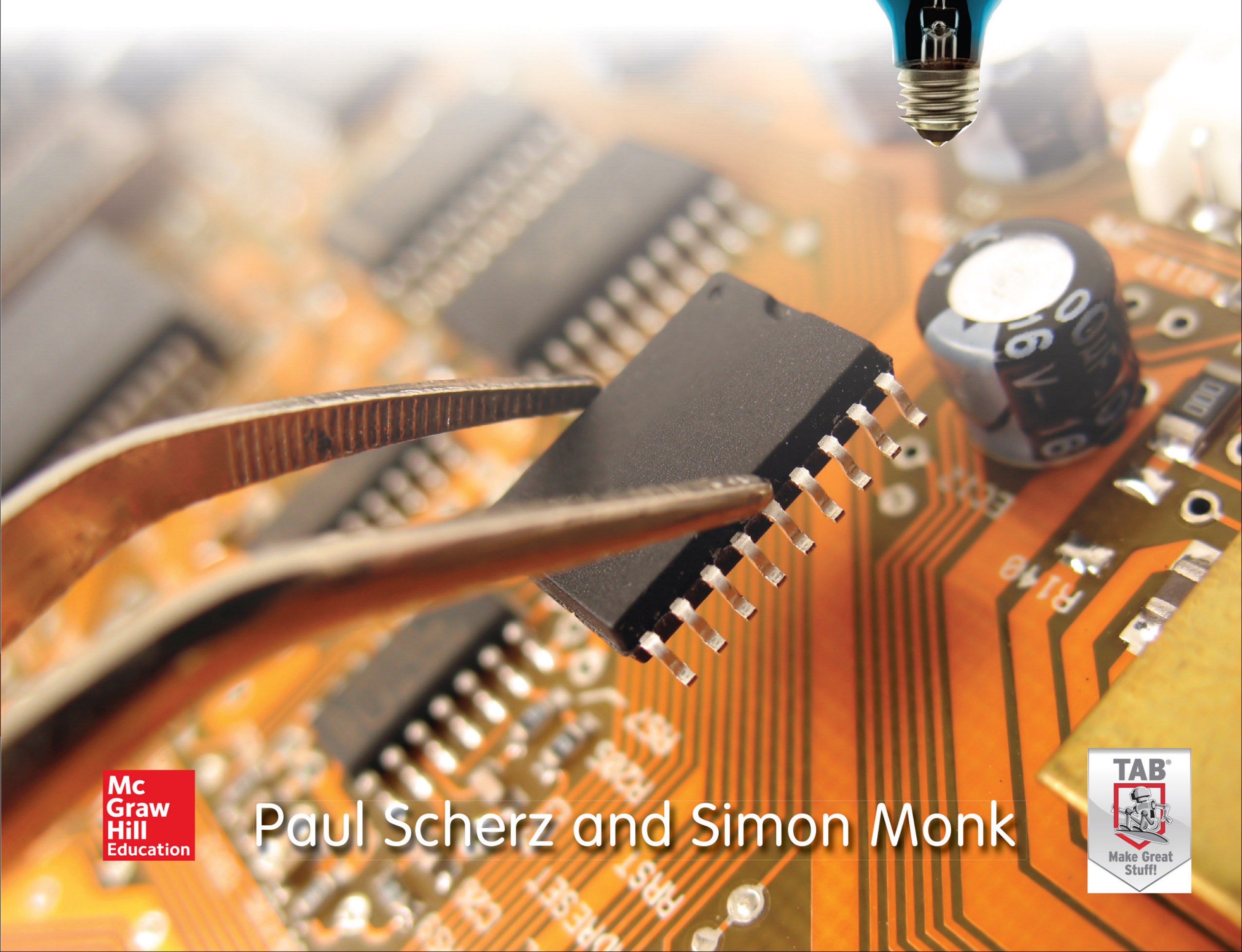
FOURTH EDITION

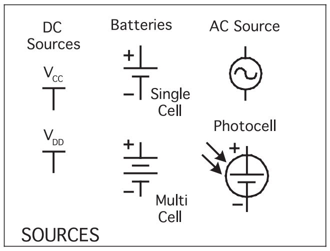
PRACTICAL ELECTRONICS FOR INVENTORS

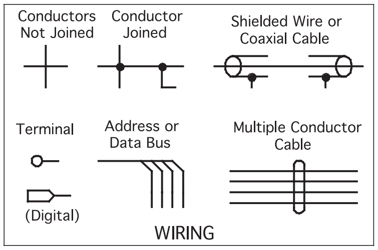


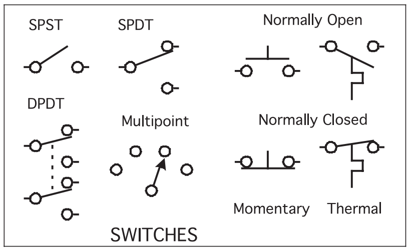
Paul Scherz and Simon Monk

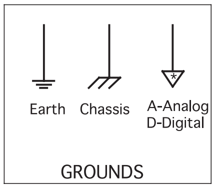
McGraw Hill Education

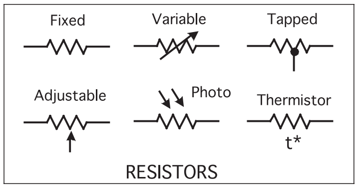
TAB
Make Great Stuff!

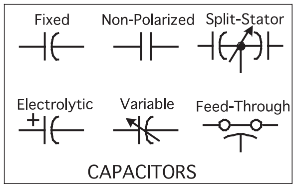

DC Sources
V_{CC}
V_{DD}
Batteries
Single Cell
Multi Cell
AC Source
Photocell
SOURCES

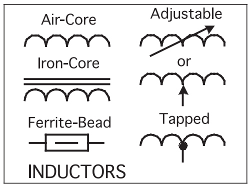

Conductors Not Joined
Conductor Joined
Shielded Wire or Coaxial Cable
Terminal
(Digital)
Address or Data Bus
Multiple Conductor Cable
WIRING

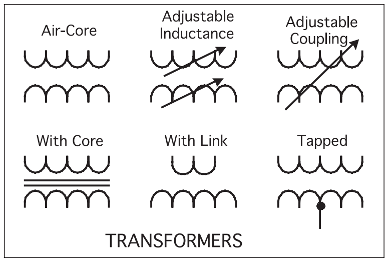

SPST
SPDT
Normally Open
DPDT
Multipoint
Normally Closed
Momentary
Thermal
SWITCHES

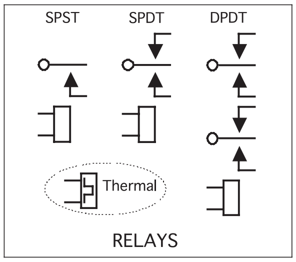

Earth
Chassis
A-Analog
D-Digital
GROUNDS

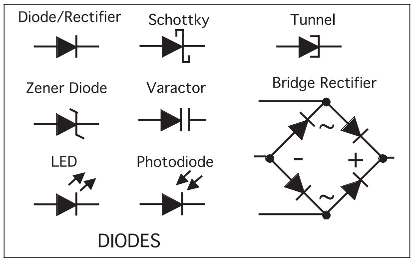

Fixed
Variable
Tapped
Adjustable
Photo
Thermistor
t*
RESISTORS

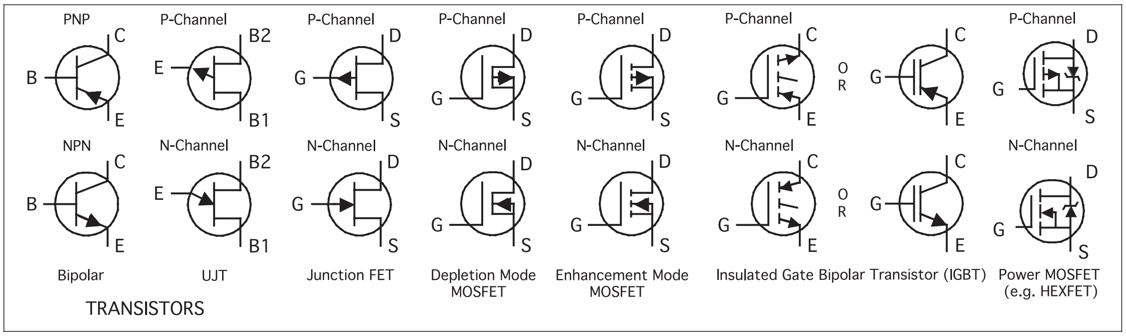

Fixed
Non-Polarized
Split-Stator
Electrolytic
Variable
Feed-Through
CAPACITORS

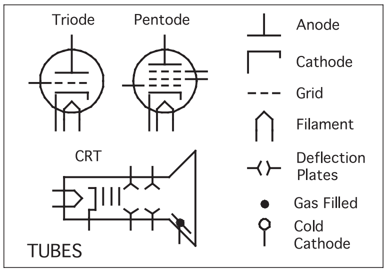

Air-Core
Iron-Core
Ferrite-Bead
Adjustable
or
Tapped
INDUCTORS

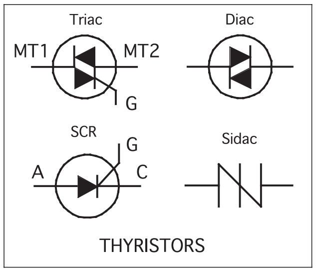

Air-Core
Adjustable Inductance
Adjustable Coupling
With Core
With Link
Tapped
TRANSFORMERS

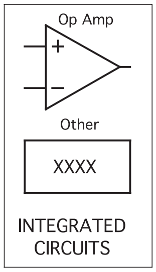

SPST
SPDT
DPDT
Thermal
RELAYS

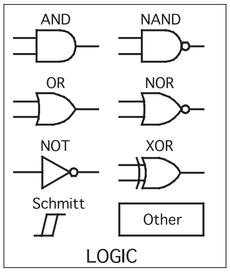

Diode/Rectifier
Schottky
Tunnel
Zener Diode
Varactor
Bridge Rectifier
LED
Photodiode
~
-
+
~
DIODES

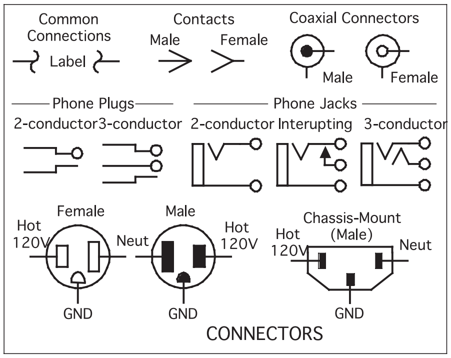

PNP
B
C
E
NPN
B
C
E
Bipolar
P-Channel
E
B2
B1
N-Channel
E
B2
B1
UJT
P-Channel
G
D
S
N-Channel
G
D
S
Junction FET
P-Channel
G
D
S
N-Channel
G
D
S
Depletion Mode MOSFET
P-Channel
G
D
S
N-Channel
G
D
S
Enhancement Mode MOSFET
P-Channel
G
C
E
OR
G
C
E
N-Channel
G
C
E
OR
G
C
E
Insulated Gate Bipolar Transistor (IGBT)
P-Channel
G
D
S
N-Channel
G
D
S
Power MOSFET (e.g. HEXFET)
TRANSISTORS

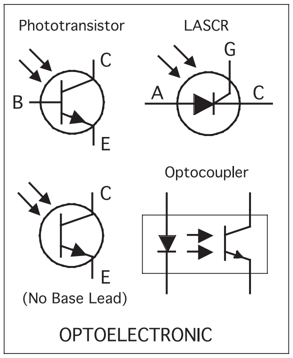

Triode
Pentode
CRT
Anode
Cathode
Grid
Filament
Deflection Plates
Gas Filled
Cold Cathode
TUBES

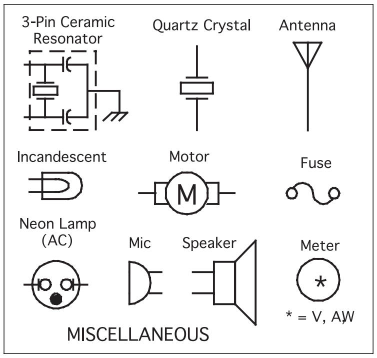

Triac
MT1
MT2
G
Diac
SCR
A
G
C
Sidac
THYRISTORS


Op Amp
+
-
Other
XXXX
INTEGRATED CIRCUITS


AND
NAND
OR
NOR
NOT
XOR
Schmitt
Other
LOGIC


Common Connections
Label
Contacts
Male
Female
Coaxial Connectors
Male
Female
Phone Plugs
2-conductor
3-conductor
Phone Jacks
2-conductor
Interupting
3-conductor
Female
Hot 120V
Neut
GND
Male
Hot 120V
GND
Chassis-Mount (Male)
Hot 120V
Neut
GND
CONNECTORS


Phototransistor
B
C
E
LASCR
A
G
C
C
E
(No Base Lead)
Optocoupler
OPTOELECTRONIC


3-Pin Ceramic Resonator
Quartz Crystal
Antenna
Incandescent
Motor
M
Fuse
Neon Lamp (AC)
Mic
Speaker
Meter
*
* = V, A, W
MISCELLANEOUS

Resistor Labels

Conversion Calculator

k = 1,000 ; M = 1,000,000

1MΩ = 1,000,000 Ω = 1 x 10^6Ω

1kΩ = 1,000 Ω = 1 x 10^3Ω

Examples:

3.3 kΩ = 3,300 Ω = 3.3 x 10^3Ω

22 kΩ = 22,000 Ω = 22 x 10^3Ω

2 MΩ = 2,000,000 Ω = 2 x 10^6Ω

1.68 MΩ = 1,680,000 Ω = 1.68 x 10^6Ω

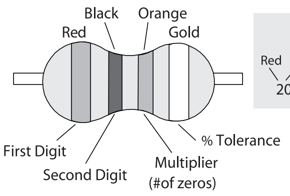
Resistor Color Code

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)

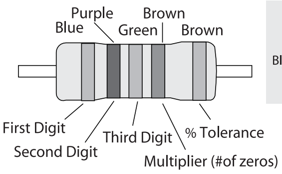


Label Meaning

Red Black Orange Gold

20 x 1,000 = 20k Ω ± 5%

5-Band Resistor Code (3-digit)

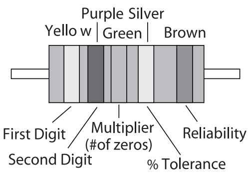


Label Meaning

Purple Brown Blue Green Brown

675 x 10 = 6750 Ω ± 1%

5-Band Resistor Code (Reliability)



Label Meaning

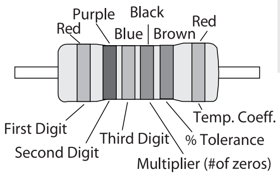
Yellow Green Purple Silver

47 x 100,000 = 4.7 MΩ ± 10%

1% Reliablity/1000 Hr — Brown

Color	Reliability (%/1000 Hr)
Brown	1
Red	0.1
Orange	0.01
Yellow	0.001

6-Band Resistor Code



Label Meaning

Purple Black Red Blue Brown

276 x 1 = 276Ω ± 1%

TC of 50 ppm — Red

Color	Temp. Coeff.
Brown	100 ppm
Red	50 ppm
Orange	15 ppm
Yellow	25 ppm

Surface Mount Resistor Code

3-digit Label

	Label Meaning
101	10 and 1 zero = 100 Ω
105	10 and 5 zero = 1,000,000 Ω
224	22 and 4 zeros = 220,000 Ω
1R0	1.0 and no zeros = 1 Ω
22R	22.0 and no zeros = 22 Ω
R10	0.1 and no zeros = 0.1 Ω

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

	Label Meaning
1001	100 and 1 zero =1000 Ω
22R0	22.0 and no zeros = 22 Ω

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

Tolerance Label

	Label Meaning
101F	100 Ω ± 1%
1R0D	1.0 Ω ± 0.5%

Letter	*Tolerance*
D	±0.5 %
F	±1.0 %
G	± 2.0 %
J	±5.0 %

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: 51Ω, 510Ω, 5.1kΩ, 51kΩ, 510kΩ, 5.1MΩ.

1% example resistors: 1.21Ω, 12.1Ω, 121Ω, 1.21kΩ, 12.1kΩ, 121kΩ, 1.21MΩ

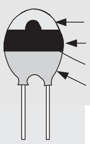
Capacitor Markings

Capacitance Conversion Calculator

1 F = 1 x 10^6 µF = 1 x 10^9 nF = 1 x 10^{12} pF
1 µF = 1 x 10^{-6} F = 1 x 10^3 nF = 1 x 10^6 pF
1 nF = 1 x 10^{-9} F = 1 x 10^{-3} µF = 1 x 10^3 pF
1 pF = 1 x 10^{-12} F = 1 x 10^{-6} µF = 1 x 10^{-3} nF
F = Farad, µ = micro, n = nano, p = pico

1000 µF = 1,000,000 nF = 10 x 10^8 pF
100 µF = 100,000 nF = 10 x 10^7 pF
10 µF = 10,000 nF = 10 x 10^6 pF
1 µF = 1,000 nF = 10 x 10^5 pF
0.1 µF = 100 nF = 10 x 10^4 pF
0.01 µF = 10 nF = 10 x 10^3 pF
0.001 µF = 1 nF = 10 x 10^2 pF

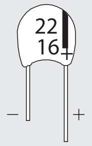
Tantalum



Label meaning 1

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

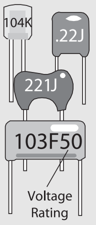
Color	S.F.	Multiplie	Voltage
Black	0	1	10V
Brown	1	10	
Red	2	100	
Orange	3	1000	
Yellow	4		6.3V
Green	5		16V
Blue	6		20V
Violet	7		
Gray	8	0.01	25V
White	9	0.1	3V
Pink			35V



Label meaning 2

Marking	Actual
22	22µF, 16 V

Mylar (Polyester Film)
Polypropylene
Dipped Mica



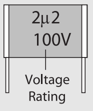
Voltage Rating

Label meaning

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

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

Metallized Polyester Film



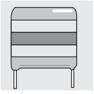
Voltage Rating

Label meaning

Marking	*Actual*
2µ2	2.2µF
µ22	0.22µF
68n	68 nF
4n7	4.7 nF

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

Polyester Color Coded



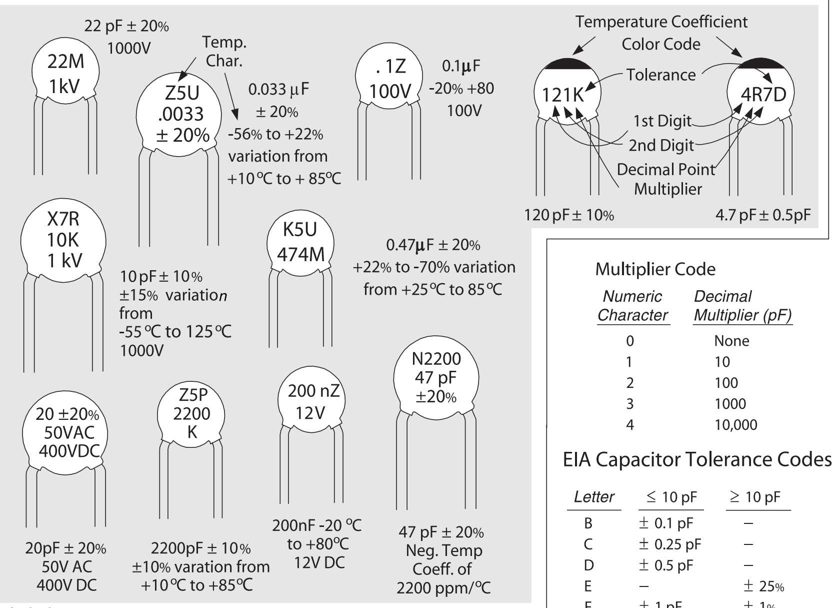
1st digit (pF)
2nd digit (pF)
Multiplier
Tolerance
Voltage

Standard color code

Black	± 20%
White	± 10%
Green	± 5%

Brown	100
Red	250
Yellow	400

Ceramic Disc Capacitors



22 pF ± 20%
1000V

0.033 µF
± 20%
-56% to +22%
variation from
+10 °C to + 85°C

0.1µF
-20% +80
100V

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

120 pF ± 10%

4.7 pF ± 0.5pF

10 pF ± 10%
±15% variation
from
-55 °C to 125 °C
1000V

0.47µF ± 20%
+22% to -70% variation
from +25 °C to 85 °C

20pF ± 20%
50V AC
400V DC

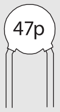
2200pF ± 10%
±10% varation from
+10 °C to +85°C

200nF -20 °C
to +80°C
12V DC

47 pF ± 20%
Neg. Temp
Coeff. of
2200 ppm/°C

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)

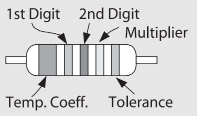


Label Meaning

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.

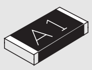
Fixed Ceramic Color Code



Color	S.F.		Tolerance >10pF	Tolerance <10pF	Temp. Coeff. ppm/°C
Black	0	1	± 20%	2.0 pF	-0
Brown	1	10	± 1%		-30
Red	2	100	± 2%		-80
Orange	3	1000			-150
Yellow	4				-220
Green	5		± 5%	0.5pF	-330
Blue	6				-470
Violet	7				-750
Gray	8	0.01		0.25pF	30
White	9	0.1	± 10%	1.0pF	500

Surface Mount Capacitors

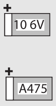
SMD Ceramic



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

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

Multiplier Code

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

EIA Capacitor Tolerance Codes

Letter	≤ 10 pF	≥ 10 pF
B	± 0.1 pF	–
C	± 0.25 pF	–
D	± 0.5 pF	–
E	–	± 25%
F	± 1 pF	± 1%
G	–	± 2%
H	–	± 2.5%
J	–	± 5%
K	–	± 10%
M	–	± 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	A	± 1.0%
Y	-35° C	4	+65° C	B	± 1.5 %
Z	+10° C	5	+85° C	C	± 2.2%
		6	+105° C	D	± 3.3%
		7	+125° C	E	± 4.7%
				F	± 7.5%
				P	± 10%
				R	± 15%
				S	± 22%
				T	-33%, + 22%
				U	-56%, + 22%
				V	-82%, + 22%

EIA Temperature Coefficient Color Codes

Color	*Temp. Coeff. Industry*	*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

1µF, 50V

Label: Usually self-explanatory

Practical Electronics for Inventors

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Practical Electronics for Inventors

Fourth Edition

Paul Scherz

Simon Monk

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CONTENTS

CHAPTER 6 Sensors 525

CHAPTER 7 Hands-on Electronics 551

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.

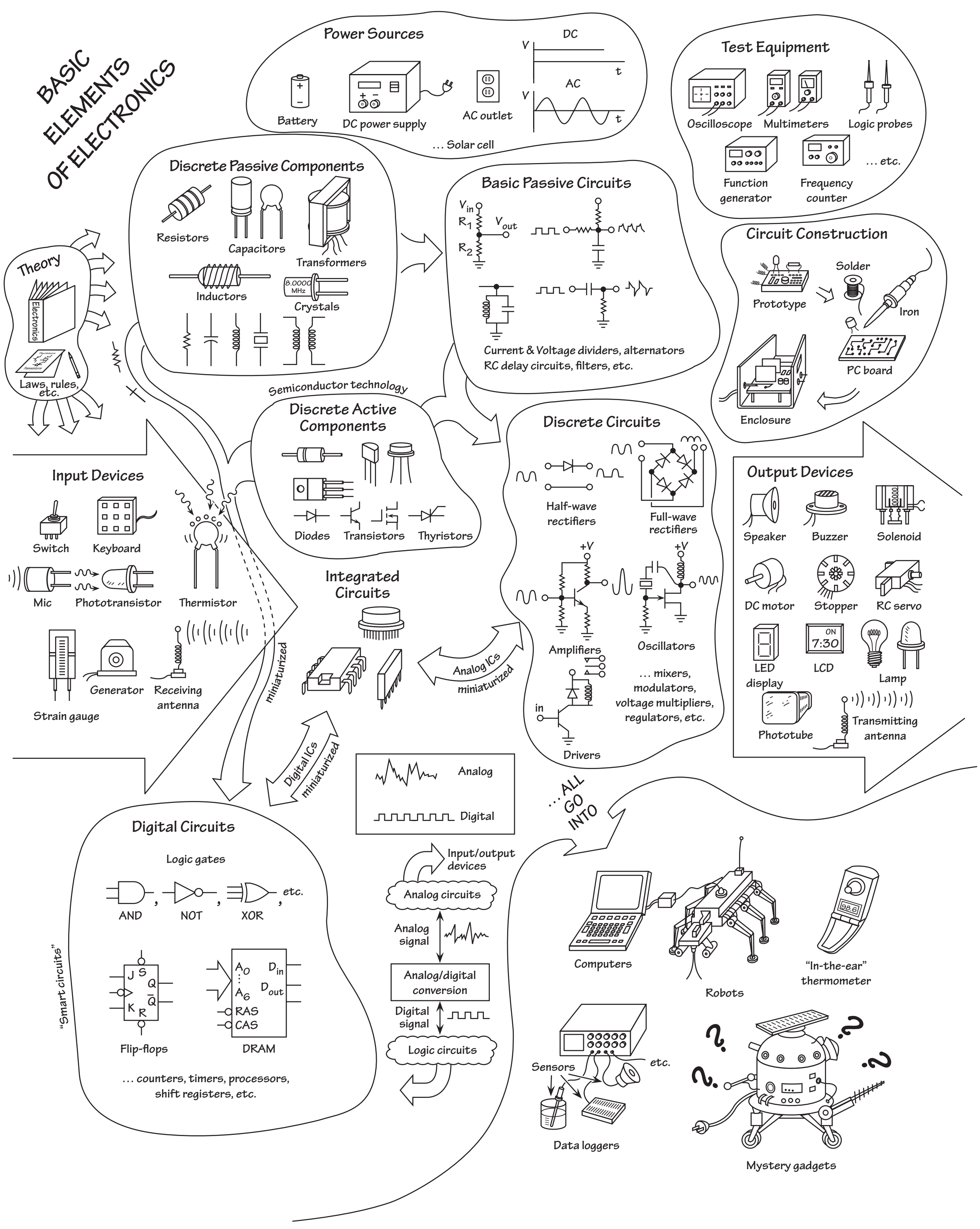
BASIC ELEMENTS OF ELECTRONICS
Power Sources
Battery
DC power supply
AC outlet
... Solar cell
V
DC
t
V
AC
t
Test Equipment
Oscilloscope
Multimeters
Logic probes
Function generator
Frequency counter
... etc.
Theory
Electronics
Laws, rules, etc.
Discrete Passive Components
Resistors
Capacitors
Transformers
Inductors
Crystals
8.0000 MHz
Basic Passive Circuits
V_{in}
R_1
V_{out}
R_2
Current & Voltage dividers, alternators
RC delay circuits, filters, etc.
Circuit Construction
Prototype
Solder
Iron
PC board
Enclosure
Semiconductor technology
Discrete Active Components
Diodes
Transistors
Thyristors
Discrete Circuits
Half-wave rectifiers
Full-wave rectifiers
+V
+V
Amplifiers
Oscillators
in
Drivers
... mixers, modulators, voltage multipliers, regulators, etc.
Input Devices
Switch
Keyboard
Mic
Phototransistor
Thermistor
Strain gauge
Generator
Receiving antenna
Output Devices
Speaker
Buzzer
Solenoid
DC motor
Stopper
RC servo
LED display
ON
7:30
LCD
Lamp
Phototube
Transmitting antenna
Integrated Circuits
miniaturized
Analog ICs miniaturized
Digital ICs miniaturized
Analog
Digital
... ALL GO INTO
Digital Circuits
Logic gates
AND
NOT
XOR
etc.
"Smart circuits"
J
S
Q
K
R
$\overline{Q}$
Flip-flops
A_0
A_6
D_{in}
D_{out}
RAS
CAS
DRAM
... counters, timers, processors, shift registers, etc.
Input/output devices
Analog circuits
Analog signal
Analog/digital conversion
Digital signal
Logic circuits
Computers
Robots
"In-the-ear" thermometer
98.6
Sensors
etc.
Data loggers
Mystery gadgets

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:

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

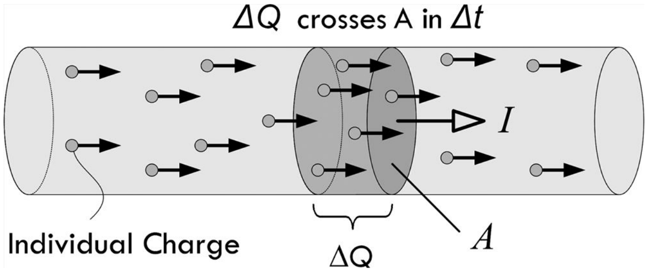

FIGURE 2.1

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

$$\mathrm{I} = \lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t} = \frac{dQ}{dt} \tag{2.1}$$

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

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

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* ($1\ \mu\text{A} = 1 \times 10^{-6}\ \text{A}$), 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:

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

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:

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

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

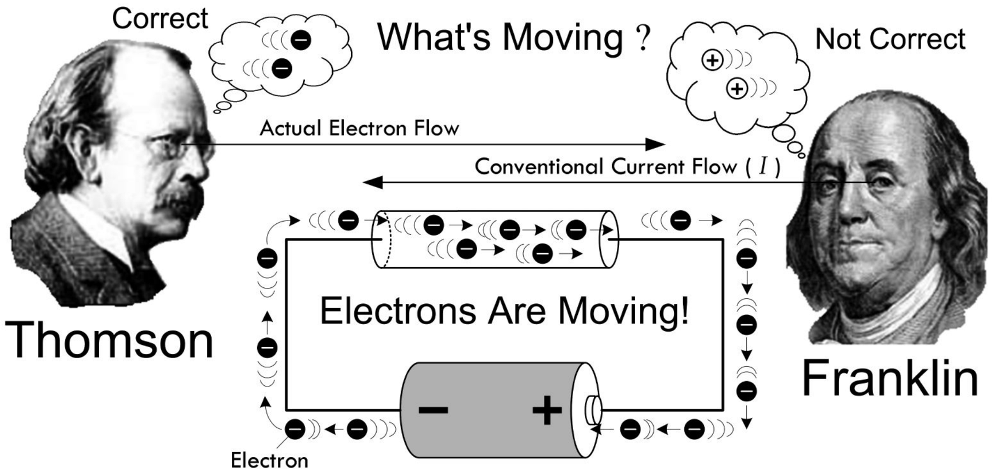

FIGURE 2.2 Thomson changed the notion that positive charges were what were moving in conductors, contrary to Franklin's notion. However, negative electrons going one way is equivalent to positive charges going the opposite direction, so the old formulas still work. Since you deal with the old formulas, 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?

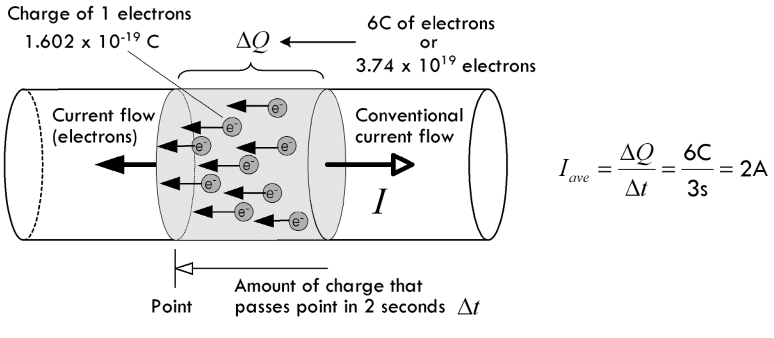

FIGURE 2.3

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 1.6×10^{-19} 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 $t = 3$ 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).