

FOURTH EDITION

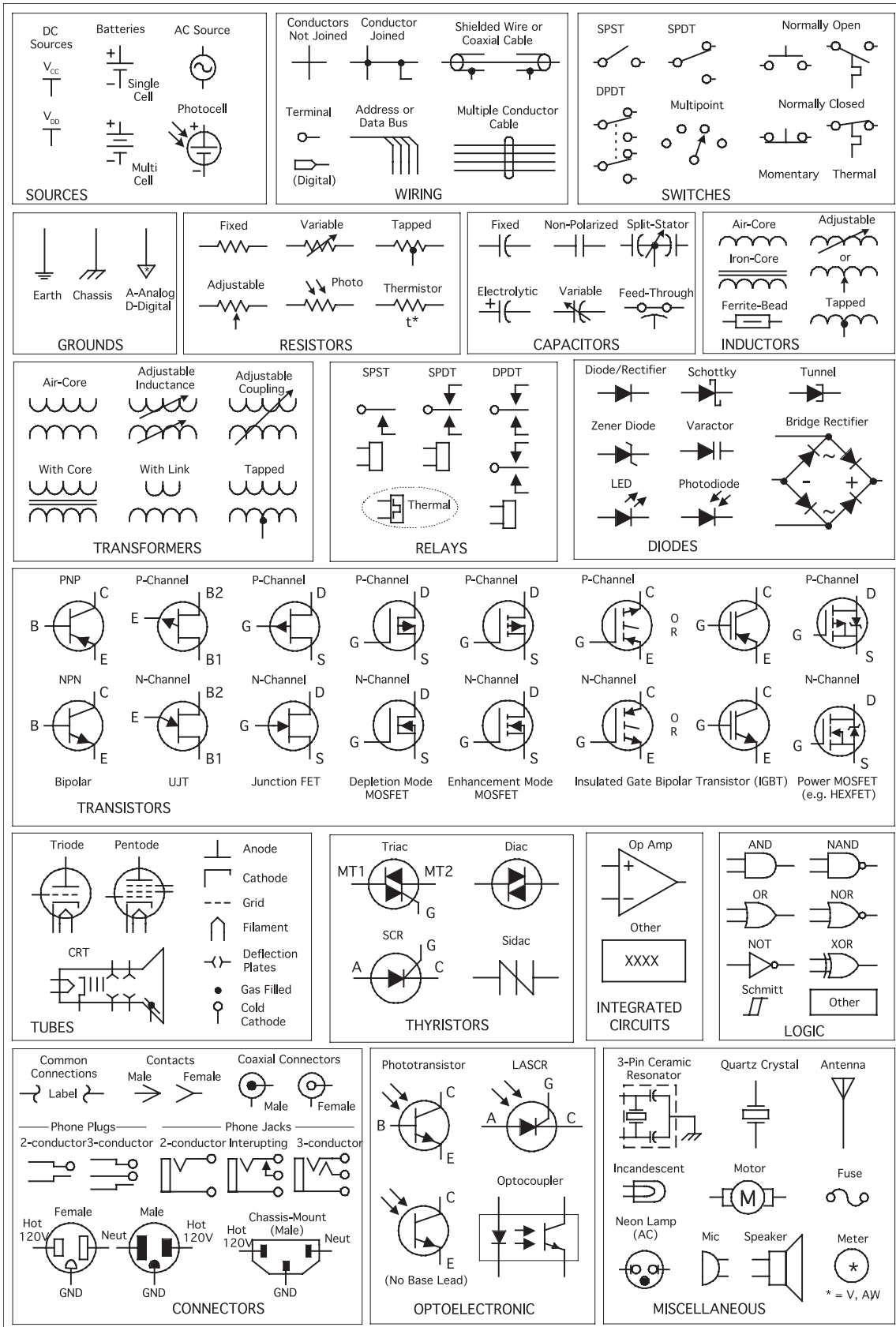
PRACTICAL ELECTRONICS FOR INVENTORS



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Paul Scherz and Simon Monk





Resistor Labels

Conversion Calculator

$k = 1,000$; $M = 1,000,000$
 $1M\Omega = 1,000,000 \Omega = 1 \times 10^6 \Omega$
 $1k\Omega = 1,000 \Omega = 1 \times 10^3 \Omega$

Examples:

$3.3 k\Omega = 3,300 \Omega = 3.3 \times 10^3 \Omega$
 $22 k\Omega = 22,000 \Omega = 22 \times 10^3 \Omega$
 $2 M\Omega = 2,000,000 \Omega = 2 \times 10^6 \Omega$
 $1.68 M\Omega = 1,680,000 \Omega = 1.68 \times 10^6 \Omega$

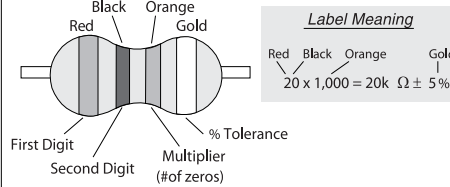
Resistor Color Code

Color	Sig. Fig.	Decimal Multiplier	Tolerance (%)
Black	0	1	-
Brown	1	10	1
Red	2	100	2
Orange	3	1,000	-
Yellow	4	10,000	-
Green	5	100,000	0.5
Blue	6	1,000,000	0.25
Purple	7	10,000,000	0.1
Gray	8	100,000,000	-
White	9	1,000,000,000	-
Gold	-	0.1	5
Silver	-	0.01	10
No Color	-	-	20

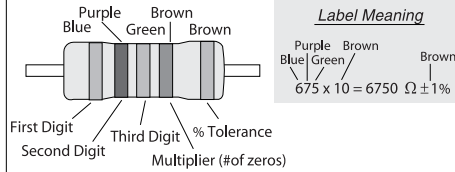
Body Color

The body color of a resistor typically doesn't carry meaning, except in some instances where it may specify temperature coefficient. However, if you find resistors within a circuit that are white/gray or blue in color, they may be non-flammable or fusible resistors. Care must be taken when replacing such resistors—don't substitute ordinary resistors in their place.

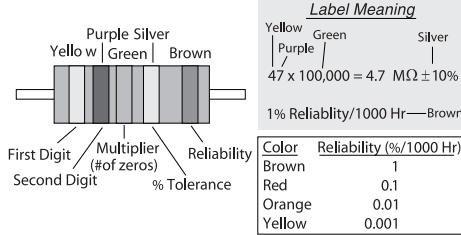
4-Band Resistor Code (Most Common)



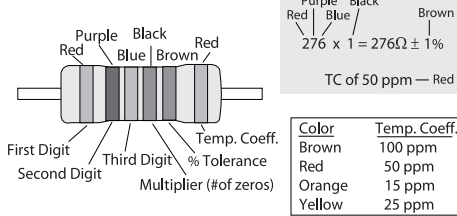
5-Band Resistor Code (3-digit)



5-Band Resistor Code (Reliability)

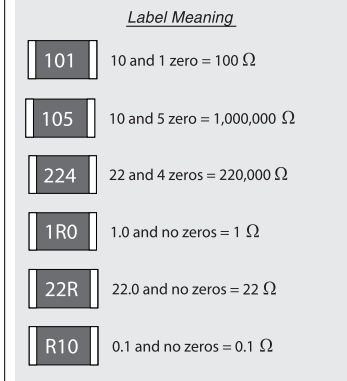


6-Band Resistor Code



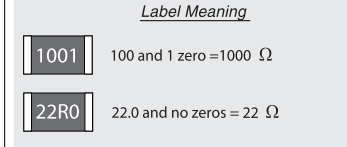
Surface Mount Resistor Code

3-digit Label



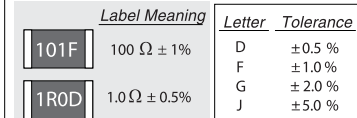
The first two digits represent significant figures; the last digit specifies the multiplier. For values under 100 Ω , the letter R is substituted for one of the significant digits and represents a decimal point.

4-digit Label



The first three digits represent significant figures; the last digit specifies the multiplier. R represents a decimal point

Tolerance Label



Standard Resistor Values (1%, 5% and 10% Tolerance)

1%								5%		10%
1.00	1.02	1.05	1.07	1.10	1.13	1.15	1.18	10	11	10
1.21	1.24	1.27	1.30	1.33	1.37	1.40	1.43	12	13	12
1.47	1.50	1.54	1.58	1.62	1.65	1.69	1.74	15	16	15
1.78	1.82	1.87	1.91	1.96	2.00	2.05	2.10	18	20	18
2.15	2.21	2.26	2.32	2.37	2.43	2.49	2.55	22	24	22
2.61	2.67	2.74	2.80	2.87	2.94	3.01	3.09	27	30	27
3.16	3.24	3.32	3.40	3.48	3.57	3.65	3.74	33	36	33
3.83	3.92	4.02	4.12	4.22	4.32	4.42	4.53	39	43	39
4.64	4.75	4.87	4.99	5.11	5.23	5.36	5.49	47	51	47
5.62	5.76	5.90	6.04	6.19	6.34	6.49	6.65	56	62	56
6.81	6.98	7.15	7.32	7.50	7.68	7.87	8.06	68	75	68
8.25	8.45	8.66	8.87	9.09	9.31	9.53	9.76	82	91	82

Standard resistance value is obtained from the above chart by multiply by powers of 10.

5% example resistors: 51 Ω , 510 Ω , 5.1k Ω , 51k Ω , 510k Ω , 5.1M Ω .

1% example resistors: 1.21 Ω , 12.1 Ω , 121 Ω , 1.21k Ω , 12.1k Ω , 121k Ω , 1.21M Ω

Capacitor Markings

Capacitance Conversion Calculator

$1 \text{ F} = 1 \times 10^6 \mu\text{F} = 1 \times 10^9 \text{ nF} = 1 \times 10^{12} \text{ pF}$
 $1 \mu\text{F} = 1 \times 10^{-6} \text{ F} = 1 \times 10^3 \text{ nF} = 1 \times 10^6 \text{ pF}$
 $1 \text{ nF} = 1 \times 10^{-9} \text{ F} = 1 \times 10^{-3} \mu\text{F} = 1 \times 10^3 \text{ pF}$
 $1 \text{ pF} = 1 \times 10^{-12} \text{ F} = 1 \times 10^{-6} \mu\text{F} = 1 \times 10^{-3} \text{ nF}$
 $\text{F} = \text{Farad}, \mu = \text{micro}, \text{n} = \text{nano}, \text{p} = \text{pico}$

$1000 \mu\text{F} = 1,000,000 \text{ nF} = 10 \times 10^8 \text{ pF}$
 $100 \mu\text{F} = 100,000 \text{ nF} = 10 \times 10^7 \text{ pF}$
 $10 \mu\text{F} = 10,000 \text{ nF} = 10 \times 10^6 \text{ pF}$
 $1 \mu\text{F} = 1,000 \text{ nF} = 10 \times 10^5 \text{ pF}$
 $0.1 \mu\text{F} = 100 \text{ nF} = 10 \times 10^4 \text{ pF}$
 $0.01 \mu\text{F} = 10 \text{ nF} = 10 \times 10^3 \text{ pF}$
 $0.001 \mu\text{F} = 1 \text{ nF} = 10 \times 10^2 \text{ pF}$

Tantalum

Label meaning 1

1st significant figure in μF
 2nd significant figure in μF
 Multiplier (See table)
 Voltage

Color	S.F.	Multiplie	Voltage
Black	0	1	10V
Brown	1	10	
Red	2	100	
Orange	3	1000	
Yellow	4		6.3V
Green	5		16V
Blue	6		20V
Violet	7		
Gray	8	0.01	25V
White	9	0.1	3V
Pink			35V

Label meaning 2

Marking	Actual
22	22 μF , 16V

Mylar (Polyester Film)

Polypropylene

Dipped Mica

Label meaning

Marking	Actual
.001K*	0.001 μF , $\pm 10\%$
104K	0.1 μF , $\pm 10\%$
.22J*	0.22 μF , $\pm 5\%$
472K	0.0047 μF , $\pm 10\%$
221J	220 pF, $\pm 5\%$
470J	47 pF, $\pm 5\%$
102J	1000 pF, $\pm 5\%$
103F	0.01 μF , $\pm 1\%$
223F	0.022 μF , $\pm 1\%$
104F	0.1 μF , $\pm 1\%$

Labels: 1st digit, 2nd digit, multiplier in pF (or μF if decimal before digits), and tolerance.

Metallized Polyester Film

Label meaning

Marking	Actual
2 μ 2	2.2 μF
μ 22	0.22 μF
68n	68 nF
4n7	4.7 nF

Label: "u" place of decimal in microfarads
 "n" place of decimal in nanofarads

Polyester Color Coded

1st digit (pF)	2nd digit (pF)	Multiplier	Tolerance	Voltage
Black			$\pm 20\%$	
White			$\pm 10\%$	
Green			$\pm 5\%$	
Brown				100
Red				250
Yellow				400

Ceramic Disc Capacitors

Label: Varies widely according to manufacturer. Usually given in pF (see multiplier code table) but may be given in μF when there is a decimal before digits. See other tables for temperature and tolerance markings.

Ceramic Disc (European Markings)

Label Meaning

Marking	Actual	Marking	Actual
p68	0.68 pF	22p	22 pF
1p0	1.0 pF	n10	0.1 nF
4p7	4.7 pF	n27	0.27 nF

Label: p = picofarads, n = nanofarads; location of p or n signifies decimal point.

Fixed Ceramic Color Code

1st Digit	2nd Digit	Multiplier	Temp. Coeff.	Tolerance
Black	0	1	$\pm 20\%$	2.0 pF
Brown	1	10	$\pm 1\%$	-30
Red	2	100	$\pm 2\%$	-60
Orange	3	1000		-150
Yellow	4			-220
Green	5			-330
Blue	6		$\pm 5\%$	-470
Violet	7			-750
Gray	8	0.01		0.25pF
White	9	0.1	$\pm 10\%$	1.0pF

Surface Mount Capacitors

SMD Ceramic

Label meaning

Marking	Actual
N1	33 pF
A4	0.01 μF
S6	4.7 μF

SMD Electrolytic

Label meaning 1

Marking	Actual
10 6V	10 μF , 6V

Label meaning 2

Marking	Actual
A475	4.7 μF , 10V

Significant Figure Code

Char.	S. F.	Char.	S. F.
A	1.0	T	5.1
B	1.1	U	5.6
C	1.2	V	6.2
D	1.3	W	6.8
E	1.5	X	7.5
F	1.6	Y	8.2
G	1.8	Z	9.1
H	2.0	a	2.5
J	2.2	b	3.5
K	2.4	d	4.0
L	2.7	e	4.5
M	3.0	f	5.0
N	3.3	m	6.0
P	3.6	n	7.0
Q	3.9	t	8.0
R	4.3	y	9.0
S	4.7		

Multiplier Code

Numeric Character	Decimal Multiplier (pF)
0	1
1	10
2	100
3	1,000
4	10,000
5	100,000
6	1,000,000
7	10,000,000
8	100,000,000
9	0.1

Label 2: Voltage (see table below), 1st digit, 2nd digit, multiplier (pF).

Char.	Voltage
e	2.5
G	4
J	6.3
A	10
C	16
D	20
E	25
V	35
H	50

Temperature Coefficient
 Color Code
 Tolerance
 1st Digit
 2nd Digit
 Decimal Point
 Multiplier

121K: 120 pF $\pm 10\%$

4R7D: 4.7 pF $\pm 0.5\text{pF}$

Multiplier Code

Numeric Character	Decimal Multiplier (pF)
0	None
1	10
2	100
3	1000
4	10,000

EIA Capacitor Tolerance Codes

Letter	$\leq 10 \text{ pF}$	$\geq 10 \text{ pF}$
B	$\pm 0.1 \text{ pF}$	-
C	$\pm 0.25 \text{ pF}$	-
D	$\pm 0.5 \text{ pF}$	-
E	-	$\pm 25\%$
F	$\pm 1 \text{ pF}$	$\pm 1\%$
G	-	$\pm 2\%$
H	-	$\pm 2.5\%$
J	-	$\pm 5\%$
K	-	$\pm 10\%$
M	-	$\pm 20\%$
P	-	-0 + 100%
S	-	-20 + 50%
W	-	-0 + 200%
X	-	-20 + 40%
Z	-	-20 + 80%

EIA Temperature Characteristic Codes

Minimum temperature	Maximum temperature	Max cap. change over temp. range
X	-55°C	2 +45°C
Y	-35°C	4 +65°C
Z	+10°C	5 +85°C
		6 +105°C
		7 +125°C

Letter	Temp. Coeff.
A	$\pm 1.0\%$
B	$\pm 1.5\%$
C	$\pm 2.2\%$
D	$\pm 3.3\%$
E	$\pm 4.7\%$
F	$\pm 7.5\%$
P	$\pm 10\%$
R	$\pm 15\%$
S	$\pm 22\%$
T	-33%, +22%
U	-56%, +22%
V	-82%, +22%

EIA Temperature Coefficient Color Codes

Color	Temp. Coeff.	EIA
Black	NP0	C0G
Brown	N030/N033	S1G
Red	N075/N080	U1G
Orange	N 150	P2G
Yellow	N 220	R2G
Green	N 330	S2H
Blue	N 470	U2J
Violet	N 750	
Gray		
White	P 100	
Red/Violet	P 100	

Electrolytic Capacitors

Label: Usually self-explanatory

Practical Electronics for Inventors

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Practical Electronics for Inventors

Fourth Edition

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CONTENTS

	Preface	xxiii
	Acknowledgments	xxv
CHAPTER 1	Introduction to Electronics	1
CHAPTER 2	Theory	5
2.1	Theory of Electronics	5
2.2	Electric Current	6
2.2.1	Currents in Perspective	9
2.3	Voltage	9
2.3.1	The Mechanisms of Voltage	11
2.3.2	Definition of Volt and Generalized Power Law	14
2.3.3	Combining Batteries	15
2.3.4	Other Voltage Sources	16
2.3.5	Water Analogies	17
2.4	A Microscopic View of Conduction (for Those Who Are Interested)	18
2.4.1	Applying a Voltage	21
2.5	Resistance, Resistivity, Conductivity	23
2.5.1	How the Shape of a Conductor Affects Resistance	24
2.5.2	Resistivity and Conductivity	25
2.6	Insulators, Conductors, and Semiconductors	28
2.7	Heat and Power	31
2.8	Thermal Heat Conduction and Thermal Resistance	34
2.8.1	Importance of Heat Production	37
2.9	Wire Gauges	39
2.10	Grounds	40
2.10.1	Earth Ground	42
2.10.2	Different Types of Ground Symbols	45
2.10.3	Loose Ends on Grounding	47

2.11	Electric Circuits	49
2.12	Ohm's Law and Resistors	50
	2.12.1 Resistor Power Ratings	51
	2.12.2 Resistors in Parallel	52
	2.12.3 Resistors in Series	55
	2.12.4 Reducing a Complex Resistor Network	58
	2.12.5 Multiple Voltage Dividers	61
2.13	Voltage and Current Sources	62
2.14	Measuring Voltage, Current, and Resistance	65
2.15	Combining Batteries	67
2.16	Open and Short Circuits	68
2.17	Kirchhoff's Laws	69
2.18	Superposition Theorem	74
2.19	Thevenin's and Norton's Theorems	76
	2.19.1 Thevenin's Theorem	76
	2.19.2 Norton's Theorem	77
2.20	AC Circuits	80
	2.20.1 Generating AC	81
	2.20.2 Water Analogy of AC	82
	2.20.3 Pulsating DC	82
	2.20.4 Combining Sinusoidal Sources	83
	2.20.5 AC Waveforms	84
	2.20.6 Describing an AC Waveform	84
	2.20.7 Frequency and Period	85
	2.20.8 Phase	86
2.21	AC and Resistors, RMS Voltage, and Current	87
2.22	Mains Power	92
2.23	Capacitors	94
	2.23.1 Determining Capacitance	97
	2.23.2 Commercial Capacitors	99
	2.23.3 Voltage Rating and Dielectric Breakdown	99
	2.23.4 Maxwell's Displacement Current	100
	2.23.5 Charge-Based Model of Current Through a Capacitor	102
	2.23.6 Capacitor Water Analogy	104
	2.23.7 Energy in a Capacitor	105
	2.23.8 RC Time Constant	105
	2.23.9 Stray Capacitance	108
	2.23.10 Capacitors in Parallel	108
	2.23.11 Capacitors in Series	109
	2.23.12 Alternating Current in a Capacitor	110
	2.23.13 Capacitive Reactance	111
	2.23.14 Capacitive Divider	113
	2.23.15 Quality Factor	113
2.24	Inductors	113
	2.24.1 Electromagnetism	114
	2.24.2 Magnetic Fields and Their Influence	117

2.24.3	Self-Inductance	120
2.24.4	Inductors	121
2.24.5	Inductor Water Analogy	127
2.24.6	Inductor Equations	128
2.24.7	Energy Within an Inductor	133
2.24.8	Inductor Cores	133
2.24.9	Understanding the Inductor Equations	138
2.24.10	Energizing RL Circuit	142
2.24.11	Deenergizing RL Circuit	144
2.24.12	Voltage Spikes Due to Switching	147
2.24.13	Straight-Wire Inductance	147
2.24.14	Mutual Inductance and Magnetic Coupling	148
2.24.15	Unwanted Coupling: Spikes, Lightning, and Other Pulses	149
2.24.16	Inductors in Series and Parallel	149
2.24.17	Alternating Current and Inductors	150
2.24.18	Inductive Reactance	151
2.24.19	Nonideal Inductor Model	153
2.24.20	Quality Factor	154
2.24.21	Inductor Applications	155
2.25	Modeling Complex Circuits	155
2.26	Complex Numbers	159
2.27	Circuit with Sinusoidal Sources	164
2.27.1	Analyzing Sinusoidal Circuits with Complex Impedances	165
2.27.2	Sinusoidal Voltage Source in Complex Notation	167
2.27.3	Odd Phenomena in Reactive Circuits	175
2.28	Power in AC Circuits (Apparent Power, Real Power, Reactive Power)	176
2.28.1	Power Factor	178
2.29	Thevenin's Theorem in AC Form	186
2.30	Resonant Circuits	188
2.30.1	Resonance in RLC Circuits	191
2.30.2	Q (Quality Factor) and Bandwidth	193
2.30.3	Bandwidth	194
2.30.4	Voltage Drop Across Components in RLC Resonant Circuit	195
2.30.5	Capacitor Losses	195
2.30.6	Parallel-Resonant Circuits	196
2.30.7	The Q of Loaded Circuits	202
2.31	Lecture on Decibels	204
2.31.1	Alternative Decibel Representations	207
2.32	Input and Output Impedance	207
2.32.1	Input Impedance	207
2.32.2	Output Impedance	208
2.33	Two-Port Networks and Filters	210
2.33.1	Filters	210
2.33.2	Attenuators	221

2.34	Transient Circuits	223
2.34.1	Series RLC Circuit	231
2.35	Circuits with Periodic Nonsinusoidal Sources	235
2.35.1	Fourier Series	236
2.36	Nonperiodic Sources	243
2.37	SPICE	245
2.37.1	How SPICE Works	246
2.37.2	Limitations of SPICE and Other Simulators	249
2.37.3	A Simple Simulation Example	249

CHAPTER 3 Basic Electronic Circuit Components 253

3.1	Wires, Cables, and Connectors	253
3.1.1	Wires	253
3.1.2	Cables	256
3.1.3	Connectors	256
3.1.4	Wiring and Connector Symbols	261
3.1.5	High-Frequency Effects Within Wires and Cables	262
3.2	Batteries	271
3.2.1	How a Cell Works	272
3.2.2	Primary Batteries	274
3.2.3	Comparing Primary Batteries	275
3.2.4	Secondary Batteries	279
3.2.5	Battery Capacity	287
3.2.6	Note on Internal Voltage Drop of a Battery	289
3.3	Switches	290
3.3.1	How a Switch Works	291
3.3.2	Describing a Switch	291
3.3.3	Kinds of Switches	292
3.3.4	Simple Switch Applications	294
3.4	Relays	295
3.4.1	Specific Kinds of Relays	297
3.4.2	A Few Notes about Relays	298
3.4.3	Some Simple Relay Circuits	299
3.5	Resistors	299
3.5.1	Resistance and Ohm's Law	301
3.5.2	Resistors in Series and Parallel	302
3.5.3	Reading Resistor Labels	304
3.5.4	Real Resistor Characteristics	306
3.5.5	Types of Resistors	314
3.5.6	Variable Resistors (Rheostats, Potentiometers, Trimmers)	320
3.5.7	Potentiometer Characteristics	322
3.6	Capacitors	324
3.6.1	Capacitance	326
3.6.2	Capacitors in Parallel	326
3.6.3	Capacitors in Series	327

3.6.4	RC Time Constant	327
3.6.5	Capacitive Reactance	328
3.6.6	Real Capacitors	329
3.6.7	Capacitor Specifications	329
3.6.8	Types of Capacitors	333
3.6.9	Capacitor Applications	341
3.6.10	Timing and Sample and Hold	347
3.6.11	RC Ripple Filter	348
3.6.12	Arc Suppression	350
3.6.13	Supercapacitor Applications	352
3.6.14	Problems	352
3.7	Inductors	355
3.7.1	Inductance	357
3.7.2	Constructing Inductors	357
3.7.3	Inductors in Series and Parallel	357
3.7.4	RL Time Constant	359
3.7.5	Inductive Reactance	360
3.7.6	Real Inductors	361
3.7.7	Inductor Specifications	361
3.7.8	Types of Inductors	363
3.7.9	Reading Inductor Labels	367
3.7.10	Inductor Applications	369
3.7.11	EMI/EMC Design Tips	373
3.8	Transformers	374
3.8.1	Basic Operations	374
3.8.2	Transformer Construction	385
3.8.3	Autotransformers and Variable Transformers	387
3.8.4	Circuit Isolation and the Isolation Transformer	389
3.8.5	Various Standard and Specialized Transformers	390
3.8.6	Transformer Applications	392
3.9	Fuses and Circuit Breakers	397
3.9.1	Types of Fuses and Circuit Breakers	398
CHAPTER 4 Semiconductors		401
4.1	Semiconductor Technology	401
4.1.1	What Is a Semiconductor?	401
4.1.2	Applications of Silicon	406
4.2	Diodes	407
4.2.1	How p-n Junction Diodes Work	407
4.2.2	Diode Water Analogy	409
4.2.3	Kinds of Rectifiers/Diodes	409
4.2.4	Practical Considerations	411
4.2.5	Diode/Rectifier Applications	412
4.2.6	Zener Diodes	420
4.2.7	Zener Diode Applications	423
4.2.8	Varactor Diodes (Variable Capacitance Diodes)	424

4.2.9	PIN Diodes	426
4.2.10	Microwave Diodes (IMPATT, Gunn, Tunnel, etc.)	426
4.2.11	Problems	427
4.3	Transistors	429
4.3.1	Introduction to Transistors	429
4.3.2	Bipolar Transistors	430
4.3.3	Junction Field-Effect Transistors	449
4.3.4	Metal Oxide Semiconductor Field-Effect Transistors	459
4.3.5	Insulated Gate Bipolar Transistors (IGBTs)	468
4.3.6	Unijunction Transistors	468
4.4	Thyristors	472
4.4.1	Introduction	472
4.4.2	Silicon-Controlled Rectifiers	473
4.4.3	Silicon-Controlled Switches	476
4.4.4	Triacs	477
4.4.5	Four-Layer Diodes and Diacs	480
4.5	Transient Voltage Suppressors	481
4.5.1	Lecture on Transients	482
4.5.2	Devices Used to Suppress Transients	483
4.6	Integrated Circuits	491
4.6.1	IC Packages	492

CHAPTER 5 Optoelectronics 495

5.1	A Little Lecture on Photons	495
5.2	Lamps	497
5.3	Light-Emitting Diodes	499
5.3.1	How an LED Works	500
5.3.2	Kinds of LEDs	501
5.3.3	More on LEDs	502
5.3.4	LED Applications	505
5.3.5	Laser Diodes	506
5.4	Photoresistors	512
5.4.1	How a Photoresistor Works	512
5.4.2	Technical Stuff	513
5.4.3	Applications	513
5.5	Photodiodes	514
5.5.1	How a Photodiode Works	514
5.5.2	Basic Operations	515
5.5.3	Kinds of Photodiodes	515
5.6	Solar Cells	516
5.6.1	Basic Operations	517
5.7	Phototransistors	517
5.7.1	How a Phototransistor Works	518
5.7.2	Basic Configurations	518
5.7.3	Kinds of Phototransistors	519
5.7.4	Technical Stuff	519
5.7.5	Applications	520

5.8	Photothyristors	521
5.8.1	How LASCRs Work	521
5.8.2	Basic Operation	521
5.9	Optoisolators	522
5.9.1	Integrated Optoisolators	522
5.9.2	Applications	523
5.10	Optical Fiber	524

CHAPTER 6 Sensors 525

6.1	General Principals	525
6.1.1	Precision, Accuracy, and Resolution	525
6.1.2	The Observer Effect	526
6.1.3	Calibration	526
6.2	Temperature	528
6.2.1	Thermistors	529
6.2.2	Thermocouples	531
6.2.3	Resistive Temperature Detectors	532
6.2.4	Analog Output Thermometer ICs	532
6.2.5	Digital Thermometer ICs	533
6.2.6	Infrared Thermometers/Pyrometers	534
6.2.7	Summary	534
6.3	Proximity and Touch	535
6.3.1	Touch Screens	535
6.3.2	Ultrasonic Distance	536
6.3.3	Optical Distance	537
6.3.4	Capacitive Sensors	539
6.3.5	Summary	539
6.4	Movement, Force, and Pressure	540
6.4.1	Passive Infrared	540
6.4.2	Acceleration	541
6.4.3	Rotation	542
6.4.4	Flow	543
6.4.5	Force	544
6.4.6	Tilt	545
6.4.7	Vibration and Mechanical Shock	545
6.4.8	Pressure	545
6.5	Chemical	546
6.5.1	Smoke	546
6.5.2	Gas	546
6.5.3	Humidity	547
6.6	Light, Radiation, Magnetism, and Sound	547
6.6.1	Light	547
6.6.2	Ionizing Radiation	547
6.6.3	Magnetic Fields	548
6.6.4	Sound	549
6.7	GPS	549

CHAPTER 7	Hands-on Electronics	551
7.1	Safety	551
	7.1.1 Lecture on Safety	551
	7.1.2 Damaging Components with Electrostatic Discharge	555
	7.1.3 Component Handling Precautions	555
7.2	Constructing Circuits	556
	7.2.1 Drawing a Circuit Schematic	556
	7.2.2 A Note on Circuit Simulator Programs	558
	7.2.3 Making a Prototype of Your Circuit	558
	7.2.4 The Final Circuit	559
	7.2.5 Making a PCB	562
	7.2.6 Special Pieces of Hardware Used in Circuit Construction	567
	7.2.7 Soldering	568
	7.2.8 Desoldering	569
	7.2.9 Enclosing the Circuit	569
	7.2.10 Useful Items to Keep Handy	570
	7.2.11 Troubleshooting the Circuits You Build	570
7.3	Multimeters	571
	7.3.1 Basic Operation	572
	7.3.2 How Analog VOMs Work	573
	7.3.3 How Digital Multimeters Work	574
	7.3.4 A Note on Measurement Errors	574
7.4	Oscilloscopes	575
	7.4.1 How Scopes Work	576
	7.4.2 Interior Circuitry of a Scope	578
	7.4.3 Aiming the Beam	579
	7.4.4 Scope Usage	580
	7.4.5 What All the Little Knobs and Switches Do	581
	7.4.6 Measuring Things with Scopes	586
	7.4.7 Scope Applications	590
	7.4.8 Measuring Impedances	592
7.5	The Electronics Laboratory	594
	7.5.1 Work Area	594
	7.5.2 Test Equipment	595
	7.5.3 Multimeters	596
	7.5.4 DC Power Supplies	597
	7.5.5 Oscilloscope	598
	7.5.6 Oscilloscope Probes	600
	7.5.7 General-Purpose Function Generator	607
	7.5.8 Frequency Counter	608
	7.5.9 Computer	608
	7.5.10 Miscellaneous Test Equipment	609
	7.5.11 Multifunction PC Instruments	610
	7.5.12 Isolation Transformers	611
	7.5.13 Variable Transformers, or Variacs	613

7.5.14	Substitution Boxes	614
7.5.15	Test Cables, Connectors, and Adapters	616
7.5.16	Soldering Equipment	618
7.5.17	Prototyping Boards	621
7.5.18	Hand Tools	622
7.5.19	Wires, Cables, Hardware, and Chemicals	624
7.5.20	Electronics Catalogs	626
7.5.21	Recommended Electronics Parts	627
7.5.22	Electronic CAD Programs	630
7.5.23	Building Your Own Workbench	631
CHAPTER 8	Operational Amplifiers	635
8.1	Operational Amplifier Water Analogy	636
8.2	How Op Amps Work (The “Cop-Out” Explanation)	637
8.3	Theory	638
8.4	Negative Feedback	639
8.5	Positive Feedback	644
8.6	Real Kinds of Op Amps	645
8.7	Op Amp Specifications	647
8.8	Powering Op Amps	649
8.9	Some Practical Notes	650
8.10	Voltage and Current Offset Compensation	651
8.11	Frequency Compensation	652
8.12	Comparators	652
8.13	Comparators with Hysteresis	654
	8.13.1 Inverting Comparator with Hysteresis	654
	8.13.2 Noninverting Comparator with Hysteresis	655
8.14	Using Single-Supply Comparators	656
8.15	Window Comparator	656
8.16	Voltage-Level Indicator	657
8.17	Instrumentation Amplifiers	657
8.18	Applications	658
CHAPTER 9	Filters	663
9.1	Things to Know Before You Start Designing Filters	664
9.2	Basic Filters	665
9.3	Passive Low-Pass Filter Design	666
9.4	A Note on Filter Types	670
9.5	Passive High-Pass Filter Design	670
9.6	Passive Bandpass Filter Design	672
9.7	Passive Notch Filter Design	674
9.8	Active Filter Design	675
	9.8.1 Active Low-Pass Filter Example	676
	9.8.2 Active High-Pass Filter Example	677
	9.8.3 Active Bandpass Filters	678
	9.8.4 Active Notch Filters	680
9.9	Integrated Filter Circuits	681

CHAPTER 10	Oscillators and Timers	683
10.1	<i>RC</i> Relaxation Oscillators	684
10.2	The 555 Timer IC	686
10.2.1	How a 555 Works (Astable Operation)	687
10.2.2	Basic Astable Operation	688
10.2.3	How a 555 Works (Monostable Operation)	689
10.2.4	Basic Monostable Operation	690
10.2.5	Some Important Notes about 555 Timers	690
10.2.6	Simple 555 Applications	691
10.3	Voltage-Controlled Oscillators	692
10.4	Wien-Bridge and Twin-T Oscillators	693
10.5	<i>LC</i> Oscillators (Sinusoidal Oscillators)	693
10.6	Crystal Oscillators	696
10.7	Microcontroller Oscillators	698
CHAPTER 11	Voltage Regulators and Power Supplies	699
11.1	Voltage-Regulator ICs	701
11.1.1	Fixed-Regulator ICs	701
11.1.2	Adjustable-Regulator ICs	702
11.1.3	Regulator Specifications	702
11.2	A Quick Look at a Few Regulator Applications	702
11.3	The Transformer	703
11.4	Rectifier Packages	703
11.5	A Few Simple Power Supplies	704
11.6	Technical Points about Ripple Reduction	707
11.7	Loose Ends	709
11.8	Switching Regulator Supplies (Switchers)	710
11.9	Switch-Mode Power Supplies (SMPS)	713
11.10	Kinds of Commercial Power Supply Packages	714
11.11	Power Supply Construction	716
CHAPTER 12	Digital Electronics	717
12.1	The Basics of Digital Electronics	717
12.1.1	Digital Logic States	717
12.1.2	Number Codes Used in Digital Electronics	718
12.1.3	Clock Timing and Parallel versus Serial Transmission	725
12.2	Logic Gates	726
12.2.1	Multiple-Input Logic Gates	727
12.2.2	Digital Logic Gate ICs	727
12.2.3	Applications for a Single Logic Gate	728
12.2.4	Combinational Logic	730
12.2.5	Keeping Circuits Simple (Karnaugh Maps)	738
12.3	Combinational Devices	740
12.3.1	Multiplexers (Data Selectors) and Bilateral Switches	741

12.3.2	Demultiplexers (Data Distributors) and Decoders	743
12.3.3	Encoders and Code Converters	746
12.3.4	Binary Adders	749
12.3.5	Binary Adder/Subtractor	751
12.3.6	Comparators and Magnitude Comparator ICs	751
12.3.7	A Note on Obsolescence and the Trend Toward Microcontroller Control	752
12.4	Logic Families	753
12.4.1	CMOS Family of ICs	754
12.4.2	I/O Voltages and Noise Margins	755
12.4.3	Current Ratings, Fanout, and Propagation Delays	756
12.5	Powering and Testing Logic ICs	756
12.5.1	Power Supply Decoupling	756
12.5.2	Unused Inputs	757
12.5.3	Logic Probes and Logic Pulsers	757
12.6	Sequential Logic	758
12.6.1	SR Flip-Flops	759
12.6.2	SR Flip-Flop ICs	763
12.6.3	D-Type Flip-Flops	764
12.6.4	Quad and Octal D Flip-Flops	768
12.6.5	JK Flip-Flops	769
12.6.6	Practical Timing Considerations with Flip-Flops	773
12.6.7	Digital Clock Generators and Single-Pulse Generators	774
12.6.8	Automatic Power-Up Clear (Reset) Circuits	777
12.6.9	Pullup and Pulldown Resistors	779
12.7	Counter ICs	780
12.7.1	Asynchronous Counter (Ripple Counter) ICs	780
12.7.2	Synchronous Counter ICs	782
12.7.3	A Note on Counters with Displays	787
12.8	Shift Registers	789
12.8.1	Serial-In/Serial-Out Shift Registers	789
12.8.2	Serial-In/Parallel-Out Shift Registers	790
12.8.3	Parallel-In/Serial-Out Shift Registers	790
12.8.4	Ring Counter (Shift Register Sequencer)	791
12.8.5	Johnson Shift Counter	791
12.8.6	Shift Register ICs	792
12.8.7	Simple Shift Register Applications	796
12.9	Analog/Digital Interfacing	799
12.9.1	Triggering Simple Logic Responses from Analog Signals	799
12.9.2	Using Logic to Drive External Loads	800
12.9.3	Analog Switches	802
12.9.4	Analog Multiplexer/Demultiplexer	802
12.9.5	Analog-to-Digital and Digital-to-Analog Conversion	803
12.9.6	Analog-to-Digital Converters	811

12.10	Displays	813
12.10.1	LED Displays	813
12.10.2	Liquid-Crystal Displays	815
12.11	Memory Devices	828
12.11.1	Read-Only Memory	829
12.11.2	Simple ROM Made Using Diodes	830
12.11.3	Memory Size and Organization	830
12.11.4	Simple Programmable ROM	831
12.11.5	ROM Devices	832
12.11.6	RAM	836
CHAPTER 13 Microcontrollers		843
13.1	Basic Structure of a Microcontroller	844
13.2	Example Microcontrollers	844
13.2.1	The ATtiny85 Microcontroller	845
13.2.2	The PIC16Cx Microcontrollers	849
13.2.3	32-Bit Microcontrollers	862
13.2.4	Digital Signal Processing	862
13.3	Evaluation/Development Boards	863
13.4	Arduino	864
13.4.1	A Tour of Arduino	864
13.4.2	The Arduino IDE	865
13.4.3	Arduino Board Models	865
13.4.4	Shields	866
13.4.5	The Arduino C Library	868
13.4.6	Arduino Example Project	870
13.4.7	Taking the Arduino Offboard	872
13.5	Interfacing with Microcontrollers	874
13.5.1	Switches	874
13.5.2	Analog Inputs	878
13.5.3	High-Power Digital Outputs	879
13.5.4	Sound Interfaces	883
13.5.5	Serial Interfaces	884
13.5.6	Level Conversion	892
13.5.7	LED Display Interfaces	892
CHAPTER 14 Programmable Logic		897
14.1	Programmable Logic	898
14.2	FPGAs	899
14.3	ISE and the Elbert V2	900
14.3.1	Installing ISE	901
14.4	The Elbert 2 Board	901
14.4.1	Installing the Elbert Software	902
14.5	Downloads	903
14.6	Drawing Your FPGA Logic Design	903
14.6.1	Example 1: A Data Selector	903
14.6.2	Example 2: A 4-bit Ripple Counter	912

14.7	Verilog	914
14.7.1	Modules	915
14.7.2	Wires, Registers, and Busses	915
14.7.3	Parallel Execution	915
14.7.4	Number Format	915
14.8	Describing Your FPGA Design in Verilog	916
14.8.1	A Data Selector in Verilog	916
14.8.2	A Ripple Counter in Verilog	919
14.9	Modular Design	920
14.9.1	Counter/Decoder Example	921
14.9.2	Multiplexed 7-Segment Counter Example	924
14.9.3	Parameterized Modules	928
14.10	Simulation	928
14.11	VHDL	931
CHAPTER 15	Motors	933
15.1	DC Continuous Motors	933
15.2	Speed Control of DC Motors	934
15.3	Directional Control of DC Motors	935
15.4	RC Servos	936
15.5	Stepper Motors	938
15.6	Kinds of Stepper Motors	939
15.7	Driving Stepper Motors	941
15.8	Controlling the Driver with a Translator	943
15.9	A Final Word on Identifying Stepper Motors	945
CHAPTER 16	Audio Electronics	947
16.1	A Little Lecture on Sound	947
16.2	Microphones	949
16.3	Microphone Specifications	950
16.4	Audio Amplifiers	951
16.4.1	Inverting Amplifier	951
16.4.2	Noninverting Amplifier	952
16.4.3	Digital Amplifiers	952
16.4.4	Reducing Hum in Audio Amplifiers	954
16.5	Preamplifiers	954
16.6	Mixer Circuits	955
16.7	A Note on Impedance Matching	955
16.8	Speakers	956
16.9	Crossover Networks	957
16.10	Simple ICs Used to Drive Speakers	959
16.11	Audible-Signal Devices	960
16.12	Miscellaneous Audio Circuits	960
CHAPTER 17	Modular Electronics	963
17.1	There's an IC for It	963
17.2	Breakout Boards and Modules	963

17.2.1	Radio Frequency Modules	964
17.2.2	Audio Modules	967
17.3	Plug-and-Play Prototyping	968
17.4	Open Source Hardware	970
APPENDIX A	Power Distribution and Home Wiring	973
A.1	Power Distribution	973
A.2	A Closer Look at Three-Phase Electricity	974
A.3	Home Wiring	976
A.4	Electricity in Other Countries	977
APPENDIX B	Error Analysis	979
B.1	Absolute Error, Relative Error, and Percent Error	979
B.2	Uncertainty Estimates	980
APPENDIX C	Useful Facts and Formulas	983
C.1	Greek Alphabet	983
C.2	Powers of 10 Unit Prefixes	983
C.3	Linear Functions ($y = mx + b$)	983
C.4	Quadratic Equation ($y = ax^2 + bx + c$)	984
C.5	Exponents and Logarithms	984
C.6	Trigonometry	984
C.7	Complex Numbers	985
C.8	Differential Calculus	985
C.9	Integral Calculus	987
	Index	989

PREFACE

Inventors in the field of electronics are individuals who possess the knowledge, intuition, creativity, and technical know-how to turn their ideas into real-life electrical gadgets. We hope that this book will provide you with an intuitive understanding of the theoretical and practical aspects of electronics in a way that fuels your creativity.

This book is designed to help beginning inventors invent. It assumes little to no prior knowledge of electronics. Therefore, educators, students, and aspiring hobbyists will find this book a good initial text. At the same time, technicians and more advanced hobbyists may find this book a useful resource.

Notes about the Fourth Edition

The main addition to the fourth edition is a new chapter on programmable logic. This chapter focuses on the use of FPGAs (field-programmable gate arrays) and shows you how to program an FPGA evaluation board using both a schematic editor and the Verilog hardware definition language.

The book has also undergone numerous minor updates and fixes to errors discovered in the third edition. In addition, there has been some pruning of outdated material that is no longer relevant to modern electronics.

ACKNOWLEDGMENTS

We would like to thank the many people who have helped in the production of this book. Special thanks are due to the technical reviewers Michael Margolis, Chris Fitzer, and David Buckley.

We have been able to greatly improve the accuracy of the book thanks to the very detailed and helpful errata for the second edition that were collated by Martin Ligare at Bucknell University. Contributors to these errata were Steve Baker (Naval Postgraduate School), George Caplan (Wellesley College), Robert Drehmel, Earl Morris, Robert Strzelczyk (Motorola), Lloyd Lowe (Boise State University), John Kelty (University of Nebraska), Perry Spring (Cascadia Community College), Michael B. Allen, Jeffrey Audia, Ken Ballinger (EIT), Clement Jacob, Jamie Masters, and Marco Ariano. Thank you all for taking the time to make this a better book.

Many thanks to Michael McCabe, the ever-patient Apoorva Goel, and everyone from McGraw-Hill Education, for their support and skill in converting this manuscript into a great book.

—*Paul Scherz and Simon Monk*

Practical Electronics for Inventors

CHAPTER 1

Introduction to Electronics

Perhaps the most common predicament newcomers face when learning electronics is figuring out exactly what it is they must learn. What topics are worth covering, and in which general order should they be covered? A good starting point for answering these questions is the flowchart presented in Fig. 1.1. This chart provides an overview of the basic elements that go into designing practical electrical gadgets and represents the information you will find in this book. This chapter introduces these basic elements.

At the top of the chart comes the theory. This involves learning about voltage, current, resistance, capacitance, inductance, and various laws and theorems that help predict the size and direction of voltages and currents within circuits. As you learn the basic theory, you will be introduced to basic passive components such as resistors, capacitors, inductors, and transformers.

Next down the line are discrete passive circuits. Discrete passive circuits include current-limiting networks, voltage dividers, filter circuits, attenuators, and so on. These simple circuits, by themselves, are not very interesting, but they are vital ingredients in more complex circuits.

After you have learned about passive components and circuits, you move on to discrete active devices, which are built from semiconductor materials. These devices consist mainly of diodes (one-way current-flow gates) and transistors (electrically controlled switches/amplifiers).

Once you have covered the discrete active devices, you get to discrete active/passive circuits. Some of these circuits include rectifiers (ac-to-dc converters), amplifiers, oscillators, modulators, mixers, and voltage regulators. This is where things start getting interesting.

Throughout your study of electronics, you will learn about various input/output (I/O) devices (transducers). Input devices (sensors) convert physical signals, such as sound, light, and pressure, into electrical signals that circuits can use. These devices include microphones, phototransistors, switches, keyboards, thermistors, strain gauges, generators, and antennas. Output devices convert electrical signals into physical signals. Output devices include lamps, LED and LCD displays, speakers, buzzers, motors (dc, servo, and stepper), solenoids, and antennas. These I/O devices allow humans and circuits to communicate with one another.

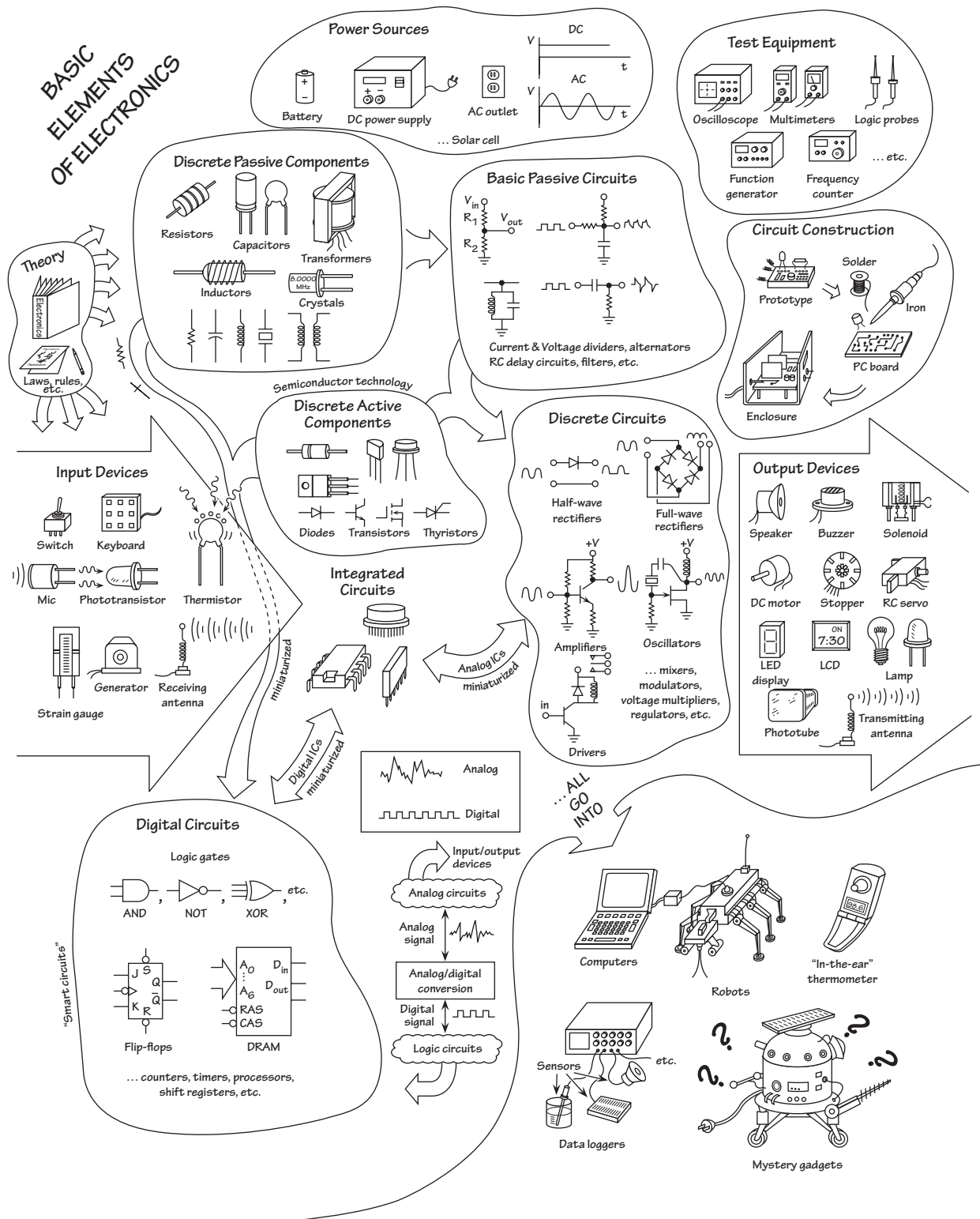


FIGURE 1.1

To make things easier on the circuit designer, manufacturers have created integrated circuits (ICs), which contain discrete circuits (like the ones mentioned in the previous paragraph) that are crammed onto a tiny chip of silicon. The chip is usually housed within a plastic package, where little internal wires link the chip to external metal terminals. ICs such as amplifiers and voltage regulators are referred to as *analog devices*, which means that they respond to and produce signals of varying degrees of voltage. (This is unlike *digital ICs*, which work with only two voltage levels.) Becoming familiar with ICs is a necessity for any practical circuit designer.

Digital electronics comes next. Digital circuits work with only two voltage states: *high* (such as 5 V) or *low* (such as 0 V). The reason for having only two voltage states has to do with the ease of processing data (numbers, symbols, and control information) and storage. The process of encoding information into signals that digital circuits can use involves combining bits (1s and 0s, equivalent to *high* and *low* voltages) into discrete-meaning “words.” The designer dictates what these words will mean to a specific circuit. Unlike analog electronics, digital electronics uses a whole new set of components, which at the heart are all integrated in form.

A huge number of specialized ICs are used in digital electronics. Some of these ICs are designed to perform logical operations on input information; others are designed to count; while still others are designed to store information that can be retrieved later on. Digital ICs include logic gates, flip-flops, shift registers, counters, memories, processors, and so on. Digital circuits are what give electrical gadgets “brains.” In order for digital circuits to interact with analog circuits, special analog-to-digital (A/D) conversion circuits are needed to convert analog signals into strings of 1s and 0s. Likewise, digital-to-analog conversion circuits are used to convert strings of 1s and 0s into analog signals.

With an understanding of the principals behind digital electronics, we are free to explore the world of microcontrollers. These are programmable digital electronics that can read values from sensors and control output devices using the I/O pins, all on a single IC controlled by a little program.

And mixed in among all this is the practical side of electronics. This involves learning to read schematic diagrams, constructing circuit prototypes using breadboards, testing prototypes (using multimeters, oscilloscopes, and logic probes), revising prototypes (if needed), and constructing final circuits using various tools and special circuit boards.

In the next chapter, we will start at the beginning by looking at the theory of electronics.

CHAPTER 2

Theory

2.1 Theory of Electronics

This chapter covers the basic concepts of electronics, such as current, voltage, resistance, electrical power, capacitance, and inductance. After going through these concepts, this chapter illustrates how to mathematically model currents and voltage through and across basic electrical elements such as resistors, capacitors, and inductors. By using some fundamental laws and theorems, such as Ohm's law, Kirchhoff's laws, and Thevenin's theorem, the chapter presents methods for analyzing complex networks containing resistors, capacitors, and inductors that are driven by a power source. The kinds of power sources used to drive these networks, as we will see, include direct current (dc) sources, alternating current (ac) sources (including sinusoidal and nonsinusoidal periodic sources), and nonsinusoidal nonperiodic sources. We will also discuss transient circuits, where sudden changes in state (such as flipping a switch within a circuit) are encountered. At the end of the chapter, the approach needed to analyze circuits that contain nonlinear elements (diodes, transistors, integrated circuits, etc.) is discussed.

We recommend using a circuit simulator program if you're just starting out in electronics. The web-based simulator CircuitLab (www.circuitlab.com) is extremely easy to use and has a nice graphical interface. There are also online calculators that can help you with many of the calculations in this chapter. Using a simulator program as you go through this chapter will help crystallize your knowledge, while providing an intuitive understanding of circuit behavior. Be careful—simulators can lie, or at least they can appear to lie when you don't understand all the necessary parameters the simulator needs to make a realistic simulation. It is always important to get your hands dirty—get out the breadboards, wires, resistors, power supplies, and so on, and construct. It is during this stage that you gain the greatest practical knowledge that is necessary for an inventor.

It is important to realize that components mentioned in this chapter are only "theoretically" explained. For example, in regard to capacitors, you'll learn how a capacitor works, what characteristic equations are used to describe a capacitor under certain conditions, and various other basic tricks related to predicting basic behavior. To get important practical insight into capacitors, however, such as real-life capacitor

applications (filtering, snubbing, oscillator design, etc.), what type of real capacitors exist, how these real capacitors differ in terms of nonideal characteristics, which capacitors work best for a particular application, and, more important, how to read a capacitor label, requires that you jump to Chap. 3, Sec. 3.6, which is dedicated to these issues. This applies to other components mentioned in this theory portion of the book.

The theoretical and practical information regarding transformers and nonlinear devices, such as diodes, transistors, and analog and digital integrated circuits (ICs), is not treated within this chapter. Transformers are discussed in full in Chap. 3, Sec. 3.8, while the various nonlinear devices are treated separately in the remaining chapters of this book.

A word of advice: if the math in a particular section of this chapter starts looking scary, don't worry. As it turns out, most of the nasty math in this chapter is used to prove, say, a theorem or law or to give you an idea of how hard things can get if you do not use some mathematical tricks. The actual amount of math you will need to know to design most circuits is surprisingly small; in fact, basic algebra may be all you need to know. Therefore, when the math in a particular section in this chapter starts looking ugly, skim through the section until you locate the useful, nonugly formulas, rules, and so on, that do not have weird mathematical expressions in them. You don't have to be a mathematical whiz to be able to design decent circuits.

2.2 Electric Current

Electric current is the total charge that passes through some cross-sectional area A per unit time. This cross-sectional area could represent a disk placed in a gas, plasma, or liquid, but in electronics, this cross-sectional area is most frequently a slice through a solid material, such as a conductor.

If ΔQ is the amount of charge passing through an area in a time interval Δt , then the *average current* I_{ave} is defined as:

$$I_{\text{ave}} = \frac{\Delta Q}{\Delta t}$$

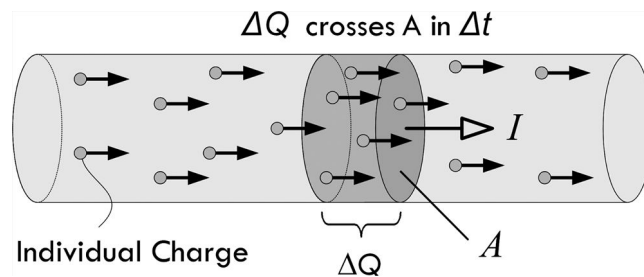


FIGURE 2.1

If the current changes with time, we define the *instantaneous current* I by taking the limit as $\Delta t \rightarrow 0$, so that the current is the instantaneous rate at which charge passes through an area:

$$I = \lim_{\Delta t \rightarrow 0} \frac{\Delta Q}{\Delta t} = \frac{dQ}{dt} \quad (2.1)$$

The unit of current is coulombs per second, but this unit is also called the *ampere* (A), named after Andre-Marie Ampere:

$$1 \text{ A} = 1 \text{ C/s}$$

To sound less nerdy, the term *amp* can be used in place of ampere. Because the ampere is a rather large unit, current is also expressed in *milliamps* ($1 \text{ mA} = 1 \times 10^{-3} \text{ A}$), *microamps* ($1 \text{ }\mu\text{A} = 1 \times 10^{-6} \text{ A}$), and *nanoamps* ($1 \text{ nA} = 1 \times 10^{-9} \text{ A}$).

Within conductors such as copper, electrical current is made up of free electrons moving through a lattice of copper ions. Copper has one free electron per copper atom. The charge on a single electron is given by:

$$Q_{\text{electron}} = (-e) = -1.602 \times 10^{-19} \text{ C} \quad (2.2.a)$$

This is equal to, but opposite in sign of, the charge of a single copper ion. (The positive charge is a result of the atom donating one electron to the “sea” of free electrons randomly moving about the lattice. The loss of the electron means there is one more proton per atom than electrons.) The charge of a proton is:

$$Q_{\text{proton}} = (+e) = +1.602 \times 10^{-19} \text{ C} \quad (2.2.b)$$

The conductor, as a whole, is neutral, since there are equal numbers of electrons and protons. Using Eq. 2.2, we see that if a current of 1 A flows through a copper wire, the number of electrons flowing by a cross section of the wire in 1 s is equal to:

$$1 \text{ A} = \left(\frac{1 \text{ C}}{1 \text{ s}} \right) \left(\frac{\text{electron}}{-1.602 \times 10^{-19} \text{ C}} \right) = -6.24 \times 10^{18} \text{ electrons/s}$$

Now, there is a problem! How do we get a negative number of electrons flowing per second, as our result indicates? The only two possibilities for this would be to say that either electrons must be flowing in the opposite direction as the defined current, or positive charges must be moving in our wire instead of electrons to account for the sign. The last choice is an incorrect one, since experimental evidence exists to prove electrons are free to move, not positive charges, which are fixed in the lattice network of the conductor. (Note, however, there are media in which positive charge flow is possible, such as positive ion flow in liquids, gases, and plasmas.) It turns out that the first choice—namely, electrons flowing in the opposite direction as the defined current flow—is the correct answer.

Long ago, when Benjamin Franklin (often considered the father of electronics) was doing his pioneering work in early electronics, he had a convention of assigning positive charge signs to the mysterious (at that time) things that were moving and doing work. Sometime later, a physicist by the name of Joseph Thomson performed an experiment that isolated the mysterious moving charges. However, to measure and record his experiments, as well as to do his calculations, Thomson had to stick with using the only laws available to him—those formulated using Franklin’s positive currents. But these moving charges that Thomson found (which he called electrons) were moving in the opposite direction of the conventional current I used in the equations, or moving against convention. See Fig. 2.2.

What does this mean to us, to those of us not so interested in the detailed physics and such? Well, not too much. We could pretend that there were positive charges moving in the wires and various electrical devices, and everything would work out fine: negative electrons going one way are equivalent to positive charges going in

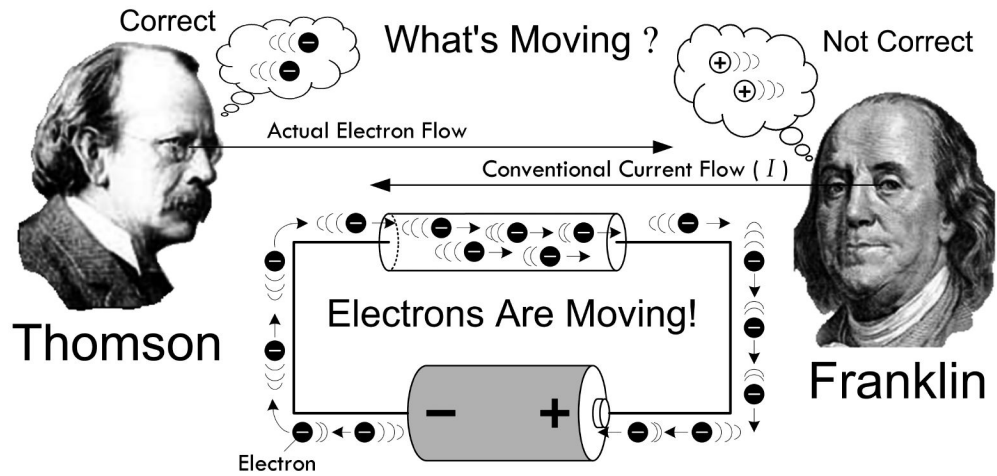


FIGURE 2.2 Thomson changed the notion that positive charges were what were moving in conductors, contrary to Franklin’s notion. However, negative electrons going one way is equivalent to positive charges going the opposite direction, so the old formulas still work. Since you deal with the old formulas, it’s practical to adopt Franklin’s conventional current—though realize that what’s actually moving in conductors is electrons.

the opposite direction. In fact, all the formulas used in electronics, such as Ohm’s law ($V = IR$), “pretend” that the current I is made up of positive charge carriers. We will always be stuck with this convention. In a nutshell, it’s convenient to pretend that positive charges are moving. So when you see the term *electron flow*, make sure you realize that the conventional current flow I is moving in the opposite direction. In a minute, we’ll discuss the microscopic goings-on within a conductor that will clarify things a bit better.

Example 1: How many electrons pass a given point in 3 s if a conductor is carrying a 2-A current?

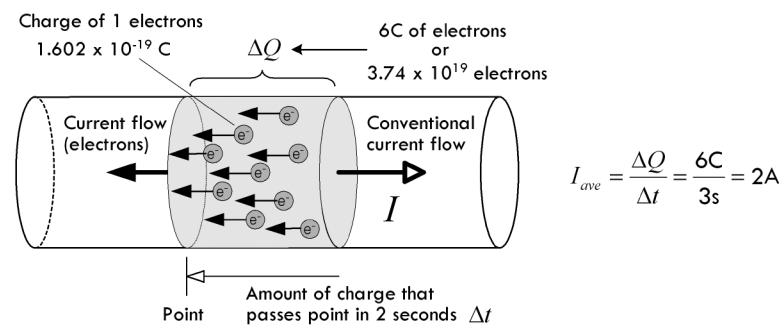


FIGURE 2.3

Answer: The charge that passes a given point in 3 s is:

$$\Delta Q = I \times \Delta t = (2 \text{ A})(3 \text{ s}) = 6 \text{ C}$$

One electron has a charge of $1.6 \times 10^{-19} \text{ C}$, so 6 C worth of electrons is:

$$\# \text{ Electrons} = 6 \text{ C} / 1.602 \times 10^{-19} \text{ C} = 3.74 \times 10^{19}$$

Example 2: Charge is changing in a circuit with time according to $Q(t) = (0.001 \text{ C}) \sin [(1000/\text{s}) t]$. Calculate the instantaneous current flow.

$$\begin{aligned} I &= \frac{dQ}{dt} = \frac{d}{dt}[(0.001 \text{ C}) \sin(1000/\text{s} \cdot t)] = (0.001 \text{ C})(1000/\text{s}) \cos(1000/\text{s} \cdot t) \\ &= (1 \text{ A}) \cos(1000/\text{s} \cdot t) \end{aligned}$$

Answer: If we plug in a specific time within this equation, we get an instantaneous current for that time. For example, if $t = 1$, the current would be 0.174 A. At $t = 3 \text{ s}$, the current would be -0.5 A , the negative sign indicating that the current is in the opposite direction—a result of the sinusoidal nature.

Note: The last example involved using calculus—you can read about the basics of calculus in App. C if you're unfamiliar with it. Fortunately, as we'll see, rarely do you actually need to work in units of charge when doing electronics. Usually you worry only about current, which can be directly measured using an ammeter, or calculated by applying formulas that usually require no calculus whatsoever.

2.2.1 Currents in Perspective

What's considered a lot or a little amount of current? It's a good idea to have a gauge of comparison when you start tinkering with electronic devices. Here are some examples: a 100-W lightbulb draws about 1 A; a microwave draws 8 to 13 A; a laptop computer, 2 to 3 A; an electric fan, 1 A; a television, 1 to 3 A; a toaster, 7 to 10 A; a fluorescent light, 1 to 2 A; a radio/stereo, 1 to 4 A; a typical LED, 20 mA; a mobile (smart) phone accessing the web uses around 200 mA; an advanced low-power microchip (individual), a few μA to perhaps even several pA; an automobile starter, around 200 A; a lightning strike, around 1000 A; a sufficient amount of current to induce cardiac/respiratory arrest, around 100 mA to 1 A.

2.3 Voltage

To get electrical current to flow from one point to another, a voltage must exist between the two points. A voltage placed across a conductor gives rise to an *electromotive force* (EMF) that is responsible for giving all *free electrons* within the conductor a push.

As a technical note, before we begin, voltage is also referred to as a *potential difference* or just *potential*—they all mean the same thing. We'll avoid using these terms, however, because it is easy to confuse them with the term *potential energy*, which is not the same thing.

A simple flashlight circuit, consisting of a battery connected to a lamp, through two conductors and a switch, is shown in Fig. 2.4. When the switch is open (“off”), no current will flow. The moment the switch is closed, however, the resistance of the switch falls to almost zero, and current will flow. This voltage then drives all free electrons, everywhere within the circuit, in a direction that points from negative to positive; conventional current flow, of course, points in the opposite direction (see Benjamin Franklin).