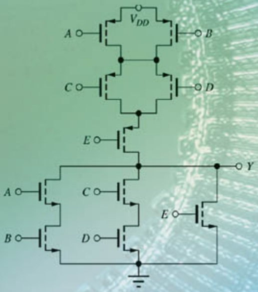
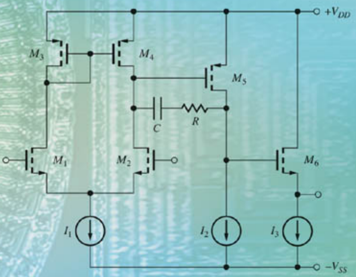
FOURTH EDITION

MICROELECTRONIC Circuit Design





RICHARD C. JAEGER | TRAVIS N. BLALOCK

MICROELECTRONIC CIRCUIT DESIGN

This page intentionally left blank

Fourth Edition

MICROELECTRONIC CIRCUIT DESIGN

Richard C. Jaeger
Auburn University

Travis N. Blalock
University of Virginia

McGraw Hill
Connect Learn Succeed™

The McGraw·Hill Companies

MICROELECTRONIC CIRCUIT DESIGN, FOURTH EDITION

Published by McGraw-Hill, a business unit of The McGraw-Hill Companies, Inc., 1221 Avenue of the Americas, New York, NY 10020.

This book is printed on recycled, acid-free paper containing 10% postconsumer waste.

1 2 3 4 5 6 7 8 9 0 WDQ/WDQ 1 0 9 8 7 6 5 4 3 2 1 0

ISBN 978-0-07-338045-2
MHID 0-07-338045-8

Vice President & Editor-in-Chief: *Marty Lange*
Vice President, EDP / Central Publishing Services: *Kimberly Meriwether-David*
Global Publisher: *Raghothaman Srinivasan*
Director of Development: *Kristine Tibbetts*
Developmental Editor: *Darlene M. Schueller*
Senior Sponsoring Editor: *Peter E. Massar*
Senior Marketing Manager: *Curt Reynolds*
Senior Project Manager: *Jane Mohr*
Senior Production Supervisor: *Kara Kudronowicz*
Senior Media Project Manager: *Sandra M. Schnee*
Design Coordinator: *Brenda A. Rolwes*
Cover Designer: *Studio Montage, St. Louis, Missouri*
Senior Photo Research Coordinator: *John C. Leland*
Photo Research: *LouAnn K. Wilson*
Compositor: *MPS Limited, A Macmillan Company*
Typeface: *10/12 Times Roman*
Printer: *Worldcolor*

Library of Congress Cataloging-in-Publication Data

Jaeger, Richard C.
Microelectronic circuit design / Richard C. Jaeger, Travis N. Blalock. — 4th ed.
p. cm.
ISBN 978-0-07-338045-2
1. Integrated circuits—Design and construction. 2. Semiconductors—Design and construction. 3. Electronic circuit design. I. Blalock, Travis N. II. Title.
TK7874.J333 2010
621.3815—dc22 2009049847

www.mhhe.com

TO

To Joan, my loving wife and partner

—Richard C. Jaeger

In memory of my father, Professor Theron Vaughn Blalock, an inspiration to me and to the countless students whom he mentored both in electronic design and in life.

—Travis N. Blalock

BRIEF CONTENTS

CONTENTS

PART TWO
DIGITAL ELECTRONICS 285

CHAPTER 6
INTRODUCTION TO DIGITAL ELECTRONICS 287

CHAPTER 7
COMPLEMENTARY MOS (CMOS) LOGIC DESIGN 367

CHAPTER 8
MOS MEMORY AND STORAGE CIRCUITS 416

CHAPTER 9
BIPOLAR LOGIC CIRCUITS 460

CHAPTER 15

DIFFERENTIAL AMPLIFIERS AND OPERATIONAL AMPLIFIER DESIGN 968

CHAPTER 16

ANALOG INTEGRATED CIRCUIT DESIGN TECHNIQUES 1046

APPENDIXES

PREFACE

Through study of this text, the reader will develop a comprehensive understanding of the basic techniques of modern electronic circuit design, analog and digital, discrete and integrated. Even though most readers may not ultimately be engaged in the design of integrated circuits (ICs) themselves, a thorough understanding of the internal circuit structure of ICs is prerequisite to avoiding many pitfalls that prevent the effective and reliable application of integrated circuits in system design.

Digital electronics has evolved to be an extremely important area of circuit design, but it is included almost as an afterthought in many introductory electronics texts. We present a more balanced coverage of analog and digital circuits. The writing integrates the authors' extensive industrial backgrounds in precision analog and digital design with their many years of experience in the classroom. A broad spectrum of topics is included, and material can easily be selected to satisfy either a two-semester or three-quarter sequence in electronics.

IN THIS EDITION

This edition continues to update the material to achieve improved readability and accessibility to the student. In addition to general material updates, a number of specific changes have been included in Parts I and II, Solid-State Electronics and Devices and Digital Electronics, respectively. A new closed-form solution to four-resistor MOSFET biasing is introduced as well as an improved iterative strategy for diode Q-point analysis. JFET devices are important in analog design and have been reintroduced at the end of Chapter 4. Simulation-based logic gate scaling is introduced in the MOS logic chapters, and an enhanced discussion of noise margin is included as a new Electronics-in-Action (EIA) feature. Current-mode logic (CML) is heavily used in high performance SiGe ICs, and a CML section is added to the Bipolar Logic chapter.

This revision contains major reorganization and revision of the analog portion (Part III) of the text. The introductory amplifier material (old Chapter 10) is now introduced in a "just-in-time" basis in the three op-amp chapters. Specific sections have been added with qualitative descriptions of the operation of basic op-amp circuits and each transistor amplifier configuration as well as the transistors themselves.

Feedback analysis using two-ports has been eliminated from Chapter 18 in favor of a consistent loop-gain analysis approach to all feedback configurations that begins in the op-amp chapters. The important successive voltage and current injection technique for finding loop-gain is now included in Chapter 11, and Blackman's theorem is utilized to find input and output resistances of closed-loop amplifiers. SPICE examples have been modified to utilize three- and five-terminal built-in op-amp models.

Chapter 10, Analog Systems and Ideal Operational Amplifiers, provides an introduction to amplifiers and covers the basic ideal op-amp circuits.

Chapter 11, Characteristics and Limitations of Operational Amplifiers, covers the limitations of nonideal op amps including frequency response and stability and the four classic feedback circuits including series-shunt, shunt-shunt, shunt-series and series-series feedback amplifiers.

Chapter 12, Operational Amplifier Applications, collects together all the op-amp applications including multistage amplifiers, filters, A/D and D/A converters, sinusoidal oscillators, and multivibrators.

Redundant material in transistor amplifier chapters 13 and 14 has been merged or eliminated wherever possible. Other additions to the analog material include discussion of relations between MOS logic inverters and common-source amplifiers, distortion reduction through feedback, the relationship between step response and phase margin, NMOS differential amplifiers with NMOS load transistors, the regulated cascode current source, and the Gilbert multiplier.

Because of the renaissance and pervasive use of RF circuits, the introductory section on RF amplifiers, now in Chapter 17, has been expanded to include shunt-peaked and tuned amplifiers, and the use of inductive degeneration in common-source amplifiers. New material on mixers includes passive, active, single- and double-balanced mixers and the widely used Gilbert mixer.

Chapter 18, Transistor Feedback Amplifiers and Oscillators, presents examples of transistor feedback amplifiers and transistor oscillator implementations. The transistor oscillator section has been expanded to include a discussion of negative resistance in oscillators and the negative G_m oscillator cell.

Several other important enhancements include:

- SPICE support on the web now includes examples in NI Multisim™ software in addition to PSpice®.
- At least 35 percent revised or new problems.
- New PowerPoint® slides are available from McGraw-Hill.
- A group of tested design problems are also available.

The Structured Problem Solving Approach continues to be utilized throughout the examples. We continue to expand the popular Electronics-in-Action Features with the addition of Diode Rectifier as an AM Demodulator; High Performance CMOS Technologies; A Second Look at Noise Margins (graphical flip-flop approach); Offset Voltage, Bias Current and CMRR Measurement; Sample-and-Hold Circuits; Voltage Regulator with Series Pass Transistor; Noise Factor, Noise Figure and Minimum Detectable Signal; Series-Parallel and Parallel-Series Network Transformations; and Passive Diode Ring Mixer.

Chapter Openers enhance the readers understanding of historical developments in electronics. Design notes highlight important ideas that the circuit designer should remember. The World Wide Web is viewed as an integral extension of the text, and a wide range of supporting materials and resource links are maintained and updated on the McGraw-Hill website (www.mhhe.com/jaeger).

Features of the book are outlined below.

The Structured Problem-Solving Approach is used throughout the examples.

Electronics-in-Action features in each chapter.

Chapter openers highlighting developments in the field of electronics.

Design Notes and emphasis on practical circuit design.

Broad use of SPICE throughout the text and examples.

Integrated treatment of device modeling in SPICE.

Numerous Exercises, Examples, and Design Examples.

Large number of new problems.

Integrated web materials.

Continuously updated web resources and links.

Placing the digital portion of the book first is also beneficial to students outside of electrical engineering, particularly computer engineering or computer science majors, who may only take the first course in a sequence of electronics courses.

The material in Part II deals primarily with the internal design of logic gates and storage elements. A comprehensive discussion of NMOS and CMOS logic design is presented in Chapters 6 and 7, and a discussion of memory cells and peripheral circuits appears in Chapter 8. Chapter 9 on bipolar logic design includes discussion of ECL, CML and TTL. However, the material on bipolar logic has been reduced in deference to the import of MOS technology. This text does not include any substantial design at the logic block level, a topic that is fully covered in digital design courses.

Parts I and II of the text deal only with the large-signal characteristics of the transistors. This allows readers to become comfortable with device behavior and i-v characteristics before they have to grasp the concept of splitting circuits into different pieces (and possibly different topologies) to perform dc and ac small-signal analyses. (The concept of a small-signal is formally introduced in Part III, Chapter 13.)

Although the treatment of digital circuits is more extensive than most texts, more than 50 percent of the material in the book, Part III, still deals with traditional analog circuits. The analog section begins in Chapter 10 with a discussion of amplifier concepts and classic ideal op-amp circuits. Chapter 11 presents a detailed discussion of nonideal op amps, and Chapter 12 presents a range of op-amp applications. Chapter 13 presents a comprehensive development of the small-signal models for the diode, BJT, and FET. The hybrid-pi model and pi-models for the BJT and FET are used throughout.

Chapter 14 provides in-depth discussion of single-stage amplifier design and multistage ac coupled amplifiers. Coupling and bypass capacitor design is also covered in Chapter 14. Chapter 15 discusses dc coupled multistage amplifiers and introduces prototypical op amp circuits. Chapter 16 continues with techniques that are important in IC design and studies the classic 741 operational amplifier.

Chapter 17 develops the high-frequency models for the transistors and presents a detailed discussion of analysis of high-frequency circuit behavior. The final chapter presents examples of transistor feedback amplifiers. Discussion of feedback amplifier stability and oscillators conclude the text.

DESIGN

Design remains a difficult issue in educating engineers. The use of the well-defined problem-solving methodology presented in this text can significantly enhance the students ability to understand issues related to design. The design examples assist in building an understanding of the design process.

Part II launches directly into the issues associated with the design of NMOS and CMOS logic gates. The effects of device and passive-element tolerances are discussed throughout the text. In today's world, low-power, low-voltage design, often supplied from batteries, is playing an increasingly important role. Logic design examples have moved away from 5 V to lower power supply levels. The use of the computer, including MATLAB®, spreadsheets, or standard high-level languages to explore design options is a thread that continues throughout the text.

Methods for making design estimates and decisions are stressed throughout the analog portion of the text. Expressions for amplifier behavior are simplified beyond the standard hybrid-pi model expressions whenever appropriate. For example, the expression for the voltage gain of an amplifier in most texts is simply written as $|A_v| = g_m R_L$, which tends to hide the power supply voltage as the fundamental design variable. Rewriting this expression in approximate form as $g_m R_L \cong 10V_{CC}$ for the BJT, or $g_m R_L \cong V_{DD}$ for the FET, explicitly displays the dependence of amplifier design on the choice of power supply voltage and provides a simple first-order design estimate for the voltage gain of the common-emitter and common-source amplifiers. The gain advantage of the BJT stage is also clear. These approximation techniques and methods for performance estimation are included as often as possible. Comparisons and design tradeoffs between the properties of BJTs and FETs are included throughout Part III.

Worst-case and Monte-Carlo analysis techniques are introduced at the end of the first chapter. These are not topics traditionally included in undergraduate courses. However, the ability to design circuits in the face of wide component tolerances and variations is a key component of electronic circuit design, and the design of circuits using standard components and tolerance assignment are discussed in examples and included in many problems.

PROBLEMS AND INSTRUCTOR SUPPORT

Specific design problems, computer problems, and SPICE problems are included at the end of each chapter. Design problems are indicated by , computer problems are indicated by , and SPICE problems are indicated by . The problems are keyed to the topics in the text with the more difficult or time-consuming problems indicated by * and **. An Instructor's Manual containing solutions to all the problems is available from the authors. In addition, the graphs and figures are available as PowerPoint files and can be retrieved from the website. Instructor notes are available as PowerPoint slides.

ELECTRONIC TEXTBOOK OPTION

This text is offered through CourseSmart for both instructors and students. CourseSmart is an online resource where students can purchase the complete text online at almost half the cost of a traditional text. Purchasing the eTextbook allows students to take advantage of CourseSmart's web tools for learning, which include full text search, notes and highlighting, and email tools for sharing notes between classmates. To learn more about CourseSmart options, contact your sales representative or visit www.CourseSmart.com.

COSMOS

Complete Online Solutions Manual Organization System (COSMOS). Professors can benefit from McGraw-Hill's COSMOS electronic solutions manual. COSMOS enables instructors to generate a limitless supply of problem material for assignment, as well as transfer and integrate their own problems into the software. For additional information, contact your McGraw-Hill sales representative.

COMPUTER USAGE AND SPICE

The computer is used as a tool throughout the text. The authors firmly believe that this means more than just the use of the SPICE circuit analysis program. In today's computing environment, it is often appropriate to use the computer to explore a complex design space rather than to try to reduce a complicated set of equations to some manageable analytic form. Examples of the process of setting up equations for iterative evaluation by computer through the use of spreadsheets, MATLAB, and/or standard high-level language programs are illustrated in several places in the text. MATLAB is also used for Nyquist and Bode plot generation and is very useful for Monte Carlo analysis.

On the other hand, SPICE is used throughout the text. Results from SPICE simulation are included throughout and numerous SPICE problems are to be found in the problem sets. Wherever helpful, a SPICE analysis is used with most examples. This edition also emphasizes the differences and utility of the dc, ac, transient, and transfer function analysis modes in SPICE. A discussion of SPICE device modeling is included following the introduction to each semiconductor device, and typical SPICE model parameters are presented with the models.

ACKNOWLEDGMENTS

We want to thank the large number of people who have had an impact on the material in this text and on its preparation. Our students have helped immensely in polishing the manuscript and have managed to survive the many revisions of the manuscript. Our department heads, J. D. Irwin of Auburn University and L. R. Harriott of the University of Virginia, have always been highly supportive of faculty efforts to develop improved texts.

We want to thank all the reviewers and survey respondents including

Vijay K. Arora
Wilkes University

Kurt Behpour
California Polytechnic State University, San Luis Obispo

David A. Borkholder
Rochester Institute of Technology

Dmitri Donetski
Stony Brook University

Ethan Farquhar
The University of Tennessee, Knoxville

Melinda Holtzman
Portland State University

Anthony Johnson
The University of Toledo

Marian K. Kazimierczuk
Wright State University

G. Roientan Lahiji
Professor, *Iran University of Science and Technology*
Adjunct Professor, *University of Michigan*

Stanislaw F. Legowski
University of Wyoming

Milica Markovic
California State University Sacramento

James E. Morris
Portland State University

Maryam Moussavi
California State University Long Beach

Kenneth V. Noren
University of Idaho

John Ortiz
University of Texas at San Antonio

We are also thankful for inspiration from the classic text *Applied Electronics* by J. F. Pierce and T. J. Paulus. Professor Blalock learned electronics from Professor Pierce many years ago and still appreciates many of the analytical techniques employed in their long out-of-print text.

We would like to thank Gabriel Chindris of Technical University of Cluj-Napoca in Romania for his assistance in creating the simulations for the NI Multisim^{TM} examples.

Finally, we want to thank the team at McGraw-Hill including Raghothaman Srinivasan, Global Publisher; Darlene Schueller, Developmental Editor; Curt Reynolds, Senior Marketing Manager; Jane Mohr, Senior Project Manager; Brenda Rolwes, Design Coordinator; John Leland and LouAnn Wilson, Photo Research Coordinators; Kara Kudronowicz, Senior Production Supervisor; Sandy Schnee, Senior Media Project Manager; and Dheeraj Chahal, Full Service Project Manager, MPS Limited.

In developing this text, we have attempted to integrate our industrial backgrounds in precision analog and digital design with many years of experience in the classroom. We hope we have at least succeeded to some extent. Constructive suggestions and comments will be appreciated.

Richard C. Jaeger
Auburn University

Travis N. Blalock
University of Virginia

CHAPTER-BY-CHAPTER SUMMARY

PART I — SOLID-STATE ELECTRONICS AND DEVICES

Chapter 1 provides a historical perspective on the field of electronics beginning with vacuum tubes and advancing to giga-scale integration and its impact on the global economy. Chapter 1 also provides a classification of electronic signals and a review of some important tools from network analysis, including a review of the ideal operational amplifier. Because developing a good problem-solving methodology is of such import to an engineer's career, the comprehensive Structured Problem Solving Approach is used to help the students develop their problem solving skills. The structured approach is discussed in detail in the first chapter and used in all the subsequent examples in the text. Component tolerances and variations play an extremely important role in practical circuit design, and Chapter 1 closes with introductions to tolerances, temperature coefficients, worst-case design, and Monte Carlo analysis.

Chapter 2 deviates from the recent norm and discusses semiconductor materials including the covalent-bond and energy-band models of semiconductors. The chapter includes material on intrinsic carrier density, electron and hole populations, *n*- and *p*-type material, and impurity doping. Mobility, resistivity, and carrier transport by both drift and diffusion are included as topics. Velocity saturation is discussed, and an introductory discussion of microelectronic fabrication has been merged with Chapter 2.

Chapter 3 introduces the structure and i-v characteristics of solid-state diodes. Discussions of Schottky diodes, variable capacitance diodes, photo-diodes, solar cells, and LEDs are also included. This chapter introduces the concepts of device modeling and the use of different levels of modeling to achieve various approximations to reality. The SPICE model for the diode is discussed. The concepts of bias, operating point, and load-line are all introduced, and iterative mathematical solutions are also used to find the operating point with MATLAB and spreadsheets. Diode applications in rectifiers are discussed in detail and a discussion of the dynamic switching characteristics of diodes is also presented.

Chapter 4 discusses MOS and junction field-effect transistors, starting with a qualitative description of the MOS capacitor. Models are developed for the FET i-v characteristics, and a complete discussion of the regions of operation of the device is presented. Body effect is included. MOS transistor performance limits including scaling, cutoff frequency, and subthreshold conduction are discussed as well as basic Λ-based layout methods. Biasing circuits and load-line analysis are presented. The FET SPICE models and model parameters are discussed in Chapter 4.

Chapter 5 introduces the bipolar junction transistor and presents a heuristic development of the Transport (simplified Gummel-Poon) model of the BJT based upon superposition. The various regions of operation are discussed in detail. Common-emitter and common-base current gains are defined, and base transit-time, diffusion capacitance and cutoff frequency are all discussed. Bipolar technology and physical structure are introduced. The four-resistor bias circuit is discussed in detail. The SPICE model for the BJT and the SPICE model parameters are discussed in Chapter 5.

PART II — DIGITAL ELECTRONICS

Chapter 6 begins with a compact introduction to digital electronics. Terminology discussed includes logic levels, noise margins, rise-and-fall times, propagation delay, fan out, fan in, and power-delay product. A short review of Boolean algebra is included. The introduction to MOS logic design is now merged with Chapter 6 and follows the historical evolution of NMOS logic gates focusing on the design of saturated-load, and depletion-load circuit families. The impact of body effect on MOS logic circuit design is discussed in detail. The concept of reference inverter scaling is developed and employed to affect the design of other inverters, NAND gates, NOR gates, and complex logic functions throughout Chapters 6 and 7. Capacitances in MOS circuits are discussed, and methods for estimating the propagation delay and power-delay product of NMOS logic are presented. Details of several of the propagation delay analyses are moved to the MCD website, and the delay equation results for the various families have been collapsed into a much more compact form. The pseudo NMOS logic gate is discussed and provides a bridge to CMOS logic in Chapter 7.

CMOS represents today's most important integrated circuit technology, and **Chapter 7** provides an in-depth look at the design of CMOS logic gates including inverters, NAND and NOR gates, and complex logic gates. The CMOS designs are based on simple scaling of a reference inverter design. Noise margin and latchup are discussed as well as a comparison of the power-delay products of various MOS logic families. Dynamic logic circuits and cascade buffer design are discussed in Chapter 7. A discussion of BiCMOS logic circuitry has been added to Chapter 9 after bipolar logic is introduced.

Chapter 8 ventures into the design of memory and storage circuits, including the six-transistor, four-transistor, and one-transistor memory cells. Basic sense-amplifier circuits are introduced as well as the peripheral address and decoding circuits needed in memory designs. ROMs and flip-flop circuitry are included in Chapter 8.

Chapter 9 discusses bipolar logic circuits including emitter-coupled logic and transistor-transistor logic. The use of the differential pair as a current switch and the large-signal properties of the emitter follower are introduced. An introduction to CML, widely used in SiGe design, follows the ECL discussion. Operation of the BJT as a saturated switch is included and followed by a discussion of low voltage and standard TTL. An introduction to BiCMOS logic now concludes the chapter on bipolar logic.

PART III—ANALOG ELECTRONICS

Chapter 10 provides a succinct introduction to analog electronics. The concepts of voltage gain, current gain, power gain, and distortion are developed and have been merged on a "just-in-time" basic with the discussion of the classic ideal operational amplifier circuits that include the inverting, noninverting, summing, and difference amplifiers and the integrator and differentiator. Much care has been taken to be consistent in the use of the notation that defines these quantities as well as in the use of dc, ac, and total signal notation throughout the book. Bode plots are reviewed and amplifiers are classified by frequency response. MATLAB is utilized as a tool for producing Bode plots. SPICE simulation using built-in SPICE models is introduced.

Chapter 11 focuses on a comprehensive discussion of the characteristics and limitations of real operational amplifiers including the effects of finite gain and input resistance, nonzero output resistance, input offset voltage, input bias and offset currents, output voltage and current limits, finite bandwidth, and common-mode rejection. A consistent loop-gain analysis approach is used to study the four classic feedback configurations, and Blackman's theorem is utilized to find input and output resistances of closed-loop amplifiers. The important successive voltage and current injection technique for finding loop-gain is now included in Chapter 11. Relationships between the Nyquist and Bode techniques are explicitly discussed. Stability of first-, second- and third-order systems is discussed, and the concepts of phase and gain margin are introduced. Relationships between Nyquist and Bode techniques are explicitly discussed. A section concerning the relationship between phase margin and time domain response has been added. The macro model concept is introduced and the discussion of SPICE simulation of op-amp circuits using various levels of models continues in Chapter 11.

Chapter 12 covers a wide range of operational amplifier applications that include multistage amplifiers, the instrumentation amplifier, and continuous time and discrete time active filters. Cascade amplifiers are investigated including a discussion of the bandwidth of multistage amplifiers. An introduction to D/A and A/D converters appears in this chapter. The Barkhausen criterion for oscillation are presented and followed by a discussion of op-amp-based sinusoidal oscillators. Nonlinear circuits applications including rectifiers, Schmitt triggers, and multivibrators conclude the material in Chapter 12.

Chapter 13 begins the general discussion of linear amplification using the BJT and FET as C-E and C-S amplifiers. Biasing for linear operation and the concept of small-signal modeling are both introduced, and small-signal models of the diode, BJT, and FET are all developed. The limits for small-signal operation are all carefully defined. The use of coupling and bypass capacitors and inductors to separate the ac and dc designs is explored. The important $10V_{CC}$ and V_{DD} design estimates for the voltage gain of the C-E and C-S amplifiers are introduced, and the role of transistor amplification factor in bounding circuit performance is discussed. The role of Q-point design on power dissipation and signal range is also introduced.

Chapter 14 proceeds with an in-depth comparison of the characteristics of single-transistor amplifiers, including small-signal amplitude limitations. Appropriate points for signal injection and extraction are identified, and amplifiers are classified as inverting amplifiers (C-E, C-S), noninverting amplifiers (C-B, C-G), and followers (C-C, C-D). The treatment of MOS and bipolar devices is merged from Chapter 14 on, and design tradeoffs between the use of the BJT and the FET in amplifier circuits is an important thread that is followed through all of Part III. A detailed discussion of the design of coupling and bypass capacitors and the role of these capacitors in controlling the low frequency response of amplifiers appears in this chapter.

Chapter 15 explores the design of multistage direct coupled amplifiers. An evolutionary approach to multistage op amp design is used. MOS and bipolar differential amplifiers are first introduced. Subsequent addition of a second gain stage and then an output stage convert the differential amplifiers into simple op amps. Class A, B, and AB operation are defined. Electronic current sources are designed and used for biasing of the basic operational amplifiers. Discussion of important FET-BJT design tradeoffs are included wherever appropriate.

Chapter 16 introduces techniques that are of particular import in integrated circuit design. A variety of current mirror circuits are introduced and applied in bias circuits and as active loads in operational amplifiers. A wealth of circuits and analog design techniques are explored through the detailed analysis of the classic 741 operational amplifier. The bandgap reference and Gilbert analog multiplier are introduced in Chapter 16.

Chapter 17 discusses the frequency response of analog circuits. The behavior of each of the three categories of single-stage amplifiers (C-E/C-S, C-B/C-G, and C-C/C-D) is discussed in detail, and BJT behavior is contrasted with that of the FET. The frequency response of the transistor is discussed, and the high frequency, small-signal models are developed for both the BJT and FET. Miller multiplication is used to obtain estimates of the lower and upper cutoff frequencies of complex multistage amplifiers. Gain-bandwidth products and gain-bandwidth tradeoffs in design are discussed. Cascode amplifier frequency response, and tuned amplifiers are included in this chapter.

Because of the renaissance and pervasive use of RF circuits, the introductory section on RF amplifiers has been expanded to include shunt-peaked and tuned amplifiers, and the use of inductive degeneration in common-source amplifiers. New material on mixers includes passive and active single- and double-balanced mixers and the widely used Gilbert mixer.

Chapter 18 presents detailed examples of feedback as applied to transistor amplifier circuits. The loop-gain analysis approach introduced in Chapter 11 is used to find the closed-loop amplifier gain of various amplifiers, and Blackman's theorem is utilized to find input and output resistances of closed-loop amplifiers.

Amplifier stability is also discussed in Chapter 18, and Nyquist diagrams and Bode plots (with MATLAB) are used to explore the phase and gain margin of amplifiers. Basic single-pole op amp compensation is discussed, and the unity gain-bandwidth product is related to amplifier slew rate. Design of op amp compensation to achieve a desired phase margin is discussed. The discussion of transistor oscillator circuits includes the Colpitts, Hartley and negative G_m configurations. Crystal oscillators are also discussed.

Three **Appendices** include tables of standard component values (Appendix A), summary of the device models and sample SPICE parameters (Appendix B) and review of two-port networks (Appendix C). Data sheets for representative solid-state devices and operational amplifiers are available via the WWW.

Flexibility

The chapters are designed to be used in a variety of different sequences, and there is more than enough material for a two-semester or three-quarter sequence in electronics. One can obviously proceed directly through the book. On the other hand, the material has been written so that the BJT chapter can be used immediately after the diode chapter if so desired (i.e., a 1-2-3-5-4 chapter sequence). At the present time, the order actually used at Auburn University is:

1. Introduction
2. Solid-State Electronics
3. Diodes
4. FETs
6. Digital Logic
7. CMOS Logic
8. Memory
5. The BJT
9. Bipolar Logic
10–18. Analog in sequence

The chapters have also been written so that Part II, Digital Electronics, can be skipped, and Part III, Analog Electronics, can be used directly after completion of the coverage of the solid-state devices in Part I. If so desired, many of the quantitative details of the material in Chapter 2 may be skipped. In this case, the sequence would be

1. Introduction
2. Solid-State Electronics
3. Diodes
4. FETs
5. The BJT
10–18. Analog in sequence

PART ONE

SOLID STATE ELECTRONIC AND DEVICES

This page intentionally left blank

CHAPTER 1

INTRODUCTION TO ELECTRONICS

Chapter Outline

Chapter Goals

- Present a brief history of electronics
- Quantify the explosive development of integrated circuit technology
- Discuss initial classification of electronic signals
- Review important notational conventions and concepts from circuit theory
- Introduce methods for including tolerances in circuit analysis
- Present the problem-solving approach used in this text

Figure 1.1 John Bardeen, William Shockley, and Walter Brattain in Brattain's laboratory in 1948.
Reprinted with permission of Alacatel-Lucent USA Inc.

Figure 1.2 The first germanium bipolar transistor.
Lucent Technologies Inc./Bell Labs

November 2007 was the 60th anniversary of the 1947 discovery of the bipolar transistor by John Bardeen and Walter Brattain at Bell Laboratories, a seminal event that marked the beginning of the semiconductor age (see Figs. 1.1 and 1.2). The invention of the transistor and the subsequent development of microelectronics have done more to shape the modern era than any other event. The transistor and microelectronics have reshaped how business is transacted, machines are designed, information moves, wars are fought, people interact, and countless other areas of our lives.

This textbook develops the basic operating principles and design techniques governing the behavior of the devices and circuits that form the backbone of much of the infrastructure of our modern world. This knowledge will enable students who aspire to design and create the next generation of this technological revolution to build a solid foundation for more advanced design courses. In addition, students who expect to work in some other technology area will learn material that will help them understand microelectronics, a technology that will continue to have impact on how their chosen field develops. This understanding will enable them to fully exploit microelectronics in their own technology area. Now let us return to our short history of the transistor.

After the discovery of the transistor, it was but a few months until William Shockley developed a theory that described the operation of the bipolar junction transistor. Only 10 years later, in 1956, Bardeen, Brattain, and Shockley received the Nobel prize in physics for the discovery of the transistor.

In June 1948 Bell Laboratories held a major press conference to announce the discovery. In 1952 Bell Laboratories, operating under legal consent decrees, made licenses for the transistor available for the modest fee of $25,000 plus future royalty payments. About this time, Gordon Teal, another member of the solid-state group, left Bell Laboratories to work on the transistor at Geophysical Services, Inc., which subsequently became Texas Instruments (TI). There he made the first silicon transistors, and TI marketed the first all-transistor radio. Another early licensee of the transistor was Tokyo Tsushin Kogyo, which became the Sony Company in 1955. Sony subsequently sold a transistor radio with a marketing strategy based on the idea that everyone could now have a personal radio; thus was launched the consumer market for transistors. A very interesting account of these and other developments can be found in [1, 2] and their references.

Activity in electronics began more than a century ago with the first radio transmissions in 1895 by Marconi, and these experiments were followed after only a few years by the invention of the first electronic amplifying device, the triode vacuum tube. In this period, electronics—loosely defined as the design and application of electron devices—has had such a significant impact on our lives that we often overlook just how pervasive electronics has really become. One measure of the degree of this impact can be found in the gross domestic product (GDP) of the world. In 2008 the world GDP was approximately U.S. $71 trillion, and of this total more than 10 percent was directly traceable to electronics. See Table 1.1 [3–5].

We commonly encounter electronics in the form of telephones, radios, televisions, and audio equipment, but electronics can be found even in seemingly mundane appliances such as vacuum cleaners, washing machines, and refrigerators. Wherever one looks in industry, electronics will be found. The corporate world obviously depends heavily on data processing systems to manage its operations. In fact, it is hard to see how the computer industry could have evolved without the use of its own products. In addition, the design process depends ever more heavily on computer-aided design (CAD) systems, and manufacturing relies on electronic systems for process control—in petroleum refining, automobile tire production, food processing, power generation, and so on.

TABLE 1.1
Estimated Worldwide Electronics Market

CATEGORY	SHARE (%)
Data processing hardware	23
Data processing software and services	18
Professional electronics	10
Telecommunications	9
Consumer electronics	9
Active components	9
Passive components	7
Computer integrated manufacturing	5
Instrumentation	5
Office electronics	3
Medical electronics	2

1.1 A BRIEF HISTORY OF ELECTRONICS: FROM VACUUM TUBES TO GIGA-SCALE INTEGRATION

Because most of us have grown up with electronic products all around us, we often lose perspective of how far the industry has come in a relatively short time. At the beginning of the twentieth century, there were no commercial electron devices, and transistors were not invented until the late 1940s! Explosive growth was triggered by first the commercial availability of the bipolar transistor in the late 1950s, and then the realization of the integrated circuit (IC) in 1961. Since that time, signal processing using electron devices and electronic technology has become a pervasive force in our lives.

Table 1.2 lists a number of important milestones in the evolution of the field of electronics. The Age of Electronics began in the early 1900s with the invention of the first electronic two-terminal devices, called **diodes.** The **vacuum diode,** or diode **vacuum tube,** was invented by Fleming in 1904; in 1906 Pickard created a diode by forming a point contact to a silicon crystal. (Our study of electron devices begins with the introduction of the solid-state diode in Chapter 3.)

The invention of the three-element vacuum tube known as the **triode** was an extremely important milestone. The addition of a third element to a diode enabled electronic amplification to take place with good isolation between the input and output ports of the device. Silicon-based three-element devices now form the basis of virtually all electronic systems. Fabrication of tubes that could be used reliably in circuits followed the invention of the triode by a few years and enabled rapid circuit innovation. Amplifiers and oscillators were developed that significantly improved radio transmission and reception. Armstrong invented the super heterodyne receiver in 1920 and FM modulation in 1933. Electronics developed rapidly during World War II, with great advances in the field of radio communications and the development of radar. Although first demonstrated in 1930, television did not begin to come into widespread use until the 1950s.

An important event in electronics occurred in 1947, when John Bardeen, Walter Brattain, and William Shockley at Bell Telephone Laboratories invented the **bipolar transistor.**[1] Although field-effect devices had actually been conceived by Lilienfeld in 1925, Heil in 1935, and Shockley in 1952 [2], the technology to produce such devices on a commercial basis did not yet exist. Bipolar devices, however, were rapidly commercialized.

Then in 1958, the nearly simultaneous invention of the **integrated circuit (IC)** by Kilby at Texas Instruments and Noyce and Moore at Fairchild Semiconductor produced a new technology that would profoundly change our lives. The miniaturization achievable through IC technology made available complex electronic functions with high performance at low cost. The attendant characteristics of high reliability, low power, and small physical size and weight were additional important advantages.

In 2000, Jack St. Clair Kilby received a share of the Nobel prize for the invention of the integrated circuit. In the mind of the authors, this was an exceptional event as it represented one of the first awards to an electronic technologist.

Most of us have had some experience with personal computers, and nowhere is the impact of the integrated circuit more evident than in the area of digital electronics. For example, 4-gigabit (Gb) dynamic memory chips, similar to those in Fig. 1.3(c), contain more than 4 billion transistors. Creating this much memory using individual vacuum tubes [depicted in Fig. 1.3(a)] or even discrete transistors [shown in Fig. 1.3(b)] would be an almost inconceivable feat.

Levels of Integration

The dramatic progress of integrated circuit miniaturization is shown graphically in Figs. 1.4 and 1.5. The complexities of memory chips and microprocessors have grown exponentially with time. In the four decades since 1970, the number of transistors on a microprocessor chip has increased by

[1] The term **transistor** is said to have originated as a contraction of "transfer resistor," based on the voltage-controlled resistance of the characteristics of the MOS transistor.

TABLE 1.2
Milestones in Electronics

YEAR	EVENT
1874	Ferdinand Braun invents the solid-state rectifier.
1884	American Institute of Electrical Engineers (AIEE) formed.
1895	Marconi makes first radio transmissions.
1904	Fleming invents diode vacuum tube—Age of Electronics begins.
1906	Pickard creates solid-state point-contact diode (silicon).
1906	Deforest invents triode vacuum tube (audion).
1910–1911	"Reliable" tubes fabricated.
1912	Institute of Radio Engineers (IRE) founded.
1907–1927	First radio circuits developed from diodes and triodes.
1920	Armstrong invents super heterodyne receiver.
1925	TV demonstrated.
1925	Lilienfeld files patent application on the field-effect device.
1927–1936	Multigrid tubes developed.
1933	Armstrong invents FM modulation.
1935	Heil receives British patent on a field-effect device.
1940	Radar developed during World War II—TV in limited use.
1947	Bardeen, Brattain, and Shockley at Bell Laboratories invent bipolar transistors.
1950	First demonstration of color TV.
1952	Shockley describes the unipolar field-effect transistor.
1952	Commercial production of silicon bipolar transistors begins at Texas Instruments.
1952	Ian Ross and George Dacey demonstrate the junction field-effect transistor.
1956	Bardeen, Brattain, and Shockley receive Nobel prize for invention of bipolar transistors.
1958	Integrated circuit developed simultaneously by Kilby at Texas Instruments and Noyce and Moore at Fairchild Semiconductor.
1961	First commercial digital IC available from Fairchild Semiconductor.
1963	AIEE and IRE merge to become the Institute of Electrical and Electronic Engineers (IEEE)
1967	First semiconductor RAM (64 bits) discussed at the IEEE International Solid-State Circuits Conference (ISSCC).
1968	First commercial IC operational amplifier—the μA709—introduced by Fairchild Semiconductor.
1970	One-transistor dynamic memory cell invented by Dennard at IBM.
1970	Low-loss optical fiber invented.
1971	4004 microprocessor introduced by Intel.
1972	First 8-bit microprocessor—the 8008—introduced by Intel.
1974	First commercial 1-kilobit memory chip developed.
1974	8080 microprocessor introduced.
1978	First 16-bit microprocessor developed.
1984	Megabit memory chip introduced.
1987	Erbium doped, laser-pumped optical fiber amplifiers demonstrated.
1995	Experimental gigabit memory chip presented at the IEEE ISSCC.
2000	Alferov, Kilby, and Kromer share the Nobel prize in physics for optoelectronics, invention of the integrated circuit, and heterostructure devices, respectively.

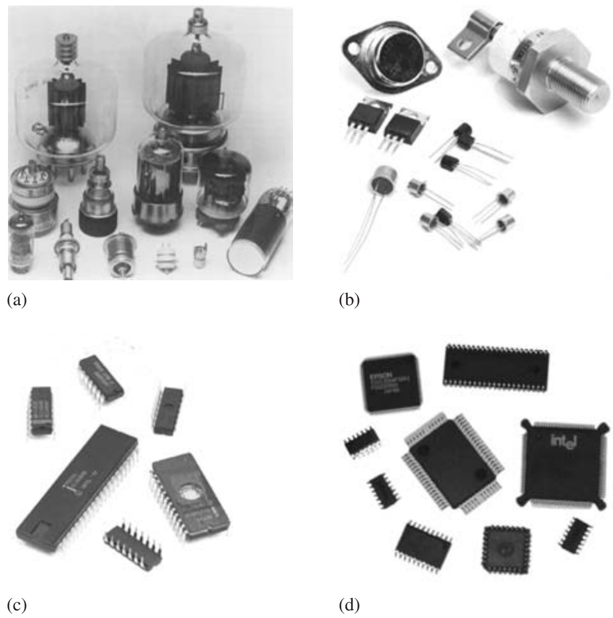


Figure 1.3 Comparison of (a) vacuum tubes, (b) individual transistors, (c) integrated circuits in dual-in-line packages (DIPs), and (d) ICs in surface mount packages.
Source: (a) Courtesy ARRL Handbook for Radio Amateurs*, 1992*

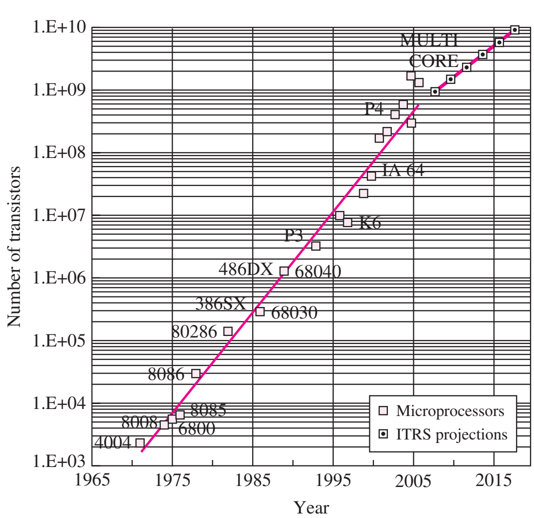


Figure 1.4 Microprocessor complexity versus time.

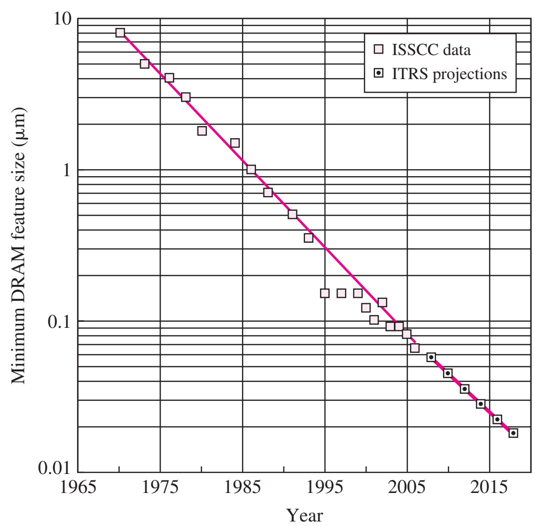


Figure 1.5 DRAM feature size versus year.

a factor of one million as depicted in Fig. 1.4. Similarly, memory density has grown by a factor of more than 10 million from a 64-bit chip in 1968 to the announcement of 4-Gbit chip production in the late 2009.

Since the commercial introduction of the integrated circuit, these increases in density have been achieved through a continued reduction in the minimum line width, or **minimum feature size,** that can be defined on the surface of the integrated circuit (see Fig. 1.5). Today most corporate semiconductor laboratories around the world are actively working on deep submicron processes with feature sizes below 50 μm—less than one two-hundredth the diameter of a human hair.

As the miniaturization process has continued, a series of commonly used abbreviations has evolved to characterize the various levels of integration. Prior to the invention of the integrated circuit, electronic systems were implemented in discrete form. Early ICs, with fewer than 100 components, were characterized as **small-scale integration,** or **SSI.** As density increased, circuits became identified as **medium-scale integration (MSI,** 100–1000 components/chip**), large-scale integration (LSI,** $10^3 - 10^4$ components/chip**)**, and **very-large-scale integration (VLSI,** 10^4–10^9 components/chip**).** Today discussions focus on **ultra-large-scale integration (ULSI)** and **giga-scale integration (GSI,** above 10^9 components/chip**).**

ELECTRONICS IN ACTION

Cellular Phone Evolution

The impact of technology scaling is ever present in our daily lives. One example appears visually in the pictures of cellular phone evolution below. Early mobile phones were often large and had to be carried in a relatively large pouch (hence the term "bag phone"). The next generation of analog phones could easily fit in your hand, but they had poor battery life caused by their analog communications technology. Implementations of second- and third-generation digital cellular technology are considerably smaller and have much longer battery life. As density continues to increase, additional functions such as personal digital assistants (PDA), cameras and GPS are integrated with the digital phone.

(a) (b) (c)

A decade of cellular phone evolution: (a) early Uniden "bag phone," (b) Nokia analog phone, and (c) Apple iPhone.
Source: (c) *iPhone:* © *Lourens Smak/Alamy/RF*

Cell phones also represent excellent examples of the application of **mixed-signal** integrated circuits that contain both analog and digital circuitry on the same chip. ICs in the cell phone contain analog radio frequency receiver and transmitter circuitry, analog-to-digital and digital-to-analog converters, CMOS logic and memory, and power conversion circuits.

1.2 CLASSIFICATION OF ELECTRONIC SIGNALS

The signals that electronic devices are designed to process can be classified into two broad categories: analog and digital. **Analog signals** can take on a continuous range of values, and thus represent continuously varying quantities; purely **digital signals** can appear at only one of several discrete levels. Examples of these types of signals are described in more detail in the next two subsections, along with the concepts of digital-to-analog and analog-to-digital conversion, which make possible the interface between the two systems.

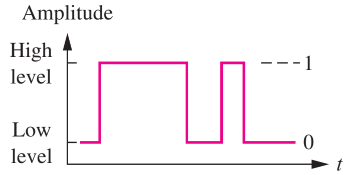


Figure 1.6 A time-varying binary digital signal.

1.2.1 DIGITAL SIGNALS

When we speak of digital electronics, we are most often referring to electronic processing of **binary digital signals,** or signals that can take on only one of two discrete amplitude levels as illustrated in Fig. 1.6. The status of binary systems can be represented by two symbols: a logical 1 is assigned to represent one level, and a logical 0 is assigned to the second level.[2] The two logic states generally correspond to two separate voltages—V_H and V_L—representing the high and low amplitude levels, and a number of voltage ranges are in common use. Although $V_H = 5$ V and $V_L = 0$ V represented the primary standard for many years, these have given way to lower voltage levels because of power consumption and semiconductor device limitations. Systems employing $V_H = 3.3$, 2.5, and 1.5 V, with $V_L = 0$ V, are now used in many types of electronics.

However, binary voltage levels can also be negative or even bipolar. One high-performance logic family called ECL uses $V_H = -0.8$ V and $V_L = -2.0$ V, and the early standard RS-422 and RS-232 communication links between a small computer and its peripherals used $V_H = +12$ V and $V_L = -12$ V. In addition, the time-varying binary signal in Fig. 1.6 could equally well represent the amplitude of a current or that of an optical signal being transmitted down a fiber in an optical digital communication system. The more recent USB and Firewire standards returned to the use of a single positive supply voltage.

Part II of this text discusses the design of a number of families of digital circuits using various semiconductor technologies. These include CMOS,[3] NMOS, and PMOS logic, which use field-effect transistors, and the TTL and ECL families, which are based on bipolar transistors.

1.2.2 ANALOG SIGNALS

Although quantities such as electronic charge and electron spin are truly discrete, much of the physical world is really analog in nature. Our senses of vision, hearing, smell, taste, and touch are all analog processes. Analog signals directly represent variables such as temperature, humidity, pressure, light intensity, or sound—all of which may take on any value, typically within some finite range. In reality, classification of digital and analog signals is largely one of perception. If we look at a digital signal similar to the one in Fig. 1.6 with an oscilloscope, we find that it actually makes a continuous transition between the high and low levels. The signal cannot make truly abrupt transitions between two levels. Designers of high-speed digital systems soon realize that they are really dealing with analog signals. The time-varying voltage or current plotted in Fig. 1.7 could be the electrical representation of temperature, flow rate, or pressure versus time, or the continuous audio output from a microphone. Some analog transducers produce output *voltages* in the range of 0 to 5 or 0 to 10 V, whereas others are designed to produce an output *current* that ranges between 4 and 20 mA. At the other extreme, signals brought in by a radio antenna can be as small as a fraction of a microvolt.

To process the information contained in these analog signals, electronic circuits are used to selectively modify the amplitude, phase, and frequency content of the signals. In addition, significant

[2] This assignment facilitates the use of Boolean algebra, reviewed in Chapter 6.

[3] For now, let us accept these initials as proper names without further definition. The details of each of these circuits are developed in Part II.

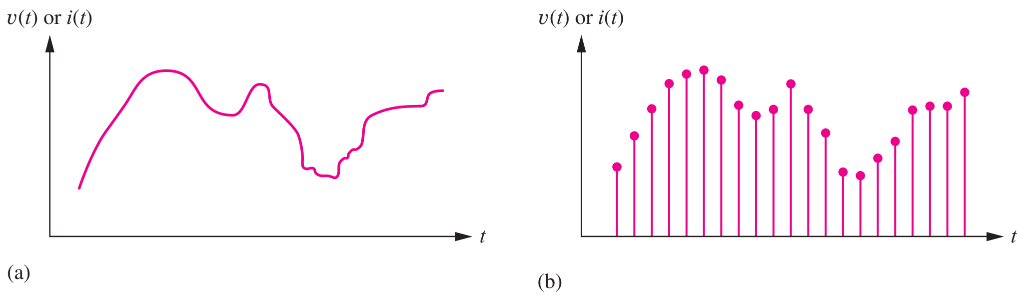


Figure 1.7 (a) A continuous analog signal; (b) sampled data version of signal in (a).

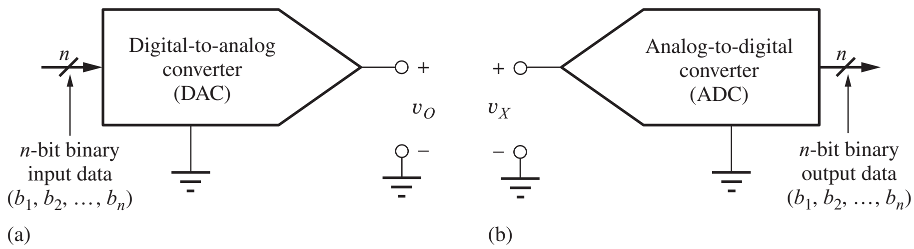


Figure 1.8 Block diagram representation for a (a) D/A converter and a (b) A/D converter.

increases in the voltage, current, and power level of the signal are usually needed. All these modifications to the signal characteristics are achieved using various forms of amplifiers, and Part III of this text discusses the analysis and design of a wide range of amplifiers using operational amplifiers and bipolar and field-effect transistors.

1.2.3 A/D AND D/A CONVERTERS—BRIDGING THE ANALOG AND DIGITAL DOMAINS

For analog and digital systems to be able to operate together, we must be able to convert signals from analog to digital form and vice versa. We sample the input signal at various points in time as in Fig. 1.7(b) and convert or quantize its amplitude into a digital representation. The quantized value can be represented in binary form or can be a decimal representation as given by the display on a digital multimeter. The electronic circuits that perform these translations are called digital-to-analog (D/A) and analog-to-digital (A/D) converters.

Digital-to-Analog Conversion

The **digital-to-analog converter,** often referred to as a **D/A converter** or **DAC,** provides an interface between the digital signals of computer systems and the continuous signals of the analog world. The D/A converter takes digital information, most often in binary form, as input and generates an output voltage or current that may be used for electronic control or analog information display. In the DAC in Fig. 1.8(a), an n-bit binary input word $(b_1, b_2, \ldots, b_n)$ is treated as a binary fraction and multiplied by a full-scale reference voltage V_{FS} to set the output of the D/A converter. The behavior of the DAC can be expressed mathematically as

$$v_O = (b_1 2^{-1} + b_2 2^{-2} + \cdots + b_n 2^{-n}) V_{FS} \qquad \text{for } b_i \in \{1, 0\} \tag{1.1}$$

Examples of typical values of the full-scale voltage V_{FS} are 1, 2, 5, 5.12, 10, and 10.24 V. The smallest voltage change that can occur at the output takes place when the **least significant bit** b_n, or **LSB,** in the digital word changes from a 0 to a 1. This minimum voltage change is also referred to as the **resolution of the converter** and is given by

$$V_{\text{LSB}} = 2^{-n} V_{FS} \tag{1.2}$$

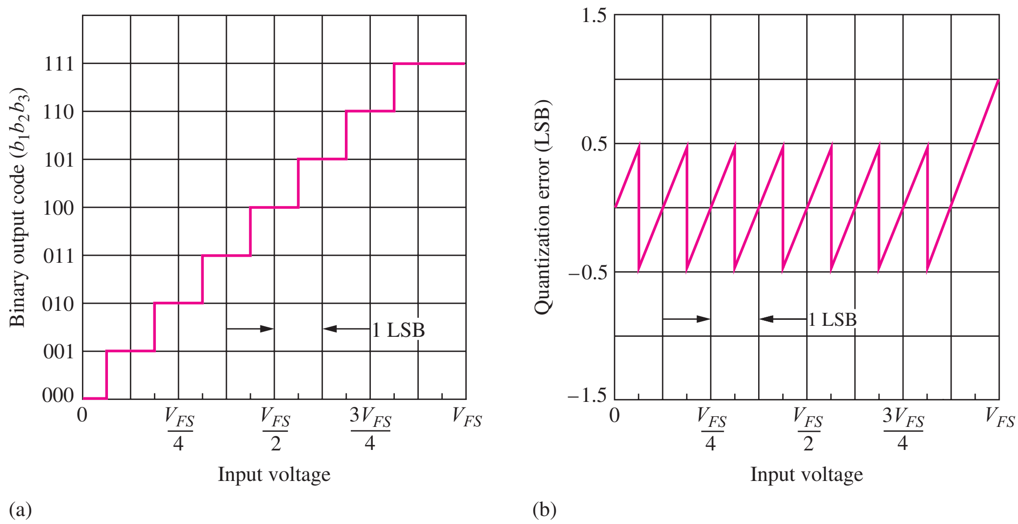


Figure 1.9 (a) Input–output relationship and (b) quantization error for 3-bit ADC.

At the other extreme, b_1 is referred to as the **most significant bit,** or **MSB,** and has a weight of one-half V_{FS}.

EXERCISE: A 10-bit D/A converter has $V_{FS} = 5.12$ V. What is the output voltage for a binary input code of (1100010001)? What is V_{LSB}? What is the size of the MSB?

ANSWERS: 3.925 V; 5 mV; 2.56 V

Analog-to-Digital Conversion

The **analog-to-digital converter (A/D converter** or **ADC)** is used to transform analog information in electrical form into digital data. The ADC in Fig. 1.8(b) takes an unknown continuous analog input signal, usually a voltage v_X, and converts it into an n-bit binary number that can be easily manipulated by a computer. The n-bit number is a binary fraction representing the ratio between the unknown input voltage v_X and the converter's full-scale voltage V_{FS}.

For example, the input–output relationship for an ideal 3-bit A/D converter is shown in Fig. 1.9(a). As the input increases from zero to full scale, the output digital code word stair-steps from 000 to 111.[4] The output code is constant for an input voltage range equal to 1 LSB of the ADC. Thus, as the input voltage increases, the output code first underestimates and then overestimates the input voltage. This error, called **quantization error,** is plotted against input voltage in Fig. 1.9(b).

For a given output code, we know only that the value of the input voltage lies somewhere within a 1-LSB quantization interval. For example, if the output code of the 3-bit ADC is 100, corresponding to a voltage $V_{FS}/2$, then the input voltage can be anywhere between $\frac{7}{16}V_{FS}$ and $\frac{9}{16}V_{FS}$, a range of $V_{FS}/8$ V or 1 LSB. From a mathematical point of view, the ADC circuitry in Fig. 1.8(b) picks the values of the bits in the binary word to minimize the magnitude of the quantization error v_ε between the unknown input voltage v_X and the nearest quantized voltage level:

$$v_\varepsilon = |v_X - (b_1 2^{-1} + b_2 2^{-2} + \cdots + b_n 2^{-n})V_{FS}| \tag{1.3}$$

[4] The binary point is understood to be to the immediate left of the digits of the code word. As the code word stair-steps from 000 to 111, the binary fraction steps from 0.000 to 0.111.

EXERCISE: An 8-bit A/D converter has $V_{FS} = 5$ V. What is the digital output code word for an input of 1.2 V? What is the voltage range corresponding to 1 LSB of the converter?

ANSWERS: 00111101; 19.5 mV

1.3 NOTATIONAL CONVENTIONS

In many circuits we will be dealing with both dc and time-varying values of voltages and currents. The following standard notation will be used to keep track of the various components of an electrical signal. Total quantities will be represented by lowercase letters with capital subscripts, such as v_T and i_T in Eq. (1.4). The dc components are represented by capital letters with capital subscripts as, for example, V_{DC} and I_{DC} in Eq. (1.4); changes or variations from the dc value are represented by signal components v_{sig} and i_{sig}.

$$v_T = V_{DC} + v_{\text{sig}} \qquad \text{or} \qquad i_T = I_{DC} + i_{\text{sig}} \tag{1.4}$$

As examples, the total base-emitter voltage v_{BE} of a transistor and the total drain current i_D of a field-effect transistor are written as

$$v_{BE} = V_{BE} + v_{be} \qquad \text{and} \qquad i_D = I_D + i_d \tag{1.5}$$

Unless otherwise indicated, the equations describing a given network will be written assuming a consistent set of units: volts, amperes, and ohms. For example, the equation $5\text{ V} = (10{,}000\ \Omega)I_1 + 0.6\text{ V}$ will be written as $5 = 10{,}000I_1 + 0.6$.

The fourth upper/lowercase combination, such as V_{be} or I_d, is reserved for the amplitude of a sinusoidal signal's phasor representation as defined in Section 1.7.

EXERCISE: Suppose the voltage at a circuit node is described by

$$v_A = (5 \sin 2000\pi t + 4 + 3 \cos 1000\pi t)\text{ V}$$

What are the expressions for V_A and v_a?

ANSWERS: $V_A = 4$ V; $v_a = (5 \sin 2000\pi t + 3 \cos 1000\pi t)$ V

Resistance and Conductance Representations

In the circuits throughout this text, resistors will be indicated symbolically as R_x or r_x, and the values will be expressed in Ω, kΩ, MΩ, and so on. During analysis, however, it may be more convenient to work in terms of conductance with the following convention:

$$G_x = \frac{1}{R_x} \qquad \text{and} \qquad g_\pi = \frac{1}{r_\pi} \tag{1.6}$$

For example, conductance G_x always represents the reciprocal of the value of R_x, and g_π represents the reciprocal of r_π. The values next to a resistor symbol will always be expressed in terms of resistance (Ω, kΩ, MΩ).

Dependent Sources

In electronics, **dependent** (or **controlled**) **sources** are used extensively. Four types of dependent sources are summarized in Fig. 1.10, in which the standard diamond shape is used for controlled sources. The **voltage-controlled current source (VCCS), current-controlled current source (CCCS),** and **voltage-controlled voltage source (VCVS)** are used routinely in this text to model

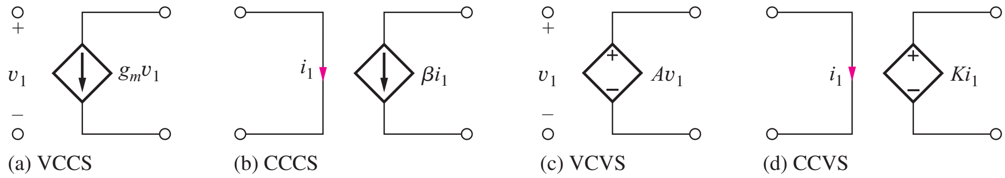


Figure 1.10 Controlled sources. (a) Voltage-controlled current source (VCCS). (b) Current-controlled current source (CCCS). (c) Voltage-controlled voltage source (VCVS). (d) Current-controlled voltage source (CCVS).

transistors and amplifiers or to simplify more complex circuits. Only the **current-controlled voltage source (CCVS)** sees limited use.

1.4 PROBLEM-SOLVING APPROACH

Solving problems is a centerpiece of an engineer's activity. As engineers, we use our creativity to find new solutions to problems that are presented to us. A well-defined approach can aid significantly in solving problems. The examples in this text highlight an approach that can be used in all facets of your career, as a student and as an engineer in industry. The method is outlined in the following nine steps:

1. State the **problem** as clearly as possible.
2. List the **known information and given data.**
3. Define the **unknowns** that must be found to solve the problem.
4. List your **assumptions.** You may discover additional assumptions as the analysis progresses.
5. Develop an **approach** from a group of possible alternatives.
6. Perform an **analysis** to find a solution to the problem. As part of the analysis, be sure to draw the circuit and label the variables.
7. **Check the results.** Has the problem been solved? Is the math correct? Have all the unknowns been found? Have the assumptions been satisfied? Do the results satisfy simple consistency checks?
8. **Evaluate the solution.** Is the solution realistic? Can it be built? If not, repeat steps 4–7 until a satisfactory solution is obtained.
9. **Computer-aided analysis.** SPICE and other computer tools are highly useful to check the results and to see if the solution satisfies the problem requirements. Compare the computer results to your hand results.

To begin solving a problem, we must try to understand its details. The first four steps, which attempt to clearly define the problem, can be the most important part of the solution process. Time spent understanding, clarifying, and defining the problem can save much time and frustration.

The first step is to write down a statement of the problem. The original problem description may be quite vague; we must try to understand the problem as well as, or even better than, the individual who posed the problem. As part of this focus on understanding the problem, we list the information that is known and unknown. Problem-solving errors can often be traced to imprecise definition of the unknown quantities. For example, it is very important for analysis to draw the circuit properly and to clearly label voltages and currents on our circuit diagrams.

Often there are more unknowns than constraints, and we need engineering judgment to reach a solution. Part of our task in studying electronics is to build up the background for selecting between various alternatives. Along the way, we often need to make approximations and assumptions that simplify the problem or form the basis of the chosen approach. It is important to state these assumptions, so that we can be sure to check their validity at the end. Throughout this text you will encounter opportunities to make assumptions. Most often, you should make assumptions that simplify your computational effort yet still achieve useful results.

The exposition of the known information, unknowns, and assumptions helps us not only to better understand the problem but also to think about various alternative solutions. We must choose the approach that appears to have the best chance of solving the problem. There may be more than one satisfactory approach. Each person will view the problem somewhat differently, and the approach that is clearest to one individual may not be the best for another. Pick the one that seems best to you. As part of defining the approach, be sure to think about what computational tools are available to assist in the solution, including MATLAB®, Mathcad®, spreadsheets, SPICE, and your calculator.

Once the problem and approach are defined as clearly as possible, then we can perform any analysis required and solve the problem. After the analysis is completed we need to check the results. A number of questions should be resolved. First, have all the unknowns been found? Do the results make sense? Are they consistent with each other? Are the results consistent with assumptions used in developing the approach to the problem?

Then we need to evaluate the solution. Are the results viable? For example, are the voltage, current, and power levels reasonable? Can the circuit be realized with reasonable yield with real components? Will the circuit continue to function within specifications in the face of significant component variations? Is the cost of the circuit within specifications? If the solution is not satisfactory, we need to modify our approach and assumptions and attempt a new solution. An iterative solution is often required to meet the specifications in realistic design situations. SPICE and other computer tools are highly useful for checking results and ensuring that the solution satisfies the problem requirements.

The solutions to the examples in this text have been structured following the problem-solving approach introduced here. Although some examples may appear trivial, the power of the structured approach increases as the problem becomes more complex.

WHAT ARE REASONABLE NUMBERS?

Part of our results check should be to decide if the answer is "reasonable" and makes sense. Over time we must build up an understanding of what numbers are reasonable. Most solid-state devices that we will encounter are designed to operate from voltages ranging from a battery voltage of 1 V on the low end to no more than 40–50 V[5] at the high end. Typical power supply voltages will be in the 10- to 20-V range, and typical resistance values encountered will range from tens of Ω up to many GΩ.

Based on our knowledge of dc circuits, we should expect that the voltages in our circuits not exceed the power supply voltages. For example, if a circuit is operating from +8- and −5-V supplies, all of our calculated dc voltages must be between −5 and +8 V. In addition, the peak-to-peak amplitude of an ac signal should not exceed 13 V, the difference of the two supply voltages. With a 10-V supply, the maximum current that can go through a 100-Ω resistor is 100 mA; the current through a 10-MΩ resistor can be no more than 1 μA. Thus we should remember the following "rules" to check our results:

1. With few exceptions, the dc voltages in our circuits cannot exceed the power supply voltages. The peak-to-peak amplitude of an ac signal should not exceed the difference of the power supply voltages.
2. The currents in our circuits will range from microamperes to no more than a hundred milliamperes or so.

[5] The primary exception is in the area of power electronics, where one encounters much larger voltages and currents than the ones discussed here.

1.5 IMPORTANT CONCEPTS FROM CIRCUIT THEORY

Analysis and design of electronic circuits make continuous use of a number of important techniques from basic network theory. Circuits are most often analyzed using a combination of **Kirchhoff's voltage law,** abbreviated **KVL,** and **Kirchhoff's current law,** abbreviated **KCL.** Occasionally, the solution relies on systematic application of **nodal** or **mesh analysis. Thévenin** and **Norton circuit transformations** are often used to help simplify circuits, and the notions of voltage and current division also represent basic tools of analysis. Models of active devices invariably involve dependent sources, as mentioned in the last section, and we need to be familiar with dependent sources in all forms. Amplifier analysis also uses two-port network theory. A review of two-port networks is deferred until the introductory discussion of amplifiers in Chapter 10. If the reader feels uncomfortable with any of the concepts just mentioned, this is a good time for review. To help, a brief review of these important circuit techniques follows.

1.5.1 VOLTAGE AND CURRENT DIVISION

Voltage and current division are highly useful circuit analysis techniques that can be derived directly from basic circuit theory. They are both used routinely throughout this text, and it is very important to be sure to understand the conditions for which each technique is valid! Examples of both methods are provided next.

Voltage division is demonstrated by the circuit in Fig. 1.11(a) in which the voltages v_1 and v_2 can be expressed as

$$v_1 = i_i R_1 \qquad \text{and} \qquad v_2 = i_i R_2 \tag{1.7}$$

Applying KVL to the single loop,

$$v_i = v_1 + v_2 = i_i(R_1 + R_2) \qquad \text{and} \qquad i_i = \frac{v_i}{R_1 + R_2} \tag{1.8}$$

Combining Eqs. (1.7) and (1.8) yields the basic voltage division formula:

$$v_1 = v_i \frac{R_1}{R_1 + R_2} \qquad \text{and} \qquad v_2 = v_i \frac{R_2}{R_1 + R_2} \tag{1.9}$$

For the resistor values in Fig. 1.11(a),

$$v_1 = 10\text{ V}\frac{8\text{ k}\Omega}{8\text{ k}\Omega + 2\text{ k}\Omega} = 8.00\text{ V} \qquad \text{and} \qquad v_2 = 10\text{ V}\frac{2\text{ k}\Omega}{8\text{ k}\Omega + 2\text{ k}\Omega} = 2.00\text{ V} \tag{1.10}$$

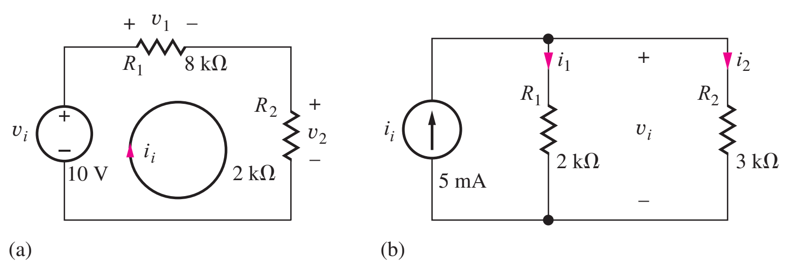


Figure 1.11 (a) A resistive voltage divider, (b) Current division in a simple network.

DESIGN NOTE VOLTAGE DIVIDER RESTRICTIONS

Note that the voltage divider relationships in Eq. (1.9) can be applied only when the current through the two resistor branches is the same. Also, note that the formulas are correct if the resistances are replaced by complex impedances and the voltages are represented as **phasors.**

$$\mathbf{V_1} = \mathbf{V_S}\frac{Z_1}{Z_1 + Z_2} \qquad \text{and} \qquad \mathbf{V_2} = \mathbf{V_S}\frac{Z_2}{Z_1 + Z_2}$$

Current division is also very useful. Let us find the currents i_1 and i_2 in the circuit in Fig. 1.11(b). Using KCL at the single node,

$$i_i = i_1 + i_2 \qquad \text{where } i_1 = \frac{v_i}{R_1} \text{ and } i_2 = \frac{v_i}{R_2} \tag{1.11}$$

and solving for v_S yields

$$v_i = i_i \frac{1}{\dfrac{1}{R_1} + \dfrac{1}{R_2}} = i_i \frac{R_1 R_2}{R_1 + R_2} = i_i (R_1 \| R_2) \tag{1.12}$$

in which the notation $R_1 \| R_2$ represents the parallel combination of resistors R_1 and R_2. Combining Eqs. (1.11) and (1.12) yields the current division formulas:

$$i_1 = i_i \frac{R_2}{R_1 + R_2} \qquad \text{and} \qquad i_2 = i_i \frac{R_1}{R_1 + R_2} \tag{1.13}$$

For the values in Fig. 1.11(b),

$$i_1 = 5\text{ mA}\frac{3\text{ k}\Omega}{2\text{ k}\Omega + 3\text{ k}\Omega} = 3.00\text{ mA} \qquad i_2 = 5\text{ mA}\frac{2\text{ k}\Omega}{2\text{ k}\Omega + 3\text{ k}\Omega} = 2.00\text{ mA}$$

DESIGN NOTE CURRENT DIVIDER RESTRICTIONS

It is important to note that the same voltage must appear across both resistors in order for the current division expressions in Eq. (1.13) to be valid. Here again, the formulas are correct if the resistances are replaced by complex impedances and the currents are represented as **phasors.**

$$\mathbf{I_1} = \mathbf{I_S}\frac{Z_2}{Z_1 + Z_2} \qquad \text{and} \qquad \mathbf{I_2} = \mathbf{I_S}\frac{Z_1}{Z_1 + Z_2}$$

1.5.2 THÉVENIN AND NORTON CIRCUIT REPRESENTATIONS

Let us now review the method for finding **Thévenin** and **Norton equivalent circuits,** including a dependent source; the circuit in Fig. 1.12(a) serves as our illustration. Because the linear network in the dashed box has only two terminals, it can be represented by either the Thévenin or Norton equivalent circuits in Figs. 1.12(b) and 1.12(c). The work of Thévenin and Norton permits us to reduce complex circuits to a single source and equivalent resistance. We illustrate these two important techniques with the next four examples.

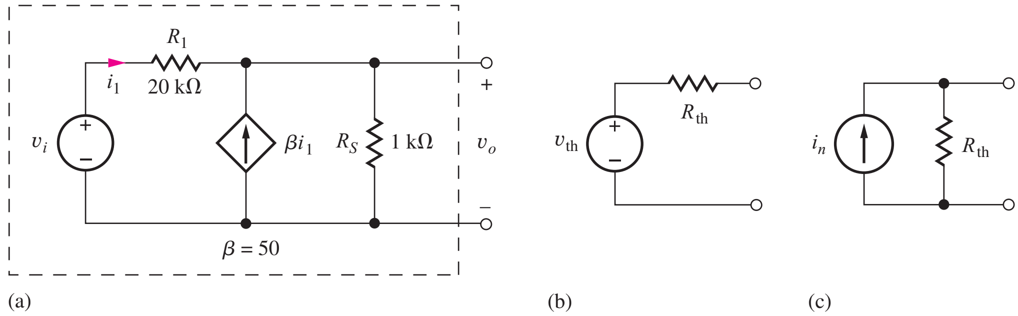


Figure 1.12 (a) Two-terminal circuit and its (b) Thévenin and (c) Norton equivalents.

EXAMPLE 1.1 THÉVENIN AND NORTON EQUIVALENT CIRCUITS

Let's practice finding the Thévenin and Norton equivalent circuits for the network in Fig. 1.12(a).

PROBLEM Find the Thévenin and Norton equivalent representations for the circuit in Fig. 1.12(a).

SOLUTION **Known Information and Given Data:** Circuit topology and values appear in Fig. 1.12(a).

Unknowns: Thévenin equivalent voltage v_{th}, Thévenin equivalent resistance R_{th}, and Norton equivalent current i_n.

Approach: Voltage source v_{th} is defined as the open-circuit voltage at the terminals of the circuit. R_{th} is the equivalent at the terminals of the circuit terminals with all independent sources set to zero. Source i_n represents the short-circuit current available at the output terminals and is equal to v_{th}/R_{th}.

Assumptions: None

Analysis: We will first find the value of v_{th}, then R_{th} and finally i_n. Open-circuit voltage v_{th} can be found by applying KCL at the output terminals.

$$\beta i_1 = \frac{v_o - v_i}{R_1} + \frac{v_o}{R_S} = G_1(v_o - v_i) + G_S v_o \qquad (1.14)$$

by applying the notational convention for conductance from Sec. 1.3 ($G_S = 1/R_S$).

Current i_1 is given by

$$i_1 = G_1(v_i - v_o) \qquad (1.15)$$

Substituting Eq. (1.15) into Eq. (1.14) and combining terms yields

$$G_1(\beta + 1)v_i = [G_1(\beta + 1) + G_S]v_o \qquad (1.16)$$

The Thévenin equivalent output voltage is then found to be

$$v_o = \frac{G_1(\beta + 1)}{[G_1(\beta + 1) + G_S]}v_i = \frac{(\beta + 1)R_S}{[(\beta + 1)R_S + R_1]}v_i \qquad (1.17)$$

where the second relationship was found by multiplying numerator and denominator by $(R_1 R_S)$. For the values in this problem,

$$v_o = \frac{(50 + 1)1\text{ k}\Omega}{[(50 + 1)\ 1\text{ k}\Omega + 20\text{ k}\Omega]}v_i = 0.718v_i \qquad \text{and} \qquad v_{th} = 0.718v_i \qquad (1.18)$$

R_{th} represents the equivalent resistance present at the output terminals with all independent sources set to zero. To find the **Thévenin equivalent resistance** R_{th}, we first set the independent sources in the network to zero. Remember, however, that any dependent sources must remain active. A test voltage or current source is then applied to the network terminals and the corresponding current or voltage calculated. In Fig. 1.13 v_i is set to zero, voltage source v_x is applied to the network, and the current i_x must be determined so that

$$R_{th} = \frac{v_x}{i_x} \tag{1.19}$$

can be calculated.

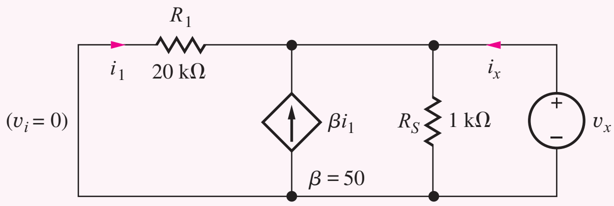


Figure 1.13 A test source v_x is applied to the network to find R_{th}.

$$i_x = -i_1 - \beta i_1 + G_S v_x \qquad \text{in which } i_1 = -G_1 v_x \tag{1.20}$$

Combining and simplifying these two expressions yields

$$i_x = [(\beta + 1)G_1 + G_S]v_x \qquad \text{and} \qquad R_{th} = \frac{v_x}{i_x} = \frac{1}{(\beta + 1)G_1 + G_S} \tag{1.21}$$

The denominator of Eq. (1.21) represents the sum of two conductances, which corresponds to the parallel combination of two resistances. Therefore, Eq. (1.21) can be rewritten as

$$R_{th} = \frac{1}{(\beta + 1)G_1 + G_S} = \frac{R_S \dfrac{R_1}{(\beta + 1)}}{R_S + \dfrac{R_1}{(\beta + 1)}} = R_S \left\| \frac{R_1}{(\beta + 1)} \right. \tag{1.22}$$

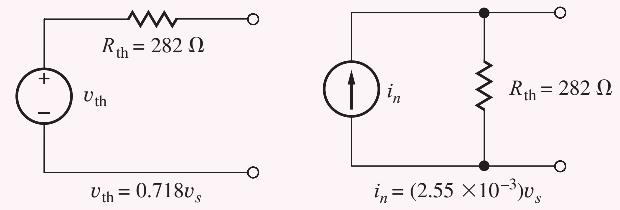
For the values in this example,

$$R_{th} = R_S \left\| \frac{R_1}{(\beta + 1)} \right. = 1\text{ k}\Omega \left\| \frac{20\text{ k}\Omega}{(50 + 1)} \right. = 1\text{ k}\Omega \| 392\ \Omega = 282\ \Omega \tag{1.23}$$

Norton source in represents the short circuit current available from the original network. Since we already have the Thévenin equivalent circuit, we can use it to fid the value of i_n.

$$i_n = \frac{v_{th}}{R_{th}} = \frac{0.718 v_i}{282\Omega} = 2.55 \times 10^{-3} v_i$$

The Thévenin and Norton equivalent circuits for Fig. 1.12 calculated in the previous example appear for comparison in Fig. 1.14.



(a) (b)

Figure 1.14 Completed (a) Thévenin and (b) Norton equivalent circuits for the two-terminal network in Fig. 1.12(a).

Check of Results: We have found the three unknowns required. A recheck of the calculations indicates they are done correctly. The value of v_{th} is the same order of magnitude as v_i, so its value should not be unusually large or small. The value of R_{th} is less than 1 kΩ, which seems reasonable, since we should not expect the resistance to exceed the value of R_S that appears in parallel with the output terminals. We can double-check everything by directly calculating i_n from the original circuit. If we short the output terminals in Fig. 1.12, we find the short-circuit current (See Ex. 1.2) to be $i_n = (\beta + 1)\, v_i / R_1 = 2.55 \times 10^{-3} v_i$ and in agreement with the other method.

EXAMPLE 1.2 NORTON EQUIVALENT CIRCUIT

Practice finding the Norton equivalent circuit for a network containing a dependent source.

PROBLEM Find the Norton equivalent (Fig. 1.12(c)) for the circuit in Fig. 1.12(a).

SOLUTION **Known Information and Given Data:** Circuit topology and circuit values appear in Fig. 1.12(a). The value of R_{th} was calculated in the previous example.

Unknowns: Norton equivalent current i_n.

Approach: The Norton equivalent current is found by determining the current coming out of the network when a short circuit is applied to the terminals.

Assumptions: None.

Analysis: For the circuit in Fig. 1.15, the output current will be

$$i_n = i_1 + \beta i_1 \qquad \text{and} \qquad i_1 = G_1 v_i \tag{1.24}$$

The short circuit across the output forces the current through R_S to be 0. Combining the two expressions in Eq. (1.24) yields

$$i_n = (\beta + 1) G_1 v_i = \frac{(\beta + 1)}{R_1} v_i \tag{1.25}$$

or

$$i_n = \frac{(50 + 1)}{20\ \text{k}\Omega} v_i = \frac{v_i}{392\ \Omega} = (2.55\ \text{mS}) v_i \tag{1.26}$$

The resistance in the Norton equivalent circuit also equals R_{th} found in Eq. (1.23).

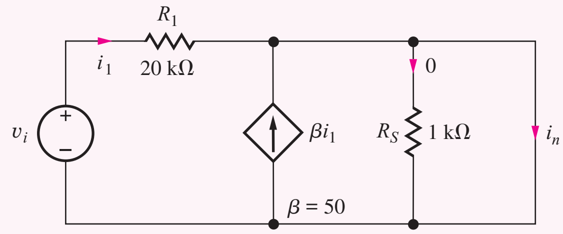


Figure 1.15 Circuit for determining short-circuit output current.

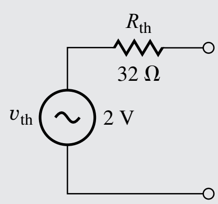
Check of Results: We have found the Norton equivalent current. Note that $v_{th} = i_n R_{th}$ and this result can be used to check the calculations: $i_n R_{th} = (2.55 \text{ mS}) v_s (282\ \Omega) = 0.719\, v_s$, which agrees within round-off error with the previous example.

ELECTRONICS IN ACTION

Player Characteristics

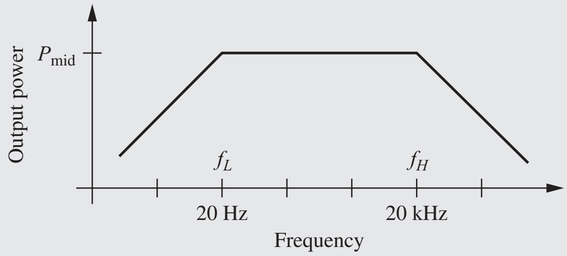
The headphone amplifier in a personal music player represents an everyday example of a basic audio amplifier. The traditional audio band spans the frequencies from 20 Hz to 20 kHz, a range that extends beyond the hearing capability of most individuals at both the upper and lower ends.

iPod: © The McGraw-Hill Companies, Inc./Jill Braaten, photographer



Thévenin equivalent circuit for output stage

The characteristics of the Apple iPod in the accompanying figure are representative of a high quality audio output stage in an MP3 player or a computer sound card. The output can be represented by a Thévenin equivalent circuit with $v_{th} = 2$ V and $R_{th} = 32$ ohms, and the output stage is designed to deliver a power of approximately 15 mW into each channel of a headphone with a matched impedance of 32 ohms. The output power is approximately constant over the 20 Hz–20 kHz frequency range. At the lower and upper cutoff frequencies, f_L and f_H, the output power will be reduced by 3 dB, a factor of 2.



Power versus frequency for an audio amplifier

The distortion characteristics of the amplifier are also important, and this is an area that often distinguishes one sound card or MP3 player from another. A good audio system will have a total harmonic distortion (THD) specification of less than 0.1 percent at full power.

1.6 FREQUENCY SPECTRUM OF ELECTRONIC SIGNALS

Fourier analysis and the **Fourier series** represent extremely powerful tools in electrical engineering. Results from Fourier theory show that complicated signals are actually composed of a continuum of sinusoidal components, each having a distinct amplitude, frequency, and phase. The **frequency spectrum** of a signal presents the amplitude and phase of the components of the signal versus frequency.

Nonrepetitive signals have continuous spectra with signals that may occupy a broad range of frequencies. For example, the amplitude spectrum of a television signal measured during a small time interval is depicted in Fig. 1.16. The TV video signal is designed to occupy the frequency range from 0 to 4.5 MHz.[6] Other types of signals occupy different regions of the frequency spectrum. Table 1.3 identifies the frequency ranges associated with various categories of common signals.

In contrast to the continuous spectrum in Fig. 1.16, Fourier series analysis shows that *any periodic* signal, such as the square wave of Fig. 1.17, contains spectral components only at discrete frequencies[7] that are related directly to the period of the signal. For example, the square wave of Fig. 1.17 having an amplitude V_O and period T can be represented by the Fourier series

$$v(t) = V_{DC} + \frac{2V_O}{\pi}\left(\sin \omega_o t + \frac{1}{3}\sin 3\omega_o t + \frac{1}{5}\sin 5\omega_o t + \cdots\right) \tag{1.27}$$

in which $\omega_o = 2\pi/T$ (rad/s) is the **fundamental radian frequency** of the square wave. We refer to $f_o = 1/T$ (Hz) as the **fundamental frequency** of the signal, and the frequency components at $2f_o$, $3f_o$, $4f_o$, ... are called the second, third, fourth, and so on **harmonic frequencies.**

[6] This signal is combined with a much higher carrier frequency prior to transmission.

[7] There are an infinite number of components, however.

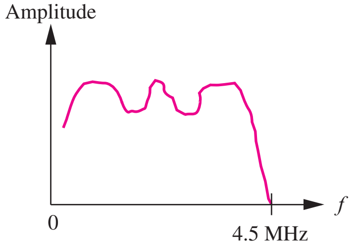


Figure 1.16 Spectrum of a TV signal.

TABLE 1.3
Frequencies Associated with Common Signals

CATEGORY	FREQUENCY RANGE
Audible sounds	20 Hz – 20 kHz
Baseband video (TV) signal	0 – 4.5 MHz
AM radio broadcasting	540 – 1600 kHz
High-frequency radio communications	1.6 – 54 MHz
VHF television (Channels 2–6)	54 – 88 MHz
FM radio broadcasting	88 – 108 MHz
VHF radio communication	108 – 174 MHz
VHF television (Channels 7–13)	174 – 216 MHz
Maritime and government communications	216 – 450 MHz
Business communications	450 – 470 MHz
UHF television (Channels 14–69)	470 – 806 MHz
Fixed and mobile communications including	806 – 902 MHz
Allocations for analog and digital cellular	928 – 960 MHz
Telephones, personal communications, and other	1710 – 1990 MHz
Wireless devices	2310 – 2690 MHz
Satellite television	3.7 – 4.2 GHz
Wireless devices	5.0 – 5.5 GHz

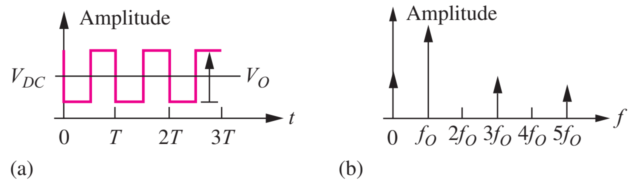


Figure 1.17 A periodic signal (a) and its amplitude spectrum (b).

1.7 AMPLIFIERS

The characteristics of analog signals are most often manipulated using linear amplifiers that affect the amplitude and/or phase of the signal without changing its frequency. Although a complex signal may have many individual components, as just described in Sec. 1.6, linearity permits us to use the **superposition principle** to treat each component individually.

For example, suppose the amplifier with voltage gain A in Fig. 1.18(a) is fed a sinusoidal input signal component v_i with amplitude V_i, frequency ω_i, and phase ϕ:

$$v_i = V_i \sin(\omega_i t + \phi) \tag{1.28}$$

Then, if the amplifier is linear, the output corresponding to this signal component will also be a sinusoidal signal at the same frequency but with a different amplitude and phase:

$$v_o = V_o \sin(\omega_i t + \phi + \theta) \tag{1.29}$$

Using phasor notation, the input and output signals would be represented as

$$\mathbf{V_i} = V_i \angle\phi \qquad \text{and} \qquad \mathbf{V_o} = V_o \angle(\phi + \theta) \tag{1.30}$$

The **voltage gain** of the amplifier is defined in terms of these phasors:

$$A = \frac{\mathbf{V_o}}{\mathbf{V_i}} = \frac{V_o \angle(\phi + \theta)}{V_i \angle\phi} = \frac{V_o}{V_i} \angle\theta \tag{1.31}$$

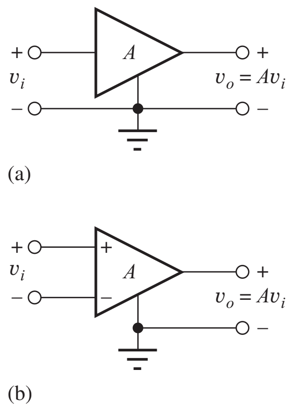


Figure 1.18 (a) Symbol for amplifier with single input and voltage gain A; (b) differential amplifier having two inputs and gain A.

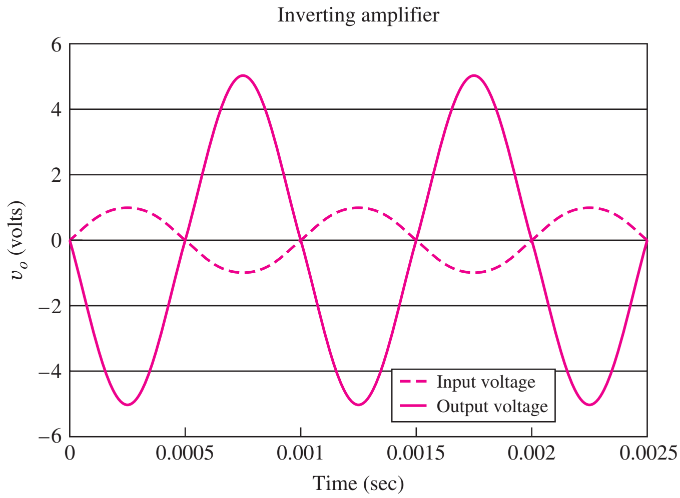


Figure 1.19 Input and output voltage waveforms for an amplifier with gain $A_v = -5$ and $v_i = 1 \sin 2000\pi t$ V.

This amplifier has a voltage gain with magnitude equal to V_o/V_i and a phase shift of θ. In general, both the magnitude and phase of the voltage gain will be a function of frequency. Note that amplifiers also often provide current gain and power gain as well as voltage gain, but these concepts will not be explored further until Chapter 10.

The curves in Fig. 1.19 represent the input and output voltage waveforms for an inverting amplifier with $A_v = -5$ and $v_i = 1 \sin 2000\pi t$ V. Both the factor of five increase in signal amplitude and the 180° phase shift (multiplication by −1) are apparent in the graph.

At this point, a note regarding the phase angle is needed. In Eqs. (1.28) and (1.29), ωt, ϕ, and θ must have the same units. With ωt normally expressed in radians, ϕ should also be in radians. However, in electrical engineering texts, ϕ is often expressed in degrees. We must be aware of this mixed system of units and remember to convert degrees to radians before making any numeric calculations.

EXERCISE: The input and output voltages of an amplifier are expressed as

$$v_i = 0.001 \sin(2000\pi t) \text{ V} \qquad \text{and} \qquad v_o = -5\cos(2000\pi t + 25^\circ) \text{ V}$$

in which v_i and v_o are specified in volts when t is seconds. What are $\mathbf{V}_i$, $\mathbf{V}_O$, and the voltage gain of the amplifier?

ANSWERS: $0.001\angle 0^\circ$; $5\angle -65^\circ$; $5000\angle -65^\circ$

1.7.1 IDEAL OPERATIONAL AMPLIFIERS

The **operational amplifier, "op amp"** for short, is a fundamental building block in electronic design and is discussed in most introductory circuit courses. A brief review of the ideal op amp is provided here; an in-depth study of the properties of ideal and nonideal op amps and the circuits used to build the op amp itself are the subjects of Chapters 11, 12, 15, and 16. Although it is impossible to realize the **ideal operational amplifier,** its use allows us to quickly understand the basic behavior to be expected from a given circuit and serves as a model to help in circuit design.