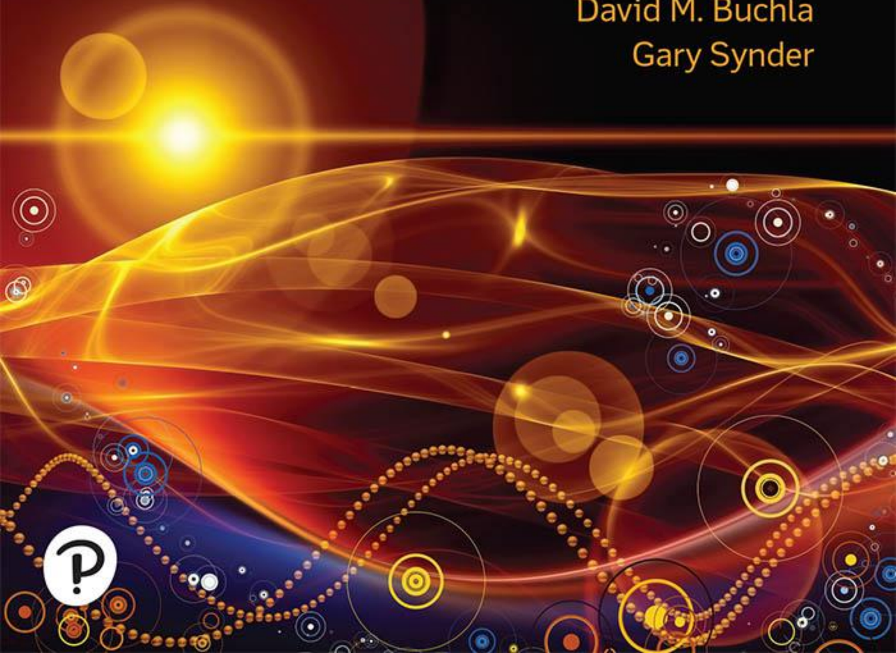
Electronics Fundamentals

circuits, devices, and applications

ninth edition

Thomas L. Floyd
David M. Buchla
Gary Synder



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Preface

It was with deep sadness that we and all those who knew and worked with Tom Floyd learned of his passing in April 2018. His textbooks over the past several decades contributed greatly to the education of many students in the field of electronics and were of invaluable assistance to the instructors in those courses. Tom brought a rare clarity, insight, and innovation to the field of electronics instruction and his persistent pursuit of excellence will be sorely missed.

This ninth edition of *Electronics Fundamentals: Circuits, Devices, and Applications* will be the first of his textbooks in which he will not actively participate. The authors, who had the privilege of working with him for over 30 years, have worked to maintain his legacy of excellence in presenting comprehensive and clear coverage of basic electrical and electronic concepts, practical applications, and troubleshooting. In addition to preserving features introduced in the eighth edition, the ninth edition expands on the previous edition by updating existing material and including a number of new topics of interest, such as new battery technologies and renewable energy.

This textbook is divided into three main parts: DC Circuits in Chapters 1 through 7, AC Circuits in Chapters 8 through 15, and Devices in Chapters 16 through 21. The DC Circuits and AC Circuits portions cover the traditional topics of resistive, capacitive, and inductive circuits with both dc and ac sources. The Devices portion provides an introduction to basic types of electronic devices and circuits but is not intended to be as comprehensive as the coverage found in textbooks totally devoted to the subject, such as Floyd's *Electronic Devices* or *Fundamentals of Analog Circuits.*

Many new examples have been added to support revised and expanded topics. All examples have been thoroughly reviewed for accuracy. Many examples are marked with a new calculator symbol ( ) that indicate that relevant step-by-step instructions are available in an on-line supplement for using two scientific graphing calculators (the TI-84 Plus CE and HP Prime). This supplement, entitled, *Introduction to Scientific Calculators*, is free to users and tracks text examples. Circuit simulation examples include new LTspice IV and new and updated Multisim circuit files. As in past editions, troubleshooting continues to be an important part of this edition with an entire section devoted to the topic in most chapters. In addition, all chapters (except chapter 1) end with an Application Assignment, which provides a practical example related to the chapter coverage.

The innovative and interactive PowerPoint slides by David Buchla have been thoroughly reviewed, enhanced and improved for this edition. These slides are coordinated with the text on a chapter-by-chapter basis, and include many examples and problems to enhance coverage in the text. The slides include a multiple-choice quiz at the end to review concepts covered. These slides, and other instructor resources may be downloaded by educators from Pearson's Instructor Resource Center at www.pearsonhighered.com/irc.

As in previous editions, *Electronics Fundamentals: Circuits, Devices, and Applications,* 9th Edition, uses the electron flow direction for assigning currents. There are two widely accepted views concerning the assumed direction of current for the purpose of envisioning and analyzing circuit behavior, *electron flow direction* and *conventional current direction.* There is no difference between the two approaches in terms of the outcome of circuit analysis. Electron flow current direction is from the negative side of a voltage source, through the load, and back to the positive side of the source and is the actual direction in which electrons move through solid conductors. Conventional current direction is from the positive side of a voltage source, through the load, and back to the negative side of the source. Although the effects of current are observable, current itself is never seen, so the direction that one assumes makes no difference as long as consistency is applied. The choice is usually a matter of preference or familiarity, and the two schools of thought concerning assumed current direction are about evenly divided between electron flow and conventional current.

What's New in This Edition?

Electronics Fundamentals: Circuits, Devices, and Applications, 9^{th} edition has been completely updated and revised to meet current industry standards. It may be purchased or rented in two general formats – print and eText. The print version is now available as an affordable rent-to-own option for students. Several options for low cost digital eTexts are also available as a subscription or ownership. For access to Pearson eText, visit Pearson.com/learner.

- Expanded coverage of recent advances in and applications of electronics technology, such as batteries, SMD components, LED applications, optocouplers and optoisolators, Hall effect sensors, and multilayer PC boards.
- Thoroughly revised Chapter 20 to include replacing outdated instrumentation amplifiers (IAs) with new IAs, new isolation amplifiers, revised applications, and Schmitt trigger circuits.
- New Application Assignment for Chapter 20 that illustrates a multilayer PC board in a motor monitoring application using newer ICs introduced in the text.
- Enhanced discussion of electrical safety including new margin Safety Notes.
- New section on Green technology including a discussion of RoHS and WEEE directives.
- Over 50 pages of new content with many new illustrations
- Discussion of basic EMC considerations for practical circuit designs
- Dimensional analysis in several chapters.
- New and expanded coverage of instruments including thermal imaging cameras, gaussmeters, arbitrary function and waveform generators, and oscilloscopes, including mixed signal oscilloscopes.
- Coverage of additional passive components, including magnetoresistive random access memory (MRAM), planar magnetic devices, pulse transformers, peaking transformers, polymer electrolytic capacitors, super capacitors, ferrite beads, thermistors, thermocouples and thermocouple signal conditioning.
- Expanded coverage of solid-state devices and design considerations, including inductive kickback circuit protection, Schottky diodes, new LED technology, new op-amps, and regulator stability.
- New and revised examples with many showing graphing calculator features, methods and related examples in the on-line companion, *Introduction to Scientific Calculators*.
- Expanded troubleshooting discussion including a comparison of an *algorithmic* approach to a heuristic approach to problem solving and use of thermal imaging cameras for detecting heat related problems.

- Multisim 14 circuit files for examples, troubleshooting problems, and chapter problems on the companion website.
- LTSpice IV tutorial and circuit files for examples on the companion website.
- Reorganized index to make it more "user friendly". Glossary terms in the index are bold and page references to figures and tables are bold.

Features

- Math level limited to basic algebra and right-angle trigonometry
- Full-color format with over 1400 illustrations.
- Each chapter begins with an introduction, outline, list of objectives, list of key terms, application assignment preview, and a website reference
- Each section within a chapter begins with an introduction and list of section objectives
- Numerous worked examples throughout each chapter, each containing a related problem with answers. Most have detailed calculator steps for related problems (available on line).
- Multisim and LTspice exercises for many examples
- Section checkups with answers at the end of the chapter
- Troubleshooting sections in most of the chapters
- An application assignment in each chapter (except Chapter 1)
- Margin features such as Safety Note, Hands On Tip, and History Note appear throughout. Many are new to this edition.
- A summary, key term glossary, and formula list at the end of each chapter
- A true/false quiz and a self-test at the end of each chapter with answers
- A set of exercises that help develop thought processes essential to troubleshooting *(Troubleshooting: Symptom and Cause)* at the end of most chapters with answers
- A sectionalized problem set organized into basic and advanced categories at the end of each chapter, with answers to odd-numbered problems at the end of the book
- A comprehensive glossary at the end of the book includes all boldface terms and denotes the chapter containing first use of each term
- Standard resistor and capacitor values are used throughout.

Student Resources

Lab Manual *Experiments in Electronics Fundamentals: Circuits, Devices & Applications, Ninth Edition* (ISBN 9780135583753) by David Buchla. Lab exercises are coordinated with the text and solutions are provided in the Instructor's Resource Manual. The revised 9th edition simplifies required parts and is designed to work with self-contained prototyping systems such as NI Elvis or Digilent's Analog Discovery Studio. Parts for lab experiments are available as a kit from Electronix Express (https://www.elexp.com/32tfdbgs1).

You can purchase the Lab Manual at your local bookstore or at Pearson.com/learner.

Multisim Files Available on the Companion Website Circuit files coordinated with this text in Version 14 of Multisim are located on the companion website at www.pearsonhighered.com/careersresources. Circuit files with prefix E are example circuits and files with prefix P are problem circuits. Older versions may also be found on the website.

In order to use the Multisim circuit files, you must have Multisim software installed on your computer. Multisim software is available at www.ni.com/Multisim. Although the Multisim circuit files are intended to complement classroom, textbook, and laboratory study, these files are not essential to successfully using *Electronics Fundamentals: Circuits, Devices, and Applications.*

***An Introductory Tutorial to LTspice IV* on the Companion Website.** An introduction to capturing, editing, and simulating circuit designs using LTSpice IV may be downloaded from the companion website at www.pearsonhighered.com/careersresources

***Introduction to Scientific Calculators* on the Companion Website.** An introduction to features and capabilities of the Texas Instruments TI-84 CE Plus and HP Prime color graphing calculators in working with and solving problems related to introductory dc and ac electronics may be downloaded from the companion website at www.pearsonhighered.com/careersresources.

Supplementary Tests. Also available on the companion website are multiple-choice, true/false, fill-in-the-blanks, and circuit analysis tests that can be used to reinforce your understanding of the topics in the textbook.

Use of Calculators with This Textbook

The solution of complex mathematical problems has always involved calculating devices. Prior to the late 1950s, slide rules were the usual means of finding answers to electronics problems. Since then the electronic calculator and personal computer have greatly simplified the calculations students and engineers must perform. Early calculators were limited to solving simple numerical problems, but today's programmable scientific graphing calculators can analyze circuits that once required computers. Two modern calculators in particular introduced in this text are the comparably priced TI-84 Plus CE and HP Prime. Both are equally capable of solving the problems associated with resistive, reactive, and complex circuits. Each was used to solve the problems in this textbook to ensure that the provided solutions are correct and develop the calculator examples that accompany this textbook. Full calculator precision was maintained while calculating the solutions to each problem, although the intermediate and final answers shown are rounded to three significant digits.

Instructor Resources

To access supplementary materials online, instructors need to request an instructor access code. Go to www.pearsonhighered.com/irc, to login or register for an instructor access code.

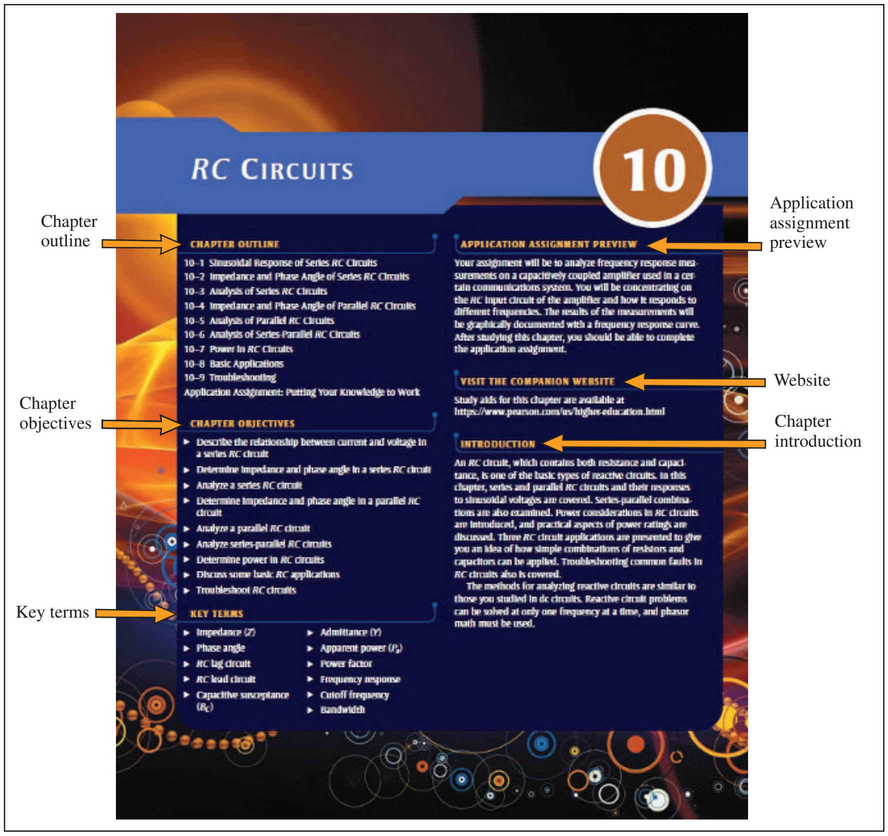
PowerPoints® Contains innovative and interactive slides for the text and lab manual by David Buchla. The slides, coordinated with each chapter in the text, provide an excellent supplement for classroom presentations and include new and revised examples and interactive problems.

Instructor's Resource Manual Includes solutions to chapter problems, solutions to Application Activity features, a revised test item file, a Multisim and LTSpice circuit file summary by Gary Snyder, solutions for the lab manual by David Buchla, and a partial list of CEMA skills.

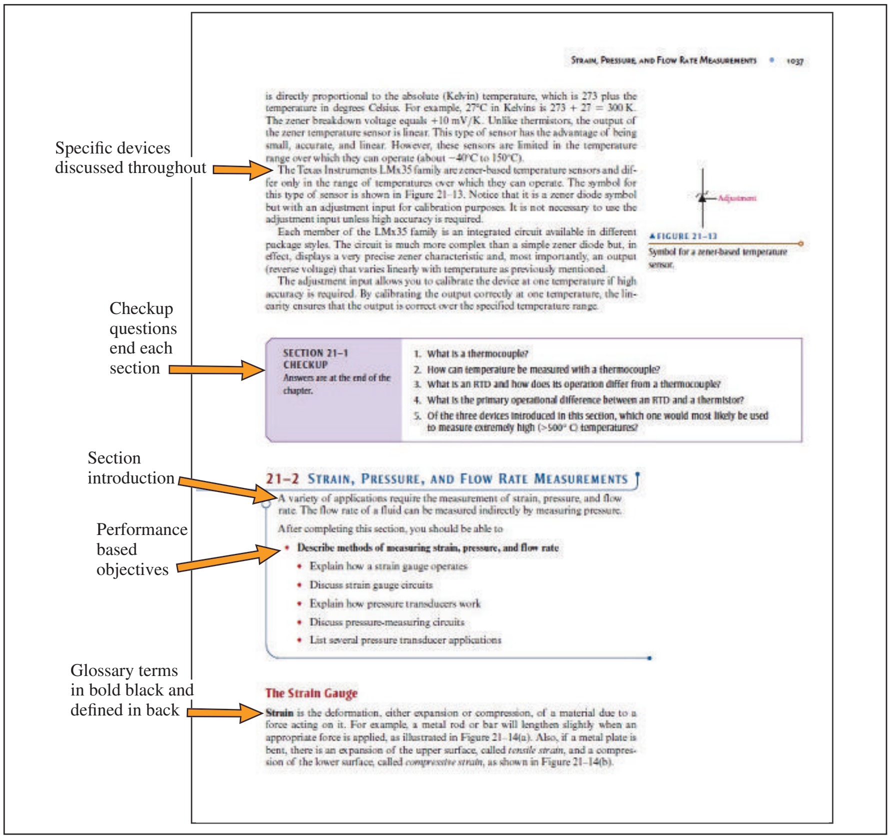
Chapter Pedagogical Features

Chapter Opener Each chapter begins with an opener page that includes an outline, a list of objectives, a list of key terms, an Application Assignment preview, a website reference, and an introduction. A typical chapter opener is shown in Figure P–1.

▸ FIGURE P–1



▸ FIGURE P–2



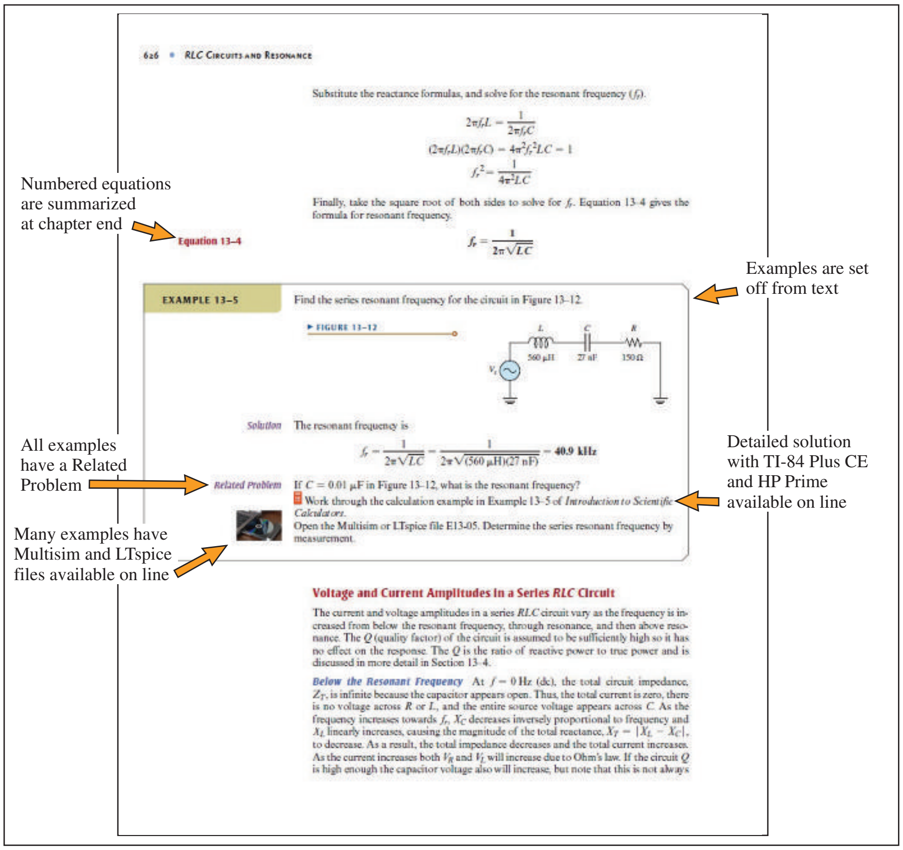
Section Opener Each section in a chapter begins with a brief introduction that includes a general overview and section objectives as related to chapter objectives. An example is shown in Figure P–2.

Section Checkup Each section ends with a review consisting of questions or exercises that emphasize the main concepts presented in the chapter, as illustrated in Figure P–2. Answers are given at the end of the chapter. Specific devices are discussed throughout the text as illustrated in Figure P-2.

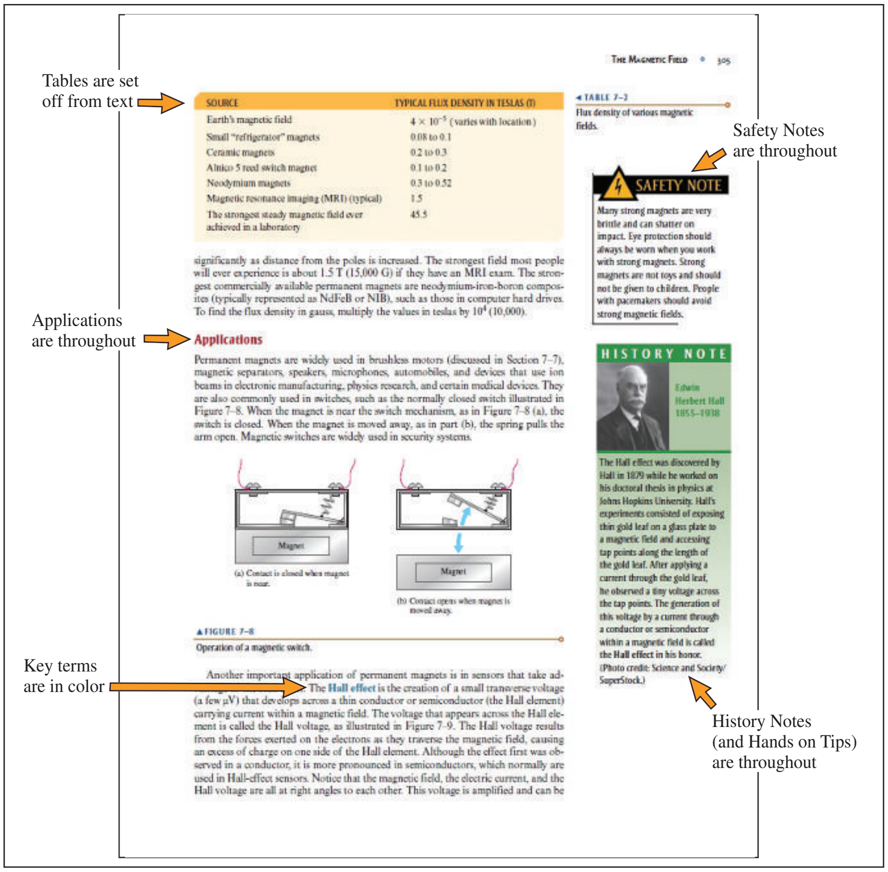
Worked Example, Related Problem, Multisim/LTspice Exercise and Programmable Calculator Steps Numerous worked examples help to illustrate and clarify basic concepts or specific procedures. Each example ends with a problem that is related to the example and reinforces or expands on the example by requiring the student to work through a similar problem. Selected examples have Multisim and LTspice exercises that reference a circuit file on the companion website. Examples requiring calculations illustrate steps for similar problems in the *Introduction to Scientific Calculators* tutorial available on the companion website. A typical example is shown in Figure P–3. Answers to the related problems are at the end of the chapter.

Tables, Applications, Key Terms, and Margin Notes Data tables are set off from the text in color. Applications are featured in many chapters and are related to the chapter topic. Key terms are new terms introduced in the chapter and defined in a list at the back of the chapter and in the end of book glossary. Topics including Safety Notes, Historical Notes and Hands on Tips are placed in the margin and introduced in various places throughout the text. These features are illustrated in Figure P-4.

Troubleshooting Section Many chapters include a section devoted to a troubleshooting topic related to chapter coverage and emphasizes logical thought as well as presenting a structured approach.



◄ FIGURE P–3



▶ FIGURE P–4

Application Assignment This feature is located at the end of most chapters. A practical application of topics covered in the chapter is presented in a step-by-step format that requires the student to perform certain tasks. A typical Application Assignment, such as shown in Figure P–5 is a multifaceted practical problem intended to present a realistic problem that is more involved, The AA is not intended to replace a laboratory experiment but does use realistic circuits including PCBs and realistic instruments, conveys certain practical aspects of a technician's job.

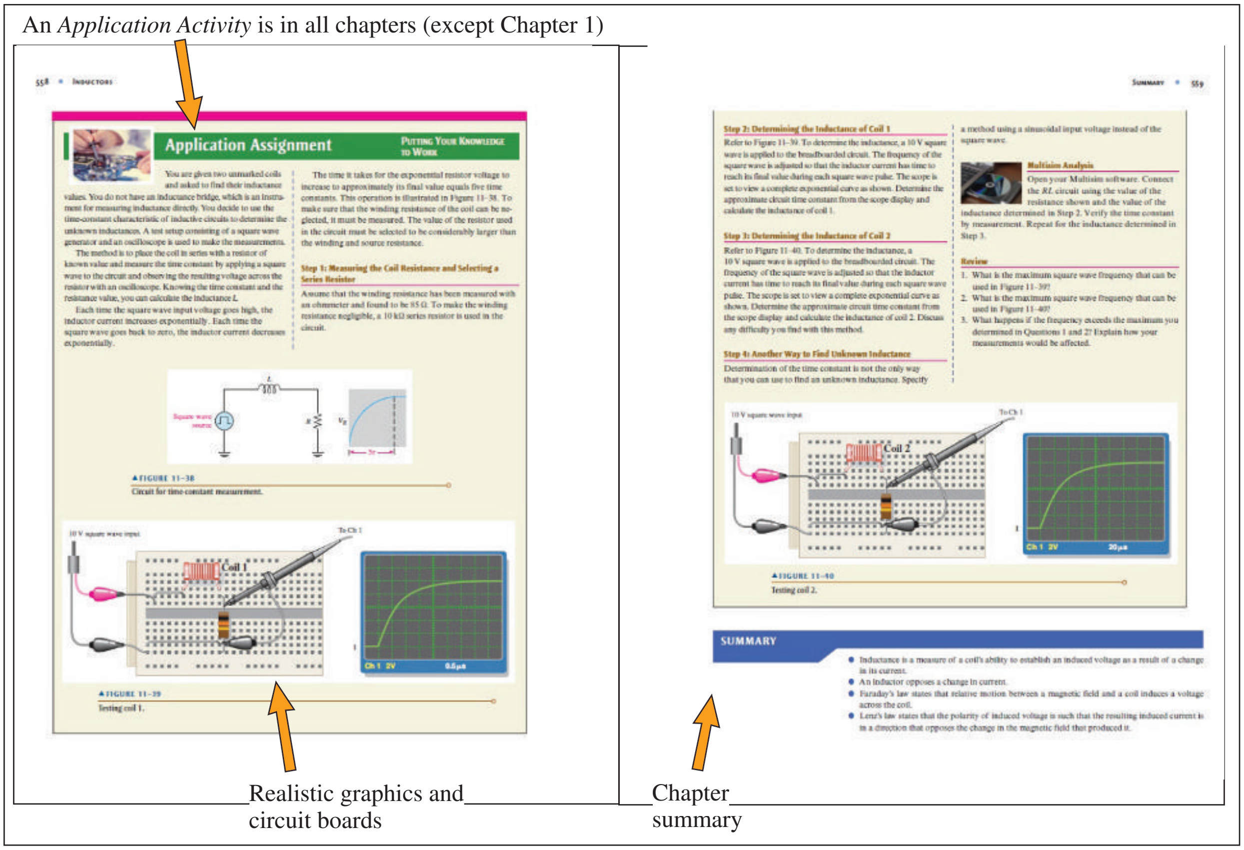
Suggestions for Using This Textbook

As mentioned before, this book is divided into three parts: DC Circuits, AC Circuits, and Devices. The organization and content of this text provide schools and instructors the flexibility in using it for a more general survey course, or a more in-depth multicourse electronics sequence. Instructors, in particular, can present material from the text as he or she feels is appropriate to the content of his or her class, and leave other topics for independent study.

To the Student

Any career training requires effort, and the electrical/electronics field is no exception. The best way to learn new material is by reading, thinking, and doing. This text is designed to help you along the way.

Read each section of the text carefully and think about what you have read. Sometimes you may need to read the section more than once. Work through each example problem step by step before you try the related problem that goes with the example. Utilize the supplemental circuit simulation and calculator resources provided on the companion website. After each section, answer the checkup questions. Answers to the related problems and the section checkup questions are at the end of the chapter.



▲ FIGURE P–5

Review the chapter summary, the key term definitions, and the formula list. Take the true/false quiz, the multiple-choice self-test, and the troubleshooting quiz. Check your answers against those at the end of the chapter. Finally, work the problems and verify your answers to the odd-numbered problems with those provided at the end of the book.

The importance of obtaining a thorough understanding of the basic principles contained in this text cannot be overemphasized. Most employers prefer to hire people who have both a thorough grounding in the basics and the ability and eagerness to grasp new concepts and techniques. If you have a good training in the basics, an employer will train you in the specifics of the job to which you are assigned.

Careers in Electronics

The fields of electricity and electronics are very diverse, and career opportunities are available in many areas. There are many types of job classifications for which a person with training in electricity and electronics technology may qualify. A few of the most common job functions are discussed briefly in the following paragraphs.

Service Shop Technician Technical personnel in this category are involved in the repair or adjustment of both commercial and consumer electronic equipment that are returned to the dealer or manufacturer for service. Specific areas include consumer electronics and computers. This area also offers opportunities for self-employment.

Industrial Manufacturing Technician Manufacturing personnel are involved in the testing of electrical and electronic products at the assembly-line level or in the maintenance and troubleshooting of electrical, electronic, and electromechanical systems used in the testing and manufacturing of products. Virtually every type of manufacturing plant, regardless of its product, uses automated equipment that is electronically controlled.

Laboratory Technician These technicians are involved in breadboarding, prototyping, and testing new or modified electronic systems in research and development laboratories. They generally work closely with engineers during the development phase of a product.

Field Service Technician Field service technicians install, maintain, service, and repair electronic equipment—for example, computer systems, radar installations, automatic banking equipment, and security systems—at the user's location. In larger systems, field service technicians frequently do customer training after installing a new system.

Engineering Assistant/Engineering Technician/Associate Engineer Personnel in this category work closely with engineers in the implementation of a concept and in the basic design and development of electrical and electronic systems. Engineering assistants are frequently involved in a project from its initial design through the early manufacturing stages.

Technical Writer Technical writers compile technical information and then use the information to write and produce manuals and audiovisual materials. A broad knowledge of a particular system and the ability to clearly explain its principles and operation are essential.

Technical Sales Technically trained people are in demand as sales representatives for high-technology products. The ability both to understand technical concepts and to communicate the technical aspects of a product to a potential customer is very valuable. In this area, as in technical writing, competency in expressing yourself orally and in writing is essential. Actually, being able to communicate well is very important in any technical job category because you must be able to record data clearly and explain procedures, conclusions, and actions taken so that others can readily understand what you are doing.

Milestones in Electronics

Let's briefly look at some of the important developments that led to the electronics technology we have today. Many of the early pioneers of electricity and electromagnetism are remembered by units named in their honor. Names such as Ohm, Ampere, Volta, Faraday, Henry, Coulomb, Tesla, and Hertz are some of the better known examples. Short biographies of these and other pioneers are located throughout the text in History Notes. Table P-1 below summarizes significant events related to the development of modern electronics.

Table P-1

YEAR	NAME	EVENT
1857	Heinrich Geißler	Development of the Geißler gas discharge tube, similar to modern neon lamps, developed
ca. 1870	David Crookes, et. al.	Development of the Crookes gas discharge tube, the predecessor to electronic vacuum tubes
1897	Sir Joseph J. Thomson	Investigation into the charge and mass characteristics of electrons using gas discharge tubes
1904	Sir John A. Fleming	Development of the Fleming valve, forerunner of the vacuum tube diode

YEAR	NAME	EVENT
1907	Lee deForest	Development of the grid Audion, an early version of the vacuum tube triode, allowing amplification of electrical signals
1909	Robert A. Millikan	Experimental determination of the charge of an electron
1912	Edwin H. Armstrong	Patent application for regenerative (positive feedback) circuit allowing much greater amplification with vacuum tubes
1920	Edwin H. Armstrong	Patent issued for superheterodyne circuit used in modern radio communications
1923	Vladimir Zworykin	Invention of first television tube
1925	Julian E. Lilienfeld	Patent application for concept of the junction field effect transistor
1927	Philo T. Farnsworth	Patent application for first complete television system
ca. 1930s	Various	Development of point contact diode
1939	John Anatasoff Clifford Berry	Construction of the Anatasoff-Berry Computer, the first electronic binary computer
	Hentry Boot John Randall	Invention of the magnetron, a vacuum tube microwave oscillator
	Russel Varian Sigurd Varian	Invention of the klystron microwave vacuum tube
1945	Percy Spencer	While working as an engineer for Raytheon, Percy Spencer notices that microwaves from nearby radar sets had begun melting a chocolate bar in his pocket, leading to the development of the now ubiquitous microwave oven.
1946	John von Neumann	Construction of ENIAC, first stored program electronic computer
1947	Walter Brattain John Bardeen William Shockley	Invention of point contact transistor, forerunner of the bipolar junction transistor
1947	Various	Introduction of the printed circuit board in manufacturing
1951	Allentown Works	Mass production of transistors begun
1957	Leo Esaki Yuriko Kurose Takashi Suzuki	Invention of the Esaki (tunnel) diode, a device exhibiting negative dynamic resistance due to the quantum mechanical property of electron "tunneling"
1958	Jack Kilby	Construction of first integrated circuit by Texas Instruments, Incorporated
1959	Mohamad M. Atalla Dahwon Kang	Invention of metal oxide semiconductor field effect transistor (MOSFET) at Bell Laboratories
1961	James A. Biard Gary Pittman	Patent application for "Semiconductor Radiant Diode", the first practical LED, with the patent issued in 1966

YEAR	NAME	EVENT
1965	Bob Widlar	Design of the Fairchild μA709, the first successful op-amp
1969	Charley Cline Bill Duvall	First successful host to host connection between UCLA's and Stanford Research Institute's interface message processors (IMPs) using ARPANET, the predecessor of the Internet
1971	Intel Corporation	Introduction of the 4004, the first microprocessor, followed that same year by the 8-bit 8008 microprocessor
	University of Hawaii	Start-up of ALOHAnet, the first professionally developed wireless network
1973	John F. Mitchell Martin Cooper	First mobile cellular handheld phone demonstrated by Motorola
1974	Hewlett-Packard	Introduction of the HP-35, the world's first handheld scientific calculator
1975	Altair	Introduction of first personal computer
1976	Steve Wozniak Steve Jobs	Introduction of the Apple 1 computer, a hand-built personal computer based on the 1.0 MHz MOS Technology 6502 microprocessor
1977	General Telephone and Electronics	First live telephone traffic carried over fiber optic cable using 0.8 μm GaAs laser transmitters
1981	IBM	Introduction of the IBM PC, a personal computer based on the 4.77 MHz Intel 8088 microprocessor
1982	Sony Corporation Pioneer Corporation	Release of the first 50 compact disk (CD) titles
1984	Apple Computer	Introduction of the Macintosh computer, a graphic user interface (GUI) personal computer released one year after the failed Apple Lisa GUI computer
1990s	Various	Proliferation of cellular communication networks
1990	Tim Berners-Lee	Release of HTML, the standard markup language for the World Wide Web
1991	Sony Corporation Asahi Kasei	Commercialization of lithium-ion batteries
1995	FCC	Allocation of frequencies for Digital Audio Radio Service (DARS)
	Jennifer Healey Rosalind Picard	Initial development and demonstration of wearable technology to collect physiological data and make decisions on the collected data, foreshadowing development of later commercial and military technology, such as smart watches and tactical sensors

YEAR	NAME	EVENT
1996	FCC	Development of standards for US digital television
	General Motors Corporation	Introduction of the GM EV1, the first modern-age electric vehicle from a major manufacturer, which would be followed by electric vehicles from other manufacturers
	U.S. Federal Government	The government global position system (GPS) is made a dual-use system, opening it to civilian use
1997	Deep Blue Garry Kasparov	Defeat of world chess champion Garry Kasparov by IBM's Deep Blue in a rematch from 1996, the first victory of a computer over the reigning human champion under tournament conditions
1999	Research in Motion	Introduction of the Blackberry 850, the forerunner of later smartphone devices
2002	European Union	Development of the Restriction of Hazardous Substances (RoHS) and Waste Electrical and Electronic Equipment (WEEE) directives, adopted the following year by EU members
2006	Blu-Ray Disc Association	Introduction of the Blu-Ray disc, intended to supersede the DVD (digital versatile disc) introduced in 1995
2007	Apple Computer	Introduction of the Apple iPhone, an innovative smartphone design
2009	FCC	End of analog television transmissions in the United States
2012	CERN	ATLAS and CMS experiments at the Super Hadron Collider discover a particle consistent with the Higgs boson, supporting the Higgs field theory of particle mass and leading to François Englert and Peter Higgs receiving the Nobel Prize in physics the following year
2015	USB Implementers Forum	Introduction of Thunderbolt 3 Active Cable USB standard, with 40 Gbps data rate and 100W maximum power, compared to the 1995 USB 1.1 standard with 12 Mbps data rate and 2.5 W maximum power
2016	MIT	Researchers announce the construction a 5-atom quantum computer
2017	Kingston Digital	Announcement of a 2 TB flash drive product, with a $942.50 price tag, at the 2017 Consumer Electronics Show
2018	Blu-Ray Disc Association	Release of v. 3.2 of the 4K Ultra HD standard, superseding previous standards released in 2015 and 2016

YEAR	NAME	EVENT
2019	Google AI NASA	Publication of paper claiming that quantum computing could solve certain problems, such as factoring operations fundamental to data encryption, that are computationally unfeasible using conventional computing methods
2020	Internet	An estimated 4.5 billion people are active Internet users, compared to 16 million 25 years early (an average 34% annual growth rate)

Acknowledgments

Many excellent reviews and surveys have contributed to this revision of *Electronics Fundamentals: Circuits, Devices, and Applications*. It has been thoroughly reviewed and checked for both content and accuracy. Our thanks go to each of the reviewers and survey participants.

Many people at Pearson Education have also contributed significantly to this project throughout the many phases of development and production and keeping the project "on track." Key people include Tara Warrens and Deepali Malhotra; all are dedicated professionals and we thank them for the support. We also express our appreciation to the hard work and support of Ashwina Ragounath of Integra for her effort to turn the manuscript into the product in your hands now. We thank Mark Walters at National Instruments Corporation and Kaitlyn Franz at Digilent for their assistance in preparing the Multisim appendix. Our thanks to all.

Thomas L. Floyd
David M. Buchla
Gary D. Snyder

PART 1

DC Circuits

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Quantities and Units

1

CHAPTER OUTLINE

CHAPTER OBJECTIVES

- Use scientific notation to represent quantities
- Work with electrical units and metric prefixes
- Convert from one unit with a metric prefix to another
- Use a typical scientific calculator to represent numbers in fixed point, scientific, and engineering notations
- Express measured data with the proper number of significant digits
- Use a typical scientific calculator to display a desired number of significant digits
- Recognize electrical hazards and practice proper safety procedures

KEY TERMS

- Scientific notation
- Power of ten
- Exponent
- Engineering notation
- SI
- Metric prefix
- Error
- Accuracy
- Precision
- Significant digit
- Round off
- Electrical shock

APPLICATION ASSIGNMENT PREVIEW

At the beginning of each chapter starting with Chapter 2, you will find an application assignment preview that relates to that chapter. The application assignments described by the previews present a variety of practical situations that you might encounter in industry.

As you study each chapter, think about how to approach the application assignment that appears as the last section in each chapter. When you have completed each chapter, you should have a sufficient knowledge of the topics covered to enable you to complete the assignment.

VISIT THE COMPANION WEBSITE

Study aids for this chapter are available at https://www.pearson.com/us/higher-education.html

INTRODUCTION

You must be familiar with the units used in electronics and know how to express electrical quantities in various ways using metric prefixes. Scientific notation and engineering notation are indispensable tools whether you use a computer, a calculator, or do computations the old-fashioned way.

1–1 Scientific and Engineering Notation

In the electrical and electronics fields, you will encounter both very small and very large quantities. For example, electrical current can range from hundreds of amperes in power applications to a few thousandths or millionths of an ampere in many electronic circuits. This range of values is typical of many other electrical quantities also. Engineering notation is a specialized form of scientific notation that is used widely in technical fields to express large and small quantities. In electronics, engineering notation is used to express values of voltage, current, power, resistance, and other quantities.

After completing this section, you should be able to

- **Use scientific notation to represent quantities**
  - Express any number using a power of ten
  - Perform calculations with powers of ten

Scientific notation* provides a convenient method for expressing large and small numbers and for performing calculations involving such numbers. In scientific notation, a quantity is expressed as a product of a number between 1 and 10 (one digit to the left of the decimal point) and a power of ten. For example, the quantity 150,000 is expressed in scientific notation as 1.5×10^5, and the quantity 0.00022 is expressed as 2.2×10^{-4}.

Powers of Ten

Table 1–1 lists some powers of ten, both positive and negative, and the corresponding decimal numbers. The **power of ten** is expressed as an *exponent* of the *base* 10 in each case.

Base ↘ ↙ Exponent

$$10^x$$

An **exponent** is a value to which a base number is raised. The exponent indicates the number of places that the decimal point is moved to the right or left to produce the decimal number. For a positive power of ten, move the decimal point to the right to get the equivalent decimal number. As an example, for an exponent of 4,

$$10^4 = 1 \times 10^4 = 1.0000. = 10,000.$$

▶ **TABLE 1–1**

Some positive and negative powers of ten.

$10^6 = 1,000,000$	$10^{-6} = 0.000001$
$10^5 = 100,000$	$10^{-5} = 0.00001$
$10^4 = 10,000$	$10^{-4} = 0.0001$
$10^3 = 1,000$	$10^{-3} = 0.001$
$10^2 = 100$	$10^{-2} = 0.01$
$10^1 = 10$	$10^{-1} = 0.1$
$10^0 = 1$	

***All bold terms are in the end-of-book glossary. The bold terms in color are key terms and are also defined at the end of the chapter.**

For a negative power of ten, move the decimal point to the left to get the equivalent decimal number. As an example, for an exponent of –4,

$$10^{-4} = 1 \times 10^{-4} = .0001. = 0.0001$$

The negative exponent does not indicate that a number is negative; it simply moves the decimal point to the left.

EXAMPLE 1–1

Express each number in scientific notation:

(a) 240 **(b)** 5100 **(c)** 85,000 **(d)** 3,350,000

Solution In each case, move the decimal point an appropriate number of places to the left to determine the positive power of ten.

(a) $240 = \mathbf{2.4 \times 10^2}$ **(b)** $5100 = \mathbf{5.1 \times 10^3}$

(c) $85{,}000 = \mathbf{8.5 \times 10^4}$ **(d)** $3{,}350{,}000 = \mathbf{3.35 \times 10^6}$

*Related Problem** Express 750,000,000 in scientific notation.

Work through the conversion examples in Example 1–1 of *Introduction to Scientific Calculators*.

*Answers are at the end of the chapter.

EXAMPLE 1–2

Express each number in scientific notation:

(a) 0.24 **(b)** 0.005 **(c)** 0.00063 **(d)** 0.000015

Solution In each case, move the decimal point an appropriate number of places to the right to determine the negative power of ten.

(a) $0.24 = \mathbf{2.4 \times 10^{-1}}$ **(b)** $0.005 = \mathbf{5 \times 10^{-3}}$

(c) $0.00063 = \mathbf{6.3 \times 10^{-4}}$ **(d)** $0.000015 = \mathbf{1.5 \times 10^{-5}}$

Related Problem Express 0.00000093 in scientific notation.

Work through the conversion examples in Example 1–2 of *Introduction to Scientific Calculators*.

EXAMPLE 1–3

Express each of the following numbers as a normal decimal number:

(a) 1×10^5 **(b)** 2.9×10^3 **(c)** 3.2×10^{-2} **(d)** 2.5×10^{-6}

Solution Move the decimal point to the right or left a number of places indicated by the positive or the negative power of ten, respectively.

(a) $1 \times 10^5 = \mathbf{100{,}000}$ **(b)** $2.9 \times 10^3 = \mathbf{2900}$

(c) $3.2 \times 10^{-2} = \mathbf{0.032}$ **(d)** $2.5 \times 10^{-6} = \mathbf{0.0000025}$

Related Problem Express 8.2×10^8 as a normal decimal number.

Work through the conversion examples in Example 1–3 of *Introduction to Scientific Calculators*.

Calculations with Powers of Ten

The advantage of scientific notation is in addition, subtraction, multiplication, and division of very small or very large numbers.

Addition The steps for adding numbers in powers of ten are as follows:

1. Express the numbers to be added in the same power of ten.
2. Add the numbers without their powers of ten to get the sum.
3. Bring down the common power of ten, which becomes the power of ten of the sum.

After performing any arithmetic operation, you may need to modify the number and exponent to conform to the scientific or engineering notation format you need.

EXAMPLE 1–4

Add 2×10^6 and 5×10^7 and express the result in scientific notation.

Solution

1. Express both numbers in the same power of ten: $(2 \times 10^6) + (50 \times 10^6)$.
2. Add $2 + 50 = 52$
3. Bring down the common power of ten (10^6); the sum is 52×10^6.

You can express this answer in scientific notation as $\mathbf{5.2 \times 10^7}$.

Related Problem Add 4.1×10^3 and 7.9×10^2.

Work through the addition example in Example 1–4 of *Introduction to Scientific Calculators*.

Subtraction The steps for subtracting numbers in powers of ten are as follows:

1. Express the numbers to be subtracted in the same power of ten.
2. Subtract the numbers without their powers of ten to get the difference.
3. Bring down the common power of ten, which becomes the power of ten of the difference.
4. If the difference is less than 1, modify the number to be between 1 and 10 and adjust the exponent accordingly.

EXAMPLE 1–5

Subtract 2.5×10^{-12} from 7.5×10^{-11} and express the result in scientific notation.

Solution

1. Express each number in the same power of ten: $(7.5 \times 10^{-11}) - (0.25 \times 10^{-11})$.
2. Subtract $7.5 - 0.25 = 7.25$.
3. Bring down the common power of ten (10^{-11}); the difference is $\mathbf{7.25 \times 10^{-11}}$.

Related Problem Subtract 3.5×10^{-6} from 2.2×10^{-5}.

Work through the subtraction example in Example 1–5 of *Introduction to Scientific Calculators*.

Multiplication The steps for multiplying numbers in powers of ten are as follows:

1. Multiply the numbers directly without their powers of ten.
2. Add the powers of ten algebraically (the exponents do not have to be the same).

EXAMPLE 1–6

Multiply 5.0×10^{12} by 3.0×10^{-6} and express the result in scientific notation.

Solution Multiply the numbers, and algebraically add the powers.

$$(5.0 \times 10^{12})(3.0 \times 10^{-6}) = 15 \times 10^{12+(-6)} = 15 \times 10^{6} = \mathbf{1.5 \times 10^{7}}$$

Related Problem Multiply 1.2×10^{3} by 4.0×10^{2}.

Work through the multiplication example in Example 1–6 of *Introduction to Scientific Calculators*.

Division The steps for dividing numbers in powers of ten are as follows:

1. Divide the numbers directly without their powers of ten.
2. Subtract the power of ten in the denominator from the power of ten in the numerator (the exponents do not have to be the same).

EXAMPLE 1–7

Divide 5.0×10^{8} by 2.5×10^{3} and express the result in scientific notation.

Solution Write the division problem with a numerator and denominator.

$$\frac{5.0 \times 10^{8}}{2.5 \times 10^{3}}$$

Divide the numbers and subtract the powers of ten (3 from 8).

$$\frac{5.0 \times 10^{8}}{2.5 \times 10^{8}} = 2.0 \times 10^{8-3} = \mathbf{2.0 \times 10^{5}}$$

Related Problem Divide 8.0×10^{-6} by 2.0×10^{-10}.

Work through the division example in Example 1–7 of *Introduction to Scientific Calculators*.

Scientific Notation on a Calculator Entering a number in scientific notation is accomplished on most calculators using the EE key as follows: Enter the number with one digit to the left of the decimal point, press EE, and enter the power of ten. This method requires that the power of ten be determined before entering the number. Some calculators can be placed in a mode that will automatically convert any decimal number entered into scientific notation.

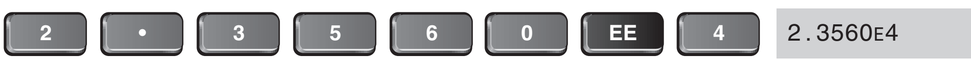
EXAMPLE 1–8

Enter 23,560 in scientific notation using the EE key.

Solution Move the decimal point four places to the left so that it comes after the digit 2. This results in the number expressed in scientific notation as

$$2.3560 \times 10^{4}$$

Enter this number on your calculator as follows:



Related Problem Enter the number 573,946 using the EE key.

Work through the number entry example in Example 1–8 of *Introduction to Scientific Calculators*.

Engineering Notation

Engineering notation is similar to scientific notation. However, in **engineering notation** a number can have from one to three digits to the left of the decimal point and the power-of-ten exponent must be a multiple of three. For example, the number 33,000 expressed in engineering notation is 33×10^3. In scientific notation, it is expressed as 3.3×10^4. As another example, the number 0.045 is expressed in engineering notation as 45×10^{-3}. In scientific notation, it is expressed as 4.5×10^{-2}. Engineering notation is useful in electrical and electronic calculations that use metric prefixes (discussed in Section 1–2).

EXAMPLE 1–9

Express the following numbers in engineering notation:

(a) 82,000 **(b)** 243,000 **(c)** 1,956,000

Solution In engineering notation,

(a) 82,000 is expressed as $\mathbf{82 \times 10^3}$.

(b) 243,000 is expressed as $\mathbf{243 \times 10^3}$.

(c) 1,956,000 is expressed as $\mathbf{1.956 \times 10^6}$.

Related Problem Express 36,000,000,000 in engineering notation.

Work through the engineering notation examples in Example 1–9 of *Introduction to Scientific Calculators*.

EXAMPLE 1–10

Convert each of the following numbers to engineering notation:

(a) 0.0022 **(b)** 0.000000047 **(c)** 0.00033

Solution In engineering notation,

(a) 0.0022 is expressed as $\mathbf{2.2 \times 10^{-3}}$.

(b) 0.000000047 is expressed as $\mathbf{47 \times 10^{-9}}$.

(c) 0.00033 is expressed as $\mathbf{330 \times 10^{-6}}$.

Related Problem Express 0.0000000000056 in engineering notation.

Work through the engineering notation examples in Example 1–10 of *Introduction to Scientific Calculators*.

Engineering Notation on a Calculator Use the EE key to enter the number with one, two, or three digits to the left of the decimal point, press EE, and enter the power of ten that is a multiple of three. This method requires that the appropriate power of ten be determined before entering the number.

EXAMPLE 1–11

Enter 51,200,000 in engineering notation using the EE key.

Solution Move the decimal point six places to the left so that it comes between the digits 1 and 2. This results in the number expressed in engineering notation as

$$51.2 \times 10^6$$

Enter this number on your calculator as follows:

5 1 • 2 EE 6   51.2E6

Related Problem Enter the number 273,900 in engineering notation using the EE key.
Work through the engineering notation entry examples in Example 1–11 of *Introduction to Scientific Calculators*.

SECTION 1–1 CHECKUP
Answers are at the end of the chapter.

1. Scientific notation uses powers of ten. (True or False)
2. Express 100 as a power of ten.
3. Express the following numbers in scientific notation:
   (a) 4350 **(b)** 12,010 **(c)** 29,000,000
4. Express the following numbers in scientific notation:
   (a) 0.760 **(b)** 0.00025 **(c)** 0.000000597
5. Do the following operations:
   (a) $(1.0 \times 10^5) + (2.0 \times 10^5)$
   (b) $(3.0 \times 10^6)(2.0 \times 10^4)$
   (c) $(8.0 \times 10^3) \div (4.0 \times 10^2)$
   (d) $(2.5 \times 10^{-6}) - (1.3 \times 10^{-7})$
6. Enter the numbers expressed in scientific notation in Problem 3 into your calculator.
7. Express the following numbers in engineering notation:
   (a) 0.0056
   (b) 0.0000000283
   (c) 950,000
   (d) 375,000,000,000
8. Enter the numbers in Problem 7 into your calculator using engineering notation.

1–2 UNITS AND METRIC PREFIXES

In electronics, you must deal with measurable quantities. For example, you must be able to express how many volts are measured at a certain test point in a circuit, how much current there is through a conductor, or how much power a certain amplifier delivers. In this section, you are introduced to the units and symbols for most of the electrical quantities that are used throughout the book. Metric prefixes are used in conjunction with engineering notation as a "shorthand" for the certain powers of ten that commonly are used.

After completing this section, you should be able to

- **Work with electrical units and metric prefixes**
  - Name the units for twelve electrical quantities
  - Specify the symbols for the electrical units
  - List the metric prefixes
  - Change a power of ten in engineering notation to a metric prefix
  - Use metric prefixes to express electrical quantities

QUANTITY	SYMBOL	SI UNIT	SYMBOL
capacitance	*C*	farad	F
charge	*Q*	coulomb	C
conductance	*G*	siemens	S
current	*I*	ampere	A
energy or work	*W*	joule	J
frequency	*f*	hertz	Hz
impedance	*Z*	ohm	Ω
inductance	*L*	henry	H
power	*P*	watt	W
reactance	*X*	ohm	Ω
resistance	*R*	ohm	Ω
voltage	*V*	volt	V

◀ **TABLE 1–2**

Electrical quantities and their corresponding units with SI symbols.

Electrical Units

Letter symbols are used in electronics to represent both quantities and their units. One symbol is used to represent the name of the quantity, and another is used to represent the unit of measurement of that quantity. Table 1–2 lists the most important electrical quantities, along with their SI units and symbols. For example, italic *P* stands for *power* and nonitalic (roman) W stands for *watt*, which is the unit of power. In general, italic letters represent quantities and nonitalic letters represent units. Notice that energy is abbreviated with an italic *W* that represents *work*, and both *energy* and *work* have the same unit (the joule). The term **SI** is the French abbreviation for *International System* (*Système International* in French).

In addition to the common electrical units shown in Table 1–2, the SI system has many other units that are defined in terms of certain *base* (or fundamental) *units*. In 1954, by international agreement, *meter*, *kilogram*, *second*, *ampere*, *degree kelvin*, and *candela* were adopted as the basic SI units (*degree kelvin* was later changed to just *kelvin*). These units form the basis of the mks (for meter-kilogram-second) units from which all other units are derived and have become the preferred units for nearly all scientific and engineering work. Over the years, the definition for base units have changed as measurements became more precise. The latest definitions for the base units were put into effect in May of 2019 using physical constants of nature. This means that base units now can be replicated directly from the definitions by standards laboratories all over the world, rather than calibrated using primary and secondary physical standards.

An older metric system, called the cgs system, was based on the centimeter, gram, and second as base units. There are still a number of units in common use based on the cgs system. For example, the gauss is a magnetic flux unit in the cgs system and is still in common usage. In keeping with preferred practice, this text uses mks units, except when otherwise noted.

Metric Prefixes

In engineering notation **metric prefixes** represent each of the most commonly used powers of ten. These metric prefixes are listed in Table 1–3 with their symbols and corresponding powers of ten.

Metric prefixes are used only with numbers that have a unit of measure, such as volts, amperes, and ohms, and precede the unit symbol. For example, 0.025 amperes

▶ **TABLE 1–3**

Metric prefixes with their symbols and corresponding powers of ten and values.

METRIC PREFIX	SYMBOL	POWER OF TEN	VALUE
femto	f	10^{-15}	one-quadrillionth
pico	p	10^{-12}	one-trillionth
nano	n	10^{-9}	one-billionth
micro	μ	10^{-6}	one-millionth
milli	m	10^{-3}	one-thousandth
kilo	k	10^{3}	one thousand
mega	M	10^{6}	one million
giga	G	10^{9}	one billion
tera	T	10^{12}	one trillion

can be expressed in engineering notation as 25×10^{-3} A. This quantity expressed using a metric prefix is 25 mA, which is read 25 milliamps. The metric prefix *milli* has replaced 10^{-3}. As another example, 10,000,000 ohms can be expressed as $10 \times 10^{6}\ \Omega$. This quantity expressed using a metric prefix is 10 MΩ, which is read 10 megohms. The metric prefix *mega* has replaced 10^{6}.

EXAMPLE 1–12

Express each quantity using a metric prefix:

(a) 50,000 V **(b)** 25,000,000 Ω **(c)** 0.000036 A

Solution

(a) $50{,}000\ \text{V} = 50 \times 10^{3}\ \text{V} = \mathbf{50\ kV}$ **(b)** $25{,}000{,}000\ \Omega = 25 \times 10^{6}\ \Omega = \mathbf{25\ M\Omega}$

(c) $0.000036\ \text{A} = 36 \times 10^{-6}\ \text{A} = \mathbf{36\ \mu A}$

Related Problem

Express each quantity using metric prefixes:

(a) 56,000,000 Ω **(b)** 0.000470 A

Work through the metric prefix examples in Example 1–12 of *Introduction to Scientific Calculators*.

SECTION 1–2 CHECKUP

1. List the metric prefix for each of the following powers of ten: 10^{6}, 10^{3}, 10^{-3}, 10^{-6}, 10^{-9}, and 10^{-12}.
2. Use a metric prefix to express 0.000001 A.
3. Use a metric prefix to express 250,000 W.

1–3 METRIC UNIT CONVERSIONS

It is sometimes necessary or convenient to convert a quantity from one unit with a metric prefix to another, such as from milliamperes (mA) to microamperes (μA). Moving the decimal point in the number an appropriate number of places to the left or to the right, depending on the particular conversion, results in a metric unit conversion.

After completing this section, you should be able to

- **Convert from one unit with a metric prefix to another**
  - Convert between milli, micro, nano, and pico
  - Convert between kilo and mega

The following basic rules apply to metric unit conversions:

1. When converting from a larger unit to a smaller unit, move the decimal point to the right.
2. When converting from a smaller unit to a larger unit, move the decimal point to the left.
3. Determine the number of places to move the decimal point by finding the difference in the powers of ten of the units being converted.

For example, when converting from milliamperes (mA) to microamperes (μA), move the decimal point three places to the right because there is a three-place difference between the two units (mA is 10^{-3} A and μA is 10^{-6} A). The following examples illustrate a few conversions.

EXAMPLE 1–13 Convert 0.15 milliampere (0.15 mA) to microamperes (μA).

Solution Move the decimal point three places to the right.

$$0.15\text{ mA} = 0.15 \times 10^{-3}\text{ A} = 150 \times 10^{-6}\text{ A} = \mathbf{150\ \mu A}$$

Related Problem Convert 1.0 mA to microamperes.

Work through the metric unit conversion example in Example 1–13 of *Introduction to Scientific Calculators*.

EXAMPLE 1–14 Convert 4500 microvolts (4500 μV) to millivolts (mV).

Solution Move the decimal point three places to the left.

$$4500\ \mu\text{V} = 4500 \times 10^{-6}\text{ V} = 4.5 \times 10^{-3}\text{ V} = \mathbf{4.5\ mV}$$

Related Problem Convert 1000 μV to millivolts.

Work through the metric unit conversion example in Example 1–14 of *Introduction to Scientific Calculators*.

EXAMPLE 1–15 Convert 5000 nanoamperes (5000 nA) to microamperes (μA).

Solution Move the decimal point three places to the left.

$5000 \text{ nA} = 5000 \times 10^{-9} \text{ A} = 5.0 \times 10^{-6} \text{ A} = \mathbf{5.0\ \mu A}$

Related Problem Convert 893 nA to microamperes.

Work through the metric unit conversion example in Example 1–15 of *Introduction to Scientific Calculators*.

EXAMPLE 1–16 Convert 47,000 picofarads (47,000 pF) to microfarads (μF).

Solution Move the decimal point six places to the left.

$47{,}000 \text{ pF} = 47{,}000 \times 10^{-12} \text{ F} = 0.047 \times 10^{-6} \text{ F} = \mathbf{0.047\ \mu F}$

Related Problem Convert 10,000 pF to microfarads.

Work through the metric unit conversion example in Example 1–16 of *Introduction to Scientific Calculators*.

EXAMPLE 1–17 Convert 0.00022 microfarad (0.00022 μF) to picofarads (pF).

Solution Move the decimal point six places to the right.

$0.00022\ \mu\text{F} = 0.00022 \times 10^{-6} \text{ F} = 220 \times 10^{-12} \text{ F} = \mathbf{220\ pF}$

Related Problem Convert 0.0022 μF to picofarads.

Work through the metric unit conversion example in Example 1–17 of *Introduction to Scientific Calculators*.

EXAMPLE 1–18 Convert 1800 kilohms (1800 kΩ) to megohms (MΩ).

Solution Move the decimal point three places to the left.

$1800 \text{ k}\Omega = 1800 \times 10^{3}\ \Omega = 1.8 \times 10^{6}\ \Omega = \mathbf{1.8\ M\Omega}$

Related Problem Convert 2.2 kΩ to megohms.

Work through the metric unit conversion example in Example 1–18 of *Introduction to Scientific Calculators*.

When adding (or subtracting) quantities with different metric prefixes, first convert one of the quantities to the same prefix as the other quantity.

EXAMPLE 1–19 Add 15 mA and 8000 μA and express the result in milliamperes.

Solution Convert 8000 μA to 8.0 mA and add.

$$15 \text{ mA} + 8000 \text{ μA} = 15 \text{ mA} + 8.0 \text{ mA} = \mathbf{23 \text{ mA}}$$

Related Problem Add 2873 mA and 10,000 μA.

Work through the metric unit addition example in Example 1–19 of *Introduction to Scientific Calculators*.

SECTION 1–3 CHECKUP

1. Convert 0.01 MV to kilovolts (kV).
2. Convert 250,000 pA to milliamperes (mA).
3. Add 0.05 MW and 75 kW and express the result in kW.
4. Add 50 mV and 25,000 μV and express the result in mV.

1–4 MEASURED NUMBERS

Whenever a quantity is measured, there is uncertainty in the result due to limitations of the instruments used. When a measured quantity contains approximate numbers, the digits known to be correct are called significant digits. When reporting measured quantities, the number of digits that should be retained are the significant digits and no more than one uncertain digit.

After completing this section, you should be able to

- **Express measured data with the proper number of significant digits**
  - Define *accuracy*, *error*, and *precision*
  - Round numbers properly

Error, Accuracy, and Precision

Data taken in experiments are not perfect because the accuracy of the data depends on the accuracy of the test equipment and the conditions under which the measurement was made. In order to properly report measured data, the error associated with the measurement should be taken into account. Experimental error should not be thought of as a mistake. All measurements that do not involve counting are approximations of the true value. The difference between the true or best-accepted value of some quantity and the measured value is the **error**. A measurement is said to be accurate if the error is small. **Accuracy** is an indication of the range of error in a measurement. For example, if you measure thickness of a 10.00 mm gauge block with a micrometer and find that it is 10.8 mm, the reading is not accurate because a gauge block is considered to be a working standard. If you measure 10.02 mm, the reading is accurate because it is in reasonable agreement with the standard.

Another term associated with the quality of a measurement is *precision*. **Precision** is a measure of the repeatability (or consistency) of a measurement of some quantity. It is possible to have a precise measurement in which a series of readings are not scattered, but each measurement is inaccurate because of an instrument error. For example, a meter may be out of calibration and produce inaccurate but consistent (precise) results. However, it is not possible to have an accurate instrument unless it is also precise.

Significant Digits

The digits in a measured number that are known to be correct are called **significant digits**. Most measuring instruments show the proper number of significant digits, but some instruments can show digits that are not significant, leaving it to the user to determine what should be reported. This may occur because of an effect called *loading* (discussed in Section 6–4). A meter can change the actual reading in a circuit by its very presence. It is important to recognize when a reading may be inaccurate; you should not report digits that are known to be inaccurate.

Another problem with significant digits occurs when you perform mathematical operations with numbers. The number of significant digits should never exceed the number in the original measurement. For example, if 1.0 V is divided by 3.0 Ω, a calculator will show 0.33333333. Since the original numbers each contain 2 significant digits, the answer should be reported as 0.33 A, the same number of significant digits.

The rules for determining if a reported digit is significant are

1. Nonzero digits are always considered to be significant.
2. Zeros to the left of the first nonzero digit are never significant.
3. Zeros between nonzero digits are always significant.
4. Zeros to the right of the decimal point for a decimal number are significant.
5. Zeros to the left of the decimal point with a whole number may or may not be significant depending on the measurement. For example, the number 12,100 Ω can have 3, 4, or 5 significant digits. To clarify the significant digits, scientific notation (or a metric prefix) should be used. For example, 12.10 kΩ has 4 significant digits.

When a measured value is reported, one uncertain digit may be retained but other uncertain digits should be discarded. To find the number of significant digits in a number, ignore the decimal point, and count the number of digits from left to right starting with the first nonzero digit and ending with the last digit to the right. All of the digits counted are significant except zeros to the right end of the number, which may or may not be significant. In the absence of other information, the significance of the right-hand zeros is uncertain. Generally, zeros that are placeholders, and not part of a measurement, are considered to be not significant. To avoid confusion, numbers should be shown using scientific or engineering notation if it is necessary to show the significant zeros.

EXAMPLE 1–20

Express the measured number 4300 with 2, 3, and 4 significant digits.

Solution

Zeros to the right of the decimal point in a decimal number are significant. Therefore, to show two significant digits, write

$$\mathbf{4.3 \times 10^3}$$

To show three significant digits, write

$$\mathbf{4.30 \times 10^3}$$

To show four significant digits, write

$$\mathbf{4.300 \times 10^3}$$

Related Problem

How would you show the number 10,000 showing three significant digits?

Work through the significant digits example in Example 1–20 of *Introduction to Scientific Calculators*.

EXAMPLE 1–21

Underline the significant digits in each of the following measurements:

(a) 40.0 **(b)** 0.3040 **(c)** 1.20×10^5 **(d)** 120,000 **(e)** 0.00502

Solution

(a) 40.0 has three significant digits; see rule 4.

(b) 0.3040 has four significant digits; see rules 2 and 3.

(c) 1.20×10^5 has three significant digits; see rule 4.

(d) 120,000 has at least two significant digits. Although the number has the same value as in (c), zeros in this example are uncertain; see rule 5. This is *not* a recommended method for reporting a measured quantity; use scientific notation or a metric prefix in this case. See Example 1–20.

(e) 0.00502 has three significant digits; see rules 2 and 3.

Related Problem What is the difference between a measured quantity of 10 and 10.0?

Rounding Off Numbers

Since they always contain approximate numbers, measurements should be shown only with those digits that are significant plus no more than one uncertain digit. The number of digits shown is indicative of the precision of the measurement. For this reason, you should **round off** a number by dropping one or more digits to the right of the last significant digit. Use only the most significant dropped digit to decide how to round off. The rules for rounding off are

1. If the most significant digit dropped is greater than 5 or a 5 is followed by any nonzero digits, increase the last retained digit by 1.
2. If the most significant digit dropped is less than 5, do not change the last retained digit.
3. If the most significant digit dropped is 5 and there are no following nonzero digits, increase the last retained digit by 1 *if* it makes the number even. If it makes the number odd, do not change the retained digit. This is called the "round-to-even" rule.

EXAMPLE 1–22

Round each of the following numbers to three significant digits:

(a) 10.071 **(b)** 29.961 **(c)** 6.3948 **(d)** 123.52 **(e)** 122.5

Solution

(a) 10.071 rounds to **10.1**. **(b)** 29.961 rounds to **30.0**.

(c) 6.3948 rounds to **6.39**. **(d)** 123.52 rounds to **124**.

(e) 122.5 rounds to **122**.

Related Problem Round 3.2850 to three significant digits using the round-to-even rule.

In most electrical and electronics work, components have tolerances greater than 1% (5% and 10% are common). Most measuring instruments have accuracy specifications better than this, but it is unusual for measurements to be made with higher accuracy than 1 part in 1000. For this reason, three significant digits are appropriate for numbers that represent measured quantities in all but the most exacting work. If you are working with a problem with several intermediate results, keep all digits in your calculator, but round the answers to three when reporting a result.

SECTION 1–4 CHECKUP

1. What is the rule for showing zeros to the right of the decimal point?
2. What is the round-to-even rule?
3. On schematics, you will frequently see a 1000 Ω resistor listed as 1.0 kΩ. What does this imply about the value of the resistor?
4. If a power supply is required to be set to 10.00 V, what does this imply about the accuracy needed for the measuring instrument?
5. How can scientific or engineering notation be used to show the correct number of significant digits in a measurement?

1–5 Electrical Safety

Safety is a major concern when working with electricity. The possibility of an electric shock or a burn is always present, so caution should always be used. You provide a current path when voltage is applied across two points on your body, and current produces electrical shock. Electrical components often operate at high temperatures, so you can sustain skin burns when you come in contact with them. Also, the presence of electricity creates a potential fire hazard. This section will cover general electrical safety. Sections in subsequent chapters will cover safety topics specific to the topic being discussed.

After completing this section, you should be able to

- **Recognize electrical hazards and practice proper safety procedures**
  - Describe the cause of electrical shock
  - List the groups of current paths through the body
  - Discuss the effects of current on the human body
  - List general safety precautions that you should observe when you work with electricity

Electrical Shock

Current through your body, not the voltage, is the cause of **electrical shock**. Of course, it takes voltage across a resistance to produce current. When a point on your body comes in contact with a voltage and another point comes in contact with a different voltage or with ground, such as a metal chassis, there will be current through your body from one point to the other. The path of the current depends on the points across which the voltage occurs. The severity of the resulting electrical shock depends on the amount of voltage and the path that the current takes through your body.

The current path through the body determines which tissues and organs will be affected. The current paths can be placed into three groups which are referred to as *touch potential, step potential,* and *touch/step potential.* These are illustrated in Figure 1–1.

Effects of Current on the Human Body The amount of current depends on the amount of voltage and resistance of the current path. The human body has resistance that depends on many factors, which include body mass, skin moisture, and points

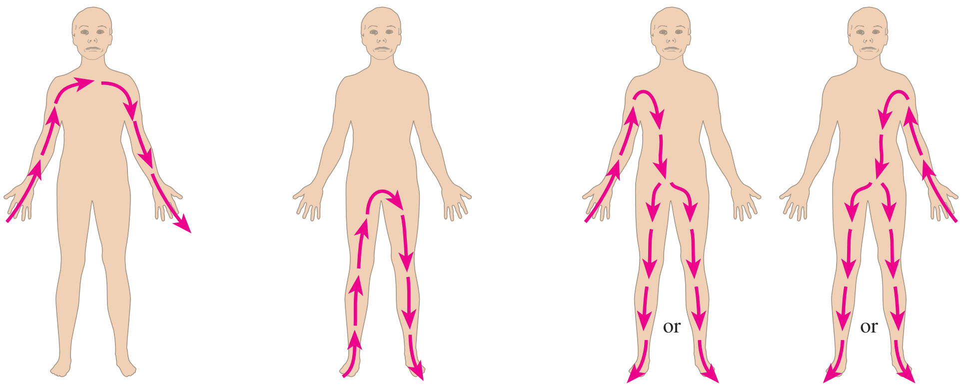


FIGURE 1–1

Shock hazard in terms of three basic current path groups.

of contact of the body with a voltage potential. Table 1–4 shows the effects for various values of current in milliamperes. Note that the “let go” threshold of 16 mA is especially critical, because at or above this level muscles in the current path contract so severely that the shock victim is unable to break contact with the voltage source without assistance.

TABLE 1–4

Physical effects of electrical current. Values vary depending on body.

CURRENT (mA)	PHYSICAL EFFECT
0.4	Slight sensation
1.1	Perception threshold
1.8	Shock, no pain, no loss of muscular control
9	Painful shock, no loss of muscular control
16	Painful shock, let-go threshold
23	Severe painful shock, muscular contractions, breathing difficulty
75	Ventricular fibrillation, threshold
235	Ventricular fibrillation, usually fatal for duration of 5 seconds or more
4000	Heart paralysis (no ventricular fibrillation)
5000	Tissue burn

Body Resistance Resistance of the human body is typically between 10 kΩ and 50 kΩ and depends on the two points between which it is measured as well as the moisture of the skin between the two contact points. The resistance determines the amount of voltage required to produce each of the effects listed in Table 1–4. For example, if you have a resistance of 10 kΩ between two given points on your body, 90 V across those two points will produce enough current (9.0 mA) to cause painful shock.

Utility Voltages

We tend to take utility voltages for granted, but they can be and have been lethal. It is best to be careful around any source of voltage (even low voltages can present a serious burn hazard). As a general rule, you should avoid working on any energized circuit, and verify that the power is off with a known good meter. Most work in educational labs uses low voltages, but you still should avoid touching any energized circuit. If you are working on a circuit that is connected to utility voltages, the service should be disconnected, a notice should be placed on the equipment or place where the service is disconnected, and a padlock should be used to prevent someone from accidentally turning on the power. This procedure is called *lockout/tagout* (or LOTO)

▲ **FIGURE 1–2**

Representative lockout/tagout notice and padlock.

and is widely used in industry. There are specific OSHA and industry standards for lockout/tagout. Figure 1–2 shows a representative lock and notice used for a lockout/tagout event.

Most laboratory equipment is connected to the utility line ("ac") and in North America, this is 120 V rms (rms is discussed in Section 8–2). A faulty piece of equipment inadvertently can cause the "hot" lead to become exposed. You should inspect cords for exposed wires and check equipment for missing covers or other potential safety problems. In the United States single-phase utility lines in homes and electrical laboratories use three insulated wires that are referred to as the "hot" (black or red wire), neutral (white wire), and safety ground (green wire). The hot and neutral wires will have current, but the green safety line should never have current in normal operation. The safety wire is connected to the metal exterior of encased equipment and is also connected to conduit and the metal boxes for housing receptacles. Figure 1–3 shows the location of these conductors on a standard receptacle. Notice on the receptacle that the neutral lead is larger than the hot lead.

The safety ground should be connected to the neutral at the service panel. The metal chassis of an instrument or appliance is also connected to ground. In the event that the hot wire accidentally contacts the ground connection, the resulting high current should trip the circuit breaker or open a fuse to remove the hazard. However, a broken or missing ground lead may not have high current until a person contacts it. This danger is one obvious reason for ensuring that line cords have not been altered by removing the ground pin.

Many circuits are further protected with a special device called a ground-fault circuit interrupter (GFCI, which is sometimes called just GFI). If a fault occurs in a GFCI circuit, a sensor detects that the current in the hot line and the neutral line are not equal as they should be and trips the circuit breaker. The GFCI breaker is very fast acting and can trip faster than the breaker on the main panel. GFCI breakers are required in areas where a shock hazard exists such as wherever there is water or moisture. Pools, bathrooms, kitchens, basements, and garages should all have GFCI outlets. Figure 1–4 shows a ground-fault receptacle with reset and test buttons. When the test button is pressed, the circuit immediately should open. The reset button restores power.

HANDS ON TIP

Focal point/ Shutterstock

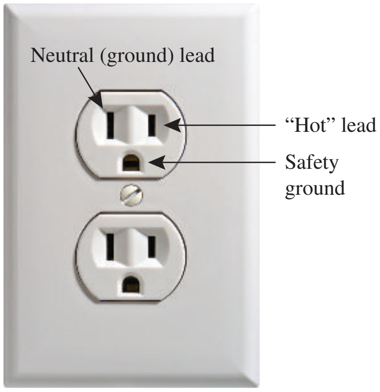
Receptacle testers are designed for use with specific receptacle types including specialized outlets. They can help trained personnel to pinpoint and identify problems such as open lines, faulty wiring, or reversed polarity by showing results with a lighted LED or neon bulb. Some testers are designed to test ground fault circuit interrupters (GFCI) for proper operation. Although electrical codes require that the wiring for polarized outlets connect the neutral (ground) wire to the larger slot and the hot wire to the smaller slot, this may not always be the case. Testing any new outlets or outlet strips with a receptacle tester before use is advisable.

Safety Precautions

There are many practical things that you should do when you work with electrical and electronic equipment. Some important precautions are listed here.

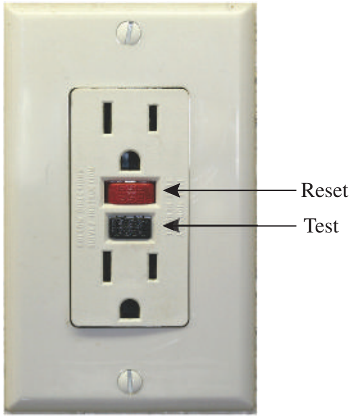
- Know and always follow safety practices for your workplace.
- Always follow any lockout/tagout (LOTO) policies for your workplace.
- Always treat electronic circuits as though they are energized. Even after you disconnect a circuit from power it can retain energy that can cause severe injury or death.
- Avoid working on circuits in wet conditions. Always wear shoes and keep them dry, do not stand on metal or wet floors when working on electrical circuits, and never handle instruments when your hands are wet.
- Ensure that your work area is free of any potential safety hazards. Report any unsafe conditions.
- Avoid contact with any voltage or current source. If the circuit on which you are working does not require power, turn off power before starting work.
- Always turn off power to circuits and equipment before leaving your work area unattended.

- Know the locations of any emergency power-off switches and emergency exits.
- Ensure that fire extinguishers in your area are rated for electrical fires and any other types of fire that could occur. Be sure that you or a designated safety officer is properly trained in the use of any emergency equipment.
- Know and use personal protective equipment (PPE) (safety glasses, insulated shoes, etc.) required for your work area and job duties.
- Never try to disable, defeat, or tamper with safety devices, such as an interlock switch or ground pin on a three-prong plug.
- Never remove any external or internal safety shields from areas of circuits that you do not need to access.
- Do not work with equipment until you know the proper procedures for doing so and are aware of potential hazards.
- Be sure to adjust power supplies to the proper levels before connecting them to and powering up circuits. Avoid connecting power supplies to circuits when the power is on (hot insertion). If you must connect a supply to a circuit while the supply is powered on, connect the higher voltage first.
- If you can adjust the current limit of your power supply, set the current limit to the lowest level that the circuit requires for safe and reliable operation.
- Never exceed the rated voltages or currents for test equipment.
- Do not work alone. A telephone or other means of communication should be available to report emergencies.
- Do not work when tired or taking medications that make you drowsy.
- Remove rings, watches, and other metallic jewelry that can come in contact with the circuit on which you are working.
- Make sure that all equipment that you are using is in good repair. In particular, ensure that power cords are in good condition and that grounding pins on the plug are not missing or bent. Remove from service and report any equipment that requires repair.
- Properly maintain your tools. Make sure that the insulation on metal tool handles is in good condition.
- Follow safe practices when using tools and maintain a neat work area.
- Always shut off power and properly discharge capacitors before you touch any part of a circuit with your hands. Never discharge a capacitor by shorting it.
- Always use insulated wires and connectors or clips with insulating shrouds when working with circuits.
- Keep cables and wires as short as possible. Connect polarized components properly.
- Do not have drinks or food near equipment.
- If another person cannot let go of an energized conductor, switch off the power to the equipment or the general area immediately. If that is not possible, use any available nonconductive object, such as a wooden broom handle or cane, to try to separate the body from the contact.



▲ FIGURE 1–3

Standard receptacle and connections.



▲ FIGURE 1–4

GFCI receptacle.

SAFETY NOTE

A GFCI outlet does not prevent shock or injury in all cases. If you are touching the hot and neutral wires without being grounded, no ground fault is detected and the GFCI breaker will not trip. In another case, the GFCI may prevent electrocution but not the initial electric shock before it interrupts the circuit. The initial shock could cause a secondary injury, such as from a fall.

SECTION 1–5 CHECKUP

1. What causes physical pain and/or damage to the body when electrical contact is made?
2. It's OK to wear a ring when working on an electrical circuit. (T or F)
3. Standing on a wet floor presents no safety hazard when working with electricity. (T or F)
4. A circuit can be rewired without removing the power if you are careful. (T or F)
5. Electrical shock can be extremely painful or even fatal. (T or F)
6. What does ***GFCI*** stand for?

SUMMARY

- Scientific notation is a method for expressing very large and very small numbers as a number between one and ten (one digit to left of decimal point) times a power of ten.
- Engineering notation is a form of scientific notation in which quantities are expressed with one, two, or three digits to the left of the decimal point times a power of ten that is a multiple of three.
- Metric prefixes are symbols used to represent powers of ten that are multiples of three.
- The uncertainty of a measured quantity depends on the accuracy and precision of the measurement.
- The number of significant digits in the result of a mathematical operation should never exceed the significant digits in the original numbers.
- Standard connections to electrical plugs include a hot wire, a neutral, and a safety ground.
- GFCI breakers sense the current in the hot wire and in the neutral wire and trip the breaker if they are different, indicating a ground fault.

KEY TERMS

These key terms are also defined in the end-of-book glossary.

Accuracy An indication of the range of error in a measurement.

Electrical shock The physical sensation resulting from current through the body.

Engineering notation A system for representing any number as a one-, two-, or three-digit number times a power of ten with an exponent that is a multiple of 3.

Error The difference between the true or best-accepted value of some quantity and the measured value.

Exponent The number to which a base number is raised.

Metric prefix A symbol that is used to replace the power of ten in numbers expressed in engineering notation.

Power of ten A numerical representation consisting of a base of 10 and an exponent; the number 10 raised to a power.

Precision A measure of the repeatability (or consistency) of a series of measurements.

Round off The process of dropping one or more digits to the right of the last significant digit in a number.

Scientific notation A system for representing any number as a number between 1 and 10 times an appropriate power of ten.

SI Standardized international system of units used for all engineering and scientific work; abbreviation for French *Le Systeme International d'Unites.*

Significant digit A digit known to be correct in a number.

TRUE/FALSE QUIZ

Answers are at the end of the chapter.

1. The number 3300 is written as 3.3×10^3 in both scientific and engineering notation.
2. A negative number that is expressed in scientific notation will always have a negative exponent.
3. When you multiply two numbers written in scientific notation, the exponents need to be the same.
4. When you divide two numbers written in scientific notation, the exponent of the denominator is subtracted from the exponent of the numerator.
5. The metric prefix *micro* has an equivalent power of ten equal to 10^6.
6. To express 56×10^6 with a metric prefix, the result is 56 M.
7. 0.047 μF is equal to 47 nF.
8. The number of significant digits in the number 0.0102 is three.
9. When you apply the *round-to-even* rule to round off 26.25 to three digits, the result is 26.3.
10. The white neutral lead for ac power should have the same current as the hot lead.

SELF-TEST

Answers are at the end of the chapter.

1. The quantity 4.7×10^{-3} is the same as
   (a) 470 **(b)** 4700 **(c)** 47,000 **(d)** 0.0047
2. The quantity 56×10^{-3} is the same as
   (a) 0.056 **(b)** 0.560 **(c)** 560 **(d)** 56,000
3. The number 3,300,000 can be expressed in engineering notation as
   (a) 3300×10^3 **(b)** 3.3×10^{-6} **(c)** 3.3×10^6 **(d)** either (a) or (c)
4. Ten milliamperes can be expressed as
   (a) 10 MA **(b)** 10 μA **(c)** 10 kA **(d)** 10 mA
5. Five thousand volts can be expressed as
   (a) 5000 V **(b)** 5.0 MV **(c)** 5.0 kV **(d)** either (a) or (c)
6. Twenty million ohms can be expressed as
   (a) 20 mΩ **(b)** 20 MW **(c)** 20 MΩ **(d)** 20 μΩ
7. 15,000 W is the same as
   (a) 15 mW **(b)** 15 kW **(c)** 15 MW **(d)** 15 μW
8. Which of the following is not an electrical quantity?
   (a) current **(b)** voltage **(c)** time **(d)** power
9. The unit of current is
   (a) volt **(b)** watt **(c)** ampere **(d)** joule
10. The unit of voltage is
    (a) ohm **(b)** watt **(c)** volt **(d)** farad
11. The unit of resistance is
    (a) ampere **(b)** henry **(c)** hertz **(d)** ohm
12. Hertz is the unit of
    (a) power **(b)** inductance **(c)** frequency **(d)** time
13. The number of significant digits in the number 0.1050 is
    (a) two **(b)** three **(c)** four **(d)** five

PROBLEMS

Answers to odd-numbered problems are at the end of the book.

BASIC PROBLEMS

SECTION 1–1 Scientific and Engineering Notation

1. Express each of the following numbers in scientific notation:
(a) 3000 **(b)** 75,000 **(c)** 2,000,000

2. Express each fractional number in scientific notation:
(a) 1/500 **(b)** 1/2000 **(c)** 1/5,000,000

3. Express each of the following numbers in scientific notation:
(a) 8400 **(b)** 99,000 **(c)** 0.2×10^6

4. Express each of the following numbers in scientific notation:
(a) 0.0002 **(b)** 0.6 **(c)** 7.8×10^{-2}

5. Express each of the following as a regular decimal number:
(a) 2.5×10^{-6} **(b)** 5.0×10^2 **(c)** 3.9×10^{-1}

6. Express each number in regular decimal form:
(a) 4.5×10^{-6} **(b)** 8.0×10^{-9} **(c)** 4.0×10^{-12}

7. Add the following numbers:
(a) $(9.2 \times 10^6) + (3.4 \times 10^7)$ **(b)** $(5.0 \times 10^3) + (8.5 \times 10^{-1})$
(c) $(5.6 \times 10^{-8}) + (4.6 \times 10^{-9})$

8. Perform the following subtractions:
(a) $(3.2 \times 10^{12}) - (1.1 \times 10^{12})$ **(b)** $(2.6 \times 10^8) - (1.3 \times 10^7)$
(c) $(1.5 \times 10^{-12}) - (8.0 \times 10^{-13})$

9. Perform the following multiplications:
(a) $(5.0 \times 10^3)(4.0 \times 10^5)$ **(b)** $(1.2 \times 10^{12})(3.0 \times 10^2)$
(c) $(2.2 \times 10^{-9})(7.0 \times 10^{-6})$

10. Divide the following:
(a) $(1.0 \times 10^3) \div (2.5 \times 10^2)$ **(b)** $(2.5 \times 10^{-6}) \div (5.0 \times 10^{-8})$
(c) $(4.2 \times 10^8) \div (2.0 \times 10^{-5})$

11. Express each number in engineering notation:
(a) 89,000 **(b)** 450,000 **(c)** 12,040,000,000,000

12. Express each number in engineering notation:
(a) 2.35×10^5 **(b)** 7.32×10^7 **(c)** 1.333×10^9

13. Express each number in engineering notation:
(a) 0.000345 **(b)** 0.025 **(c)** 0.00000000129

14. Express each number in engineering notation:
(a) 9.81×10^{-3} **(b)** 4.82×10^{-4} **(c)** 4.38×10^{-7}

15. Add the following numbers and express each result in engineering notation:
(a) $2.5 \times 10^{-3} + 4.6 \times 10^{-3}$ **(b)** $68 \times 10^6 + 33 \times 10^6$ **(c)** $1.25 \times 10^6 + 250 \times 10^3$

16. Multiply the following numbers and express each result in engineering notation:
(a) $(32 \times 10^{-3})(56 \times 10^3)$ **(b)** $(1.2 \times 10^{-6})(1.2 \times 10^{-6})$ **(c)** $100(55 \times 10^{-3})$

17. Divide the following numbers and express each result in engineering notation:
(a) $50 \div (2.2 \times 10^3)$ **(b)** $(5.0 \times 10^3) \div (25 \times 10^{-6})$ **(c)** $(560 \times 10^3) \div (660 \times 10^3)$

SECTION 1–2 Units and Metric Prefixes

18. Express each number in Problem 11 in ohms using a metric prefix.

19. Express each number in Problem 13 in amperes using a metric prefix.

20. Express each of the following as a quantity having a metric prefix:
(a) 31×10^{-3} A **(b)** 5.5×10^3 V **(c)** 20×10^{-12} F

21. Express the following using metric prefixes:
 (a) 3.0×10^{-6} F **(b)** 3.3×10^{6} Ω **(c)** 350×10^{-9} A
22. Express each quantity with a power of ten:
 (a) 5.0 μA **(b)** 43 mV **(c)** 275 kΩ **(d)** 10 MW

SECTION 1–3 Metric Unit Conversions

23. Perform the indicated conversions:
 (a) 5.0 mA to microamperes **(b)** 3200 μW to milliwatts
 (c) 5000 kV to megavolts **(d)** 10 MW to kilowatts
24. Determine the following:
 (a) The number of microamperes in 1 milliampere
 (b) The number of millivolts in 0.05 kilovolt
 (c) The number of megohms in 0.02 kilohm
 (d) The number of kilowatts in 155 milliwatts
25. Add the following quantities:
 (a) 50 mA + 680 μA **(b)** 120 kΩ + 2.2 MΩ
 (c) 0.02 μF + 3300 pF
26. Do the following operations:
 (a) 10 kΩ ÷ (2.2 kΩ + 10 kΩ) **(b)** 250 mV ÷ 50 μV
 (c) 1.0 MW ÷ 2.0 kW

SECTION 1–4 Measured Numbers

27. How many significant digits are in each of the following numbers:
 (a) 1.00×10^{3} **(b)** 0.0057 **(c)** 1502.0
 (d) 0.000036 **(e)** 0.105 **(f)** 2.6×10^{5}
28. Round each of the following numbers to three significant digits. Use the "round-to-even" rule.
 (a) 50,505 **(b)** 220.45 **(c)** 4646
 (d) 10.99 **(e)** 1.005

ANSWERS

SECTION CHECKUPS

SECTION 1–1 Scientific and Engineering Notation

1. True
2. 10^{2}
3. **(a)** 4.35×10^{3} **(b)** 1.201×10^{4} **(c)** 2.9×10^{7}
4. **(a)** 7.6×10^{-1} **(b)** 2.5×10^{-4} **(c)** 5.97×10^{-7}
5. **(a)** 3.0×10^{5} **(b)** 6.0×10^{10} **(c)** 2.0×10^{1} **(d)** 2.37×10^{-6}
6. Enter the digits, press EE, and enter the power of ten.
7. **(a)** 5.6×10^{-3} **(b)** 28.3×10^{-9} **(c)** 950×10^{3} **(d)** 375×10^{9}
8. Enter the digits, press EE, and enter the power of ten.

SECTION 1–2 Units and Metric Prefixes

1. Mega (M), kilo (k), milli (m), micro (μ), nano (n), and pico (p)
2. 1.0 μA (one microampere)
3. 250 kW (250 kilowatts)

SECTION 1–3 Metric Unit Conversions

1. 0.01 MV = 10 kV
2. 250,000 pA = 0.00025 mA
3. 125 kW
4. 75 mV

SECTION 1–4 Measured Numbers

1. Zeros should be retained only if they are significant because if they are shown, they are considered significant.
2. If the digit dropped is 5, increase the last retained digit *if* it makes it even, otherwise do not.
3. A zero to the right of the decimal point implies that the resistor is accurate to the nearest 100 Ω (0.1 kΩ).
4. The instrument must be accurate to four significant digits.
5. Scientific and engineering notation can show any number of digits to the right of a decimal. Numbers to the right of the decimal are always considered significant.

SECTION 1–5 Electrical Safety

1. Current
2. F
3. F
4. F
5. T
6. Ground-fault circuit interrupter

RELATED PROBLEMS FOR EXAMPLES

1–1 7.5×10^{8}

1–2 9.3×10^{-7}

1–3 820,000,000

1–4 4.89×10^{3}

1–5 1.85×10^{-5}

1–6 4.8×10^{5}

1–7 4.0×10^{4}

1–8 Enter 5.73946; press EE, enter 5.

1–9 36×10^{9}

1–10 5.6×10^{-12}

1–11 Enter 273.9, press EE, enter 3.

1–12 **(a)** 56 MΩ **(b)** 470 μA

1–13 1000 μA

1–14 1.0 mV

1–15 0.893 μA

1–16 0.01 μF

1–17 2200 pF

1–18 0.0022 MΩ

1–19 2883 mA

1–20 10.0×10^{3}

1–21 The number 10 has two significant digits; the number 10.0 has three.

1–22 3.28

TRUE/FALSE QUIZ

1. T
2. F
3. F
4. T
5. F
6. T
7. T
8. T
9. F
10. T

SELF-TEST

1. (b)
2. (a)
3. (c)
4. (d)
5. (d)
6. (c)
7. (b)
8. (c)
9. (c)
10. (c)
11. (d)
12. (c)
13. (c)

2 Voltage, Current, and Resistance

Chapter Outline

Chapter Objectives

- Describe the basic structure of an atom
- Explain the concept of electrical charge
- Define *voltage* and discuss its characteristics
- Define *current* and discuss its characteristics
- Define *resistance* and discuss its characteristics
- Describe the basic construction and characteristics of an alkaline dry cell
- Describe a basic electric circuit
- Describe the construction and features of printed circuit boards
- Make basic circuit measurements
- Use a typical scientific calculator to perform calculations involving electrical quantities

Key Terms

- Atom
- Electron
- Free electron
- Conductor
- Semiconductor
- Insulator
- Charge
- Coulomb's law
- Coulomb (C)
- Voltage
- Volt (V)
- Voltage source
- Cell
- Battery
- Redox reaction
- Fuel cell
- Current
- Ampere (A)
- Current source
- Resistance
- Ohm (Ω)
- Conductance
- Siemens (S)
- Resistor
- Color codes
- Potentiometer
- Rheostat
- Circuit
- Load
- Schematic
- Closed circuit
- Open circuit
- Switch
- Fuse
- Circuit breaker
- AWG
- Ground
- Reference ground
- Printed circuit board
- Layer
- Plane
- Via
- Voltmeter
- Ammeter
- Ohmmeter
- DMM
- Green
- RoHS (Restriction of Hazardous Substances)
- WEEE (Waste Electrical and Electronic Equipment)

Application Assignment Preview

Assume you wanted to have an interactive quiz board as part of a science fair display. The quiz board will use a rotary switch to select one of four options that represent battery types. Each position of the switch lights a light. The person viewing the display selects the matching answer by pressing a pushbutton next to one of the four possible answers. If the correct pushbutton is pressed, a "correct" light is illuminated; otherwise, nothing happens. The overall brightness of the lights is controlled by a single rheostat.

After studying this chapter, you should be able to complete the application assignment in the last section of the chapter.

Visit the Companion Website

Study aids for this chapter are available at
https://www.pearson.com/us/higher-education.html

Introduction

Three basic electrical quantities presented in this chapter are voltage, current, and resistance. No matter what type of electrical or electronic equipment you may work with, these quantities will always be of primary importance. This is true for dc and ac circuits, but our focus will be dc circuits in Part 1 of this book. Because of its importance in electrical applications, an ac circuit may be used occasionally to illustrate a particular concept; however, in these special cases the analysis and calculations are the same as for an equivalent dc circuit.

To help you understand voltage, current, and resistance, the basic structure of the atom is discussed and the concept of charge is introduced. The basic electric circuit is studied, along with techniques for measuring voltage, current, and resistance.

2–1 ATOMS

All matter is made of atoms, and all atoms consist of electrons, protons, and neutrons. The configuration of certain electrons in an atom is the key factor in determining how well a conductive or semiconductive material conducts electric current.

After completing this section, you should be able to

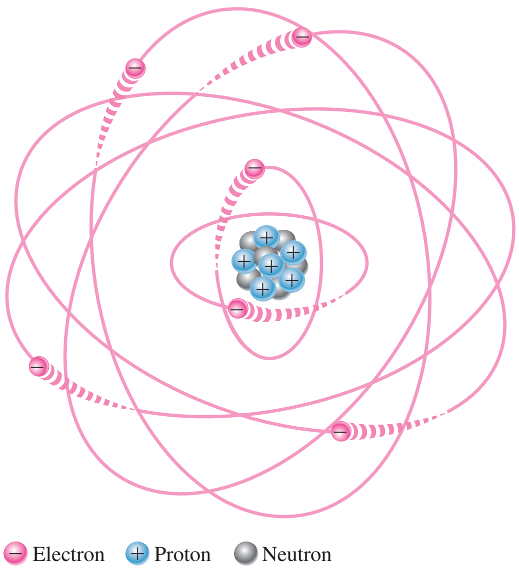
- **Describe the basic structure of an atom**
  - Define *nucleus, proton, neutron,* and *electron*
  - Define *atomic number*
  - Define *shell*
  - Explain what a valence electron is
  - Describe ionization
  - Explain what a free electron is
  - Define *conductor, semiconductor,* and *insulator*

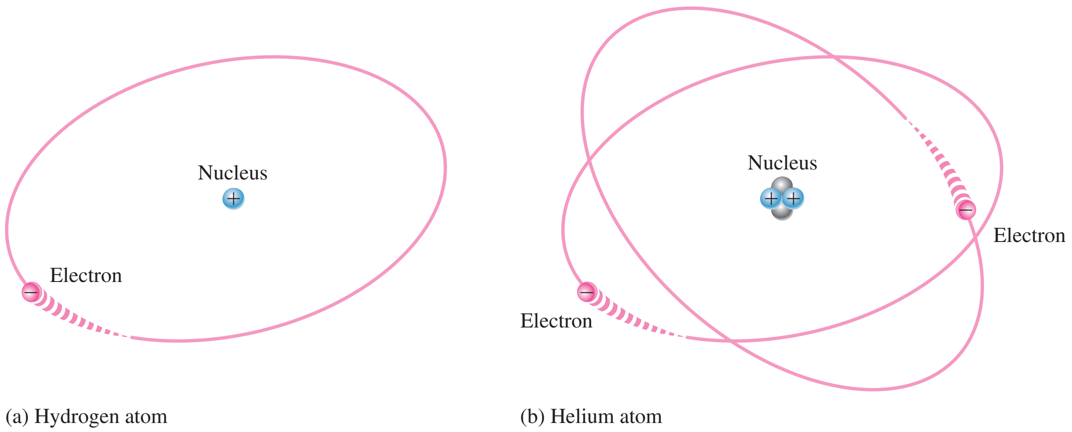
An **atom** is the smallest particle of an **element** that retains the characteristics of that element. Each of the known 118 elements consists of atoms with a unique atomic number that are different from the atoms of all other elements. This gives each element a unique atomic structure. According to the classic Bohr model, an atom is visualized as having a planetary type of structure that consists of a central nucleus surrounded by orbiting electrons, as illustrated in Figure 2–1. The **nucleus** consists of positively charged particles called **protons** and uncharged particles called **neutrons.** The basic particles of negative charge are called **electrons**. Electrons orbit the nucleus.

Each type of atom has a certain number of protons that distinguishes it from the atoms of all other elements. For example, the simplest atom is that of hydrogen, which has one proton and one electron, as pictured in Figure 2–2(a). As another example, the helium atom, shown in Figure 2–2(b), has two protons and two neutrons in the nucleus and two electrons orbiting the nucleus.

▶ FIGURE 2–1

The Bohr model of an atom showing electrons in circular orbits around the nucleus. The "tails" on the electrons indicate they are moving.





▲ FIGURE 2–2

The two simplest atoms, hydrogen and helium.

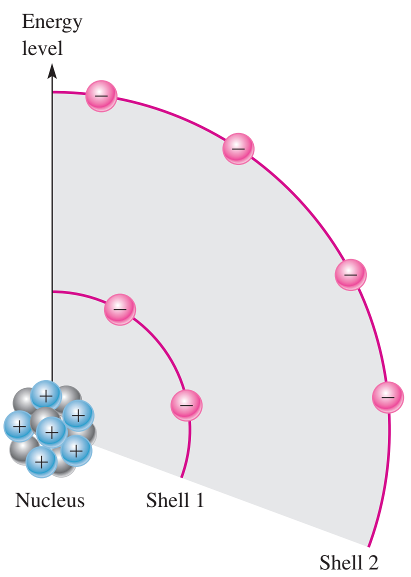
Atomic Number

All elements are arranged in the periodic table of the elements in order according to their **atomic number**. The atomic number equals the number of protons in the nucleus. For example, hydrogen has an atomic number of 1 and helium has an atomic number of 2. In their normal (or neutral) state, all atoms of a given element have the same number of electrons as protons. Because the positive charges cancel the negative charges, the atom has a net charge of zero, making it electrically balanced, or neutral.

Electron Shells and Orbits

Electrons orbit the nucleus of an atom at certain distances from the nucleus. Electrons near the nucleus have less energy than those in more distant **orbits.** It is known that only discrete (separate and distinct) values of electron energies exist within atomic structures. Therefore, electrons must orbit only at discrete distances from the nucleus.

Energy Levels Each discrete distance (orbit) from the nucleus corresponds to a certain energy level. In an atom, the orbits are grouped into energy bands known as **shells**. A given atom has a fixed number of shells. Each shell has a fixed maximum number of electrons at permissible energy levels (orbits). The shells are designated 1, 2, 3, and so on, with 1 being closest to the nucleus. This energy band concept is illustrated in Figure 2–3, which shows



◀ FIGURE 2–3

Energy levels increase as the distance from the nucleus increases.

two energy levels. Additional shells may exist in other types of atoms, depending on the element.

The number of electrons in each shell follows a predictable pattern according to the formula, $2N^2$, where N is the number of the shell. The first shell of any atom ($N = 1$) can have up to two electrons, the second shell ($N = 2$) up to eight electrons, the third shell up to 18 electrons, and the fourth shell up to 32 electrons. In many elements, electrons start filling the fourth shell after eight electrons are in the third shell.

Valence Electrons

Electrons that are in orbits farther from the nucleus have higher energy and are less tightly bound to the atom than those closer to the nucleus. This is because the force of attraction between the positively charged nucleus and the negatively charged electron decreases with increasing distance from the nucleus. Electrons with the highest energy levels exist in the outermost shell of an atom and are relatively loosely bound to the atom. This outermost shell is known as the **valence shell**, and electrons in this shell are called **valence electrons.** These valence electrons contribute to chemical reactions and bonding within the structure of a material, and they determine a material's electrical properties.

Free Electrons and Ions

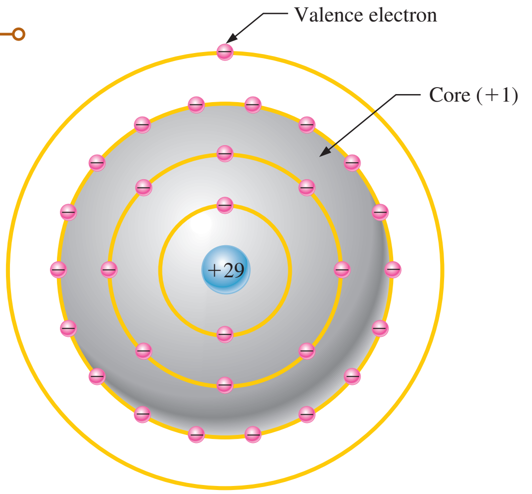
If an electron absorbs a **photon** of sufficient energy, it escapes from the atom and becomes a **free electron**. Any time an atom or group of atoms is left with a net charge, it is called an **ion.** When an electron escapes from the neutral hydrogen atom (designated H), the atom is left with a net positive charge and becomes a *positive ion* (designated H^+). In other cases, an atom or group of atoms can acquire an electron, in which case it becomes a *negative ion.*

The Copper Atom

Copper is the most commonly used metal in **electrical** applications. The copper atom has 29 electrons that orbit the nucleus in four shells, as shown in Figure 2–4. Notice that the fourth or outermost shell, the valence shell, has only one valence electron. The inner shells are called the core. When the valence electron in the outer shell of the copper atom gains sufficient thermal energy, it can break away from the parent atom and become a free electron. In a piece of copper at room temperature, a "sea" of these free electrons is present. These electrons are not bound to a given atom but are free to move in the copper material. Free electrons make copper an excellent conductor and make electrical current possible.

FIGURE 2–4

The copper atom.



Categories of Materials

Three categories of materials are used in electronics: conductors, semiconductors, and insulators.

Conductors **Conductors** are materials that readily allow current. They have a large number of free electrons and are characterized by one to three valence electrons in their structure. Most metals are good conductors. Silver is the best conductor, and copper is next. Copper is the most widely used conductive material because it is less expensive than silver, although some applications will use aluminum because it is cheaper than copper. Copper wire is commonly used as a conductor in electric circuits.

Semiconductors **Semiconductors** are classed below the conductors in their ability to carry current because they have fewer free electrons than do conductors. Semiconductors have four valence electrons in their atomic structures. However, because of their unique characteristics, certain semiconductor materials are the basis for **electronic** devices such as the diode, transistor, and integrated circuit. Silicon and germanium are common semiconductive materials.

Insulators **Insulators** are non-metallic materials that are poor conductors of electric current and are used to prevent current where it is not wanted. Insulators have no free electrons in their structure. The valence electrons are bound to the nucleus and not considered "free." Although nonmetal elements are generally considered to be insulators, most practical insulators used in electrical and electronic applications are compounds such as glass, porcelain, Teflon^{TM}, and polyethylene, to name a few.

SECTION 2–1 CHECKUP
Answers are at the end of the chapter.

1. What is the basic particle of negative charge?
2. Define *atom.*
3. What does an atom consist of?
4. Define *atomic number.*
5. Do all elements have the same types of atoms?
6. What is a free electron?
7. What is a shell in the atomic structure?
8. Name two conductive materials.

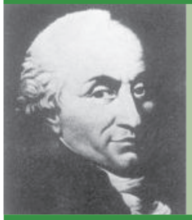
2–2 ELECTRICAL CHARGE

As you know, in the Bohr model, an electron is the smallest particle that exhibits negative electrical charge. When an excess of electrons exists in a material, there is a net negative electrical charge. When a deficiency of electrons exists, there is a net positive electrical charge.

After completing this section, you should be able to

- **Explain the concept of electrical charge**
    - Name the unit of charge
    - Name the types of charge
    - Describe the forces between charges
    - Determine the amount of charge on a given number of electrons

HISTORY NOTE

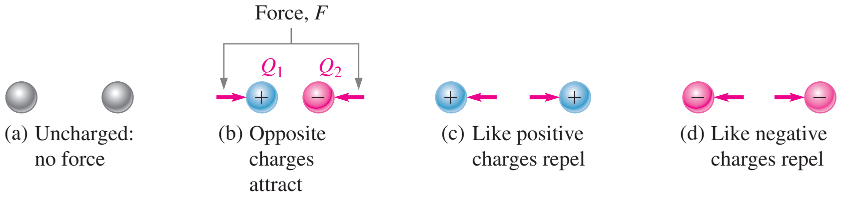


Charles Augustin Coulomb 1736–1806

Coulomb, a Frenchman, spent many years as a military engineer. When bad health forced him to retire, he devoted his time to scientific research. He is best known for his work on electricity and magnetism due to his development of the inverse square law for the force between two charges. The unit of electrical charge is named in his honor. (Photo credit: Courtesy of the Smithsonian Institution. Photo number 52,597.)

The charge of an electron and that of a proton are equal in **magnitude** and opposite in sign. Electrical **charge** is an electrical property of matter that exists because of an excess or deficiency of electrons. Charge is symbolized by Q. Static electricity is the presence of a net positive or negative charge in a material. Everyone has experienced the effects of static electricity from time to time, such as when attempting to touch a metal surface or another person or when the clothes in a dryer cling together.

Materials with charges of opposite polarity are attracted to each other, whereas materials with charges of the same polarity are repelled, as indicated symbolically in Figure 2–5. A force acts between charges, as evidenced by the attraction or repulsion. This is caused by an *electric field,* which consists of invisible lines of force as represented in Figure 2–6.

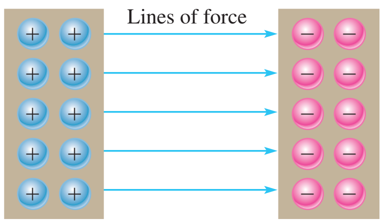


▲ **FIGURE 2–5**

Attraction and repulsion of electrical charges.

▶ **FIGURE 2–6**

Electric field between two oppositely charged surfaces.



Coulomb's law states

A force (F) exists between two point-source charges (Q_1, Q_2) that is directly proportional to the product of the two charges and inversely proportional to the square of the distance (d) between the charges.

Coulomb: The Unit of Charge

The unit for electrical charge is the **coulomb**, symbolized by C.

One coulomb is the total charge possessed by 6.25×10^{18} electrons.

A single electron has a charge of 1.6×10^{-19} C. The total charge Q, expressed in coulombs, for a given number of electrons is found by the following formula:

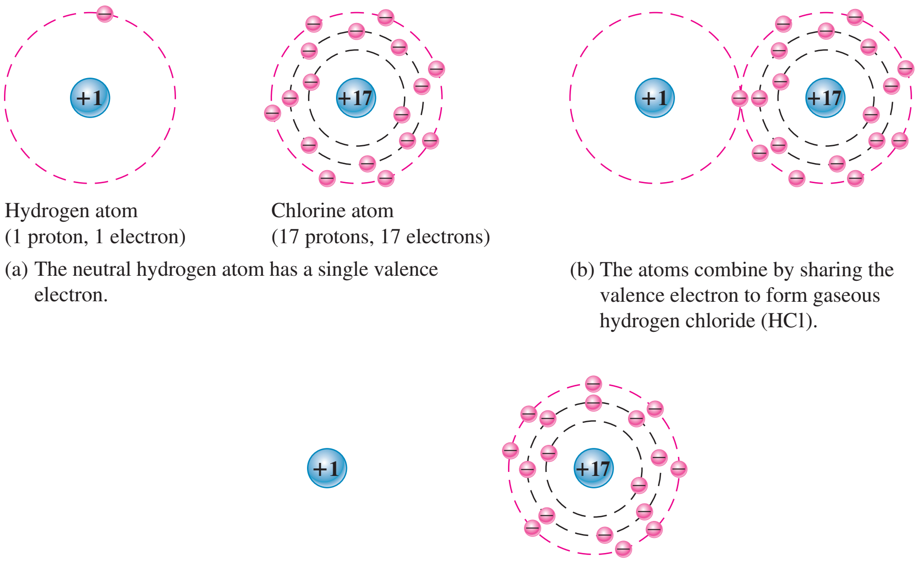
Equation 2–1

$$Q = \frac{\text{number of electrons}}{6.25 \times 10^{18}\ \text{electrons/C}}$$

Positive and Negative Charge

Consider a neutral atom—that is, one that has the same number of electrons and protons and thus has no net charge. As you know, when a valence electron is pulled away from the atom by the application of energy, the atom is left with a net positive charge (more protons than electrons) and becomes a positive ion. A **positive ion** is defined as an atom or group of atoms with a net positive charge. If an atom acquires an extra electron in its outer shell, it has a net negative charge and becomes a negative ion. A **negative ion** is defined as an atom or group of atoms with a net negative charge.

The amount of energy required to free a valence electron is related to the number of electrons in the outer shell. An atom can have up to eight valence electrons. The more complete the outer shell, the more stable the atom and thus the more energy is required to remove an electron. Figure 2–7 illustrates the creation of a positive ion and a negative ion when a hydrogen atom gives up its single valence electron to a chlorine atom, forming gaseous hydrogen chloride (HCl). When the gaseous HCl is dissolved in water, hydrochloric acid is formed.



Hydrogen atom (1 proton, 1 electron)

Chlorine atom (17 protons, 17 electrons)

(a) The neutral hydrogen atom has a single valence electron.

(b) The atoms combine by sharing the valence electron to form gaseous hydrogen chloride (HCl).

Positive hydrogen ion (1 proton, no electrons)

Negative chloride ion (17 protons, 18 electrons)

(c) When dissolved in water, hydrogen chloride gas separates into positive hydrogen ions and negative chloride ions. The chlorine atom retains the electron given up by the hydrogen atom forming both positive and negative ions in the same solution.

FIGURE 2–7

Example of the formation of positive and negative ions.

EXAMPLE 2–1

How many coulombs of charge do 93.8×10^{16} electrons represent?

Solution

$$Q = \frac{\text{number of electrons}}{6.25 \times 10^{18}\ \text{electrons/C}} = \frac{93.8 \times 10^{16}\ \text{electrons}}{6.25 \times 10^{18}\ \text{electrons/C}} = 15 \times 10^{-2}\ \text{C} = \mathbf{0.15\ C}$$

*Related Problem**

How many electrons does it take to have 3 C of charge?

Work through the calculation example in Example 2–1 of *Introduction to Scientific Calculators*.

*Answers are at the end of the chapter.

SECTION 2–2 CHECKUP

1. What is the symbol for charge?
2. What is the unit of charge, and what is the unit symbol?
3. What are the two types of charge?
4. How much charge, in coulombs, is there in 10×10^{12} electrons?

2–3 VOLTAGE

As you have learned, a force of attraction exists between a positive and a negative charge. A certain amount of energy must be exerted in the form of work to overcome the force and move the charges a given distance apart. All opposite charges possess a certain potential energy because of the separation between them. The difference in potential energy of the charges is the potential difference or *voltage.* Voltage is the driving force in electric circuits and is what establishes current.

After completing this section, you should be able to

- **Define *voltage* and discuss its characteristics**
  - State the formula for voltage
  - Name and define the unit of voltage
  - Describe the basic sources of voltage

Voltage is defined as energy per unit of charge and is expressed as

Equation 2–2

$$V = \frac{W}{Q}$$

where V is voltage in volts (V), W is energy in joules (J), and Q is charge in coulombs (C). As a simple analogy, you can think of voltage as corresponding to the pressure difference created by a pump that causes water to flow through a pipe in a closed water system.

Volt: The Unit of Voltage

The unit of voltage is the **volt**, symbolized by V.

One volt is the potential difference (voltage) between two points when one joule of energy is used to move one coulomb of charge from one point to the other.

EXAMPLE 2–2

If 50 J of energy are required to move 10 C of charge, what is the voltage?

Solution

$$V = \frac{W}{Q} = \frac{50\text{ J}}{10\text{ C}} = \mathbf{5.0\text{ V}}$$

Related Problem How much energy is required to move 50 C from one point in a circuit to another when the voltage between the two points is 12 V?

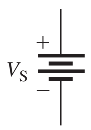
Work through the calculation example in Example 2–2 of *Introduction to Scientific Calculators*.

The DC Voltage Source

A **voltage source** provides electrical energy or electromotive force (emf), more commonly known as voltage. Voltage is produced by means of chemical energy, light energy, and magnetic energy combined with mechanical motion.

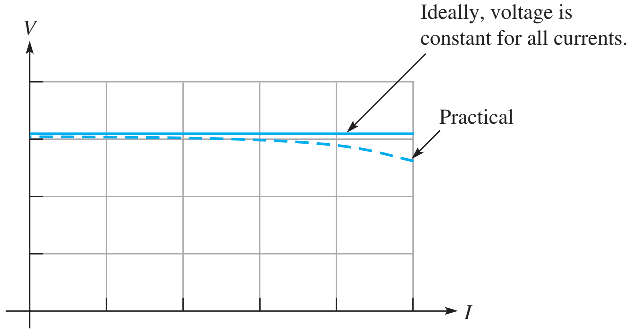
The Ideal DC Voltage Source An ideal voltage source can provide a constant voltage for any current required by a circuit. The ideal voltage source does not exist but can be closely approximated in practice. We will assume that voltage sources are ideal unless otherwise specified.

Voltage sources can be either dc or ac. A common symbol for a dc voltage source is shown in Figure 2–8.



▲ FIGURE 2–8

Symbol for dc voltage sources.



▲FIGURE 2–9

Voltage source graph.

A graph showing current versus voltage for an ideal dc voltage source is shown in Figure 2–9. As you can see, the voltage is constant for any current from the source. For a practical (nonideal) voltage source connected in a circuit, the voltage decreases slightly as the current increases, as shown by the dashed line. Current is always drawn from a voltage source when a load, such as a resistance, is connected to it.

Types of DC Voltage Sources

Cells and Batteries A **cell** is a single voltage source that converts chemical energy into electrical energy. A cell will have a certain fixed voltage, which depends on how readily one electrode gives up electrons relative to the other. A **battery** is a device composed of one or more cells with external connections to power electrical devices. Multiple cells are used when it is necessary to have a greater voltage or current than a single cell can provide. As you know, work (or energy) per charge is the basic unit for voltage, and a battery adds energy to each unit of charge. It is something of a misnomer to talk about "charging a battery" because a battery does not store charge but rather stores chemical potential energy. All batteries use a specific type of chemical reaction called an *oxidation-reduction* (or redox) reaction. In this type of reaction, electrons are transferred from one reactant (which chemically is *oxidized*) to the other (which chemically is *reduced*). If the chemicals used in the reaction are separated, it is possible to cause the electrons to travel in the external circuit, creating current. As long as there is an external path for the electrons, the reaction can proceed, and stored chemical energy is converted to electrical current. If the path is broken, the reaction stops and the battery is said to be in equilibrium. In a battery, the terminal that supplies electrons has a surplus of electrons and is the negative electrode or **anode.** The electrode that acquires electrons has a positive potential and is the **cathode.**

The modern battery evolved from various dc power sources developed in the 19th century. The voltaic pile constructed by Volta consisted of alternating zinc and copper (or silver) discs, separated by felt or other non-conductive porous material saturated with brine. It was useful for experimental purposes, but had limited practical use.

A more practical source of dc power was the Daniell cell, invented by John Frederic Daniell in 1836. The Daniell cell, like lead-acid car batteries, is a type of wet cell battery. The Daniell copper-zinc cell in Figure 2–10 shows the basic construction of a wet cell. The chemical reaction between the reagent and negative electrode (or *anode*) creates positive ions (Zn^{2+}) and free electrons (e^-). The cell creates current when these free electrons can flow to the positive electrode (or *cathode*) through an external conductive path. At the cathode the free electrons combine with the positive ions (Cu^{2+}) from the reagent, while the Zn^{2+} ions move through the salt bridge to balance out the charge of the negative SO_4^{2-} ions. An advantage of the wet cell battery is that batteries could be renewed by replacing the depleted reagents and plates. One drawback was that the containers of liquid chemicals made the battery difficult to transport. These

HISTORY NOTE

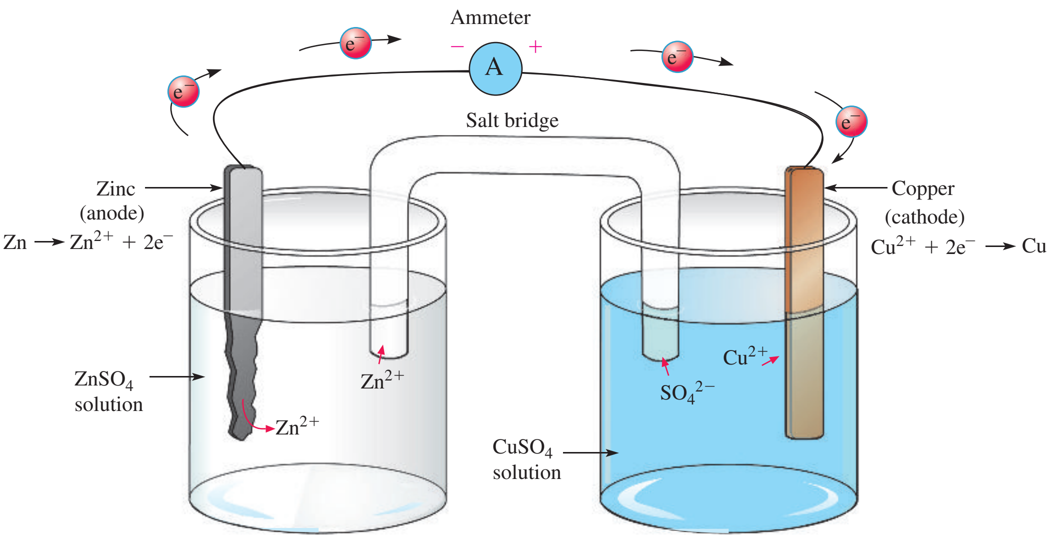
Alessandro Volta 1745–1827

Volta, an Italian, invented a device to generate static electricity and was the discoverer of methane gas. Volta investigated reactions between dissimilar metals and developed the first battery, called the voltaic pile, in 1800. Electrical potential, more commonly known as voltage, and the unit of voltage, the volt, are named in his honor. (Photo credit: Bilwissedition Ltd. & Co. KG/Alamy Stock Photo.)

SAFETY NOTE

Lead-acid batteries can be dangerous because sulfuric acid is highly corrosive and battery gases (primarily hydrogen) are explosive. The acid in the battery can cause serious eye damage if it contacts the eye and can cause skin burns or destroy clothing. You should always wear eye protection when working on or around batteries and wash well after handling batteries.

When taking a battery out of service, disconnect the ground end first (this is the negative side on all modern cars). This prevents current and avoids a potential spark when the positive lead is disconnected.



▲ **FIGURE 2–10**

A Daniell copper-zinc wet cell battery. The reaction can occur only if an external path is provided for the electrons. As the reaction proceeds, the zinc anode dissolves and copper metal deposits on the cathode.

containers also were easy to damage and the chemical reactions produced flammable hydrogen gas, which created a potential safety hazard. Despite this, the wet cell battery was the primary source of dc power through much of the 19th century and used in such applications as providing dc power for telegraph stations.

The terminal voltage of a cell will depend upon the materials used to construct the cell. In the Daniell copper-zinc cell the voltage is 1.1 V. A lead-acid cell, the kind used in car batteries, has a potential difference of about 2.1 V between the anode and cathode. Nickel-cadmium cells are about 1.3 V and lithium cell voltages can be higher than 4 V. Batteries connect multiple cells together in a single housing to produce greater voltages or currents than a single cell could produce. A standard car battery, for example, connects 6 lead-acid cells to provide 12 V at the battery terminals.

By the end of the 19th century the dry cell battery design replaced the liquid electrolyte of the wet cell battery with a moist electrolytic paste. The design of these types of cells also added a chemical, called a depolarizer, to prevent the creation of hydrogen gas in sealed dry cells. This cell design is similar to those of modern batteries in use today and allowed the production of truly portable dc products. By the 1960s, manufacturers were producing a variety of portable electric and electronic products, such as flashlights, hearing aids, watches, cameras, and portable radios, so that batteries became commonplace. In recent years the introduction of smart phones, portable computing devices, electric cars, and renewable energy sources have spurred the development and production of batteries.

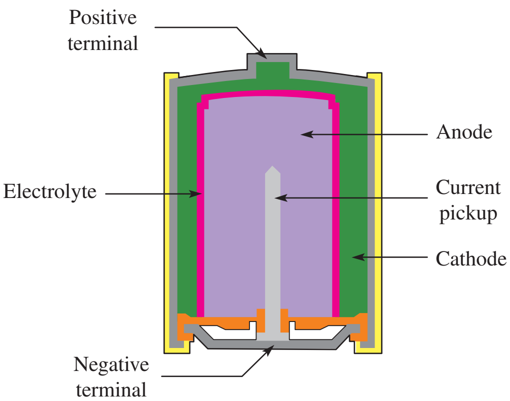
Figure 2–11 shows the basic construction of a modern alkaline cell, which is similar to the construction of other modern dry cells. The D size version of an alkaline cell is often called a flashlight battery, and is widely used because it can supply up to 1.5 A for 1 hour.

The alkaline cell consists of two electrodes, called a cathode and an anode, each of which is in contact with an alkaline electrolyte that allows ions to pass but prevents direct contact between the electrodes. The anode is zinc, which is located in the center and connects to the negative terminal through a current pickup. The cathode is manganese dioxide packed around the outer edge of the cell. The oxidation reaction of the manganese dioxide cathode creates negative hydroxide ions that pass through the electrolyte of potassium hydroxide (an alkali). The oxidation reaction of the zinc releases free electrons that create the battery current and produces positive ions. These positive ions react with the negative hydroxide ions from the cathode to balance the electrical charge within the cell. Both the zinc and manganese dioxide electrodes are consumed

HISTORY NOTE

John Frederic Daniell 1790–1845

Daniell, an English chemist, physicist, professor, and author, developed the first practical wet cell that resolved some issues with the voltaic pile. In addition to the Daniell cell, he invented the dew-point hygrometer to measure atmospheric humidity. He was honored by having a lunar crater and nearby narrow channel (or *rille*) named after him.
(Photo credit: Kings College collection/Wikipedia Commons.)



▲ FIGURE 2–11

Alkaline dry cell.

by the reaction, called a **redox reaction**. A redox reaction is a chemical reaction in which electrons are transferred from one reactant (which chemically is *oxidized*) to another (which chemically is *reduced*). The electrolyte acts only as an ion bridge and is not used up. Consequently, a discharged alkaline cell still will contain potassium hydroxide, which is a very caustic chemical, and should be disposed of properly after use. Different types of batteries have different reactions, but all batteries involve the external transfer of negatively charged electrons through a conductive path and the internal migration of positively charged ions as the battery discharges. Table 2–1 summarizes the typical construction of various cell types.

Characteristics All batteries (or cells) have certain characteristics that determine how suitable they are for specific applications. Some characteristics, such as physical size and discharge characteristics apply to all batteries, while others, such as cycle life and memory effect, apply only to rechargeable batteries.

Physical size. Batteries vary greatly in physical size and range in size from tiny batteries used in hearing aids and microelectronics to huge battery grids used to store energy from wind and solar farms. Most commercial batteries are manufactured

◀ TABLE 2–1

Typical construction of various cell types.

CELL TYPE	CATHODE	OXIDIZING REAGENT	ION TRANSPORT ELECTROLYTE	ANODE	REDUCING REAGENT	TYPICAL VOLTAGE
Daniell cell	Copper	Zinc sulfate	Sodium sulfate	Zinc	Copper sulfate	1.10 V
Lead-acid cell	Lead	N/A	Aqueous sulfuric acid	Lead oxide	N/A	2.05 V
Zinc-carbon cell	Manganese dioxide	N/A	Aqueous zinc chloride	Zinc	N/A	1.50 V
Alkaline cell	Manganese dioxide	N/A	Aqueous potassium hydroxide	Zinc	N/A	1.59 V
Nickel-cadmium cell	Nickel oxide-hydroxide	N/A	Aqueous potassium hydroxide	Cadmium	N/A	1.30 V
Lithium ion cell	Graphite	N/A	Lithium salts in organic solvents	Lithium cobalt oxide	N/A	3.60 V

in standard sizes, such as AAA, AA, C, D, and PP3 (the familiar 9 V rectangular battery commonly used to provide dc back up power for ac-powered devices). These standard sizes allow manufacturers to more easily design dc-powered electronic products. As a rule, larger batteries can provide more current for longer periods than smaller batteries of the same construction.

Shelf life. An ideal battery will hold its charge indefinitely so that it can be stored indefinitely until needed. However, the internal resistance of a practical battery will allow current to flow even if the battery is not connected to an external circuit. This gradually discharges the battery so that a practical battery has a limited shelf life, or time that they can be stored and still be usable. The self-discharging also can cause some batteries, such as alkaline cells, to leak and corrode over time as gas pressure builds up in the battery and breaches the seals. Cell chemistry determines the shelf life of a battery type. For example, a lithium-MnO_2 battery typically has three times the shelf life as a comparable carbon-zinc battery. Most batteries now typically have an expiration date printed on them.

Temperature range. Chemical reactions, including the redox reactions in batteries, will proceed more rapidly as the temperature increases and more slowly as the temperature decreases. As the battery temperature decreases, free electrons are produced and transferred more slowly. This will decrease the self-discharge current but reduce the amount of current the battery can deliver to a load. If the temperature is low enough, the battery actually can freeze and become inoperable. At higher temperatures, the battery can deliver more current, but the self-discharge current increases and chemicals can dry out, reducing the storage life of the battery. At excessive temperatures, the battery can leak or, for some types such as lithium ion, possibly explode or catch fire.

Terminal voltage. As mentioned earlier, cells will have a certain fixed voltage, which depends on how readily one electrode gives up electrons relative to the other. Typical cell voltages range from about 1.1 V for the Daniell copper-zinc cell to over 4 V for some types of lithium batteries.

Battery capacity. Batteries can provide power only for a limited amount of time, after which they must be recharged or discarded and replaced. The capacity of a battery is given in units of ampere-hours (Ah) or milliampere-hours (mAh). A battery with a 1.0 Ah rating can provide 1.0 A of current at the battery's rated voltage for 1 hour. The alkaline D cell mentioned previously has a capacity of 1.5 Ah.

Discharge characteristic. An ideal battery has no internal resistance and will provide current at its rated voltage until it is fully discharged. The internal resistance of a practical battery will increase as it discharges, so that the terminal voltage of a battery gradually decreases over time as current is drawn from it. The discharge curve varies for different battery types, with nickel-cadmium and nickel metal hydride batteries showing the best constant voltage response during discharge. The cell chemistry determines the discharge characteristics of a battery.

Memory effect. Some rechargeable batteries, particularly nickel-cadmium (NiCad) and nickel metal hydride (NiMH) batteries, exhibit an undesirable characteristic called memory effect (also called *battery effect* and *battery memory*). Consistently recharging these batteries after only partially (~75%) discharging them reduces their capacity. Because the battery seems to "remember" that charging restores only part of its total stored charge, the reduction of its rated capacity is called memory effect.

Cycle life. Although recharging reverses the chemical processes that allow rechargeable batteries to produce current, recharging cannot fully restore the