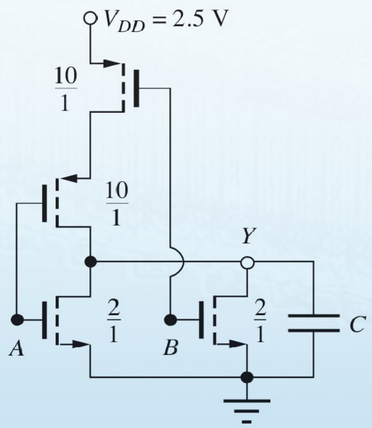
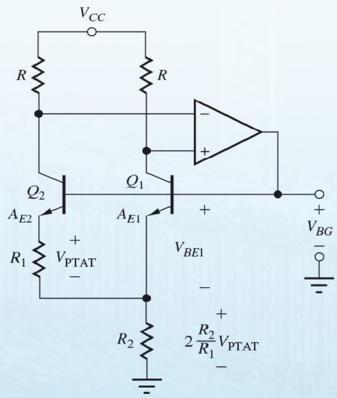
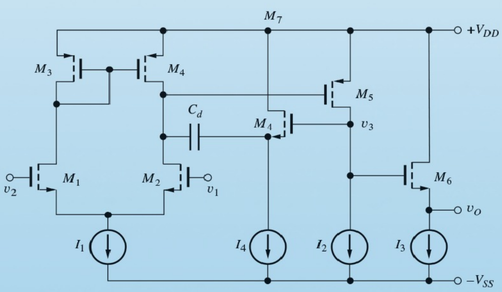
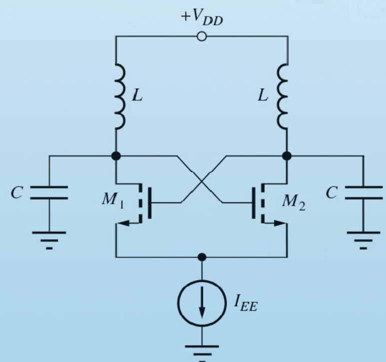
MICROELECTRONIC CIRCUIT DESIGN

RICHARD C. JAEGER • TRAVIS N. BLALOCK









FIFTH EDITION

Mc Graw Hill Education

MICROELECTRONIC CIRCUIT DESIGN

FIFTH EDITION

MICROELECTRONIC CIRCUIT DESIGN

RICHARD C. JAEGER
Auburn University

TRAVIS N. BLALOCK
University of Virginia

Mc
Graw
Hill
Education

MICROELECTRONIC CIRCUIT DESIGN, FIFTH EDITION

Published by McGraw-Hill Education, 2 Penn Plaza, New York, NY 10121.

This book is printed on acid-free paper.

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

ISBN 978-0-07-352960-8
MHID 0-07-352960-5

Senior Vice President, Products & Markets: *Kurt L. Strand*
Vice President, General Manager, Products & Markets: *Marty Lange*
Vice President, Content Design & Delivery: *Kimberly Meriwether David*
Managing Director: *Thomas Timp*
Global Publisher: *Raghu Srinivasan*
Director, Product Development: *Rose Koos*
Director, Digital Content Development: *Thomas Scaife, Ph.D*
Product Developer: *Vincent Bradshaw*
Marketing Manager: *Nick McFadden*
Director, Content Design & Delivery: *Linda Avenarius*
Program Manager: *Faye Schilling*
Content Project Managers: *Jane Mohr, Tammy Juran, and Sandra M. Schnee*
Buyer: *Jennifer Pickel*
Design: *Studio Montage, St. Louis, MO*
Content Licensing Specialist: *DeAnna Dausener*
Compositor: *MPS Limited*
Printer: *R. R. Donnelley*

Library of Congress Cataloging-in-Publication Data

Jaeger, Richard C.
Microelectronic circuit design / Richard C. Jaeger, Auburn University, Travis N. Blalock, University of Virginia. —Fifth edition.
pages cm
Includes bibliographical references and index.
ISBN 978-0-07-352960-8 (alk. paper) – ISBN 0-07-338045-8 (alk. paper)
1. Integrated circuits—Design and construction. 2. Semiconductors—Design and construction. 3. Electronic circuit design. I. Blalock, Travis N. II. Title.
TK7874.J333 2015
621.3815—dc23 2014040020

www.mhhe.com

TO

To Joan, my loving wife and life long 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

CHAPTER 5
BIPOLAR JUNCTION TRANSISTORS 215

PART TWO
DIGITAL ELECTRONICS 281

CHAPTER 6
INTRODUCTION TO DIGITAL ELECTRONICS 283

CHAPTER 7
COMPLEMENTARY MOS (CMOS) LOGIC DESIGN 359

CHAPTER 8
MOS MEMORY CIRCUITS 414

CHAPTER 9
BIPOLAR LOGIC CIRCUITS 455

PART THREE
ANALOG ELECTRONICS 515

CHAPTER 10
ANALOG SYSTEMS AND IDEAL OPERATIONAL AMPLIFIERS 517

CHAPTER 11
NONIDEAL OPERATIONAL AMPLIFIERS AND FEEDBACK AMPLIFIER STABILITY 587

CHAPTER 13

SMALL-SIGNAL MODELING AND LINEAR AMPLIFICATION 770

CHAPTER 14
SINGLE-TRANSISTOR AMPLIFIERS 841

CHAPTER 15
DIFFERENTIAL AMPLIFIERS AND OPERATIONAL AMPLIFIER DESIGN 952

CHAPTER 16
ANALOG INTEGRATED CIRCUIT DESIGN TECHNIQUES 1031

APPENDICES

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 Part I, the concept of velocity saturation from Chapter 2 is reinforced with the addition of the Unified MOS model of Rabaey and Chandrakasan in the Field Effect Transistors chapter, and the impact of velocity limitations on digital and analog circuits is now a recurrent topic throughout Parts II and III with discussion, examples, and new problems.

Part II has had flip-flops and latches included with other basic CMOS logic circuits in Chapter 7. Flash memory has become a pervasive technology. A significant addition to Chapter 8 is an introduction to flash memory technology and circuitry with accompanying problems. In Chapter 9, the material on T^2L has been reduced somewhat since its importance is waning, whereas a short discussion of Positive ECL (PECL) has been added. The material that was removed is still accessible on the web.

As noted above, Part III discusses biasing and distortion in the velocity saturated regime along with new problems. A section on Darlington pairs is a new addition to Chapter 15. Improved examples of offset voltage calculations and revision of the material on the bandgap reference are included in Chapter 16. In Chapter 17 a discussion of gate resistance in FETs now mirrors that of base resistance in the BJT. An expanded discussion of the frequency response of complementary emitter followers has been added. The discussion of the impact of the frequency-dependent current gain of the FET has also been enhanced to include both the input and output impedances of the source follower configuration. Finally, the discussion of the classic and pervasive Jones Mixer has been updated. An additional example of offset voltage calculation has been added to Chapter 18 along with enhanced discussion of MOS Op Amp compensation.

Other important elements include:

- At least 35 percent revised or new problems.
- New PowerPoint slides are available from McGraw-Hill.
- Popular digital features Connect and LearnSmart and SmartBook.
- The structured problem-solving approach continues throughout the examples.
- The popular Electronics-in-Action features have been revised and expanded to include IEEE Societies, Historical Development of SPICE, Body Sensor Networks, Jones Mixer, Advanced CMOS Technology, Flash Memory Growth, Low Voltage Differential Signaling (LVDS), and Fully Differential Amplifiers.

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.

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 problems.
- Integrated web materials.

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 the classic feedback topologies 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 including electronic current sources, current mirrors and active loads, and the bandgap reference, 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 important short-circuit and open-circuit time-constant techniques for estimating the dominant low- and high-frequency poles are introduced and covered in detail in Chapter 17. Chapter 18 presents examples of transistor feedback amplifiers and explores their stability and compensation. A discussion of high-frequency LC, negative g_m, and crystal oscillators concludes Chapter 18.

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 concentrate on lower 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 to instructors from the authors. In addition, the graphs and figures are available as PowerPoint files and can be retrieved on the Instructor's Resources section of Connect, along with various web materials referenced in the textbook for students. Instructor notes are available as PowerPoint slides.

To access the Instructor Resources through Connect, you must first contact your McGraw-Hill Learning Technology Representative to obtain a password. If you do not know your McGraw-Hill representative, please go to www.mhhe.com/rep, to find your representative.

Once you have your password, please go to connect.mheducation.com, and log in. Click on the course for which you are using *Microelectronic Circuit Design, 5e*. If you have not added a course, click "Add Course," and select "Engineering-Electrical and Computer" from the dropdown menu. Select this textbook and click "Next."

Once you have added the course, click on the "Library" link, and then click "Instructor Resources."

McGRAW-HILL CONNECT®

The online resources for this edition include McGraw-Hill Connect, a web-based assignment and assessment platform that can help students to perform better in their coursework and to master important concepts. With Connect, instructors can deliver assignments, quizzes, and tests easily online. Students can practice important skills at their own pace and on their own schedule. Ask your McGraw-Hill Representative for more detail and check it out at www.mcgrawhillconnect.com/engineering.

McGRAW-HILL LEARNSMART®

McGraw-Hill LearnSmart® is an adaptive learning system designed to help students learn faster, study more efficiently, and retain more knowledge for greater success. Through a series of adaptive questions, LearnSmart pinpoints concepts the student does not understand and maps out a personalized study plan for success. It also lets instructors see exactly what students have accomplished, and it features a built-in assessment tool for graded assignments. Ask your McGraw-Hill representative for more information, and visit www.mhlearnsmart.com for a demonstration.

McGRAW-HILL SMARTBOOK™

Powered by the intelligent and adaptive LearnSmart engine, SmartBook is the first and only continuously adaptive reading experience available today. Distinguishing what students know from what they dont, and honing in on concepts they are most likely to forget, SmartBook personalizes content for each student. Reading is no longer a passive and linear experience but an engaging and dynamic one, where students are more likely to master and retain important concepts, coming to class better prepared. SmartBook includes powerful reports that identify specific topics and learning objectives students need to study. These valuable reports also provide instructors insight into how students are progressing through textbook content and are useful for identifying class trends, focusing precious class time, providing personalized feedback to students, and tailoring assessment.

How does SmartBook work? Each SmartBook contains four components: Preview, Read, Practice, and Recharge. Starting with an initial preview of each chapter and key learning objectives, students read the material and are guided to topics for which they need the most practice based on their responses to a continuously adapting diagnostic. Read and practice continue until SmartBook directs students to recharge important material they are most likely to forget to ensure concept mastery and retention.

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.

McGRAW-HILL CREATE™

With McGraw-Hill Create, you can easily rearrange chapters, combine material from other content sources, and quickly upload content you have written, like your course syllabus or teaching notes. Find the content you need in Create by searching through thousands of leading McGraw-Hill textbooks. Arrange your book to fit your teaching style. Create even allows you to personalize your books appearance by selecting the cover and adding your name, school, and course information. Order a Create book and youll receive a complimentary print review copy in 3 to 5 business days or a complimentary electronic review copy (eComp) via e-mail in minutes. Go to www.mcgrawhillcreate.com today and register to experience how McGraw-Hill Create empowers you to teach your students your way.

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 continues to emphasize 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. The vast majority of the problems in this text can easily be checked using SPICE, and this approach is always recommended to students in search of answers.

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 and Mark Nelms of Auburn University and J. C. Lach 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

David Borkholder
Rochester Institute of Technology

Dimitri Donetski
Suny Buffalo

Barton Jay Greene
North Carolina State University

Marian Kazimierczuk
Wright State University –Dayton

Jih-Sheng Lai
Virginia Polytechnic Institute and State University

Dennis Lovely
University of New Brunswick

Kenneth Noren
University of Idaho

Marius Orlowski
Virginia Tech

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.

Those familiar with Professor Don Pederson's "Yellow Peril" will see it's influence throughout this text. Shortly after Professor Jaeger became Professor Art Brodersen's

student at the University of Florida, he was fortunate to be given a copy of Pederson's book to study from cover to cover.

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™ examples.

Finally, we want to thank the team at McGraw-Hill including Raghothaman Srinivasan, Global Publisher; Vincent Bradshaw, Product Developer; Nick McFadden, Marketing Manager; and Jane Mohr, Content Project Manager.

In developing this text, we have attempted to integrate our industrial backgrounds in 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 concept of velocity saturation from Chapter 2 is reinforced with the addition of the Unified MOS model of Rabaey and Chandrakasan to Chapter 4. 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. Chapter 6 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 Connect site. The impact of velocity limitations on digital and analog circuits is now a recurrent topic throughout Parts II and III with discussion, examples, and new problems. Detailed analysis of the pseudo NMOS logic gate has been moved to the web.

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. Cascade buffer design is discussed in Chapter 7. A discussion of BiCMOS logic circuitry appears in 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. An introduction to flash memory technology and circuitry is added with accompanying problems.

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 various forms of TTL. An introduction to BiCMOS logic 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 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 is included. 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 the transistor's intrinsic gain 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. A section on Darlington pairs is a new addition to Chapter 15.

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 Brokaw 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. The important short-circuit and open-circuit time-constant techniques for estimating the dominant low- and high-frequency poles are covered in detail.

Because of the renaissance and pervasive use of RF circuits, the introductory section on RF amplifiers includes shunt-peaked and tuned amplifiers. A discussion of gate resistance in FETs now mirrors that of base resistance in the BJT. Expanded discussion of the frequency response of complementary emitter followers has been added. The discussion of the impact of the frequency-dependent current gain of the FET has also been enhanced to include both the input and output impedances of the source follower configuration. Material on mixers includes passive and active single- and double-balanced mixers and the widely used Jones 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 has been expanded. 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. A new table has been added to Appendix C to help relate various two-port parameters that often appear in specification sheets to the FET and BJT model parameters that appear in the text.

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 ELECTRONICS AND DEVICES

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.
Reprinted with permission of Alacatel-Lucent USA Inc.

November 2017 will be the 70th 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 2012 the world GDP was approximately U.S. $72 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 cellular phones, 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 is 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	22
Data processing software and services	17
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
Automotive	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.)

Deforest's 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. A 128-Gb flash memory chip stores 2 or 3 bits per memory cell using multilevel storage techniques and has more than 17 billion transistors in the memory array alone, not counting address decoding and sensing circuitry. 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 almost inconceivable (see Prob. 1.9).

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.

[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.
1985	Flash memory introduced at ISSCC.
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.
2009	Kao shares one-half of the 2009 Nobel Prize in physics for fiber optic communication using light with Boyle and Smith for invention of the Charge-Coupled Device (CCD).

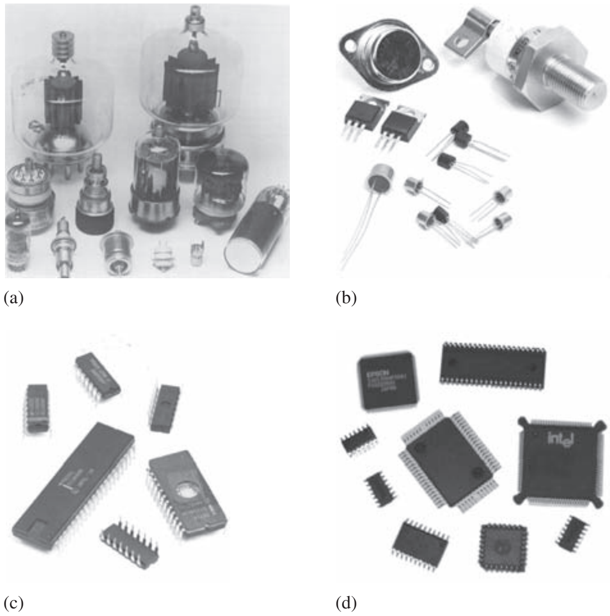


Figure 1.3 Comparison of (a) vacuum tubes, (b) individual transistors, (c) integrated circuits in dual-in-line packages (DIPs), and (d) ICs in surface mount packages.
Source: (a) Courtesy ARRL Handbook for Radio Amateurs, 1992

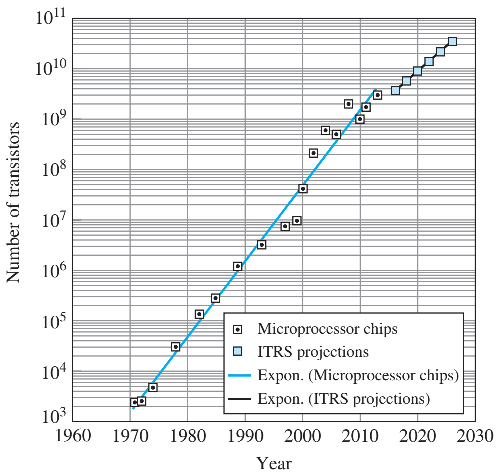


Figure 1.4 Microprocessor complexity versus time.

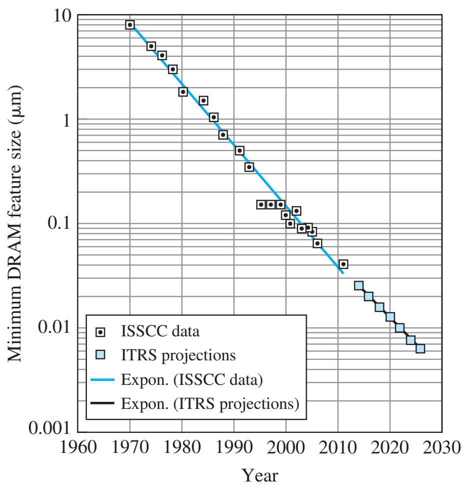


Figure 1.5 DRAM feature size versus year.

In over four decades since 1970, the number of transistors on a microprocessor chip has increased by 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-Gb 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 25 nm—less than one five-thousandth 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 **giga-scale integration (GSI,** above 10^9 components/chip) and beyond.

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 third- and fourth-generation digital cellular technology are considerably smaller and have much longer battery life. As density continues to increase, additional functions such as cameras, GPS, and Wifi 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) © *George Frey/Getty Images*

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.

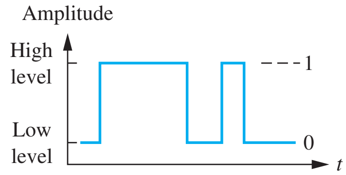


Figure 1.6 A time-varying binary digital signal.

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 $V_H = 3.3$, down to 1 V or less 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. Recent USB and Firewire standards returned to the use of a single positive supply voltage.

Part Two of this text discusses the design of a number of families of digital circuits using various semiconductor technologies. These include CMOS, NMOS, and PMOS logic[3], 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 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(a) 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 Two.