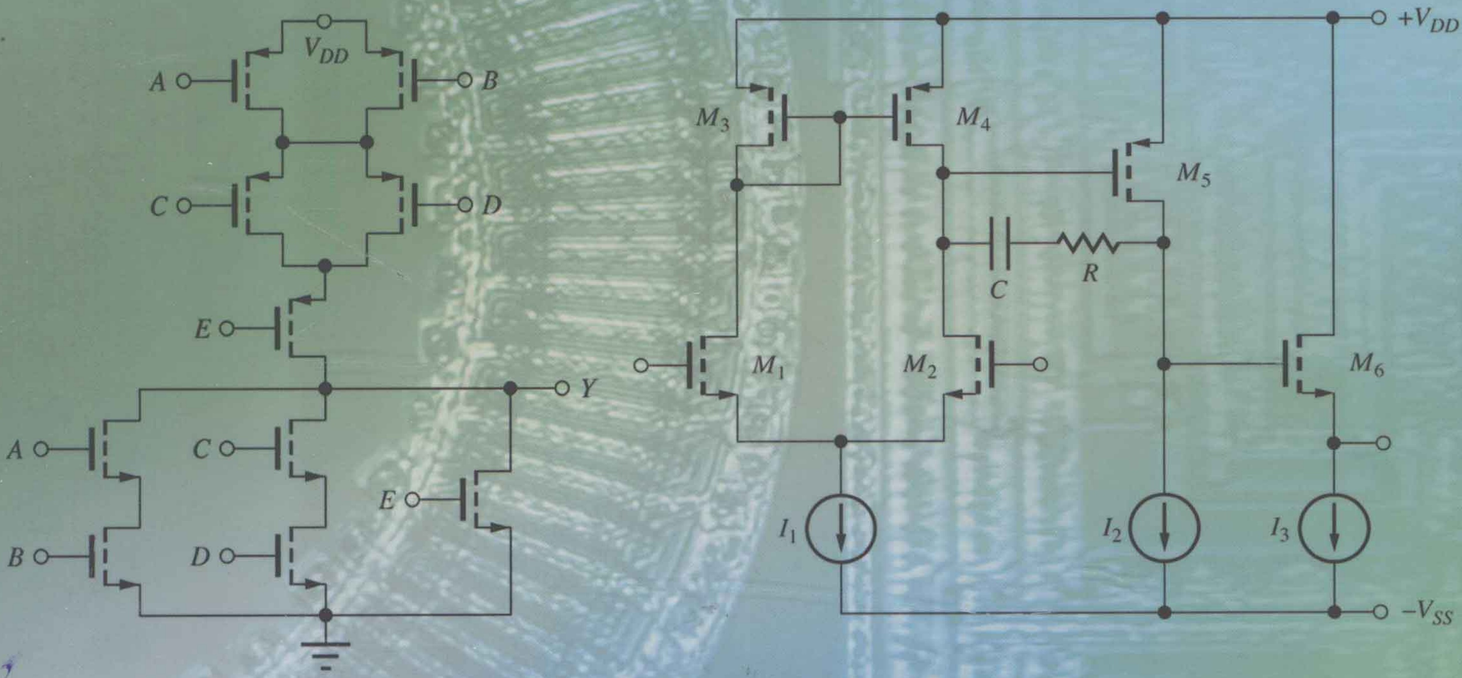
FOURTH EDITION

MICROELECTRONIC Circuit Design



RICHARD C. JAEGER | TRAVIS N. BLALOCK

FOURTH EDITION

MICROELECTRONIC CIRCUIT DESIGN

RICHARD C. JAEGER
Auburn University

TRAVIS N. BLALOCK
University of Virginia

McGraw Hill

The McGraw-Hill Companies

MICROELECTRONIC CIRCUIT DESIGN, FOURTH EDITION

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

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™ 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

BRIEF CONTENTS

CONTENTS

CHAPTER 4
FIELD-EFFECT TRANSISTORS 145

PART TWO
DIGITAL ELECTRONICS 285

CHAPTER 6
INTRODUCTION TO DIGITAL ELECTRONICS 287

CHAPTER 7
COMPLEMENTARY MOS (CMOS) LOGIC DESIGN 367