. 1.15, dc power supplies are denoted by an uppercase letter with a double-letter uppercase subscript, for example, V_{CC}, V_{DD}. A similar notation is used for the dc current drawn from the power supply, for example, I_{CC}, I_{DD}.

EXERCISES

1.10 An amplifier has a voltage gain of 100 V/V and a current gain of 1000 A/A. Express the voltage and current gains in decibels and find the power gain.
Ans. 40 dB; 60 dB; 50 dB

1.11 An amplifier operating from a single 15-V supply provides a 12-V peak-to-peak sine-wave signal to a 1-kΩ load and draws negligible input current from the signal source. The dc current drawn from the 15-V supply is 8 mA. What is the power dissipated in the amplifier, and what is the amplifier efficiency?
Ans. 120 mW; 15%

1.5 Circuit Models for Amplifiers

A substantial part of this book is concerned with the design of amplifier circuits that use transistors of various types. Such circuits will vary in complexity from those using a single transistor to those with 20 or more devices. In order to be able to apply the resulting amplifier circuit as a building block in a system, one must be able to characterize, or **model**, its terminal behavior. In this section, we study simple but effective amplifier models. These models apply irrespective of the complexity of the internal circuit of the amplifier. The values of the model parameters can be found either by analyzing the amplifier circuit or by performing measurements at the amplifier terminals.

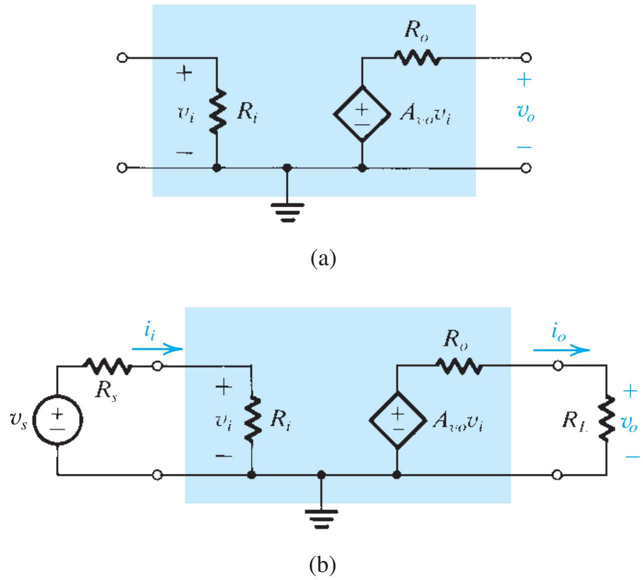


Figure 1.16 **(a)** Circuit model for the voltage amplifier. **(b)** The voltage amplifier with input signal source and load.

1.5.1 Voltage Amplifiers

Figure 1.16(a) shows a circuit model for the voltage amplifier. The model consists of a voltage-controlled voltage source having a gain factor A_{vo}, an input resistance R_i that accounts for the fact that the amplifier draws an input current from the signal source, and an output resistance R_o that accounts for the change in output voltage as the amplifier is called upon to supply output current to a load. To be specific, we show in Fig. 1.16(b) the amplifier model fed with a signal voltage source v_s having a resistance R_s and connected at the output to a load resistance R_L. The nonzero output resistance R_o causes only a fraction of $A_{vo}v_i$ to appear across the output. Using the voltage-divider rule we obtain

$$v_o = A_{vo} v_i \frac{R_L}{R_L + R_o}$$

Thus the voltage gain is given by

$$A_v \equiv \frac{v_o}{v_i} = A_{vo} \frac{R_L}{R_L + R_o} \qquad (1.12)$$

It follows that in order not to lose gain in coupling the amplifier output to a load, the output resistance R_o should be much smaller than the load resistance R_L. In other words, for a given R_L one must design the amplifier so that its R_o is much smaller than R_L. Furthermore, there are applications in which R_L is known to vary over a certain range. In order to keep the output voltage v_o as constant as possible, the amplifier is designed with R_o much smaller than the lowest value of R_L. An ideal voltage amplifier is one with $R_o = 0$. Equation (1.12) indicates also that for $R_L = \infty, A_v = A_{vo}$. Thus A_{vo} is the voltage gain of the unloaded amplifier, or the **open-circuit voltage gain**. It should also be clear that in specifying the voltage gain of an amplifier, one must also specify the value of load resistance at which this gain is measured or calculated. If a load resistance is not specified, it is normally assumed that the given voltage gain is the open-circuit gain A_{vo}.

The finite input resistance R_i introduces another voltage-divider action at the input, with the result that only a fraction of the source signal v_s actually reaches the input terminals of the amplifier; that is,

$$v_i = v_s \frac{R_i}{R_i + R_s} \tag{1.13}$$

It follows that in order not to lose a significant portion of the input signal in coupling the signal source to the amplifier input, the amplifier must be designed to have an input resistance R_i much greater than the resistance of the signal source, $R_i \gg R_s$. Furthermore, there are applications in which the source resistance is known to vary over a certain range. To minimize the effect of this variation on the value of the signal that appears at the input of the amplifier, the designer ensures that R_i is much greater than the largest value of R_s. An ideal voltage amplifier is one with $R_i = \infty$. In this ideal case both the current gain and power gain become infinite.

The overall voltage gain (v_o/v_s) can be found by combining Eqs. (1.12) and (1.13),

$$\frac{v_o}{v_s} = A_{vo} \frac{R_i}{R_i + R_s} \frac{R_L}{R_L + R_o}$$

There are situations in which one is interested not in voltage gain but only in a significant power gain. For instance, the source signal can have a respectable voltage but a source resistance that is much greater than the load resistance. Connecting the source directly to the load would result in significant signal attenuation. In such a case, one requires an amplifier with a high input resistance (much greater than the source resistance) and a low output resistance (much smaller than the load resistance) but with a modest voltage gain (or even unity gain). Such an amplifier is referred to as a **buffer amplifier**. We shall encounter buffer amplifiers often throughout this book.

EXERCISES

1.12 A sensor producing a voltage of 1 V rms with a source resistance of 1 MΩ is available to drive a 10-Ω load. If connected directly, what voltage and power levels result at the load? If a unity-gain (i.e., $A_{vo} = 1$) buffer amplifier with 1-MΩ input resistance and 10-Ω output resistance is interposed between source and load, what do the output voltage and power levels become? For the new arrangement, find the voltage gain from source to load, and the power gain (both expressed in decibels).
Ans. 10 μV rms; 10^{-11} W; 0.25 V rms; 6.25 mW; −12 dB; 44 dB

1.13 The output voltage of a voltage amplifier has been found to decrease by 20% when a load resistance of 1 kΩ is connected. What is the value of the amplifier output resistance?
Ans. 250 Ω

1.14 An amplifier with an open-circuit voltage gain of +40 dB, an input resistance of 10 kΩ, and an output resistance of 1 kΩ is used to drive a 1-kΩ load. What is the value of A_{vo}? Find the value of the power gain in decibels.
Ans. 100 V/V; 44 dB

1.5.2 Cascaded Amplifiers

To meet given amplifier specifications, we often need to design the amplifier as a cascade of two or more stages. The stages are usually not identical; rather, each is designed to serve a specific purpose. For instance, in order to provide the overall amplifier with a large input resistance, the first stage is usually required to have a large input resistance. Also, in order to equip the overall amplifier with a low output resistance, the final stage in the cascade is usually designed to have a low output resistance. To illustrate the analysis and design of cascaded amplifiers, we consider a practical example.

Example 1.3

Figure 1.17 depicts an amplifier composed of a cascade of three stages. The amplifier is fed by a signal source with a source resistance of 100 kΩ and delivers its output into a load resistance of 100 Ω. The first stage has a relatively high input resistance and a modest gain factor of 10. The second stage has a higher gain factor but lower input resistance. Finally, the last, or output, stage has unity gain but a low output resistance. We wish to evaluate the overall voltage gain, that is, v_L/v_s, the current gain, and the power gain.

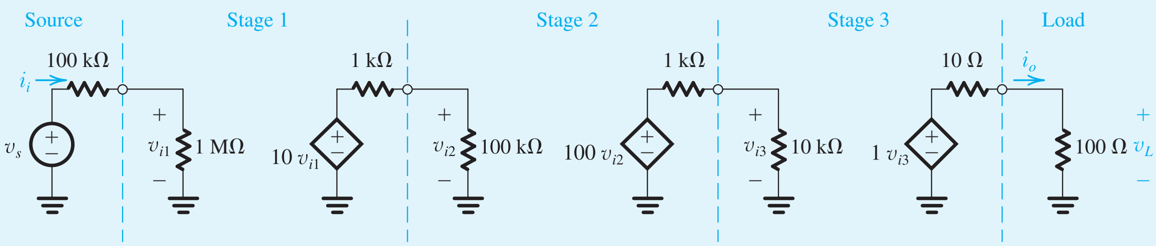


Figure 1.17 Three-stage amplifier for Example 1.3.

Solution

The fraction of source signal appearing at the input terminals of the amplifier is obtained using the voltage-divider rule at the input, as follows:

$$\frac{v_{i1}}{v_s} = \frac{1\text{ M}\Omega}{1\text{ M}\Omega + 100\text{ k}\Omega} = 0.909\text{ V/V}$$

The voltage gain of the first stage is obtained by considering the input resistance of the second stage to be the load of the first stage; that is,

$$A_{v1} \equiv \frac{v_{i2}}{v_{i1}} = 10\frac{100\text{ k}\Omega}{100\text{ k}\Omega + 1\text{ k}\Omega} = 9.9\text{ V/V}$$

Similarly, the voltage gain of the second stage is obtained by considering the input resistance of the third stage to be the load of the second stage,

$$A_{v2} \equiv \frac{v_{i3}}{v_{i2}} = 100\frac{10\text{ k}\Omega}{10\text{ k}\Omega + 1\text{ k}\Omega} = 90.9\text{ V/V}$$