THE ART OF ELECTRONICS

Paul Horowitz
Winfield Hill

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Paul Horowitz HARVARD UNIVERSITY

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TABLES

1.1 Diodes 36
2.1 Small-signal transistors 88
3.1 Operational amplifiers 108
3.2 High-voltage op-amps 114
4.1 Time-domain filter comparison 156
4.2 VCVS low-pass filters 158
5.1 Power transistors 178
5.2 Transient suppressors 188
5.3 Power-line filters 188
5.4 Rectifiers 191
5.5 Zener and reference diodes 194
5.6 IC voltage references 196
5.7 Fixed voltage regulators 200
5.8 Adjustable voltage regulators 201
5.9 Dual-tracking regulators 205
6.1 JFETs 230
6.2 MOSFETs 230
6.3 Dual matched JFETs 231
6.4 Power MOSFETs 258
7.1 Precision op-amps 272
7.2 High-speed op-amps 276
7.3 Fast buffers 278
7.4 Instrumentation amplifiers 287
8.1 4-bit integers 320
8.2 TTL and CMOS gates 327
8.3 Logic identities 332
8.4 Logic calculation 339
9.1 TTL families compared 381
9.2 Comparators 396
9.3 Voltage-controlled oscillators 431
11.1 8085 instruction set 489
11.2 8085 execution times 496
11.3 Edge-triggered latches 515
11.4 Transparent latches 515
11.5 Three-state buffers 516
11.6 IC package equivalent area 517
11.7 Parallel I/O chips 520
11.8 S100 bus signals 530
11.9 Microprocessor CPUs 533
12.1 PC graphics patterns 545
12.2 Venturi fans 550
13.1 RF transistors 563
14.1 Thermocouples 595
H1 Butterworth *LC* Filters 654

PREFACE

This volume is intended as an electronic circuit design textbook and reference book; it begins at a level suitable for those with no previous exposure to electronics, and carries the reader through to a reasonable degree of proficiency in electronic circuit design. We have used a straightforward approach to the essential ideas of circuit design, coupled with an in-depth selection of topics. We have attempted to combine the pragmatic approach of the practicing physicist with the quantitative approach of the engineer, who wants a thoroughly evaluated circuit design.

This book evolved from a set of notes written to accompany a one-semester course in laboratory electronics at Harvard. That course has a varied enrollment – undergraduates picking up skills for their eventual work in science or industry, graduate students with a field of research clearly in mind, and advanced graduate students and postdoctoral researchers who suddenly find themselves hampered by their inability to "do electronics."

It soon became clear that existing textbooks were inadequate for such a course. Although there are excellent treatments of each electronics specialty, written for the planned sequence of a four-year engineering curriculum or for the practicing engineer, those books that attempt to address the whole field of electronics seem to suffer either from excessive detail (the handbook syndrome), oversimplification (the cookbook syndrome), or poor balance of material. Much of the favorite pedagogy of beginning textbooks is quite unnecessary and, in fact, is not used by practicing engineers, while useful circuitry and methods of analysis in daily use by circuit designers lies hidden in application notes, engineering journals, and hard-to-get data books. In other words, there is a tendency among textbook writers to represent the theory, rather than the art, of electronics.

We collaborated in writing this book with the specific intention of combining the discipline of a circuit design engineer with the perspective of a practicing experimental physicist and teacher of electronics. Thus, the treatment in this book reflects our philosophy that electronics, as currently practiced, is basically a simple art, a combination of some basic laws, rules of thumb, and a large bag of tricks. For these reasons we have omitted entirely the usual discussions of solid-state physics, the *h*-parameter model of transistors, and complicated network theory, and reduced to a bare minimum the mention of load lines and the *s*-plane. The treatment is largely nonmathematical, with strong encouragement of circuit brainstorming, and mental (or, at most, back-of-the-envelope) calculation of circuit values and performance.

In addition to the subjects usually treated in electronics books, we have included the following:

- an easy-to-use transistor model
- extensive discussion of useful subcircuits, such as current sources and current mirrors
- single-supply op-amp design
- easy-to-understand discussions of topics on which practical design information is often difficult to find: op-amp frequency compensation, low-noise circuits, phase-locked loops, and precision linear design.
- simplified design of active filters, with tables and graphs
- a section on noise, shielding, and grounding
- a unique graphical method for streamlined low-noise amplifier analysis
- a chapter on voltage references and regulators, including constant current supplies

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- a discussion of monostable multivibrators and their idiosyncrasies
- a collection of digital logic pathology, and what to do about it
- an extensive discussion of interfacing to logic, with emphasis on the new NMOS and PMOS LSI
- a detailed discussion of A/D and D/A conversion techniques
- a section on digital noise generation
- a discussion of minicomputers and interfacing to data buses, with an introduction to assembly language
- a chapter on microprocessors, with actual design examples and discussion – how to design them into instruments, and how to make them do what you want
- a chapter on construction techniques: prototyping, printed circuit boards, instrument design
- a simplified way to evaluate high-speed switching circuits
- a chapter on scientific measurement and data processing: what you can measure and how accurately, and what to do with the data
- bandwidth narrowing methods made clear: signal averaging, multichannel scaling, lock-in amplifiers, and pulse height analysis
- amusing collections of "bad circuits," and collections of "circuit ideas"
- useful appendixes on how to draw schematic diagrams, IC generic types, LC filter design, resistor values, oscilloscopes, mathematics review, and others
- tables of diodes, transistors, FETs, op-amps, comparators, regulators, voltage references, microprocessors, and other devices, generally listing the characteristics of both the most popular and the best types.

Throughout we have adopted a philosophy of naming names, often comparing the characteristics of competing devices for use in any circuit, and the advantages of alternate circuit configurations. Example circuits are drawn with real device types, not black boxes. The overall intent is to bring the reader to the point of understanding clearly the choices one makes in designing a circuit – how to choose circuit configurations, device types, and parts values. The use of largely nonmathematical circuit design techniques does not result in circuits that cut corners or compromise performance or reliability. On the contrary, such techniques enhance one's understanding of the real choices and compromises faced in engineering a circuit, and represent the best approach to good circuit design.

This book can be used for a full-year electronic circuit design course at the college level, with only a minimum mathematical prerequisite, namely some acquaintance with trigonometric and exponential functions, and preferably a bit of differential calculus. (A short review of complex numbers and derivatives is included as an appendix.) If the less essential sections are omitted, it can serve as the text for a one-semester course (as it does at Harvard). To assist the reader in navigation we have designated with open boxes in the margin those sections within each chapter that we feel can be safely passed over in an abbreviated reading. For a one-semester course it would probably be wise to omit in addition the materials of Chapter 4 (first half), 7, 12, 13, and possibly 14, as explained in the introductory paragraphs of those chapters.

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Winfield Hill

May 1980

CONTENTS

List of tables **xv**

Preface **xvii**

CHAPTER 1
FOUNDATIONS **1**

Introduction **1**

Voltage, current, and resistance **2**

1.01 Voltage and current 2
1.02 The relationship between voltage and current: resistors 3
1.03 Voltage dividers 7
1.04 Voltage and current sources 7
1.05 Thévenin's theorem 8
1.06 Small signal resistance 11

Signals **13**

1.07 Sinusoidal signals 13
1.08 Signal amplitudes and decibels 14
1.09 Other signals 14
1.10 Logic levels 16
1.11 Signal sources 17

Capacitors and ac circuits **17**

1.12 Capacitors 18
1.13 *RC* Circuits: *V* and *I* versus time 20
1.14 Differentiators 22
1.15 Integrators 23

Inductors and transformers **24**

1.16 Inductors 24
1.17 Transformers 24

Impedance and reactance **25**

1.18 Frequency analysis of reactive circuits 25
1.19 *RC* Filters 29
1.20 Phasor diagrams 32
1.21 "Poles" and decibels per octave 33
1.22 Resonant circuits and active filters 33
1.23 Other capacitor applications 34
1.24 Thévenin's theorem generalized 35

Diodes and diode circuits **35**

1.25 Diodes 35
1.26 Rectification 37
1.27 Power-supply filtering 37
1.28 Rectifier configurations for power supplies 38
1.29 Regulators 39
1.30 Circuit applications of diodes 40
1.31 Inductive loads and diode protection 43

Other passive components **44**

1.32 Electromechanical devices 45
1.33 Indicators 47
1.34 Variable components 47
Additional exercises *48*

CHAPTER 2
TRANSISTORS **50**

Introduction **50**

2.01 First model: current amplifier 51

Some basic transistor circuits **52**

2.02 Transistor switch 52
2.03 Emitter follower 53
2.04 Emitter followers as voltage regulators 55
2.05 Emitter follower biasing 56
2.06 Transistor current source 59
2.07 Common-emitter amplifier 62
2.08 Unity-gain phase splitter 63
2.09 Transconductance 64

Ebers-Moll model applied to basic transistor circuits 65

2.10 Improved transistor model: transconductance amplifier 65
2.11 The common-emitter amplifier revisited 67
2.12 Biasing the common-emitter amplifier 68
2.13 Current mirrors 71

Some amplifier building blocks 74

2.14 Push-pull output stages 74
2.15 Darlington connection 77
2.16 Bootstrapping 78
2.17 Differential amplifiers 80
2.18 Capacitance and Miller effect 83
2.19 Field-effect transistors 85

Some typical transistor circuits 85

2.20 Regulated power supply 85
2.21 Temperature controller 87
2.22 Simple logic with transistors and diodes 87

Self-explanatory circuits 89

2.23 Bad circuits 89
Additional exercises 89

CHAPTER 3
FEEDBACK AND OPERATIONAL AMPLIFIERS 92

Introduction to feedback and operational amplifiers 92

3.01 Introduction to feedback 92
3.02 Operational amplifiers 93
3.03 The golden rules 94

Basic op-amp circuits 94

3.04 Inverting amplifier 94
3.05 Noninverting amplifier 95
3.06 Follower 95
3.07 Current sources 96
3.08 Basic cautions for op-amp circuits 97

An op-amp smorgasbord 98

3.09 Linear circuits 98
3.10 Nonlinear circuits 102

A detailed look at op-amp behavior 103

3.11 Departure from ideal op-amp performance 103
3.12 Effects of op-amp limitations on circuit behavior 107
3.13 Low-power and programmable op-amps 116

A detailed look at selected op-amp circuits 117

3.14 Logarithmic amplifier 117
3.15 Active peak detector 118
3.16 Active clamp 120
3.17 Absolute-value circuit 120
3.18 Integrators 121
3.19 Differentiators 122

Op-amp operation with a single power supply 122

3.20 Biasing single-supply ac amplifiers 122
3.21 Single-supply op-amps 123

Comparators and Schmitt trigger 124

3.22 Comparators 124
3.23 Schmitt trigger 125

Feedback with finite-gain amplifiers 127

3.24 Gain equation 127
3.25 Effects of feedback on amplifier circuits 127
3.26 Two examples of transistor amplifiers with feedback 130

Some typical op-amp circuits 132

3.27 General-purpose lab amplifier 132
3.28 Voltage-controlled oscillator 132
3.29 TTL zero-crossing detector 134
3.30 Load-current-sensing circuit 134

Feedback amplifier frequency compensation 136

3.31 Gain and phase shift versus frequency 136
3.32 Amplifier compensation methods 137
3.33 Frequency response of the feedback network 139

Self-explanatory circuits 142

3.34 Circuit ideas 142
3.35 Bad circuits 142
Additional exercises 142

CHAPTER 4
ACTIVE FILTERS AND OSCILLATORS 148

Active filters 148

4.01 Frequency response with *RC* filters 148
4.02 Ideal performance with *LC* filters 150
4.03 Enter active filters: an overview 150
4.04 Key filter performance criteria 152
4.05 Filter types 153

Active filter circuits 156

4.06 VCVS circuits 157
4.07 VCVS filter design using our simplified table 158
4.08 State-variable filters 160
4.09 Twin-T notch filters 160
4.10 Gyrator filter realizations 161

Oscillators 162

4.11 Introduction to oscillators 162
4.12 Relaxation oscillators 162
4.13 The classic timer chip: the 555 164
4.14 Wien bridge and *LC* oscillators 165
4.15 *LC* oscillators 166
4.16 Quartz-crystal oscillators 167

Self-explanatory circuits 171

4.17 Circuit ideas 171
Additional exercises 171

CHAPTER 5
VOLTAGE REGULATORS AND POWER CIRCUITS 172

Basic regulator circuits with the classic 723 172

5.01 The 723 regulator 172
5.02 Positive regulator 174
5.03 High-current regulator 176

Heat and power design 177

5.04 Power transistors and heat sinking 177
5.05 Foldback current limiting 180
5.06 Overvoltage crowbars 182
5.07 Further considerations in high-current power-supply design 183
5.08 Programmable supplies 185
5.09 Power-supply circuit example 185

The unregulated supply 187

5.10 ac Line components 187
5.11 Transformer 189
5.12 dc Components 190

Voltage references 192

5.13 Zener diodes 192
5.14 Bandgap (V_{BE}) reference 195

Three-terminal and four-terminal regulators 199

5.15 Three-terminal regulators 199
5.16 Four-terminal regulators 199
5.17 Three-terminal adjustable regulators 202
5.18 Additional comments about 3-terminal regulators 202

Special-purpose power-supply circuits 204

5.19 Dual-tracking regulators 204
5.20 High-voltage regulators 207
5.21 Switching regulators 210
5.22 dc-to-dc Converters 211
5.23 Energy-storage inductor 213
5.24 Constant-current supplies 216

Self-explanatory circuits 218

5.25 Circuit ideas 218
5.26 Bad circuits 218
Additional exercises 218

CHAPTER 6
FIELD-EFFECT TRANSISTORS 223

FET characteristics 223

6.01 JFETs 223
6.02 MOSFETs 224
6.03 Universal FET characteristics 225
6.04 FET drain characteristics 226
6.05 Manufacturing spread of FET characteristics 229

Basic FET circuits 231

6.06 JFET current sources 231
6.07 FET amplifiers 232
6.08 Source followers 234
6.09 JFET input impedance and gate leakage 237
6.10 FETs as variable resistors 240
6.11 Op-amp controlled current sources 241

FET switches 242

6.12 FET linear switches 242
6.13 FETs as logic switches 244
6.14 FET linear switch applications 245
6.15 Limitations of FET switches 247

Some additional FET circuit ideas 250

6.16 Amplifiers 250
6.17 Pinch-off reference 253
6.18 Switch circuits 253
6.19 BiFET integrated circuits 255
6.20 Power MOSFETs 256

Self-explanatory circuits 257

6.21 Circuit ideas 257
6.22 Bad circuits 257

CHAPTER 7
PRECISION CIRCUITS AND LOW-NOISE TECHNIQUES 262

Precision op-amp design techniques 262

7.01 Precision versus dynamic range 262
7.02 Error budget 263
7.03 Example circuit: precision amplifier with automatic null offset 263
7.04 A precision-design error budget 264
7.05 Component errors 264
7.06 Amplifier input errors 266
7.07 Amplifier output errors 271

Differential and instrumentation amplifiers 279

7.08 Differencing amplifier 279
7.09 Standard three-op-amp instrumentation amplifier 282

Amplifier noise 286

7.10 Origins and kinds of noise 288
7.11 Signal-to-noise ratio and noise figure 290
7.12 Transistor amplifier voltage and current noise 291
7.13 Low-noise design with transistors 293
7.14 FET noise 298
7.15 Selecting low-noise transistors 299
7.16 Noise in differential and feedback amplifiers 299

Noise measurements and noise sources 303

7.17 Measurement without a noise source 303
7.18 Measurement with noise source 304
7.19 Noise and signal sources 305
7.20 Bandwidth limiting and rms voltage measurement 306

Interference: shielding and grounding 307

7.21 Interference 307
7.22 Signal grounds 308
7.23 Grounding between instruments 309

Self-explanatory circuits 313

7.24 Circuit ideas 313
Additional exercises 313

CHAPTER 8
DIGITAL ELECTRONICS 316

Basic logic concepts 316

8.01 Digital versus analog 316
8.02 Logic states 317
8.03 Number codes 318
8.04 Gates and truth tables 321
8.05 Discrete circuits for gates 323
8.06 Gate circuit example 324
8.07 Assertion-level logic notation 325

TTL and CMOS 326

8.08 Catalog of common gates 326
8.09 IC gate circuits 328
8.10 TTL and CMOS characteristics 328
8.11 Three-state and open-collector devices 329

Combinational logic 331

8.12 Logic identities 332
8.13 Minimization and Karnaugh maps 333
8.14 Combinational functions available as ICs 334
8.15 Implementing arbitrary truth tables 338

Sequential logic 341

8.16 Devices with memory: flip flops 341
8.17 Clocked flip-flops 343
8.18 Combining memory and gates: sequential logic 347
8.19 Synchronizer 349

Monostable multivibrators 351

8.20 One-shot characteristics 351
8.21 Monostable circuit example 353
8.22 Cautionary notes about monostables 354
8.23 Timing with counters 356

Sequential functions available as ICs 357

8.24 Latches and registers 357
8.25 Counters 358
8.26 Shift registers 359
8.27 Miscellaneous sequential functions 362

Some typical digital circuits 365

8.28 Modulo-*n* counter 365
8.29 Multiplexed LED digital display 365
8.30 Siderial telescope drive 367
8.31 FIFO-buffered keyboard 370
8.32 *n*-Pulse generator 371

Logic pathology 373

8.33 dc Problems 374
8.34 Switching problems 374
8.35 Congenital weaknesses of TTL and CMOS 375

Self-explanatory circuits 377

8.36 Circuit ideas 377
8.37 Bad circuits 377
Additional exercises 377

CHAPTER 9
DIGITAL MEETS ANALOG 380

TTL and CMOS logic interfacing 380

9.01 TTL and CMOS logic families 380
9.02 Input and output characteristics of TTL and CMOS 382
9.03 Interfacing between TTL and CMOS 384
9.04 Driving TTL and CMOS inputs 386
9.05 Driving digital logic from comparators and op-amps 388
9.06 Some comments about logic inputs 389
9.07 Comparators 390
9.08 Driving external digital loads from TTL and CMOS 393

n-channel and p-channel MOS LSI interfacing 398

9.09 NMOS inputs 398
9.10 NMOS outputs 399
9.11 PMOS inputs 400

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9.12 PMOS outputs 401
9.13 Summarizing MOS family characteristics 402

Digital signals and long wires 402

9.14 On-board interconnections 403
9.15 Intercard connections 405
9.16 Data buses 405
9.17 Driving cables 406

Analog/digital conversion 408

9.18 Introduction to A/D conversion 408
9.19 Digital-to analog-converters (DACs) 410
9.20 Time domain (averaging) DACs 413
9.21 Multiplying DACs 414
9.22 Analog-to-digital converters 415
9.23 Charge-balancing techniques 417

Some A/D conversion examples 420

9.24 16-Channel A/D data acquisition system 420
9.25 3½-Digit voltmeter 423
9.26 Delta-sigma continuous-integrating converter 423
9.27 Coulomb meter 425

Phase-locked loops 428

9.28 Introduction to phase-locked loops 428
9.29 PLL components 429
9.30 PLL design 431
9.31 Design example: frequency multiplier 432
9.32 PLL capture and lock 435
9.33 Some PLL applications 436

Pseudo-random-bit sequences and noise generation 437

9.34 Digital noise generation 437
9.35 Feedback shift register sequences 438
9.36 Analog noise generation from maximal-length sequences 440
9.37 Power spectrum of shift register sequences 440
9.38 Low-pass filtering 442
9.39 Wrap-up 443
9.40 Digital filters 446

Self-explanatory circuits 448

9.41 Circuit ideas 448
9.42 Bad circuits 451
Additional exercises 451

CHAPTER 10
MINICOMPUTERS 453

Minicomputers, microcomputers, and microprocessors 453

10.01 Computer architecture 454

A computer instruction set 456

10.02 Assembly language and machine language 456
10.03 The MC-16 instruction set 457
10.04 A programming example 458

Bus signals and interfacing 458

10.05 Fundamental bus signals: data, address, strobe 459
10.06 Programmed I/O: data out 459
10.07 Programmed I/O: data in 461
10.08 Programmed I/O: status registers 462
10.09 Interrupts 465
10.10 Interrupt handling method I: device polling 466
10.11 Interrupt handling method II: vectored interrupt 466
10.12 Direct memory access 468
10.13 Synchronous versus asynchronous communication 469
10.14 Connecting peripherals to the computer 470

Software system concepts 472

10.15 Programming 472
10.16 Operating systems, files, and use of memory 473

Data communications concepts 475

10.17 Alphanumeric codes and serial communication 475
10.18 Numeric data interfacing 478
Additional exercises 481

CHAPTER 11
MICROPROCESSORS 484

A detailed look at the 8085 485

11.1 Architecture 485
11.2 Internal operation 487
11.3 Instruction set 489
11.4 Machine-language representation 495

A complete design example: 6-channel event counter 501

11.5 Circuit design 501
11.6 Programming the 6-channel event counter 505
11.7 Program timing and performance 512

Microprocessor support chips 514

11.8 Medium-scale integration 514
11.9 Peripheral LSI chips 517
11.10 Memory 521
11.11 Designing a system with LSI 523

Further topics in microprocessor system design 529

11.12 The S100 bus 529
11.13 Other microprocessors 530
11.14 Evaluation boards, development systems, and emulators 532

CHAPTER 12
ELECTRONIC CONSTRUCTION TECHNIQUES 536

Prototyping methods 536

12.01 Breadboards 536
12.02 PC prototyping boards 537
12.03 Wire-wrap panels 538

Printed circuits 540

12.04 PC board fabrication 540
12.05 PC board design 542
12.06 Stuffing PC boards 544
12.07 Some further thoughts on PC boards 546

Instrument construction 546

12.08 Housing circuit boards in an instrument 546
12.09 Cabinets 547
12.10 Construction hints 548
12.11 Cooling 549
12.12 Some electrical hints 550
12.13 Where to get components 553

CHAPTER 13
HIGH-FREQUENCY AND HIGH-SPEED TECHNIQUES 554

High-frequency amplifiers 554

13.01 Transistor amplifiers at high frequencies: first look 554
13.02 High-frequency amplifiers: the ac model 555
13.03 A high-frequency calculation example 557
13.04 High-frequency amplifier configurations 558
13.05 A wideband design example 560
13.06 Some refinements to the ac model 562
13.07 The shunt-series pair 562
13.08 Modular amplifiers 564

Radiofrequency circuit elements 565

13.09 Transmission lines 565
13.10 Stubs, baluns, and transformers 567
13.11 Tuned amplifiers 568
13.12 Radiofrequency circuit elements 570

Radiofrequency communications: AM 573

13.13 Some communications concepts 573
13.14 Amplitude modulation 573
13.15 Superheterodyne receiver 575

Advanced modulation methods 576

13.16 Single sideband 576
13.17 Frequency modulation 577
13.18 Frequency-shift keying 579
13.19 Pulse-modulation schemes 579

Radiofrequency circuit tricks 580

13.20 Special construction techniques 580
13.21 Exotic RF amplifiers and devices 581

High-speed switching 582

13.22 Transistor model and equations 582

Some switching-speed examples 585

13.23 High-voltage driver 585
13.24 Open-collector bus driver 586
13.25 Example: photomultiplier preamp 587
13.26 Circuit ideas 589
Additional exercises 589

CHAPTER 14
MEASUREMENTS AND SIGNAL PROCESSING 591

Overview 591

Measurement transducers 592

14.01 Temperature 592
14.02 Light level 597
14.03 Strain and displacement 601
14.04 Acceleration, pressure, force, velocity 605
14.05 Magnetic field 607
14.06 Vacuum gauges 608
14.07 Particle detectors 608
14.08 Biological and chemical voltage probes 612

Precision standards and precision measurements 615

14.09 Frequency standards 615
14.10 Frequency, period, and time-interval measurements 617
14.11 Voltage and resistance standards and measurements 623

Bandwidth-narrowing techniques 624

14.12 The problem of signal-to-noise ratio 624
14.13 Signal averaging and multichannel averaging 624
14.14 Making a signal periodic 627
14.15 Lock-in detection 628
14.16 Pulse height analysis 631
14.17 Time-to-amplitude converters 632

Spectrum analysis and Fourier transforms 633

14.18 Spectrum analyzers 633
14.19 Off-line spectrum analysis 635

APPENDIXES

Appendix A
The oscilloscope 638

Appendix B
Math review 642

Appendix C
The 5% resistor color code 645

Appendix D
1% Precision resistors 646

Appendix E
How to draw schematic diagrams 647

Appendix F
Load lines 650

Appendix G
Transistor saturation 652

Appendix H
***LC* Butterworth filters 654**

Appendix I
Electronics magazines and journals 657

Appendix J
IC generic types 659

Appendix K
Data sheets 661
1N914 signal diode 662
2N4400-1 NPN transistor 666
LM394 NPN matched pair 671
LF355-7 JFET operational amplifier 677
LM317 3-terminal adjustable regulator 691
96LS02 TTL monostable multivibrator 699

Bibliography 705

Index 709

FOUNDATIONS

CHAPTER 1

INTRODUCTION

Developments in the field of electronics have constituted one of the great success stories of this century. Beginning with crude spark-gap transmitters and "cat's-whisker" detectors at the turn of the century, we have passed through a vacuum-tube era of considerable sophistication to a solid-state era in which the flood of stunning advances shows no signs of abating. Calculators, computers, and even talking machines with vocabularies of several hundred words are routinely manufactured on single chips of silicon as part of the technology of large-scale integration (LSI), and current developments in very large scale integration (VLSI) promise even more remarkable devices.

Perhaps as noteworthy is the pleasant trend toward increased performance per dollar. The cost of an electronic microcircuit routinely decreases to a fraction of its initial cost as the manufacturing process is perfected (see Fig. 11.18 for an example). In fact, it is often the case that the panel controls and cabinet hardware of an instrument cost more than the electronics inside.

On reading of these exciting new developments in electronics, you may get the impression that you should be able to construct powerful, elegant, yet inexpensive, little gadgets to do almost any conceivable task – all you need to know is how all these miracle devices work. If you've had that feeling, this book is for you. In it we have attempted to convey the excitement and know-how of the subject of electronics.

In this chapter we begin the study of the laws, rules of thumb, and tricks that constitute the art of electronics as we see it. It is necessary to begin at the beginning – with talk of voltage, current, power, and the components that make up electronic circuits. Since you can't touch, see, smell, or hear electricity, there will be a certain amount of abstraction (particularly in the first chapter), as well as some dependence on such visualizing instruments as oscilloscopes and voltmeters. In many ways the first chapter is also the most mathematical, in spite of our efforts to keep mathematics to a minimum in order to foster a good intuitive understanding of circuit design and behavior.

Once we have considered the foundations of electronics, we will quickly get into the "active" circuits (amplifiers, oscillators, logic circuits, etc.) that make electronics the exciting field it is. The reader with some background in electronics may wish to skip over this chapter, since it assumes no prior knowledge of electronics. Further generalizations at this time would be pointless, so let's just dive right in.

VOLTAGE, CURRENT, AND RESISTANCE

1.01 Voltage and current

There are two quantities that we like to keep track of in electronic circuits: voltage and current. These are usually changing with time; otherwise nothing interesting is happening.

Voltage (symbol: *V*, or sometimes *E*). The voltage between two points is the cost in energy (work done) required to move a unit of positive charge from the more negative point (lower potential) to the more positive point (higher potential). Equivalently, it is the energy released when a unit charge moves "downhill" from the higher potential to the lower. Voltage is also called *potential difference* or *electromotive force* (EMF). The unit of measure is the *volt*, with voltages usually expressed in volts (V), kilovolts ($1\text{kV} = 10^3\text{V}$), millivolts ($1\text{mV} = 10^{-3}\text{V}$), or microvolts ($1\mu\text{V} = 10^{-6}\text{V}$) (see the box on prefixes). A joule of work is needed to move a coulomb of charge through a potential difference of one volt. (The coulomb is the unit of electric charge, and it equals the charge of 6×10^{18} electrons, approximately.) For reasons that will become clear later, the opportunities to talk about nanovolts ($1\text{nV} = 10^{-9}\text{V}$) and megavolts ($1\text{MV} = 10^6\text{V}$) are rare.

Current (symbol: *I*). Current is the rate of flow of electric charge past a point. The unit of measure is the ampere, or amp, with currents usually expressed in amperes (A), milliamperes ($1\text{mA} = 10^{-3}\text{A}$), microamperes ($1\mu\text{A} = 10^{-6}\text{A}$), nanoamperes ($1\text{nA} = 10^{-9}\text{A}$), or occasionally picoamperes ($1\text{pA} = 10^{-12}\text{A}$). A current of one ampere equals a flow of one coulomb of charge per second. By convention, current in a circuit is considered to flow from a more positive point to a more negative point, even though the actual electron flow is in the opposite direction.

Important: Always refer to voltage *between* two points or *across* two points in a circuit. Always refer to current *through* a device or connection in a circuit.

To say something like "the voltage through a resistor . . ." is nonsense, or worse. However, we do frequently speak of the voltage *at a point* in a circuit. This is always understood to mean voltage between that point and "ground," a common point in the circuit that everyone seems to know about. Soon you will, too.

We *generate* voltages by doing work on charges in devices such as batteries (electrochemical), generators (magnetic forces), solar cells (photovoltaic conversion of the energy of photons), etc. We *get* currents by placing voltages across things.

At this point you may well wonder how to "see" voltages and currents. The single most useful electronic instrument is the oscilloscope, which allows you to look at voltages (or occasionally currents) in a circuit as a function of time. We will deal with oscilloscopes, and also voltmeters, when we discuss signals shortly; for a preview, see the oscilloscope appendix (Appendix A) and the multimeter box later in this chapter.

In real circuits we connect things together with wires, metallic conductors, each of which has the same voltage on it everywhere (with respect to ground, say). (In the domain of high frequencies or low impedances, that isn't strictly true, and we will have more to say about this later. For now, it's a good approximation.) We mention this now so that you will realize that an actual circuit doesn't have to look like its schematic diagram, since wires can be rearranged.

Here are some simple rules about voltage and current:

1. The sum of the currents into a point in a circuit equals the sum of the currents out (conservation of charge). This is sometimes called Kirchhoff's current law. Engineers like to refer to such a point as a *node*. From this, we get the following: For a series circuit (a bunch of two-terminal things all connected end-to-end) the current is the same everywhere.

2. Things hooked in parallel (Fig. 1.1) have the same voltage across them. Restated, the sum of the "voltage drops" from *A* to *B*

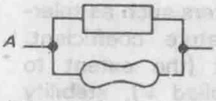

Figure 1.1

via one path through a circuit equals the sum by any other route equals the voltage between *A* and *B*. Sometimes this is stated as follows: The sum of the voltage drops around any closed circuit is zero. This is Kirchhoff's voltage law.

3. The power (work per unit time) consumed by a circuit device is

$$P = VI$$

This is simply (work/charge) × (charge/time). For V in volts and I in amps, P comes out in watts. Watts are joules per second (1W = 1J/s).

Power goes into heat (usually), or sometimes mechanical work (motors), radiated energy (lamps, transmitters), or stored energy (batteries, capacitors). Managing the heat load in a complicated system (e.g., a computer, in which many kilowatts of electrical energy are converted to heat, with the energetically insignificant by-product of a few pages of computational results) can be a crucial part of the system design.

Soon, when we deal with periodically varying voltages and currents, we will have to generalize the simple equation $P = VI$, but it's correct as a statement of instantaneous power just as it stands.

Incidentally, don't call current "amperage"; that's strictly bush-league. The same caution will apply to the term "ohmage" when we get to resistance in the next section.

1.02 Relationship between voltage and current: resistors

This is a long and interesting story. It is the heart of electronics. Crudely speaking, the name of the game is to make and use gadgets that have interesting and useful I versus V characteristics. Resistors (I simply proportional to V), capacitors (I proportional to rate of change of V), diodes (I only flows in one direction), thermistors (temperature-dependent resistor), photoresistors (light-dependent resistor), strain gauges (strain-dependent resistor), etc., are examples. We will gradually get into some of these exotic devices; for now, we will start with the most

PREFIXES

These prefixes are universally used to scale units in science and engineering:

Multiple	*Prefix*	*Symbol*
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f

When abbreviating a unit with a prefix, the symbol for the unit follows the prefix without space. Be careful about upper-case and lower-case letters (especially m and M) in both prefix and unit: 1mW is a milliwatt, or one-thousandth of a watt; 1MHz is 1 million hertz. In general, units are spelled with lower-case letters, even when they are derived from proper names. The unit name is not capitalized when it is spelled out and used with a prefix, only when abbreviated. Thus: hertz and kilohertz, but Hz and kHz; watt, milliwatt, and megawatt, but W, mW, and MW.

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