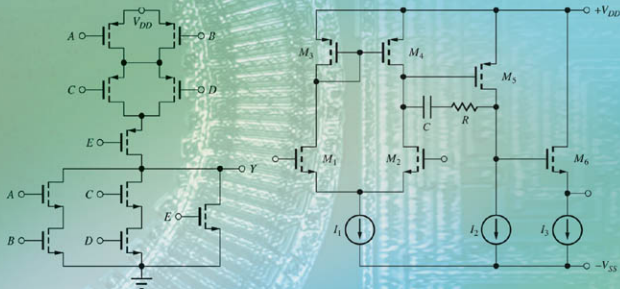
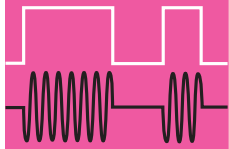


FOURTH EDITION

MICROELECTRONIC Circuit Design



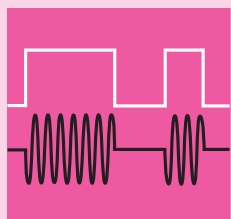
RICHARD C. JAEGER | TRAVIS N. BLALOCK



MICROELECTRONIC CIRCUIT DESIGN

This page intentionally left blank

FOURTH EDITION



MICROELECTRONIC CIRCUIT DESIGN

RICHARD C. JAEGER
Auburn University

TRAVIS N. BLALOCK
University of Virginia

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. Copyright © 2011 by The McGraw-Hill Companies, Inc. All rights reserved. Previous editions © 2008, 2004, and 1997. No part of this publication may be reproduced or distributed in any form or by any means, or stored in a database or retrieval system, without the prior written consent of The McGraw-Hill Companies, Inc., including, but not limited to, in any network or other electronic storage or transmission, or broadcast for distance learning.

Some ancillaries, including electronic and print components, may not be available to customers outside the United States.



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*

All credits appearing on page or at the end of the book are considered to be an extension of the copyright page.

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

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

Preface xx

PART ONE

SOLID STATE ELECTRONICS AND DEVICES

- 1 Introduction to Electronics 3
- 2 Solid-State Electronics 42
- 3 Solid-State Diodes and Diode Circuits 74
- 4 Field-Effect Transistors 145
- 5 Bipolar Junction Transistors 217

PART TWO

DIGITAL ELECTRONICS

- 6 Introduction to Digital Electronics 287
- 7 Complementary MOS (CMOS) Logic Design 367
- 8 MOS Memory and Storage Circuits 416
- 9 Bipolar Logic Circuits 460

PART THREE

ANALOG ELECTRONICS

- 10 Analog Systems and Ideal Operational Amplifiers 529
- 11 Nonideal Operational Amplifiers and Feedback Amplifier Stability 600

- 12 Operational Amplifier Applications 697
- 13 Small-Signal Modeling and Linear Amplification 786
- 14 Single-Transistor Amplifiers 857
- 15 Differential Amplifiers and Operational Amplifier Design 968
- 16 Analog Integrated Circuit Design Techniques 1046
- 17 Amplifier Frequency Response 1128
- 18 Transistor Feedback Amplifiers and Oscillators 1228

APPENDICES

- A Standard Discrete Component Values 1300
- B Solid-State Device Models and SPICE Simulation Parameters 1303
- C Two-Port Review 1310

Index 1313

CONTENTS

Preface xx

PART ONE SOLID STATE ELECTRONIC AND DEVICES 1

CHAPTER 1 INTRODUCTION TO ELECTRONICS 3

- 1.1 A Brief History of Electronics:
From Vacuum Tubes to Giga-Scale
Integration 5
- 1.2 Classification of Electronic Signals 8
 - 1.2.1 Digital Signals 9
 - 1.2.2 Analog Signals 9
 - 1.2.3 A/D and D/A Converters—Bridging
the Analog and Digital
Domains 10
- 1.3 Notational Conventions 12
- 1.4 Problem-Solving Approach 13
- 1.5 Important Concepts from Circuit Theory 15
 - 1.5.1 Voltage and Current Division 15
 - 1.5.2 Thévenin and Norton Circuit
Representations 16
- 1.6 Frequency Spectrum of Electronic
Signals 21
- 1.7 Amplifiers 22
 - 1.7.1 Ideal Operational Amplifiers 23
 - 1.7.2 Amplifier Frequency Response 25
- 1.8 Element Variations in Circuit Design 26
 - 1.8.1 Mathematical Modeling of
Tolerances 26
 - 1.8.2 Worst-Case Analysis 27
 - 1.8.3 Monte Carlo Analysis 29
 - 1.8.4 Temperature Coefficients 32
- 1.9 Numeric Precision 34
 - Summary* 34
 - Key Terms* 35
 - References* 36
 - Additional Reading* 36
 - Problems* 37

CHAPTER 2 SOLID-STATE ELECTRONICS 42

- 2.1 Solid-State Electronic Materials 44
- 2.2 Covalent Bond Model 45
- 2.3 Drift Currents and Mobility in
Semiconductors 48
 - 2.3.1 Drift Currents 48
 - 2.3.2 Mobility 49
 - 2.3.3 Velocity Saturation 49
- 2.4 Resistivity of Intrinsic Silicon 50
- 2.5 Impurities in Semiconductors 51
 - 2.5.1 Donor Impurities in Silicon 52
 - 2.5.2 Acceptor Impurities in Silicon 52
- 2.6 Electron and Hole Concentrations in Doped
Semiconductors 52
 - 2.6.1 n -Type Material ($N_D > N_A$) 53
 - 2.6.2 p -Type Material ($N_A > N_D$) 54
- 2.7 Mobility and Resistivity in Doped
Semiconductors 55
- 2.8 Diffusion Currents 59
- 2.9 Total Current 60
- 2.10 Energy Band Model 61
 - 2.10.1 Electron–Hole Pair Generation in an
Intrinsic Semiconductor 61
 - 2.10.2 Energy Band Model for a Doped
Semiconductor 62
 - 2.10.3 Compensated Semiconductors 62
- 2.11 Overview of Integrated Circuit
Fabrication 64
 - Summary* 67
 - Key Terms* 68
 - Reference* 69
 - Additional Reading* 69
 - Important Equations* 69
 - Problems* 70

CHAPTER 3 SOLID-STATE DIODES AND DIODE CIRCUITS 74

- 3.1 The pn Junction Diode 75
 - 3.1.1 pn Junction Electrostatics 75
 - 3.1.2 Internal Diode Currents 79

- 3.2 The i - v Characteristics of the Diode 80
 - 3.3 The Diode Equation: A Mathematical Model for the Diode 82
 - 3.4 Diode Characteristics Under Reverse, Zero, and Forward Bias 85
 - 3.4.1 Reverse Bias 85
 - 3.4.2 Zero Bias 85
 - 3.4.3 Forward Bias 86
 - 3.5 Diode Temperature Coefficient 89
 - 3.6 Diodes Under Reverse Bias 89
 - 3.6.1 Saturation Current in Real Diodes 90
 - 3.6.2 Reverse Breakdown 91
 - 3.6.3 Diode Model for the Breakdown Region 92
 - 3.7 pn Junction Capacitance 92
 - 3.7.1 Reverse Bias 92
 - 3.7.2 Forward Bias 93
 - 3.8 Schottky Barrier Diode 93
 - 3.9 Diode SPICE Model and Layout 94
 - 3.10 Diode Circuit Analysis 96
 - 3.10.1 Load-Line Analysis 96
 - 3.10.2 Analysis Using the Mathematical Model for the Diode 98
 - 3.10.3 The Ideal Diode Model 102
 - 3.10.4 Constant Voltage Drop Model 104
 - 3.10.5 Model Comparison and Discussion 105
 - 3.11 Multiple-Diode Circuits 106
 - 3.12 Analysis of Diodes Operating in the Breakdown Region 109
 - 3.12.1 Load-Line Analysis 109
 - 3.12.2 Analysis with the Piecewise Linear Model 109
 - 3.12.3 Voltage Regulation 110
 - 3.12.4 Analysis Including Zener Resistance 111
 - 3.12.5 Line and Load Regulation 112
 - 3.13 Half-Wave Rectifier Circuits 113
 - 3.13.1 Half-Wave Rectifier with Resistor Load 113
 - 3.13.2 Rectifier Filter Capacitor 114
 - 3.13.3 Half-Wave Rectifier with RC Load 115
 - 3.13.4 Ripple Voltage and Conduction Interval 116
 - 3.13.5 Diode Current 118
 - 3.13.6 Surge Current 120
 - 3.13.7 Peak-Inverse-Voltage (PIV) Rating 120
 - 3.13.8 Diode Power Dissipation 120
 - 3.13.9 Half-Wave Rectifier with Negative Output Voltage 121
 - 3.14 Full-Wave Rectifier Circuits 123
 - 3.14.1 Full-Wave Rectifier with Negative Output Voltage 124
 - 3.15 Full-Wave Bridge Rectification 125
 - 3.16 Rectifier Comparison and Design Tradeoffs 125
 - 3.17 Dynamic Switching Behavior of the Diode 129
 - 3.18 Photo Diodes, Solar Cells, and Light-Emitting Diodes 130
 - 3.18.1 Photo Diodes and Photodetectors 130
 - 3.18.2 Power Generation from Solar Cells 131
 - 3.18.3 Light-Emitting Diodes (LEDs) 132
 - Summary* 133
 - Key Terms* 134
 - Reference* 135
 - Additional Reading* 135
 - Problems* 135
- ## CHAPTER 4
- ### FIELD-EFFECT TRANSISTORS 145
- 4.1 Characteristics of the MOS Capacitor 146
 - 4.1.1 Accumulation Region 147
 - 4.1.2 Depletion Region 148
 - 4.1.3 Inversion Region 148
 - 4.2 The NMOS Transistor 148
 - 4.2.1 Qualitative i - v Behavior of the NMOS Transistor 149
 - 4.2.2 Triode Region Characteristics of the NMOS Transistor 150
 - 4.2.3 On Resistance 153
 - 4.2.4 Saturation of the i - v Characteristics 154
 - 4.2.5 Mathematical Model in the Saturation (Pinch-Off) Region 155
 - 4.2.6 Transconductance 157
 - 4.2.7 Channel-Length Modulation 157
 - 4.2.8 Transfer Characteristics and Depletion-Mode MOSFETS 158
 - 4.2.9 Body Effect or Substrate Sensitivity 159
 - 4.3 PMOS Transistors 161
 - 4.4 MOSFET Circuit Symbols 163
 - 4.5 Capacitances in MOS Transistors 165
 - 4.5.1 NMOS Transistor Capacitances in the Triode Region 165
 - 4.5.2 Capacitances in the Saturation Region 166
 - 4.5.3 Capacitances in Cutoff 166
 - 4.6 MOSFET Modeling in SPICE 167

4.7	MOS Transistor Scaling	169	5.3	The <i>pnp</i> Transistor	225
4.7.1	Drain Current	169	5.4	Equivalent Circuit Representations for the Transport Models	227
4.7.2	Gate Capacitance	169	5.5	The <i>i-v</i> Characteristics of the Bipolar Transistor	228
4.7.3	Circuit and Power Densities	170	5.5.1	Output Characteristics	228
4.7.4	Power-Delay Product	170	5.5.2	Transfer Characteristics	229
4.7.5	Cutoff Frequency	171	5.6	The Operating Regions of the Bipolar Transistor	230
4.7.6	High Field Limitations	171	5.7	Transport Model Simplifications	231
4.7.7	Subthreshold Conduction	172	5.7.1	Simplified Model for the Cutoff Region	231
4.8	MOS Transistor Fabrication and Layout Design Rules	172	5.7.2	Model Simplifications for the Forward-Active Region	233
4.8.1	Minimum Feature Size and Alignment Tolerance	173	5.7.3	Diodes in Bipolar Integrated Circuits	239
4.8.2	MOS Transistor Layout	173	5.7.4	Simplified Model for the Reverse-Active Region	240
4.9	Biassing the NMOS Field-Effect Transistor	176	5.7.5	Modeling Operation in the Saturation Region	242
4.9.1	Why Do We Need Bias?	176	5.8	Nonideal Behavior of the Bipolar Transistor	245
4.9.2	Constant Gate-Source Voltage Bias	178	5.8.1	Junction Breakdown Voltages	246
4.9.3	Load Line Analysis for the Q-Point	181	5.8.2	Minority-Carrier Transport in the Base Region	246
4.9.4	Four-Resistor Biassing	182	5.8.3	Base Transit Time	247
4.10	Biassing the PMOS Field-Effect Transistor	188	5.8.4	Diffusion Capacitance	249
4.11	The Junction Field-Effect Transistor (JFET)	190	5.8.5	Frequency Dependence of the Common-Emitter Current Gain	250
4.11.1	The JFET with Bias Applied	191	5.8.6	The Early Effect and Early Voltage	250
4.11.2	JFET Channel with Drain-Source Bias	191	5.8.7	Modeling the Early Effect	251
4.11.3	<i>n</i> -Channel JFET <i>i-v</i> Characteristics	193	5.8.8	Origin of the Early Effect	251
4.11.4	The <i>p</i> -Channel JFET	195	5.9	Transconductance	252
4.11.5	Circuit Symbols and JFET Model Summary	195	5.10	Bipolar Technology and SPICE Model	253
4.11.6	JFET Capacitances	196	5.10.1	Qualitative Description	253
4.12	JFET Modeling in SPICE	197	5.10.2	SPICE Model Equations	254
4.13	Biassing the JFET and Depletion-Mode MOSFET	198	5.10.3	High-Performance Bipolar Transistors	255
	Summary	200	5.11	Practical Bias Circuits for the BJT	256
	Key Terms	202	5.11.1	Four-Resistor Bias Network	258
	References	203	5.11.2	Design Objectives for the Four-Resistor Bias Network	260
	Problems	204	5.11.3	Iterative Analysis of the Four-Resistor Bias Circuit	266
CHAPTER 5			5.12	Tolerances in Bias Circuits	266
BIPOLAR JUNCTION TRANSISTORS			5.12.1	Worst-Case Analysis	267
5.1	Physical Structure of the Bipolar Transistor	218	5.12.2	Monte Carlo Analysis	269
5.2	The Transport Model for the <i>npn</i> Transistor	219		Summary	272
5.2.1	Forward Characteristics	220		Key Terms	274
5.2.2	Reverse Characteristics	222		References	274
5.2.3	The Complete Transport Model Equations for Arbitrary Bias Conditions	223		Problems	275

PART TWO

DIGITAL ELECTRONICS 285

CHAPTER 6

INTRODUCTION TO DIGITAL ELECTRONICS 287

- 6.1 Ideal Logic Gates 289
- 6.2 Logic Level Definitions and Noise Margins 289
 - 6.2.1 Logic Voltage Levels 291
 - 6.2.2 Noise Margins 291
 - 6.2.3 Logic Gate Design Goals 292
- 6.3 Dynamic Response of Logic Gates 293
 - 6.3.1 Rise Time and Fall Time 293
 - 6.3.2 Propagation Delay 294
 - 6.3.3 Power-Delay Product 294
- 6.4 Review of Boolean Algebra 295
- 6.5 NMOS Logic Design 297
 - 6.5.1 NMOS Inverter with Resistive Load 298
 - 6.5.2 Design of the W/L Ratio of M_S 299
 - 6.5.3 Load Resistor Design 300
 - 6.5.4 Load-Line Visualization 300
 - 6.5.5 On-Resistance of the Switching Device 302
 - 6.5.6 Noise Margin Analysis 303
 - 6.5.7 Calculation of V_{IL} and V_{OH} 303
 - 6.5.8 Calculation of V_{IH} and V_{OL} 304
 - 6.5.9 Load Resistor Problems 305
- 6.6 Transistor Alternatives to the Load Resistor 306
 - 6.6.1 The NMOS Saturated Load Inverter 307
 - 6.6.2 NMOS Inverter with a Linear Load Device 315
 - 6.6.3 NMOS Inverter with a Depletion-Mode Load 316
 - 6.6.4 Static Design of the Pseudo NMOS Inverter 319
- 6.7 NMOS Inverter Summary and Comparison 323
- 6.8 NMOS NAND and NOR Gates 324
 - 6.8.1 NOR Gates 325
 - 6.8.2 NAND Gates 326
 - 6.8.3 NOR and NAND Gate Layouts in NMOS Depletion-Mode Technology 327
- 6.9 Complex NMOS Logic Design 328
- 6.10 Power Dissipation 333
 - 6.10.1 Static Power Dissipation 333
 - 6.10.2 Dynamic Power Dissipation 334
 - 6.10.3 Power Scaling in MOS Logic Gates 335
- 6.11 Dynamic Behavior of MOS Logic Gates 337

- 6.11.1 Capacitances in Logic Circuits 337
- 6.11.2 Dynamic Response of the NMOS Inverter with a Resistive Load 338
- 6.11.3 Pseudo NMOS Inverter 343
- 6.11.4 A Final Comparison of NMOS Inverter Delays 344
- 6.11.5 Scaling Based Upon Reference Circuit Simulation 346
- 6.11.6 Ring Oscillator Measurement of Intrinsic Gate Delay 346
- 6.11.7 Unloaded Inverter Delay 347
- 6.12 PMOS Logic 349
 - 6.12.1 PMOS Inverters 349
 - 6.12.2 NOR and NAND Gates 352
- Summary* 352
- Key Terms* 354
- References* 355
- Additional Reading* 355
- Problems* 355

CHAPTER 7

COMPLEMENTARY MOS (CMOS) LOGIC DESIGN 367

- 7.1 CMOS Inverter Technology 368
 - 7.1.1 CMOS Inverter Layout 370
- 7.2 Static Characteristics of the CMOS Inverter 370
 - 7.2.1 CMOS Voltage Transfer Characteristics 371
 - 7.2.2 Noise Margins for the CMOS Inverter 373
- 7.3 Dynamic Behavior of the CMOS Inverter 375
 - 7.3.1 Propagation Delay Estimate 375
 - 7.3.2 Rise and Fall Times 377
 - 7.3.3 Performance Scaling 377
 - 7.3.4 Delay of Cascaded Inverters 379
- 7.4 Power Dissipation and Power Delay Product in CMOS 380
 - 7.4.1 Static Power Dissipation 380
 - 7.4.2 Dynamic Power Dissipation 381
 - 7.4.3 Power-Delay Product 382
- 7.5 CMOS NOR and NAND Gates 384
 - 7.5.1 CMOS NOR Gate 384
 - 7.5.2 CMOS NAND Gates 387
- 7.6 Design of Complex Gates in CMOS 388
- 7.7 Minimum Size Gate Design and Performance 393
- 7.8 Dynamic Domino CMOS Logic 395
- 7.9 Cascade Buffers 397
 - 7.9.1 Cascade Buffer Delay Model 397
 - 7.9.2 Optimum Number of Stages 398
- 7.10 The CMOS Transmission Gate 400
- 7.11 CMOS Latchup 401

Summary 404
 Key Terms 405
 References 406
 Problems 406

CHAPTER 8

MOS MEMORY AND STORAGE CIRCUITS 416

- 8.1 Random Access Memory 417
 - 8.1.1 Random Access Memory (RAM) Architecture 417
 - 8.1.2 A 256-Mb Memory Chip 418
 - 8.2 Static Memory Cells 419
 - 8.2.1 Memory Cell Isolation and Access—The 6-T Cell 422
 - 8.2.2 The Read Operation 422
 - 8.2.3 Writing Data into the 6-T Cell 426
 - 8.3 Dynamic Memory Cells 428
 - 8.3.1 The One-Transistor Cell 430
 - 8.3.2 Data Storage in the 1-T Cell 430
 - 8.3.3 Reading Data from the 1-T Cell 431
 - 8.3.4 The Four-Transistor Cell 433
 - 8.4 Sense Amplifiers 434
 - 8.4.1 A Sense Amplifier for the 6-T Cell 434
 - 8.4.2 A Sense Amplifier for the 1-T Cell 436
 - 8.4.3 The Boosted Wordline Circuit 438
 - 8.4.4 Clocked CMOS Sense Amplifiers 438
 - 8.5 Address Decoders 440
 - 8.5.1 NOR Decoder 440
 - 8.5.2 NAND Decoder 440
 - 8.5.3 Decoders in Domino CMOS Logic 443
 - 8.5.4 Pass-Transistor Column Decoder 443
 - 8.6 Read-Only Memory (ROM) 444
 - 8.7 Flip-Flops 447
 - 8.7.1 RS Flip-Flop 449
 - 8.7.2 The D-Latch Using Transmission Gates 450
 - 8.7.3 A Master-Slave D Flip-Flop 450
- Summary 451
 Key Terms 452
 References 452
 Problems 453

CHAPTER 9

BIPOLAR LOGIC CIRCUITS 460

- 9.1 The Current Switch (Emitter-Coupled Pair) 461
 - 9.1.1 Mathematical Model for Static Behavior of the Current Switch 462

- 9.1.2 Current Switch Analysis for $V_I > V_{REF}$ 463
- 9.1.3 Current Switch Analysis for $V_I < V_{REF}$ 464
- 9.2 The Emitter-Coupled Logic (ECL) Gate 464
 - 9.2.1 ECL Gate with $v_I = V_H$ 465
 - 9.2.2 ECL Gate with $v_I = V_L$ 466
 - 9.2.3 Input Current of the ECL Gate 466
 - 9.2.4 ECL Summary 466
- 9.3 Noise Margin Analysis for the ECL Gate 467
 - 9.3.1 V_{IL} , V_{OH} , V_{IH} , and V_{OL} 467
 - 9.3.2 Noise Margins 468
- 9.4 Current Source Implementation 469
- 9.5 The ECL OR-NOR Gate 471
- 9.6 The Emitter Follower 473
 - 9.6.1 Emitter Follower with a Load Resistor 474
- 9.7 “Emitter Dotting” or “Wired-OR” Logic 476
 - 9.7.1 Parallel Connection of Emitter-Follower Outputs 477
 - 9.7.2 The Wired-OR Logic Function 477
- 9.8 ECL Power-Delay Characteristics 477
 - 9.8.1 Power Dissipation 477
 - 9.8.2 Gate Delay 479
 - 9.8.3 Power-Delay Product 480
- 9.9 Current Mode Logic 481
 - 9.9.1 CML Logic Gates 481
 - 9.9.2 CML Logic Levels 482
 - 9.9.3 V_{EE} Supply Voltage 482
 - 9.9.4 Higher-Level CML 483
 - 9.9.5 CML Power Reduction 484
 - 9.9.6 NMOS CML 485
- 9.10 The Saturating Bipolar Inverter 487
 - 9.10.1 Static Inverter Characteristics 488
 - 9.10.2 Saturation Voltage of the Bipolar Transistor 488
 - 9.10.3 Load-Line Visualization 491
 - 9.10.4 Switching Characteristics of the Saturated BJT 491
- 9.11 A Transistor-Transistor Logic (TTL) Prototype 494
 - 9.11.1 TTL Inverter for $v_I = V_L$ 494
 - 9.11.2 TTL Inverter for $v_I = V_H$ 495
 - 9.11.3 Power in the Prototype TTL Gate 496
 - 9.11.4 V_{IH} , V_{IL} , and Noise Margins for the TTL Prototype 496
 - 9.11.5 Prototype Inverter Summary 498
 - 9.11.6 Fanout Limitations of the TTL Prototype 498
- 9.12 The Standard 7400 Series TTL Inverter 500
 - 9.12.1 Analysis for $v_I = V_L$ 500
 - 9.12.2 Analysis for $v_I = V_H$ 501

- 9.12.3 Power Consumption 503
- 9.12.4 TTL Propagation Delay and Power-Delay Product 503
- 9.12.5 TTL Voltage Transfer Characteristic and Noise Margins 503
- 9.12.6 Fanout Limitations of Standard TTL 504
- 9.13 Logic Functions in TTL 504
 - 9.13.1 Multi-Emitter Input Transistors 505
 - 9.13.2 TTL NAND Gates 505
 - 9.13.3 Input Clamping Diodes 506
- 9.14 Schottky-Clamped TTL 506
- 9.15 Comparison of the Power-Delay Products of ECL and TTL 508
- 9.16 BiCMOS Logic 508
 - 9.16.1 BiCMOS Buffers 509
 - 9.16.2 BiMOS Inverters 511
 - 9.16.3 BiCMOS Logic Gates 513
- Summary* 513
- Key Terms* 515
- References* 515
- Additional Reading* 515
- Problems* 516

PART THREE

ANALOG ELECTRONICS 527

CHAPTER 10

ANALOG SYSTEMS AND IDEAL OPERATIONAL AMPLIFIERS 529

- 10.1 An Example of an Analog Electronic System 530
- 10.2 Amplification 531
 - 10.2.1 Voltage Gain 532
 - 10.2.2 Current Gain 533
 - 10.2.3 Power Gain 533
 - 10.2.4 The Decibel Scale 534
- 10.3 Two-Port Models for Amplifiers 537
 - 10.3.1 The g -parameters 537
- 10.4 Mismatched Source and Load Resistances 541
- 10.5 Introduction to Operational Amplifiers 544
 - 10.5.1 The Differential Amplifier 544
 - 10.5.2 Differential Amplifier Voltage Transfer Characteristic 545
 - 10.5.3 Voltage Gain 545
- 10.6 Distortion in Amplifiers 548
- 10.7 Differential Amplifier Model 549
- 10.8 Ideal Differential and Operational Amplifiers 551
 - 10.8.1 Assumptions for Ideal Operational Amplifier Analysis 551
- 10.9 Analysis of Circuits Containing Ideal Operational Amplifiers 552
 - 10.9.1 The Inverting Amplifier 553
 - 10.9.2 The Transresistance Amplifier—A Current-to-Voltage Converter 556
 - 10.9.3 The Noninverting Amplifier 558
 - 10.9.4 The Unity-Gain Buffer, or Voltage Follower 561
 - 10.9.5 The Summing Amplifier 563
 - 10.9.6 The Difference Amplifier 565
- 10.10 Frequency-Dependent Feedback 568
 - 10.10.1 Bode Plots 568
 - 10.10.2 The Low-Pass Amplifier 568
 - 10.10.3 The High-Pass Amplifier 572
 - 10.10.4 Band-Pass Amplifiers 575
 - 10.10.5 An Active Low-Pass Filter 578
 - 10.10.6 An Active High-Pass Filter 581
 - 10.10.7 The Integrator 582
 - 10.10.8 The Differentiator 586
- Summary* 586
- Key Terms* 588
- References* 588
- Additional Reading* 589
- Problems* 589

CHAPTER 11

NONIDEAL OPERATIONAL AMPLIFIERS AND FEEDBACK AMPLIFIER STABILITY 600

- 11.1 Classic Feedback Systems 601
 - 11.1.1 Closed-Loop Gain Analysis 602
 - 11.1.2 Gain Error 602
- 11.2 Analysis of Circuits Containing Nonideal Operational Amplifiers 603
 - 11.2.1 Finite Open-Loop Gain 603
 - 11.2.2 Nonzero Output Resistance 606
 - 11.2.3 Finite Input Resistance 610
 - 11.2.4 Summary of Nonideal Inverting and Noninverting Amplifiers 614
- 11.3 Series and Shunt Feedback Circuits 615
 - 11.3.1 Feedback Amplifier Categories 615
 - 11.3.2 Voltage Amplifiers—Series-Shunt Feedback 616
 - 11.3.3 Transimpedance Amplifiers—Shunt-Shunt Feedback 616
 - 11.3.4 Current Amplifiers—Shunt-Series Feedback 616
 - 11.3.5 Transconductance Amplifiers—Series-Series Feedback 616
- 11.4 Unified Approach to Feedback Amplifier Gain Calculation 616

	11.4.1	Closed-Loop Gain Analysis	617
	11.4.2	Resistance Calculation Using Blackman'S Theorem	617
11.5		Series-Shunt Feedback–Voltage Amplifiers	617
	11.5.1	Closed-Loop Gain Calculation	618
	11.5.2	Input Resistance Calculation	618
	11.5.3	Output Resistance Calculation	619
	11.5.4	Series-Shunt Feedback Amplifier Summary	620
11.6		Shunt-Shunt Feedback—Transresistance Amplifiers	624
	11.6.1	Closed-Loop Gain Calculation	625
	11.6.2	Input Resistance Calculation	625
	11.6.3	Output Resistance Calculation	625
	11.6.4	Shunt-Shunt Feedback Amplifier Summary	626
11.7		Series-Series Feedback—Transconductance Amplifiers	629
	11.7.1	Closed-Loop Gain Calculation	630
	11.7.2	Input Resistance Calculation	630
	11.7.3	Output Resistance Calculation	631
	11.7.4	Series-Series Feedback Amplifier Summary	631
11.8		Shunt-Series Feedback—Current Amplifiers	633
	11.8.1	Closed-Loop Gain Calculation	634
	11.8.2	Input Resistance Calculation	635
	11.8.3	Output Resistance Calculation	635
	11.8.4	Series-Series Feedback Amplifier Summary	635
11.9		Finding the Loop Gain Using Successive Voltage and Current Injection	638
	11.9.1	Simplifications	641
11.10		Distortion Reduction Through the Use of Feedback	641
11.11		DC Error Sources and Output Range Limitations	642
	11.11.1	Input-Offset Voltage	643
	11.11.2	Offset-Voltage Adjustment	644
	11.11.3	Input-Bias and Offset Currents	645
	11.11.4	Output Voltage and Current Limits	647
11.12		Common-Mode Rejection and Input Resistance	650
	11.12.1	Finite Common-Mode Rejection Ratio	650
	11.12.2	Why Is CMRR Important?	651
	11.12.3	Voltage-Follower Gain Error Due to CMRR	654
	11.12.4	Common-Mode Input Resistance	656

	11.12.5	An Alternate Interpretation of CMRR	657
	11.12.6	Power Supply Rejection Ratio	657
11.13		Frequency Response and Bandwidth of Operational Amplifiers	659
	11.13.1	Frequency Response of the Noninverting Amplifier	661
	11.13.2	Inverting Amplifier Frequency Response	664
	11.13.3	Using Feedback to Control Frequency Response	666
	11.13.4	Large-Signal Limitations—Slew Rate and Full-Power Bandwidth	668
	11.13.5	Macro Model for Operational Amplifier Frequency Response	669
	11.13.6	Complete Op Amp Macro Models in SPICE	670
	11.13.7	Examples of Commercial General-Purpose Operational Amplifiers	670
11.14		Stability of Feedback Amplifiers	671
	11.14.1	The Nyquist Plot	671
	11.14.2	First-Order Systems	672
	11.14.3	Second-Order Systems and Phase Margin	673
	11.14.4	Step Response and Phase Margin	674
	11.14.5	Third-Order Systems and Gain Margin	677
	11.14.6	Determining Stability from the Bode Plot	678
		<i>Summary</i>	682
		<i>Key Terms</i>	684
		<i>References</i>	684
		<i>Problems</i>	685

CHAPTER 12

OPERATIONAL AMPLIFIER APPLICATIONS 697

- 12.1 Cascaded Amplifiers 698
 - 12.1.1 Two-Port Representations 698
 - 12.1.2 Amplifier Terminology Review 700
 - 12.1.3 Frequency Response of Cascaded Amplifiers 703
- 12.2 The Instrumentation Amplifier 711
- 12.3 Active Filters 714
 - 12.3.1 Low-Pass Filter 714
 - 12.3.2 A High-Pass Filter with Gain 718
 - 12.3.3 Band-Pass Filter 720
 - 12.3.4 The Tow-Thomas Biquad 722
 - 12.3.5 Sensitivity 726
 - 12.3.6 Magnitude and Frequency Scaling 727

12.4	Switched-Capacitor Circuits 728	13.5	Small-Signal Models for Bipolar Junction Transistors 799
12.4.1	A Switched-Capacitor Integrator 728	13.5.1	The Hybrid-Pi Model 801
12.4.2	Noninverting SC Integrator 730	13.5.2	Graphical Interpretation of the Transconductance 802
12.4.3	Switched-Capacitor Filters 732	13.5.3	Small-Signal Current Gain 802
12.5	Digital-to-Analog Conversion 733	13.5.4	The Intrinsic Voltage Gain of the BJT 803
12.5.1	D/A Converter Fundamentals 733	13.5.5	Equivalent Forms of the Small-Signal Model 804
12.5.2	D/A Converter Errors 734	13.5.6	Simplified Hybrid Pi Model 805
12.5.3	Digital-to-Analog Converter Circuits 737	13.5.7	Definition of a Small Signal for the Bipolar Transistor 805
12.6	Analog-to-Digital Conversion 740	13.5.8	Small-Signal Model for the <i>pnp</i> Transistor 807
12.6.1	A/D Converter Fundamentals 741	13.5.9	ac Analysis Versus Transient Analysis in SPICE 807
12.6.2	Analog-to-Digital Converter Errors 742	13.6	The Common-Emitter (C-E) Amplifier 808
12.6.3	Basic A/D Conversion Techniques 743	13.6.1	Terminal Voltage Gain 809
12.7	Oscillators 754	13.6.2	Input Resistance 809
12.7.1	The Barkhausen Criteria for Oscillation 754	13.6.3	Signal Source Voltage Gain 810
12.7.2	Oscillators Employing Frequency-Selective RC Networks 755	13.7	Important Limits and Model Simplifications 810
12.8	Nonlinear Circuit Applications 760	13.7.1	A Design Guide for the Common-Emitter Amplifier 810
12.8.1	A Precision Half-Wave Rectifier 760	13.7.2	Upper Bound on the Common-Emitter Gain 812
12.8.2	Nonsaturating Precision-Rectifier Circuit 761	13.7.3	Small-Signal Limit for the Common-emitter Amplifier 812
12.9	Circuits Using Positive Feedback 763	13.8	Small-Signal Models for Field-Effect Transistors 815
12.9.1	The Comparator and Schmitt Trigger 763	13.8.1	Small-Signal Model for the MOSFET 815
12.9.2	The Astable Multivibrator 765	13.8.2	Intrinsic Voltage Gain of the MOSFET 817
12.9.3	The Monostable Multivibrator or One Shot 766	13.8.3	Definition of Small-Signal Operation for the MOSFET 817
	<i>Summary</i> 770	13.8.4	Body Effect in the Four-Terminal MOSFET 818
	<i>Key Terms</i> 772	13.8.5	Small-Signal Model for the PMOS Transistor 819
	<i>Additional Reading</i> 773	13.8.6	Small-Signal Model for the Junction Field-Effect Transistor 820
	<i>Problems</i> 773	13.9	Summary and Comparison of the Small-Signal Models of the BJT and FET 821
CHAPTER 13		13.10	The Common-Source Amplifier 824
SMALL-SIGNAL MODELING AND LINEAR AMPLIFICATION 786		13.10.1	Common-Source Terminal Voltage Gain 825
13.1	The Transistor as an Amplifier 787	13.10.2	Signal Source Voltage Gain for the Common-Source Amplifier 825
13.1.1	The BJT Amplifier 788	13.10.3	A Design Guide for the Common-Source Amplifier 826
13.1.2	The MOSFET Amplifier 789	13.10.4	Small-Signal Limit for the Common-Source Amplifier 827
13.2	Coupling and Bypass Capacitors 790		
13.3	Circuit Analysis Using dc and ac Equivalent Circuits 792		
13.3.1	Menu for dc and ac Analysis 792		
13.4	Introduction to Small-Signal Modeling 796		
13.4.1	Graphical Interpretation of the Small-Signal Behavior of the Diode 796		
13.4.2	Small-Signal Modeling of the Diode 797		

- 13.10.5 Input Resistances of the Common-Emitter and Common-Source Amplifiers 829
- 13.10.6 Common-Emitter and Common-Source Output Resistances 832
- 13.10.7 Comparison of the Three Amplifier Resistances 838
- 13.11 Common-Emitter and Common-Source Amplifier Summary 838
 - 13.11.1 Guidelines for Neglecting the Transistor Output Resistance 839
- 13.12 Amplifier Power and Signal Range 839
 - 13.12.1 Power Dissipation 839
 - 13.12.2 Signal Range 840
- Summary 843*
- Key Terms 844*
- Problems 845*

CHAPTER 14

SINGLE-TRANSISTOR AMPLIFIERS 857

- 14.1 Amplifier Classification 858
 - 14.1.1 Signal Injection and Extraction—The BJT 858
 - 14.1.2 Signal Injection and Extraction—The FET 859
 - 14.1.3 Common-Emitter (C-E) and Common-Source (C-S) Amplifiers 860
 - 14.1.4 Common-Collector (C-C) and Common-Drain (C-D) Topologies 861
 - 14.1.5 Common-Base (C-B) and Common-Gate (C-G) Amplifiers 863
 - 14.1.6 Small-Signal Model Review 864
- 14.2 Inverting Amplifiers—Common-Emitter and Common-Source Circuits 864
 - 14.2.1 The Common-Emitter (C-E) Amplifier 864
 - 14.2.2 Common-Emitter Example Comparison 877
 - 14.2.3 The Common-Source Amplifier 877
 - 14.2.4 Small-Signal Limit for the Common-Source Amplifier 880
 - 14.2.5 Common-Emitter and Common-Source Amplifier Characteristics 884
 - 14.2.6 C-E/C-S Amplifier Summary 885
 - 14.2.7 Equivalent Transistor Representation of the Generalized C-E/C-S Transistor 885
- 14.3 Follower Circuits—Common-Collector and Common-Drain Amplifiers 886
 - 14.3.1 Terminal Voltage Gain 886
 - 14.3.2 Input Resistance 887
 - 14.3.3 Signal Source Voltage Gain 888
 - 14.3.4 Follower Signal Range 888
 - 14.3.5 Follower Output Resistance 889
 - 14.3.6 Current Gain 890
 - 14.3.7 C-C/C-D Amplifier Summary 890
- 14.4 Noninverting Amplifiers—Common-Base and Common-Gate Circuits 894
 - 14.4.1 Terminal Voltage Gain and Input Resistance 895
 - 14.4.2 Signal Source Voltage Gain 896
 - 14.4.3 Input Signal Range 897
 - 14.4.4 Resistance at the Collector and Drain Terminals 897
 - 14.4.5 Current Gain 898
 - 14.4.6 Overall Input and Output Resistances for the Noninverting Amplifiers 899
 - 14.4.7 C-B/C-G Amplifier Summary 902
- 14.5 Amplifier Prototype Review and Comparison 903
 - 14.5.1 The BJT Amplifiers 903
 - 14.5.2 The FET Amplifiers 905
- 14.6 Common-Source Amplifiers Using MOS Inverters 907
 - 14.6.1 Voltage Gain Estimate 908
 - 14.6.2 Detailed Analysis 909
 - 14.6.3 Alternative Loads 910
 - 14.6.4 Input and Output Resistances 911
- 14.7 Coupling and Bypass Capacitor Design 914
 - 14.7.1 Common-Emitter and Common-Source Amplifiers 914
 - 14.7.2 Common-Collector and Common-Drain Amplifiers 919
 - 14.7.3 Common-Base and Common-Gate Amplifiers 921
 - 14.7.4 Setting Lower Cutoff Frequency f_L 924
- 14.8 Amplifier Design Examples 925
 - 14.8.1 Monte Carlo Evaluation of the Common-Base Amplifier Design 934
- 14.9 Multistage ac-Coupled Amplifiers 939
 - 14.9.1 A Three-Stage ac-Coupled Amplifier 939
 - 14.9.2 Voltage Gain 941
 - 14.9.3 Input Resistance 943
 - 14.9.4 Signal Source Voltage Gain 943
 - 14.9.5 Output Resistance 943
 - 14.9.6 Current and Power Gain 944

- 14.9.7 Input Signal Range 945
- 14.9.8 Estimating the Lower Cutoff Frequency of the Multistage Amplifier 948

Summary 950

Key Terms 951

Additional Reading 952

Problems 952

CHAPTER 15

DIFFERENTIAL AMPLIFIERS AND OPERATIONAL AMPLIFIER DESIGN 968

- 15.1 Differential Amplifiers 969
 - 15.1.1 Bipolar and MOS Differential Amplifiers 969
 - 15.1.2 dc Analysis of the Bipolar Differential Amplifier 970
 - 15.1.3 Transfer Characteristic for the Bipolar Differential Amplifier 972
 - 15.1.4 ac Analysis of the Bipolar Differential Amplifier 973
 - 15.1.5 Differential-Mode Gain and Input and Output Resistances 974
 - 15.1.6 Common-Mode Gain and Input Resistance 976
 - 15.1.7 Common-Mode Rejection Ratio (CMRR) 978
 - 15.1.8 Analysis Using Differential- and Common-Mode Half-Circuits 979
 - 15.1.9 Biasing with Electronic Current Sources 982
 - 15.1.10 Modeling the Electronic Current Source in SPICE 983
 - 15.1.11 dc Analysis of the MOSFET Differential Amplifier 983
 - 15.1.12 Differential-Mode Input Signals 985
 - 15.1.13 Small-Signal Transfer Characteristic for the MOS Differential Amplifier 986
 - 15.1.14 Common-Mode Input Signals 986
 - 15.1.15 Two-Port Model for Differential Pairs 987
- 15.2 Evolution to Basic Operational Amplifiers 991
 - 15.2.1 A Two-Stage Prototype for an Operational Amplifier 992
 - 15.2.2 Improving the Op Amp Voltage Gain 997
 - 15.2.3 Output Resistance Reduction 998
 - 15.2.4 A CMOS Operational Amplifier Prototype 1002

- 15.2.5 BiCMOS Amplifiers 1004

- 15.2.6 All Transistor Implementations 1004

15.3 Output Stages 1006

- 15.3.1 The Source Follower—A Class-A Output Stage 1006
- 15.3.2 Efficiency of Class-A Amplifiers 1007
- 15.3.3 Class-B Push-Pull Output Stage 1008
- 15.3.4 Class-AB Amplifiers 1010
- 15.3.5 Class-AB Output Stages for Operational Amplifiers 1011
- 15.3.6 Short-Circuit Protection 1011
- 15.3.7 Transformer Coupling 1013

15.4 Electronic Current Sources 1016

- 15.4.1 Single-Transistor Current Sources 1017
- 15.4.2 Figure of Merit for Current Sources 1017
- 15.4.3 Higher Output Resistance Sources 1018
- 15.4.4 Current Source Design Examples 1018

Summary 1027

Key Terms 1028

References 1029

Additional Reading 1029

Problems 1029

CHAPTER 16

ANALOG INTEGRATED CIRCUIT DESIGN TECHNIQUES 1046

- 16.1 Circuit Element Matching 1047
- 16.2 Current Mirrors 1049
 - 16.2.1 dc Analysis of the MOS Transistor Current Mirror 1049
 - 16.2.2 Changing the MOS Mirror Ratio 1051
 - 16.2.3 dc Analysis of the Bipolar Transistor Current Mirror 1052
 - 16.2.4 Altering the BJT Current Mirror Ratio 1054
 - 16.2.5 Multiple Current Sources 1055
 - 16.2.6 Buffered Current Mirror 1056
 - 16.2.7 Output Resistance of the Current Mirrors 1057
 - 16.2.8 Two-Port Model for the Current Mirror 1058
 - 16.2.9 The Widlar Current Source 1060
 - 16.2.10 The MOS Version of the Widlar Source 1063

16.3	High-Output-Resistance Current Mirrors	1063
16.3.1	The Wilson Current Sources	1064
16.3.2	Output Resistance of the Wilson Source	1065
16.3.3	Cascode Current Sources	1066
16.3.4	Output Resistance of the Cascode Sources	1067
16.3.5	Regulated Cascode Current Source	1068
16.3.6	Current Mirror Summary	1069
16.4	Reference Current Generation	1072
16.5	Supply-Independent Biasing	1073
16.5.1	A V_{BE} -Based Reference	1073
16.5.2	The Widlar Source	1073
16.5.3	Power-Supply-Independent Bias Cell	1074
16.5.4	A Supply-Independent MOS Reference Cell	1075
16.6	The Bandgap Reference	1077
16.7	The Current Mirror As an Active Load	1081
16.7.1	CMOS Differential Amplifier with Active Load	1081
16.7.2	Bipolar Differential Amplifier with Active Load	1088
16.8	Active Loads in Operational Amplifiers	1092
16.8.1	CMOS Op Amp Voltage Gain	1092
16.8.2	dc Design Considerations	1093
16.8.3	Bipolar Operational Amplifiers	1095
16.8.4	Input Stage Breakdown	1096
16.9	The $\mu A741$ Operational Amplifier	1097
16.9.1	Overall Circuit Operation	1097
16.9.2	Bias Circuitry	1098
16.9.3	dc Analysis of the 741 Input Stage	1099
16.9.4	ac Analysis of the 741 Input Stage	1102
16.9.5	Voltage Gain of the Complete Amplifier	1103
16.9.6	The 741 Output Stage	1107
16.9.7	Output Resistance	1109
16.9.8	Short Circuit Protection	1109
16.9.9	Summary of the $\mu A741$ Operational Amplifier Characteristics	1109
16.10	The Gilbert Analog Multiplier	1110
	Summary	1112
	Key Terms	1113
	References	1114
	Problems	1114

CHAPTER 17

AMPLIFIER FREQUENCY RESPONSE 1128

17.1	Amplifier Frequency Response	1129
17.1.1	Low-Frequency Response	1130
17.1.2	Estimating ω_L in the Absence of a Dominant Pole	1130
17.1.3	High-Frequency Response	1133
17.1.4	Estimating ω_H in the Absence of a Dominant Pole	1133
17.2	Direct Determination of the Low-Frequency Poles and Zeros—The Common-Source Amplifier	1134
17.3	Estimation of ω_L Using the Short-Circuit Time-Constant Method	1139
17.3.1	Estimate of ω_L for the Common-Emitter Amplifier	1140
17.3.2	Estimate of ω_L for the Common-Source Amplifier	1144
17.3.3	Estimate of ω_L for the Common-Base Amplifier	1145
17.3.4	Estimate of ω_L for the Common-Gate Amplifier	1146
17.3.5	Estimate of ω_L for the Common-Collector Amplifier	1147
17.3.6	Estimate of ω_L for the Common-Drain Amplifier	1147
17.4	Transistor Models at High Frequencies	1148
17.4.1	Frequency-Dependent Hybrid-Pi Model for the Bipolar Transistor	1148
17.4.2	Modeling C_π and C_μ in SPICE	1149
17.4.3	Unity-Gain Frequency f_T	1149
17.4.4	High-Frequency Model for the FET	1152
17.4.5	Modeling C_{GS} and C_{GD} in SPICE	1153
17.4.6	Channel Length Dependence of f_T	1153
17.4.7	Limitations of the High-Frequency Models	1155
17.5	Base Resistance in the Hybrid-Pi Model	1155
17.5.1	Effect of Base Resistance on Midband Amplifiers	1156
17.6	High-Frequency Common-Emitter and Common-Source Amplifier Analysis	1158
17.6.1	The Miller Effect	1159
17.6.2	Common-Emitter and Common-Source Amplifier High-Frequency Response	1160
17.6.3	Direct Analysis of the Common-Emitter Transfer Characteristic	1162

17.6.4	Poles of the Common-Emitter Amplifier	1163
17.6.5	Dominant Pole for the Common-Source Amplifier	1166
17.6.6	Estimation of ω_H Using the Open-Circuit Time-Constant Method	1167
17.6.7	Common-Source Amplifier with Source Degeneration Resistance	1170
17.6.8	Poles of the Common-Emitter with Emitter Degeneration Resistance	1172
17.7	Common-Base and Common-Gate Amplifier High-Frequency Response	1174
17.8	Common-Collector and Common-Drain Amplifier High-Frequency Response	1177
17.9	Single-Stage Amplifier High-Frequency Response Summary	1179
17.9.1	Amplifier Gain-Bandwidth Limitations	1180
17.10	Frequency Response of Multistage Amplifiers	1181
17.10.1	Differential Amplifier	1181
17.10.2	The Common-Collector/Common-Base Cascade	1182
17.10.3	High-Frequency Response of the Cascode Amplifier	1184
17.10.4	Cutoff Frequency for the Current Mirror	1185
17.10.5	Three-Stage Amplifier Example	1187
17.11	Introduction to Radio Frequency Circuits	1193
17.11.1	Radio Frequency Amplifiers	1194
17.11.2	The Shunt-Peaked Amplifier	1194
17.11.3	Single-Tuned Amplifier	1197
17.11.4	Use of a Tapped Inductor—The Auto Transformer	1199
17.11.5	Multiple Tuned Circuits—Synchronous and Stagger Tuning	1201
17.11.6	Common-Source Amplifier with Inductive Degeneration	1202
17.12	Mixers and Balanced Modulators	1205
17.12.1	Introduction to Mixer Operation	1205
17.12.2	A Single-Balanced Mixer	1206
17.12.3	The Differential Pair as a Single-Balanced Mixer	1207
17.12.4	A Double-Balanced Mixer	1208
17.12.5	The Gilbert Multiplier as a Double-Balanced Mixer/Modulator	1210

Summary	1213
Key Terms	1215
Reference	1215
Problems	1215

CHAPTER 18

TRANSISTOR FEEDBACK AMPLIFIERS AND OSCILLATORS 1228

18.1	Basic Feedback System Review	1229
18.1.1	Closed-Loop Gain	1229
18.1.2	Closed-Loop Impedances	1230
18.1.3	Feedback Effects	1230
18.2	Feedback Amplifier Analysis at Midband	1232
18.3	Feedback Amplifier Circuit Examples	1234
18.3.1	Series-Shunt Feedback—Voltage Amplifiers	1234
18.3.2	Differential Input Series-Shunt Voltage Amplifier	1239
18.3.3	Shunt-Shunt Feedback—Transresistance Amplifiers	1242
18.3.4	Series-Series Feedback—Transconductance Amplifiers	1248
18.3.5	Shunt-Series Feedback—Current Amplifiers	1251
18.4	Review of Feedback Amplifier Stability	1254
18.4.1	Closed-Loop Response of the Uncompensated Amplifier	1254
18.4.2	Phase Margin	1256
18.4.3	Higher-Order Effects	1259
18.4.4	Response of the Compensated Amplifier	1260
18.4.5	Small-Signal Limitations	1262
18.5	Single-Pole Operational Amplifier Compensation	1262
18.5.1	Three-Stage Op Amp Analysis	1263
18.5.2	Transmission Zeros in FET Op Amps	1265
18.5.3	Bipolar Amplifier Compensation	1266
18.5.4	Slew Rate of the Operational Amplifier	1266
18.5.5	Relationships Between Slew Rate and Gain-Bandwidth Product	1268
18.6	High-Frequency Oscillators	1277
18.6.1	The Colpitts Oscillator	1278
18.6.2	The Hartley Oscillator	1279
18.6.3	Amplitude Stabilization in LC Oscillators	1280
18.6.4	Negative Resistance in Oscillators	1280

18.6.5 Negative G_M Oscillator 1281

18.6.6 Crystal Oscillators 1283

Summary 1287

Key Terms 1289

References 1289

Problems 1289

APPENDICES

A Standard Discrete Component Values 1300

B Solid-State Device Models and SPICE
Simulation Parameters 1303

C Two-Port Review 1310

Index 1313

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 multi-stage 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 non-ideal 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- π model and π -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- π 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 in-

dicated 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, cut-off 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” basis 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 am-

plifiers 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:

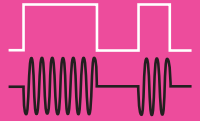
1. Introduction
2. Solid-State Electronics
3. Diodes
4. FETs
6. Digital Logic
7. CMOS Logic
8. Memory
5. The BJT
9. Bipolar Logic
- 10–18. Analog in sequence

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



CHAPTER 1
INTRODUCTION TO ELECTRONICS 3

CHAPTER 2
SOLID-STATE ELECTRONICS 42

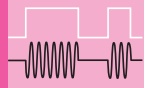
CHAPTER 3
SOLID-STATE DIODES AND DIODE CIRCUITS 74

CHAPTER 4
FIELD-EFFECT TRANSISTORS 145

CHAPTER 5
BIPOLAR JUNCTION TRANSISTORS 217

This page intentionally left blank

CHAPTER 1



INTRODUCTION TO ELECTRONICS

CHAPTER OUTLINE

- 1.1 A Brief History of Electronics: From Vacuum Tubes to Ultra-Large-Scale Integration 5
- 1.2 Classification of Electronic Signals 8
- 1.3 Notational Conventions 12
- 1.4 Problem-Solving Approach 13
- 1.5 Important Concepts from Circuit Theory 15
- 1.6 Frequency Spectrum of Electronic Signals 21
- 1.7 Amplifiers 22
- 1.8 Element Variations in Circuit Design 26
- 1.9 Numeric Precision 34
- Summary 34
- Key Terms 35
- References 36
- Additional Reading 36
- Problems 37

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

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



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

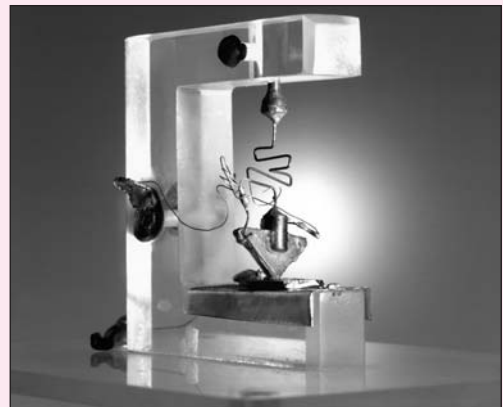


Figure 1.2 The first germanium bipolar transistor. Lucent Technologies Inc./Bell Labs

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 μ A709—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.

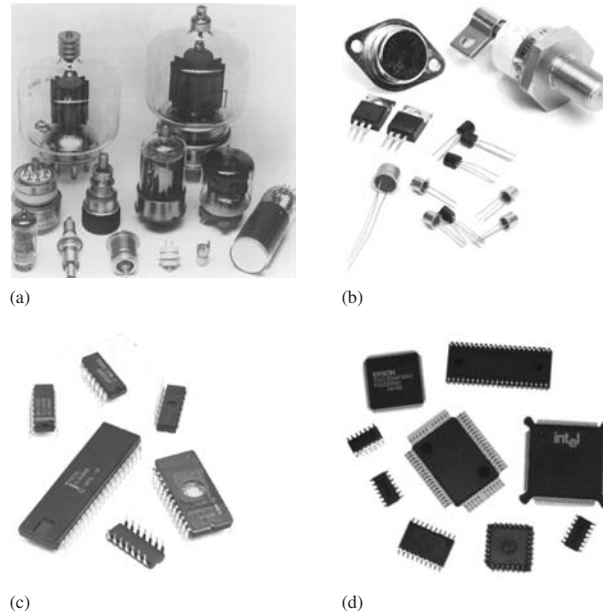


Figure 1.3 Comparison of (a) vacuum tubes, (b) individual transistors, (c) integrated circuits in dual-in-line packages (DIPs), and (d) ICs in surface mount packages.

Source: (a) Courtesy ARRL Handbook for Radio Amateurs, 1992

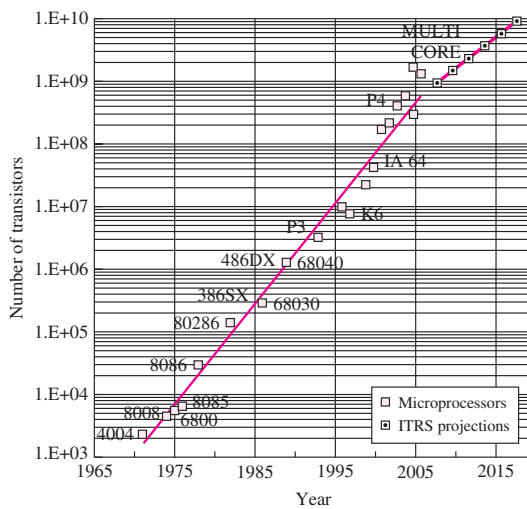


Figure 1.4 Microprocessor complexity versus time.

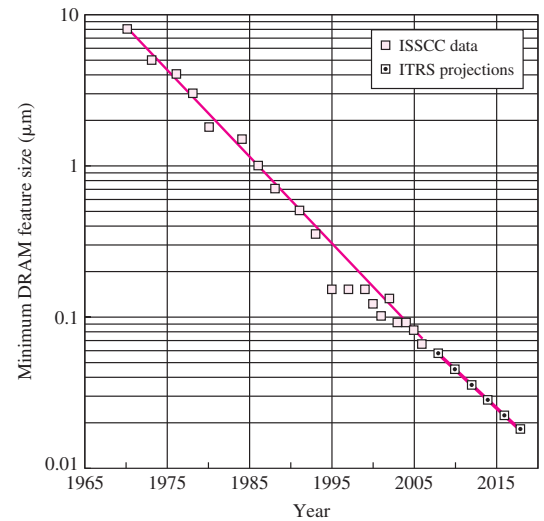


Figure 1.5 DRAM feature size versus year.

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.

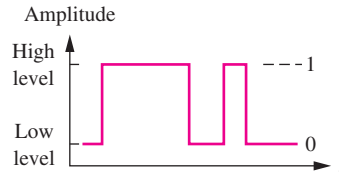


Figure 1.6 A time-varying binary digital signal.

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 $V_H = 5\text{ V}$ and $V_L = 0\text{ V}$ 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 $V_L = 0\text{ V}$, 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 $V_H = -0.8\text{ V}$ and $V_L = -2.0\text{ V}$, and the early standard RS-422 and RS-232 communication links between a small computer and its peripherals used $V_H = +12\text{ V}$ and $V_L = -12\text{ V}$. 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.

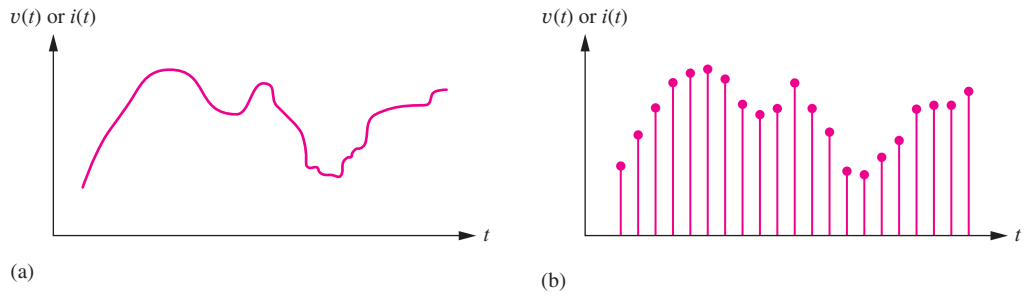


Figure 1.7 (a) A continuous analog signal; (b) sampled data version of signal in (a).

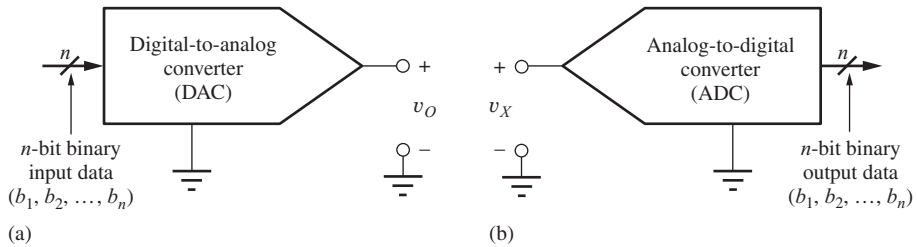


Figure 1.8 Block diagram representation for a (a) D/A converter and a (b) A/D converter.

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, \dots, 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

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

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

$$V_{LSB} = 2^{-n} V_{FS} \quad (1.2)$$

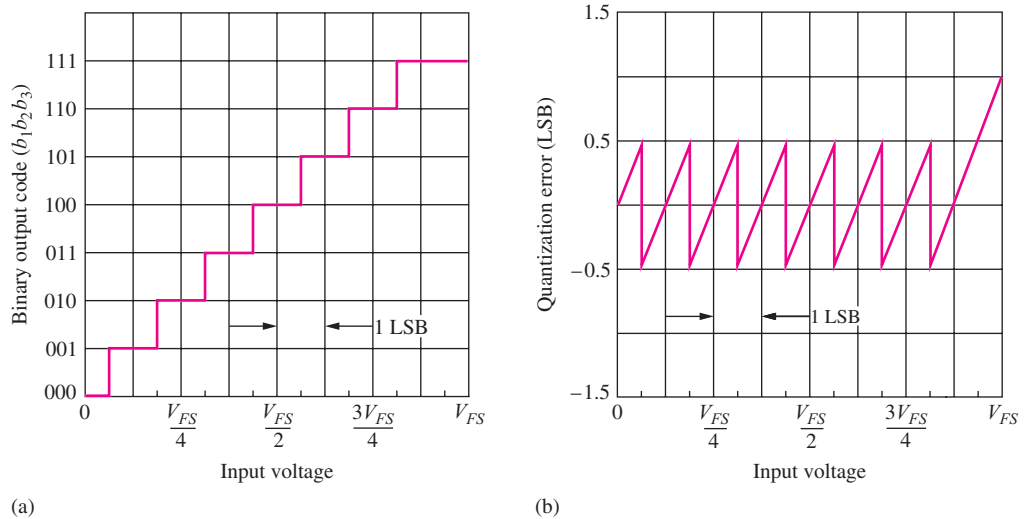


Figure 1.9 (a) Input–output relationship and (b) quantization error for 3-bit ADC.

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:

$$v_\epsilon = |v_X - (b_12^{-1} + b_22^{-2} + \cdots + b_n2^{-n})V_{FS}| \quad (1.3)$$

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} .

$$v_T = V_{DC} + v_{sig} \quad \text{or} \quad i_T = I_{DC} + i_{sig} \quad (1.4)$$

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

$$v_{BE} = V_{BE} + v_{be} \quad \text{and} \quad i_D = I_D + i_d \quad (1.5)$$

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

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 , $\text{k}\Omega$, $\text{M}\Omega$, and so on. During analysis, however, it may be more convenient to work in terms of conductance with the following convention:

$$G_x = \frac{1}{R_x} \quad \text{and} \quad g_\pi = \frac{1}{r_\pi} \quad (1.6)$$

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 , $\text{k}\Omega$, $\text{M}\Omega$).

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

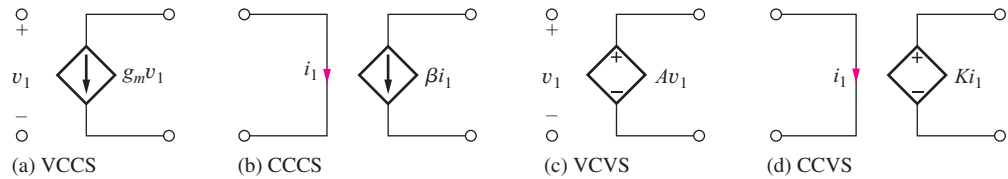


Figure 1.10 Controlled sources. (a) Voltage-controlled current source (VCCS). (b) Current-controlled current source (CCCS). (c) Voltage-controlled voltage source (VCVS). (d) Current-controlled voltage source (CCVS).

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 V⁵ 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 $G\Omega$.

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-M Ω resistor can be no more than 1 μ A. 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

$$v_1 = i_i R_1 \quad \text{and} \quad v_2 = i_i R_2 \quad (1.7)$$

Applying KVL to the single loop,

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

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

$$v_1 = v_i \frac{R_1}{R_1 + R_2} \quad \text{and} \quad v_2 = v_i \frac{R_2}{R_1 + R_2} \quad (1.9)$$

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

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

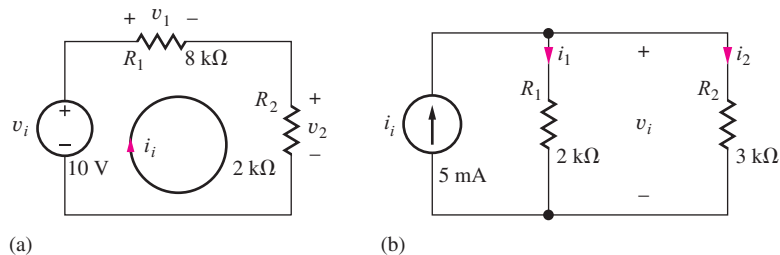
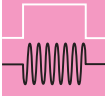


Figure 1.11 (a) A resistive voltage divider, (b) Current division in a simple network.



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**.

$$\mathbf{V}_1 = \mathbf{V}_s \frac{Z_1}{Z_1 + Z_2} \quad \text{and} \quad \mathbf{V}_2 = \mathbf{V}_s \frac{Z_2}{Z_1 + Z_2}$$

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,

$$i_i = i_1 + i_2 \quad \text{where } i_1 = \frac{v_i}{R_1} \text{ and } i_2 = \frac{v_i}{R_2} \quad (1.11)$$

and solving for v_s yields

$$v_i = i_i \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = i_i \frac{R_1 R_2}{R_1 + R_2} = i_i (R_1 \parallel R_2) \quad (1.12)$$

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

$$i_1 = i_i \frac{R_2}{R_1 + R_2} \quad \text{and} \quad i_2 = i_i \frac{R_1}{R_1 + R_2} \quad (1.13)$$

For the values in Fig. 1.11(b),

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



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**.

$$\mathbf{I}_1 = \mathbf{I}_s \frac{Z_2}{Z_1 + Z_2} \quad \text{and} \quad \mathbf{I}_2 = \mathbf{I}_s \frac{Z_1}{Z_1 + Z_2}$$

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.

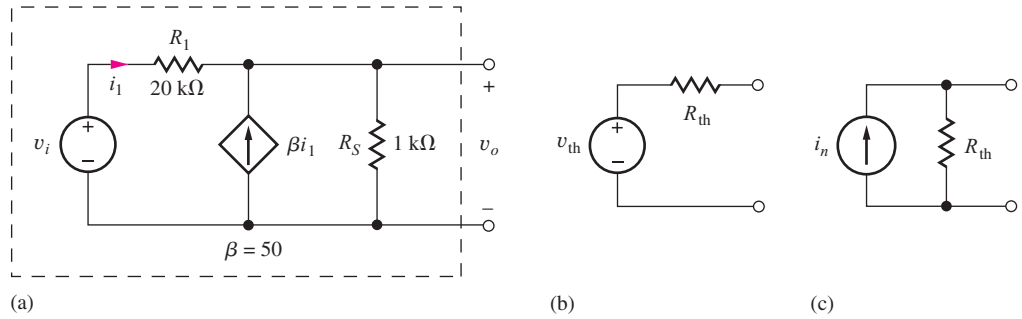


Figure 1.12 (a) Two-terminal circuit and its (b) Thévenin and (c) Norton equivalents.

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.

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

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

Current i_1 is given by

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

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

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

The Thévenin equivalent output voltage is then found to be

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

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

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

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

$$R_{th} = \frac{v_x}{i_x} \quad (1.19)$$

can be calculated.

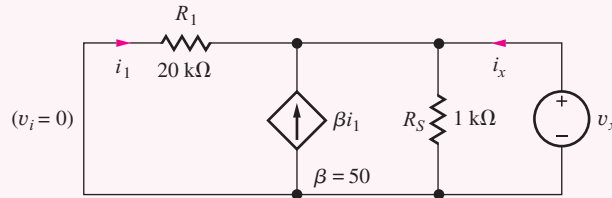


Figure 1.13 A test source v_x is applied to the network to find R_{th} .

$$i_x = -i_1 - \beta i_1 + G_S v_x \quad \text{in which } i_1 = -G_1 v_x \quad (1.20)$$

Combining and simplifying these two expressions yields

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

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

$$R_{th} = \frac{1}{(\beta + 1)G_1 + G_S} = \frac{R_S \frac{R_1}{(\beta + 1)}}{R_S + \frac{R_1}{(\beta + 1)}} = R_S \parallel \frac{R_1}{(\beta + 1)} \quad (1.22)$$

For the values in this example,

$$R_{th} = R_S \parallel \frac{R_1}{(\beta + 1)} = 1 \text{ k}\Omega \parallel \frac{20 \text{ k}\Omega}{(50 + 1)} = 1 \text{ k}\Omega \parallel 392 \Omega = 282 \Omega \quad (1.23)$$

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 find 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.

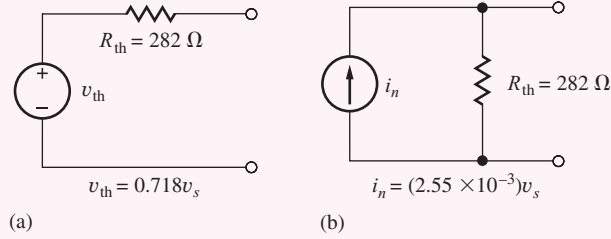


Figure 1.14 Completed (a) Thévenin and (b) Norton equivalent circuits for the two-terminal network in Fig. 1.12(a).

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

$$i_n = i_1 + \beta i_1 \quad \text{and} \quad i_1 = G_1 v_i \quad (1.24)$$

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

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

or

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

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

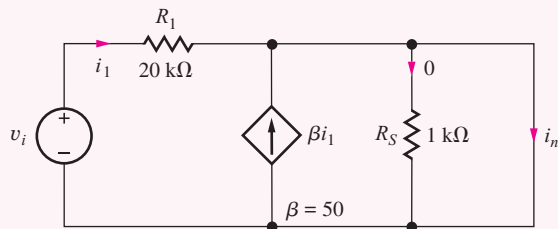


Figure 1.15 Circuit for determining short-circuit output current.

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: $i_n R_{th} = (2.55 \text{ mS})v_s(282 \text{ } \Omega) = 0.719 v_s$, which agrees within round-off error with the previous example.



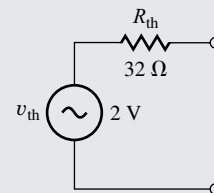
ELECTRONICS IN ACTION

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.

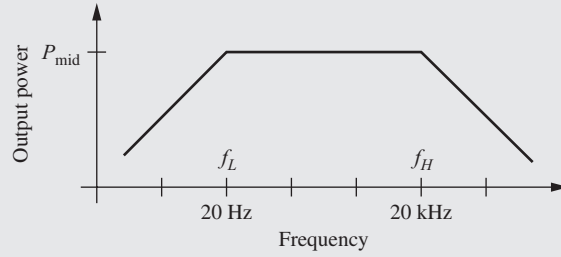


iPod: © The McGraw-Hill Companies, Inc./Jill Braaten, photographer



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 $v_{th} = 2 \text{ V}$ and $R_{th} = 32 \text{ ohms}$, 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 frequencies⁷ 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

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

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 $2f_o$, $3f_o$, $4f_o$, \dots 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.

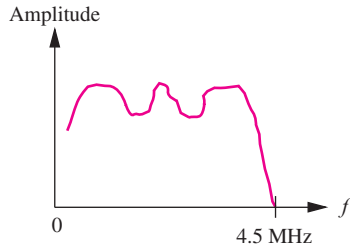


Figure 1.16 Spectrum of a TV signal.

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

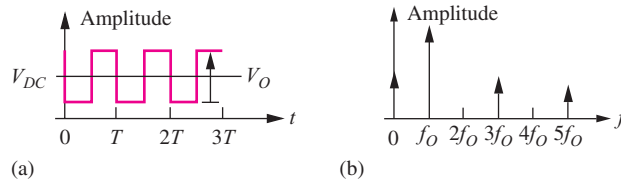


Figure 1.17 A periodic signal (a) and its amplitude spectrum (b).

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 :

$$v_i = V_i \sin(\omega_i t + \phi) \quad (1.28)$$

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:

$$v_o = V_o \sin(\omega_i t + \phi + \theta) \quad (1.29)$$

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

$$\mathbf{V}_i = V_i \angle \phi \quad \text{and} \quad \mathbf{V}_o = V_o \angle (\phi + \theta) \quad (1.30)$$

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

$$A = \frac{\mathbf{V}_o}{\mathbf{V}_i} = \frac{V_o \angle (\phi + \theta)}{V_i \angle \phi} = \frac{V_o}{V_i} \angle \theta \quad (1.31)$$

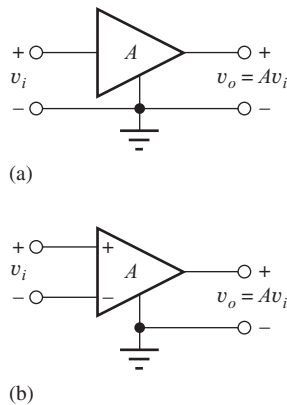


Figure 1.18 (a) Symbol for amplifier with single input and voltage gain A ; (b) differential amplifier having two inputs and gain A .

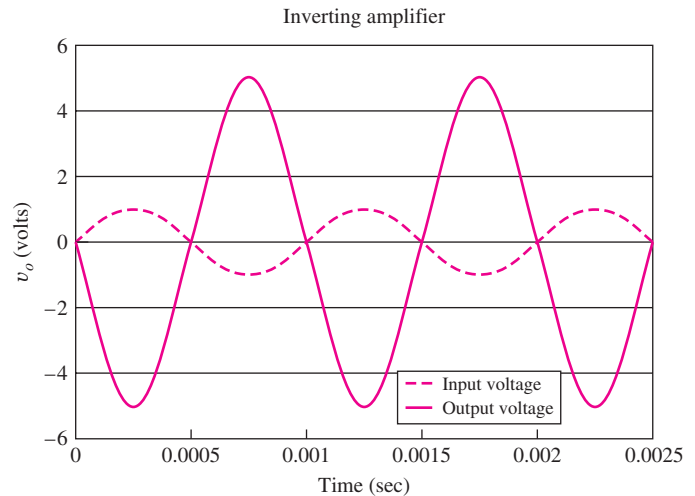


Figure 1.19 Input and output voltage waveforms for an amplifier with gain $A_v = -5$ and $v_i = 1 \sin 2000\pi t$ V.

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

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

in which v_i and v_o are specified in volts when t is seconds. What are V_i , 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.