

# CONTENTS

List of tables	xvi
Preface	xix
Preface to first edition	xxi
CHAPTER 1	
FOUNDATIONS 1	
Introduction	1
Voltage, current, and resistance	2
1.01 Voltage and current	2
1.02 Relationship between voltage and current: resistors	4
1.03 Voltage dividers	8
1.04 Voltage and current sources	9
1.05 Thévenin's equivalent circuit	11
1.06 Small-signal resistance	13
Signals	15
1.07 Sinusoidal signals	15
1.08 Signal amplitudes and decibels	16
1.09 Other signals	17
1.10 Logic levels	19
1.11 Signal sources	19
Capacitors and ac circuits	20
1.12 Capacitors	20
1.13 $RC$ circuits: $V$ and $I$ versus time	23
1.14 Differentiators	25
1.15 Integrators	26
Inductors and transformers	28
1.16 Inductors	28
1.17 Transformers	28
Impedance and reactance	29
1.18 Frequency analysis of reactive circuits	30
1.19 $RC$ filters	35
1.20 Phasor diagrams	39
1.21 "Poles" and decibels per octave	40
1.22 Resonant circuits and active filters	41
1.23 Other capacitor applications	42
1.24 Thévenin's theorem generalized	44
Diods and diode circuits	44
1.25 Diodes	44
1.26 Rectification	44
1.27 Power-supply filtering	45
1.28 Rectifier configurations for power supplies	46
1.29 Regulators	48
1.30 Circuit applications of diodes	48
1.31 Inductive loads and diode protection	52
Other passive components	53
1.32 Electromechanical devices	53
1.33 Indicators	57
1.34 Variable components	57
<i>Additional exercises</i>	58
CHAPTER 2	
TRANSISTORS 61	
Introduction	61
2.01 First transistor model: current amplifier	62
Some basic transistor circuits	63
2.02 Transistor switch	63
2.03 Emitter follower	65

- 2.04 Emitter followers as voltage regulators 68
- 2.05 Emitter follower biasing 69
- 2.06 Transistor current source 72
- 2.07 Common-emitter amplifier 76
- 2.08 Unity-gain phase splitter 77
- 2.09 Transconductance 78
- Ebers-Moll model applied to basic transistor circuits 79
- 2.10 Improved transistor model: transconductance amplifier 79
- 2.11 The emitter follower revisited 81
- 2.12 The common-emitter amplifier revisited 82
- 2.13 Biasing the common-emitter amplifier 84
- 2.14 Current mirrors 88
- Some amplifier building blocks 91
- 2.15 Push-pull output stages 91
- 2.16 Darlington connection 94
- 2.17 Bootstrapping 96
- 2.18 Differential amplifiers 98
- 2.19 Capacitance and Miller effect 102
- 2.20 Field-effect transistors 104
- Some typical transistor circuits 104
- 2.21 Regulated power supply 104
- 2.22 Temperature controller 105
- 2.23 Simple logic with transistors and diodes 107
- Self-explanatory circuits 107
- 2.24 Good circuits 107
- 2.25 Bad circuits 107
- Additional exercises* 107
- CHAPTER 3**  
**FIELD-EFFECT TRANSISTORS 113**
- Introduction 113
- 3.01 FET characteristics 114
- 3.02 FET types 117
- 3.03 Universal FET characteristics 119
- 3.04 FET drain characteristics 121
- 3.05 Manufacturing spread of FET characteristics 122
- Basic FET circuits 124
- 3.06 JFET current sources 125
- 3.07 FET amplifiers 129
- 3.08 Source followers 133
- 3.09 FET gate current 135
- 3.10 FETs as variable resistors 138
- FET switches 140
- 3.11 FET analog switches 141
- 3.12 Limitations of FET switches 144
- 3.13 Some FET analog switch examples 151
- 3.14 MOSFET logic and power switches 153
- 3.15 MOSFET handling precautions 169
- Self-explanatory circuits 171
- 3.16 Circuit ideas 171
- 3.17 Bad circuits 171 vskip6pt
- CHAPTER 4**  
**FEEDBACK AND OPERATIONAL AMPLIFIERS 175**
- Introduction 175
- 4.01 Introduction to feedback 175
- 4.02 Operational amplifiers 176
- 4.03 The golden rules 177
- Basic op-amp circuits 177
- 4.04 Inverting amplifier 177
- 4.05 Noninverting amplifier 178
- 4.06 Follower 179
- 4.07 Current sources 180
- 4.08 Basic cautions for op-amp circuits 182
- An op-amp smorgasbord 183
- 4.09 Linear circuits 183
- 4.10 Nonlinear circuits 187
- A detailed look at op-amp behavior 188
- 4.11 Departure from ideal op-amp performance 189
- 4.12 Effects of op-amp limitations on circuit behavior 193
- 4.13 Low-power and programmable op-amps 210

**A detailed look at selected op-amp circuits 213**

- 4.14 Logarithmic amplifier 213
- 4.15 Active peak detector 217
- 4.16 Sample-and-hold 220
- 4.17 Active clamp 221
- 4.18 Absolute-value circuit 221
- 4.19 Integrators 222
- 4.20 Differentiators 224

**Op-amp operation with a single power supply 224**

- 4.21 Biasing single-supply ac amplifiers 225
- 4.22 Single-supply op-amps 225

**Comparators and Schmitt trigger 229**

- 4.23 Comparators 229
- 4.24 Schmitt trigger 231

**Feedback with finite-gain amplifiers 232**

- 4.25 Gain equation 232
- 4.26 Effects of feedback on amplifier circuits 233
- 4.27 Two examples of transistor amplifiers with feedback 236

**Some typical op-amp circuits 238**

- 4.28 General-purpose lab amplifier 238
- 4.29 Voltage-controlled oscillator 240
- 4.30 JFET linear switch with  $R_{ON}$  compensation 241
- 4.31 TTL zero-crossing detector 242
- 4.32 Load-current-sensing circuit 242

**Feedback amplifier frequency compensation 242**

- 4.33 Gain and phase shift versus frequency 243
- 4.34 Amplifier compensation methods 245
- 4.35 Frequency response of the feedback network 247

**Self-explanatory circuits 250**

- 4.36 Circuit ideas 250

- 4.37 Bad circuits 250
- Additional exercises* 251

**CHAPTER 5  
ACTIVE FILTERS AND  
OSCILLATORS 263**

**Active filters 263**

- 5.01 Frequency response with  $RC$  filters 263
- 5.02 Ideal performance with  $LC$  filters 265
- 5.03 Enter active filters: an overview 266
- 5.04 Key filter performance criteria 267
- 5.05 Filter types 268
- Active filter circuits 272
- 5.06 VCVS circuits 273
- 5.07 VCVS filter design using our simplified table 274
- 5.08 State-variable filters 276
- 5.09 Twin-T notch filters 279
- 5.10 Gyrator filter realizations 281
- 5.11 Switched-capacitor filters 281

**Oscillators 284**

- 5.12 Introduction to oscillators 284
- 5.13 Relaxation oscillators 284
- 5.14 The classic timer chip: the 555 286
- 5.15 Voltage-controlled oscillators 291
- 5.16 Quadrature oscillators 291
- 5.17 Wien bridge and  $LC$  oscillators 296
- 5.18  $LC$  oscillators 297
- 5.19 Quartz-crystal oscillators 300

**Self-explanatory circuits 303**

- 5.20 Circuit ideas 303
- Additional exercises* 303

**CHAPTER 6  
VOLTAGE REGULATORS AND POWER  
CIRCUITS 307**

- Basic regulator circuits with the classic 723 307

6.01 The 723 regulator 307  
 6.02 Positive regulator 309  
 6.03 High-current regulator 311  
 Heat and power design 312  
 6.04 Power transistors and heat sinking 312  
 6.05 Foldback current limiting 316  
 6.06 Overvoltage crowbars 317  
 6.07 Further considerations in high-current power-supply design 320  
 6.08 Programmable supplies 321  
 6.09 Power-supply circuit example 323  
 6.10 Other regulator ICs 325  
 The unregulated supply 325  
 6.11 ac line components 326  
 6.12 Transformer 328  
 6.13 dc components 329  
 Voltage references 331  
 6.14 Zener diodes 332  
 6.15 Bandgap ( $V_{BE}$ ) reference 335  
 Three-terminal and four-terminal regulators 341  
 6.16 Three-terminal regulators 341  
 6.17 Three-terminal adjustable regulators 344  
 6.18 Additional comments about 3-terminal regulators 345  
 6.19 Switching regulators and dc-dc converters 355  
 Special-purpose power-supply circuits 368  
 6.20 High-voltage regulators 368  
 6.21 Low-noise, low-drift supplies 374  
 6.22 Micropower regulators 376  
 6.23 Flying-capacitor (charge pump) voltage converters 377  
 6.24 Constant-current supplies 379  
 6.25 Commercial power-supply modules 382  
 Self-explanatory circuits 384  
 6.26 Circuit ideas 384  
 6.27 Bad circuits 384  
*Additional exercises* 384

**CHAPTER 7  
 PRECISION CIRCUITS AND LOW-NOISE  
 TECHNIQUES 391**

Precision op-amp design techniques 391  
 7.01 Precision versus dynamic range 391  
 7.02 Error budget 392  
 7.03 Example circuit: precision amplifier with automatic null offset 392  
 7.04 A precision-design error budget 394  
 7.05 Component errors 395  
 7.06 Amplifier input errors 396  
 7.07 Amplifier output errors 403  
 7.08 Auto-zeroing (chopper-stabilized) amplifiers 415  
 Differential and instrumentation amplifiers 421  
 7.09 Differencing amplifier 421  
 7.10 Standard three-op-amp instrumentation amplifier 425  
 Amplifier noise 428  
 7.11 Origins and kinds of noise 430  
 7.12 Signal-to-noise ratio and noise figure 433  
 7.13 Transistor amplifier voltage and current noise 436  
 7.14 Low-noise design with transistors 438  
 7.15 FET noise 443  
 7.16 Selecting low-noise transistors 445  
 7.17 Noise in differential and feedback amplifiers 445  
 Noise measurements and noise sources 449  
 7.18 Measurement without a noise source 449  
 7.19 Measurement with noise source 450  
 7.20 Noise and signal sources 452  
 7.21 Bandwidth limiting and rms voltage measurement 453  
 7.22 Noise potpourri 454

- Interference: shielding and grounding 455
- 7.23 Interference 455
- 7.24 Signal grounds 457
- 7.25 Grounding between instruments 457
- Self-explanatory circuits 466
- 7.26 Circuit ideas 466
- Additional exercises* 466
- CHAPTER 8**  
**DIGITAL ELECTRONICS 471**
- Basic logic concepts 471
- 8.01 Digital versus analog 471
- 8.02 Logic states 472
- 8.03 Number codes 473
- 8.04 Gates and truth tables 478
- 8.05 Discrete circuits for gates 480
- 8.06 Gate circuit example 481
- 8.07 Assertion-level logic notation 482
- TTL and CMOS 484
- 8.08 Catalog of common gates 484
- 8.09 IC gate circuits 485
- 8.10 TTL and CMOS characteristics 486
- 8.11 Three-state and open-collector devices 487
- Combinational logic 490
- 8.12 Logic identities 491
- 8.13 Minimization and Karnaugh maps 492
- 8.14 Combinational functions available as ICs 493
- 8.15 Implementing arbitrary truth tables 500
- Sequential logic 504
- 8.16 Devices with memory: flip-flops 504
- 8.17 Clocked flip-flops 507
- 8.18 Combining memory and gates: sequential logic 512
- 8.19 Synchronizer 515
- Monostable multivibrators 517
- 8.20 One-shot characteristics 517
- 8.21 Monostable circuit example 519
- 8.22 Cautionary notes about monostables 519
- 8.23 Timing with counters 522
- Sequential functions available as ICs 523
- 8.24 Latches and registers 523
- 8.25 Counters 524
- 8.26 Shift registers 525
- 8.27 Sequential PALs 527
- 8.28 Miscellaneous sequential functions 541
- Some typical digital circuits 544
- 8.29 Modulo- $n$  counter: a timing example 544
- 8.30 Multiplexed LED digital display 546
- 8.31 Sidereal telescope drive 548
- 8.32 An  $n$ -pulse generator 548
- Logic pathology 551
- 8.33 dc problems 551
- 8.34 Switching problems 552
- 8.35 Congenital weaknesses of TTL and CMOS 554
- Self-explanatory circuits 556
- 8.36 Circuit ideas 556
- 8.37 Bad circuits 556
- Additional exercises* 556
- CHAPTER 9**  
**DIGITAL MEETS ANALOG 565**
- CMOS and TTL logic interfacing 565
- 9.01 Logic family chronology 565
- 9.02 Input and output characteristics 570
- 9.03 Interfacing between logic families 572
- 9.04 Driving CMOS and TTL inputs 575
- 9.05 Driving digital logic from comparators and op-amps 577

9.06 Some comments about logic inputs 579

9.07 Comparators 580

9.08 Driving external digital loads from CMOS and TTL 582

9.09 NMOS LSI interfacing 588

9.10 Opto-electronics 590

Digital signals and long wires 599

9.11 On-board interconnections 599

9.12 Intercard connections 601

9.13 Data buses 602

9.14 Driving cables 603

Analog/digital conversion 612

9.15 Introduction to A/D conversion 612

9.16 Digital-to-analog converters (DACs) 614

9.17 Time-domain (averaging) DACs 618

9.18 Multiplying DACs 619

9.19 Choosing a DAC 619

9.20 Analog-to-digital converters 621

9.21 Charge-balancing techniques 626

9.22 Some unusual A/D and D/A converters 630

9.23 Choosing an ADC 631

Some A/D conversion examples 636

9.24 16-Channel A/D data-acquisition system 636

9.25  $3\frac{1}{2}$ -Digit voltmeter 638

9.26 Coulomb meter 640

Phase-locked loops 641

9.27 Introduction to phase-locked loops 641

9.28 PLL design 646

9.29 Design example: frequency multiplier 647

9.30 PLL capture and lock 651

9.31 Some PLL applications 652

Pseudo-random bit sequences and noise generation 655

9.32 Digital noise generation 655

9.33 Feedback shift register sequences 655

9.34 Analog noise generation from maximal-length sequences 658

9.35 Power spectrum of shift register sequences 658

9.36 Low-pass filtering 660

9.37 Wrap-up 661

9.38 Digital filters 664

Self-explanatory circuits 667

9.39 Circuit ideas 667

9.40 Bad circuits 668

*Additional exercises* 668

CHAPTER 10  
MICROCOMPUTERS 673

Minicomputers, microcomputers, and microprocessors 673

10.01 Computer architecture 674

A computer instruction set 678

10.02 Assembly language and machine language 678

10.03 Simplified 8086/8 instruction set 679

10.04 A programming example 683

Bus signals and interfacing 684

10.05 Fundamental bus signals: data, address, strobe 684

10.06 Programmed I/O: data out 685

10.07 Programmed I/O: data in 689

10.08 Programmed I/O: status registers 690

10.09 Interrupts 693

10.10 Interrupt handling 695

10.11 Interrupts in general 697

10.12 Direct memory access 701

10.13 Summary of the IBM PC's bus signals 704

10.14 Synchronous versus asynchronous bus communication 707

10.15 Other microcomputer buses 708

10.16 Connecting peripherals to the computer 711

- Software system concepts 714
- 10.17 Programming 714
- 10.18 Operating systems, files, and use of memory 716
- Data communications concepts 719
- 10.19 Serial communication and ASCII 720
- 10.20 Parallel communication: Centronics, SCSI, IPI, GPIB (488) 730
- 10.21 Local area networks 734
- 10.22 Interface example: hardware data packing 736
- 10.23 Number formats 738
- CHAPTER 11**  
**MICROPROCESSORS 743**
- A detailed look at the 68008 744
- 11.01 Registers, memory, and I/O 744
- 11.02 Instruction set and addressing 745
- 11.03 Machine-language representation 750
- 11.04 Bus signals 753
- A complete design example: analog signal averager 760
- 11.05 Circuit design 760
- 11.06 Programming: defining the task 774
- 11.07 Programming: details 777
- 11.08 Performance 796
- 11.09 Some afterthoughts 797
- Microprocessor support chips 799
- 11.10 Medium-scale integration 800
- 11.11 Peripheral LSI chips 802
- 11.12 Memory 812
- 11.13 Other microprocessors 820
- 11.14 Emulators, development systems, logic analyzers, and evaluation boards 821
- CHAPTER 12**  
**ELECTRONIC CONSTRUCTION TECHNIQUES 827**
- Prototyping methods 827
- 12.01 Breadboards 827
- 12.02 PC prototyping boards 828
- 12.03 Wire-Wrap panels 828
- Printed circuits 830
- 12.04 PC board fabrication 830
- 12.05 PC board design 835
- 12.06 Stuffing PC boards 838
- 12.07 Some further thoughts on PC boards 840
- 12.08 Advanced techniques 841
- Instrument construction 852
- 12.09 Housing circuit boards in an instrument 852
- 12.10 Cabinets 854
- 12.11 Construction hints 855
- 12.12 Cooling 855
- 12.13 Some electrical hints 858
- 12.14 Where to get components 860
- CHAPTER 13**  
**HIGH-FREQUENCY AND HIGH-SPEED TECHNIQUES 863**
- High-frequency amplifiers 863
- 13.01 Transistor amplifiers at high frequencies: first look 863
- 13.02 High-frequency amplifiers: the ac model 864
- 13.03 A high-frequency calculation example 866
- 13.04 High-frequency amplifier configurations 868
- 13.05 A wideband design example 869
- 13.06 Some refinements to the ac model 872
- 13.07 The shunt-series pair 872
- 13.08 Modular amplifiers 873
- Radiofrequency circuit elements 879
- 13.09 Transmission lines 879

13.10 Stubs, baluns, and transformers 881

13.11 Tuned amplifiers 882

13.12 Radiofrequency circuit elements 884

13.13 Measuring amplitude or power 888

Radiofrequency communications:  
AM 892

13.14 Some communications concepts 892

13.15 Amplitude modulation 894

13.16 Superheterodyne receiver 895

Advanced modulation methods 897

13.17 Single sideband 897

13.18 Frequency modulation 898

13.19 Frequency-shift keying 900

13.20 Pulse-modulation schemes 900

Radiofrequency circuit tricks 902

13.21 Special construction techniques 902

13.22 Exotic RF amplifiers and devices 903

High-speed switching 904

13.23 Transistor model and equations 905

13.24 Analog modeling tools 908

Some switching-speed examples 909

13.25 High-voltage driver 909

13.26 Open-collector bus driver 910

13.27 Example: photomultiplier preamp 911

Self-explanatory circuits 913

13.28 Circuit ideas 913

*Additional exercises* 913

**CHAPTER 14**  
**LOW-POWER DESIGN 917**

Introduction 917

14.01 Low-power applications 918

Power sources 920

14.02 Battery types 920

14.03 Wall-plug-in units 931

14.04 Solar cells 932

14.05 Signal currents 933

Power switching and micropower regulators 938

14.06 Power switching 938

14.07 Micropower regulators 941

14.08 Ground reference 944

14.09 Micropower voltage references and temperature sensors 948

**Linear micropower design techniques 948**

14.10 Problems of micropower linear design 950

14.11 Discrete linear design example 950

14.12 Micropower operational amplifiers 951

14.13 Micropower comparators 965

14.14 Micropower timers and oscillators 965

**Micropower digital design 969**

14.15 CMOS families 969

14.16 Keeping CMOS low power 970

14.17 Micropower microprocessors and peripherals 974

14.18 Microprocessor design example: degree-day logger 978

**Self-explanatory circuits 985**

14.19 Circuit ideas 985

**CHAPTER 15**  
**MEASUREMENTS AND SIGNAL PROCESSING 987**

**Overview 987**

**Measurement transducers 988**

15.01 Temperature 988

15.02 Light level 996

15.03 Strain and displacement 1001

---

15.04 Acceleration, pressure, force, velocity 1004	APPENDIXES 1043
15.05 Magnetic field 1007	Appendix A
15.06 Vacuum gauges 1007	The oscilloscope 1045
15.07 Particle detectors 1008	Appendix B
15.08 Biological and chemical voltage probes 1012	Math review 1050
Precision standards and precision measurements 1016	Appendix C
15.09 Frequency standards 1016	The 5% resistor color code 1053
15.10 Frequency, period, and time- interval measurements 1019	Appendix D
15.11 Voltage and resistance standards and measurements 1025	1% Precision resistors 1054
Bandwidth-narrowing techniques 1026	Appendix E
15.12 The problem of signal-to-noise ratio 1026	How to draw schematic diagrams 1056
15.13 Signal averaging and multichannel averaging 1026	Appendix F
15.14 Making a signal periodic 1030	Load lines 1059
15.15 Lock-in detection 1031	Appendix G
15.16 Pulse-height analysis 1034	Transistor saturation 1062
15.17 Time-to-amplitude converters 1035	Appendix H
Spectrum analysis and Fourier transforms 1035	LC Butterworth filters 1064
15.18 Spectrum analyzers 1035	Appendix I
15.19 Off-line spectrum analysis 1038	Electronics magazines and journals 1068
Self-explanatory circuits 1038	Appendix J
15.20 Circuit ideas 1038	IC prefixes 1069
	Appendix K
	Data sheets 1072
	2N4400-1 NPN transistor 1073
	LF411-12 JFET operational amplifier 1078
	LM317 3-terminal adjustable regulator 1086
	Bibliography 1095
	Index 1101