

GLOBAL
EDITION



Principles of Electric Circuits

Conventional Current

TENTH EDITION

Thomas L. Floyd • David M. Buchla



PRINCIPLES OF ELECTRIC CIRCUITS

Conventional Current

Tenth Edition
Global Edition

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KAO Two
KAO Park
Hockham Way
Harlow
CM17 9SR
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In memory of Thomas L. Floyd

Author, educator, and friend

The first edition of *Principles of Electric Circuits*, released in 1981, was a breakthrough text that featured Tom Floyd's unique ability to present electronics clearly and precisely. As electronics evolved, Tom improved and updated this best-selling text through several editions, and it continued to be one of the most popular basic electronics books on the market. Although his health intervened with writing, Tom outlined changes he thought should be made to the text and asked me to implement his ideas in this new edition. I am honored for the opportunity and hope I succeeded in that endeavor.

PREFACE

In the years that have passed since the last edition of this classic text, there have been many changes in technology. Fundamental circuit laws and components remain the focus of the text but with updated instruments and methods including new computer simulations with both Multisim and LTSpice. One important change to this edition is illustrated steps for solving problems with simultaneous equations and complex mathematics using a graphing calculator. Graphing calculators have increased capabilities and are much more affordable, so are an important tool in basic electronics. The numerous pedagogical features that have been hallmarks of this book have been retained and expanded. This includes practical application of basic concepts, basic troubleshooting, and use of instruments.

The entire text has been reviewed with an eye for improving and updating it. Every example has been reworked and checked. In that process, the full resolution of a calculator was kept until the end before final roundoff to three digits. This has improved round-off errors from previous editions. The entire text was also reviewed for improving readability and clarity, with many modifications. Our effort has been to continue the tradition of having the best introduction to basic electronics on the market.

New in This Edition

- ◆ Numerous examples including step-by-step procedures for solving problems with the TI-84 Plus CE graphing calculator including graphing examples, matrix algebra, phasors and more
- ◆ New instruments described with expanded discussion and use of arbitrary function generators (AFGs), arbitrary waveform generators (AWGs), oscilloscopes and probes, gaussmeters, LCR meters, thermal imaging devices, and current pulser and tracers
- ◆ New devices and applications such as magnetoresistive random access memory (MRAM), magnetohydrodynamic (MHD) generators, and wave traps in power line carrier communications (PLCC)
- ◆ Many examples now include LTSpice including two examples of Bode plots with both Multisim and LTSpice results
- ◆ New discussion of dimensional analysis with examples
- ◆ New or enhanced discussion of SMD resistors, resistor power ratings, batteries, thermal imaging, ferrites and ferrite beads, contactors, and motor starters
- ◆ Added examples, safety notes, tech tips, checkup questions, history notes, new illustrations, and new and revised problems
- ◆ Expanded glossary, key terms, and biographies of famous people

Features

- ◆ Full-color, reader-friendly text design
- ◆ Chapter openers include a chapter outline, introduction, objectives, key term list, *Application Activity Preview*, and website reference
- ◆ An *Application Activity* at the end of most chapters
- ◆ Abundant illustrations
- ◆ Margin features include Safety Notes, History Notes, and Tech Notes
- ◆ Abundance of worked examples, each with a *Related Problem* and selected examples with a Multisim exercise and/or LTSpice exercise
- ◆ Each section in a chapter begins with an introduction and section objectives
- ◆ Section Checkups with answers at end of chapter
- ◆ Troubleshooting sections in many chapters
- ◆ Summary, key terms glossary, and formula list at the end of each chapter
- ◆ True/False Quiz, multiple-choice Self-Test, and Circuit Dynamics Quiz at the end of each chapter with answers at the end of the chapter
- ◆ Sectionalized problem set at the end of each chapter with more difficult problems indicated with an asterisk and answers to odd-numbered problems at the end of the book
- ◆ Comprehensive glossary of all bold-face terms in the text, including key terms, at the end of the book
- ◆ Conventional current direction

Student Resources

Digital Resources (www.pearsonglobaleditions.com) This section offers students an online lab manual and MultiSIM files that they can use for better understanding of the subject.

Circuit Simulations (www.pearsonglobaleditions.com) These online files include simulation circuits in Multisim[®] 14 and LT Spice IV for selected examples, troubleshooting sections, and selected problems in the text. Circuit files with prefix E are example circuits and files with prefix P are problem circuits. These circuits were created for use with Multisim[®] or LT Spice software. These circuit simulation programs are widely regarded as excellent for classroom and laboratory learning.

MultiSIM and LTSpice odd answers are shown with the results that the simulations actually show, so they are not rounded off as are other answers.

In order to use the Multisim circuit files, you must have Multisim software installed on your computer. Multisim software is available at 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 *Principles of Electric Circuits, Tenth Edition, Global Edition*.

Experiments in Basic Circuits, Tenth Edition, lab manual by David Buchla (ISBN 10: 0134879988/ISBN-13: 9780134879987). Lab exercises are coordinated with the text and solutions are provided in the Instructor's Resource Manual.

Experiments in Electric Circuits, Tenth Edition, lab manual by Brian Stanley (ISBN 10: 0134879996/ISBN-13: 9780134879994). Lab solutions are provided in the Instructor's Resource Manual.

Introduction to Multisim for the DC/AC Course by Gary Snyder (ISBN: 013508041X). A thorough introduction and detailed guide to the use of Multisim in DC/AC circuit analysis.

Instructor Resources

To access supplementary materials online, instructors can go to www.pearsonglobaleditions.com.

PowerPoint® Slides A set of innovative PowerPoint® slides, dynamically illustrates key concepts in the text. Each slide contains a summary with examples, key term definitions, and a quiz for each chapter. This is an excellent tool for classroom presentation to supplement the textbook. Another folder of PowerPoint® slides contains all figures from the text. The PowerPoints® are available at the instructor resource website at www.pearsonglobaleditions.com.

Instructor's Resource Manual Includes solutions to chapter problems, solutions to *Application Activity* features, a test item file, Multisim circuit file summary, and solutions to both lab manuals. Available online at www.pearsonglobaleditions.com.

Pearson TestGen This is a computerized test bank. Available online at www.pearsonglobaleditions.com.

Illustration of Chapter Features

Chapter Opener Each chapter begins as shown in Figure P-1. Each chapter opener includes the chapter number and title, a brief introduction, lists of text sections and chapter objectives, a key terms list, an *Application Activity* preview, and a website reference for study aids and supplementary materials.

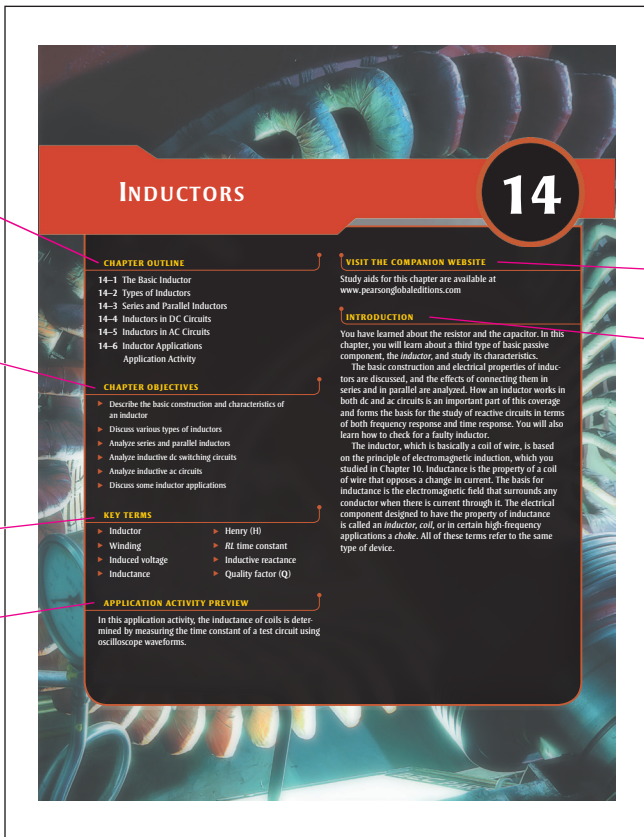
Worked Examples and Related Problems Numerous worked examples throughout each chapter help to illustrate and clarify basic concepts or specific procedures. Each example ends with a Related Problem that reinforces or expands on the example by requiring the student to work through a problem similar to the example. Many examples have a Multisim circuit exercise and most also have an LTSpice circuit exercise. A typical worked example with a Related Problem is shown in Figure P-2.

Section Opener Each section in a chapter begins with a brief introduction that includes a general overview and section objectives. An illustration is given in Figure P-2.

Section Checkup Each section in a chapter ends with a review consisting of questions or exercises that emphasize the main concepts covered in the section. An example is shown in Figure P-2. Answers to the Section Checkups are at the end of the chapter.

Application Activity Each chapter (except Chapters 1 and 21) presents a practical application of certain topics covered in the chapter. In each activity, students apply the concepts covered in the chapter in a practical problem. Many of the activities involve comparing circuit board layouts with schematics, analyzing circuits, using measurements to determine circuit operation, and in some cases, developing simple test procedures. Results and answers are found in the Instructor's Resource Manual. A typical Application Activity is shown in Figure P-3.

Troubleshooting Sections Many chapters include a troubleshooting section that relates to the topics covered in the chapter and emphasizes logical thinking as well as a structured approach called APM (analysis, planning, and measurement) where applicable. Particular troubleshooting methods, such as half-splitting, are applied when appropriate.



Chapter outline

List of performance-based objectives

Key terms

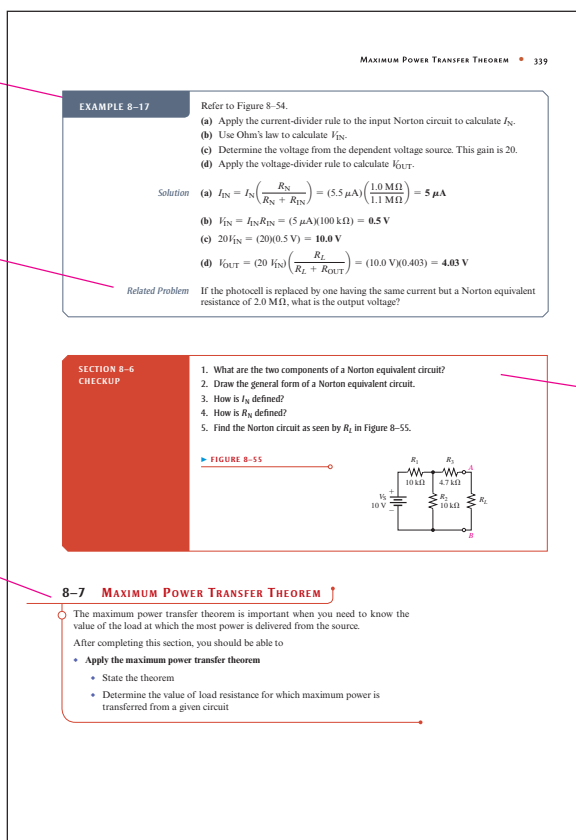
Application activity preview

Website reference

Chapter introduction

FIGURE P-1

A typical chapter opener.



Examples are set off from text

All examples include a related problem. (Many also include Multisim and LTSpice references.)

Section openers include opening paragraph and objectives

Sections end with checkup exercises, set off from text.

FIGURE P-2

Typical chapter features.

Application activities are set off from text and relate theory to practice.

APPLICATION ACTIVITY • 349

Application Activity

The Wheatstone bridge circuit was introduced in Chapter 7 and expanded in this chapter to include the use of Thevenin's theorem. In Chapter 7, the circuit application used a thermistor in one arm of the bridge to sense temperature. The bridge was used to compare the resistance of the thermistor with the resistance of a rheostat, which set the temperature at which the output would switch from one polarity to the opposite for turning on a heater in a tank filled with a liquid. In this application activity, you will work with a similar circuit, but this time it will be used to monitor the temperature in the tank to provide a visual indication that the temperature is within a specified range.

The Temperature Monitor

The basic measuring circuit in the temperature monitor is a Wheatstone bridge with an ammeter and a series resistor acting as the load. The meter is an analog panel meter with a sensitivity of 50 μA full scale. The Wheatstone bridge temperature-measuring circuit is shown in Figure 8-69(a), and the meter panel is shown in Figure 8-69(b).

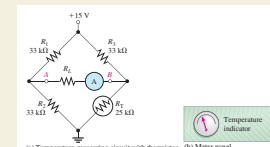

The Thermistor

The thermistor is the same one used in the circuit application of Chapter 7, specifically a Thermometrics RL2006-13.3K-140-D1 thermistor with a specified resistance of 23 k Ω at 25°C and a β of 4615K. Recall that β is a constant supplied by the manufacturer that indicates the shape of the temperature-resistance characteristic. As given in Chapter 7, the exponential equation for the resistance of a thermistor is approximated by

$$R_T = R_0 e^{\beta \left(\frac{1}{T} - \frac{1}{T_0} \right)}$$

where:

- R_T = the resistance at a given temperature
- R_0 = the resistance at a reference temperature
- T_0 = the reference temperature in K (typically 298 K, which is 25°C)

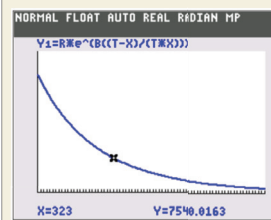



(a) Temperature-measuring circuit with thermistor (b) Meter panel

350 • CIRCUIT THEOREMS AND CONVERSIONS

FIGURE 8-70

Thermistor resistance as a function of temperature.



X=323 Y=7540.0163

FIGURE 8-71

Table of calculated resistance (blue) as a function of temperature in Celsius (red).

X	Y1	Y2
298	25000	25
303	19362	30
308	15121	35
313	11902	40
318	9429.3	45
323	7540	50
328	6064.3	55
333	4989.4	60
338	3999.4	65
343	3277.6	70
348	2761.5	75

Y1=7540.0162731075

thermistor temperature is 50°C and its resistance is the value calculated previously. Draw the Thevenin circuit for this temperature but do not show a load.

3. Show the load resistor for the Thevenin circuit you drew. The load is a resistor in series with the ammeter, which will have a current of 50 μA at full scale (50°C). You can find the value of the required load resistor by applying the superposition theorem to the two sources and calculating the total resistance from Ohm's law (using the full-scale deflection as the current). Subtract the Thevenin resistance of each arm from the total resistance to obtain the required load resistance. Neglect the meter resistance. Show the value calculated on the Thevenin circuit.

4. Calculate the thermistor resistance for the lower and upper limits of temperature (30°C and 40°C). Draw Thevenin circuits for each temperature and calculate the current through the load resistor.

The Meter Scale

A requirement for the temperature monitor is to mark three color bands on the meter to indicate that the temperature is within the desired range. The desired range is between a low of 30°C and 40°C. The meter should indicate a too-cold range from 20°C to 30°C, a proper operating range from 30°C to 40°C, and a too-hot range from 40°C and 50°C. Full-scale deflection of the meter should be set for 50°C.

5. Indicate how you would mark the meter to have a quick visual indication of the temperature in the tank.

Review

6. At 35°C, what is the current in the meter?
7. What change is needed if a 100 μA meter is used instead of a 50 μA meter?

▲ FIGURE P-3

Typical application assignment.

Chapter End Matter The following pedagogical features are found at the end of each chapter:

- ◆ Summary
- ◆ Key terms glossary
- ◆ Formula list
- ◆ True/False Quiz
- ◆ Self-Test
- ◆ Circuit Dynamics Quiz
- ◆ Problems
- ◆ Answers to section checkups, related problems for examples, true/false quiz, self-test, and the circuit dynamics quiz

Suggestions for Teaching with *Principles of Electric Circuits*

Selected Course Emphasis and Flexibility of the Text This textbook is designed primarily for use in a two-term course sequence in which dc topics (Chapters 1 through 10) are covered in the first term and ac topics (Chapters 11 through 21) are covered in the second term. A one-term course covering dc and ac topics is possible but would require very selective and abbreviated coverage of many topics.

If time limitations or course emphasis restricts the topics that can be covered, as is usually the case, there are several options for selective coverage. The following

suggestions for light treatment or omission do not necessarily imply that a certain topic is less important than others but that, in the context of a specific program, the topic may not require the emphasis that the more fundamental topics do. Because course emphasis, level, and available time vary from one program to another, the omission or abbreviated treatment of selected topics must be made on an individual basis. Therefore, the following suggestions are intended only as a general guide.

1. Chapters that may be considered for omission or selective coverage:
 - ◆ Chapter 8, Circuit Theorems and Conversions
 - ◆ Chapter 9, Branch, Loop, and Node Analyses
 - ◆ Chapter 10, Magnetism and Electromagnetism
 - ◆ Chapter 18, Passive Filters
 - ◆ Chapter 19, Circuit Theorems in AC Analysis
 - ◆ Chapter 20, Time Response of Reactive Circuits
 - ◆ Chapter 21, Three-Phase Systems in Power Applications
2. *Application Activity* features and troubleshooting sections can be omitted without affecting other material.
3. Other specific topics may be omitted or covered lightly on a section-by-section basis at the discretion of the instructor. The order in which certain topics appear in the text can be altered at the instructor's discretion. For example, the topics of capacitors and inductors (Chapters 12 and 14) can be covered at the end of the dc course in the first term by delaying coverage of the ac topics in Sections 12–6, 12–7, 14–5, and 14–6 until the ac course in the second term. Another possibility is to cover Chapters 12 and 14 first, move on to Chapters 16 and 13, and cover Chapter 15 last.

Application Activity These features are useful for motivation and for introducing applications of basic concepts and components. Suggestions for using these sections are:

- ◆ As an integral part of the chapter to illustrate how the concepts and components can be applied in a practical situation. The activities can be assigned for homework.
- ◆ As extra credit assignments.
- ◆ As in-class activities to promote discussion and interaction and to help students understand why they need to know the material.

Coverage of Reactive Circuits Chapters 13, 15, and 17 have been designed to provide two approaches to teaching these topics on reactive circuits.

The first option is to cover the topics on the basis of components. That is, first cover all of Chapter 13 (*RC Circuits*), then all of Chapter 15 (*RL Circuits*), and, finally, all of Chapter 17 (*RLC Circuits and Resonance*).

The second option is to cover the topics on the basis of circuit type. That is, first cover all topics related to series reactive circuits, then all topics related to parallel reactive circuits, and finally, all topics related to series-parallel reactive circuits. To facilitate this second approach, Chapters 13, 15, and 17 have been divided into the following parts: *Part 1: Series Circuits*, *Part 2: Parallel Circuits*, *Part 3: Series-Parallel Circuits*, and *Part 4: Special Topics*. So, for series reactive circuits, cover Part 1 of all three chapters in sequence. For parallel reactive circuits, cover Part 2 of all three chapters in sequence. For series-parallel reactive circuits, cover Part 3 of all three chapters in sequence. Finally, for special topics, cover Part 4 of all three chapters.

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. After each section, answer the checkup questions. Answers to the related problems and the section checkup questions are at the end of the chapter.

Review the chapter summary, the key term definitions, and the formula list. Take the True/False Quiz, the multiple-choice Self-Test, and the Circuit Dynamics 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 paragraph.

Service Shop Technician Technical personnel in this category are involved in the repair or adjustment of both commercial and consumer electronic equipment that is 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 personnel service and repair electronic equipment—for example, computer systems, radar installations, automatic banking equipment, and security systems.

Engineering Assistant/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. The names of many of the early pioneers in electricity and electromagnetics still live on in terms of familiar units and quantities. Names such as Ohm, Ampere, Volta, Faraday, Henry, Coulomb, Tesla, Gauss, and Hertz are some of the better known examples. More widely known names such as Franklin and Edison are also significant in the history of electricity and electronics because of their tremendous contributions. Short biographies of some of these pioneers are located throughout the text in History Notes.

The Beginning of Electronics Early experiments with electronics involved electric currents in vacuum tubes. Heinrich Geissler (1814–1879) removed most of the air from a glass tube and found that the tube glowed when there was current through it. Later, Sir William Crookes (1832–1919) found the current in vacuum tubes seemed to consist of particles. Thomas Edison (1847–1931) experimented with carbon filament bulbs with plates and discovered that there was a current from the hot filament to a positively charged plate. He patented the idea but never used it.

Other early experimenters measured the properties of the particles that flowed in vacuum tubes. Sir Joseph Thompson (1856–1940) measured properties of these particles, later called electrons.

Although wireless telegraphic communication dates back to 1844, electronics is basically a 20th century concept that began with the invention of the vacuum tube amplifier. An early vacuum tube that allowed current in only one direction was constructed by John A. Fleming in 1904. Called the Fleming valve, it was the forerunner of vacuum tube diodes. In 1907, Lee deForest added a grid to the vacuum tube. The new device, called the audiotron, could amplify a weak signal. By adding the control element, deForest ushered in the electronics revolution. It was with an improved version of his device that made transcontinental telephone service and radios possible. In 1912, a radio amateur in San Jose, California, was regularly broadcasting music!

In 1921, the secretary of commerce, Herbert Hoover, issued the first license to a broadcast radio station; within two years over 600 licenses were issued. By the end of the 1920s radios were in many homes. A new type of radio, the superheterodyne radio, invented by Edwin Armstrong, solved problems with high-frequency communication. In 1923, Vladimir Zworykin, an American researcher, invented the first television picture tube, and in 1927 Philo T. Farnsworth applied for a patent for a complete television system.

The 1930s saw many developments in radio, including metal tubes, automatic gain control, “midget sets,” directional antennas, and more. Also started in this decade was the development of the first electronic computers. Modern computers trace their origins to the work of John Atanasoff at Iowa State University. Beginning in 1937, he envisioned a binary machine that could do complex mathematical work. By 1939, he and graduate student Clifford Berry had constructed a binary machine called ABC (for Atanasoff-Berry Computer) that used vacuum tubes for logic and condensers (capacitors) for memory. In 1939, the magnetron, a microwave oscillator, was invented in Britain by Henry Boot and John Randall. In the same year, the klystron microwave tube was invented in America by Russell and Sigurd Varian.

During World War II, electronics developed rapidly. Radar and very high-frequency communication were made possible by the magnetron and klystron. Cathode ray tubes were improved for use in radar. Computer work continued during the war. By 1946, John von Neumann had developed the first stored program computer, the Eniac, at

the University of Pennsylvania. The decade ended with one of the most important inventions ever, the transistor.

Solid-State Electronics The crystal detectors used in early radios were the forerunners of modern solid-state devices. However, the era of solid-state electronics began with the invention of the transistor in 1947 at Bell Labs. The inventors were Walter Brattain, John Bardeen, and William Shockley. PC (printed circuit) boards were introduced in 1947, the year the transistor was invented. Commercial manufacturing of transistors began in Allentown, Pennsylvania, in 1951.

The most important invention of the 1950s was the integrated circuit. On September 12, 1958, Jack Kilby, at Texas Instruments, made the first integrated circuit. This invention literally created the modern computer age and brought about sweeping changes in medicine, communication, manufacturing, and the entertainment industry. Many billions of “chips”—as integrated circuits came to be called—have since been manufactured.

The 1960s saw the space race begin and spurred work on miniaturization and computers. The space race was the driving force behind the rapid changes in electronics that followed. The first successful “op-amp” was designed by Bob Widlar at Fairchild Semiconductor in 1965. Called the $\mu A709$, it was very successful but suffered from “latch-up” and other problems. Later, the most popular op-amp ever, the 741, was taking shape at Fairchild. This op-amp became the industry standard and influenced design of op-amps for years to come.

By 1971, a new company that had been formed by a group from Fairchild introduced the first microprocessor. The company was Intel and the product was the 4004 chip, which had the same processing power as the Eniac computer. Later in the same year, Intel announced the first 8-bit processor, the 8008. In 1975, the first personal computer was introduced by Altair, and *Popular Science* magazine featured it on the cover of the January, 1975, issue. The 1970s also saw the introduction of the pocket calculator and new developments in optical integrated circuits. An HP-65 programmable hand-held calculator was taken into space in 1975 to provide backup calculations for course corrections for docking the Apollo-Soyuz rendezvous.

By the 1980s, half of all U.S. homes were using cable hookups instead of television antennas. The reliability, speed, and miniaturization of electronics continued throughout the 1980s, including automated testing and calibrating of PC boards. The computer became a part of instrumentation and the virtual instrument was created. Computers became a standard tool on the workbench.

The 1990s saw a widespread application of the Internet. In 1993, there were 130 websites, and now there are nearly 2 billion. Companies scrambled to establish a home page and many of the early developments of radio broadcasting had parallels with the Internet. In 1995, the FCC allocated spectrum space for a new service called Digital Audio Radio Service. Digital television standards were adopted in 1996 by the FCC for the nation’s next generation of broadcast television. Kodak introduced the first digital camera in 1991 with a 1.3-megapixel sensor.

The 21st century dawned in January 2001 (although many people celebrated it a year earlier). One of the major technology stories of the first decade of the 21st century was the continuous and explosive growth of the Internet. Wireless broadband access fueled the growth tremendously and saw new developments and standards for routers and wireless connectivity. The processing speed of computers continued to increase. Another advancement was in digital storage devices including improved optical disc storage technologies such as Blu-ray for high-definition video storage. In 2007, Steve Jobs of Apple Computer introduced one of the most significant developments of the first decade of the 21st century when he announced the Apple iPhone. In addition to the phone function, the first-generation iPhone featured Internet access, music application technology and a 2-megapixel camera plus other features. Smart

phones, as they have come to be known, have become ubiquitous in the years since the iPhone's introduction.

The second decade of the 21st century has seen continued growth and innovation. New developments in electronics include printed electronics, polymer electronics, and organic electronics for creating both active and passive components. Printable electronics included both electronic and optical components, which has enabled products such as biomedical wristbands and curved OLED TVs. In addition, the continued quest to move to renewable energy has led to intensive research and development in the areas of batteries, solar cells, fuel cells, wind energy, and other technology.

Acknowledgments

Many people have been part of this revision of *Principles of Electric Circuits*. It has been thoroughly reviewed and checked for both content and accuracy. Gary Snyder did an outstanding job of accuracy checking and made numerous suggestions for improving the wording of revised material. His accuracy check included working every example and reviewing the entire text, adding many suggestions along the way. He also created the circuit files for the Multisim and LTSpice features in this edition. I also want to acknowledge the suggestions from Tom Floyd for changes he wanted in this revision. Tom had a huge interest in keeping this book as one of top basic electronics texts available and made numerous suggestions. Sadly, he did not live to see them implemented.

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David M. Buchla

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Contributors

Murat Doğruel, *Marmara University*
Nalan Özkurt, *Yaşar University*

Reviewers

Gokhan Bora Esmer, *Marmara University*
Quang Ha, *University of Technology Sydney*
Nalan Özkurt, *Yaşar University*
Ha Pham, *University of Technology Sydney*
Branislav Vuksanovic, *University of Portsmouth*

CONTENTS

1 Quantities and Units 17

- 1-1 Units of Measurement 18
- 1-2 Scientific Notation 20
- 1-3 Engineering Notation and Metric Prefixes 23
- 1-4 Metric Unit Conversions 26
- 1-5 Measured Numbers 28

2 Voltage, Current, and Resistance 37

- 2-1 Atomic Structure 38
- 2-2 Electrical Charge 42
- 2-3 Voltage 44
- 2-4 Current 50
- 2-5 Resistance 53
- 2-6 The Electric Circuit 61
- 2-7 Basic Circuit Measurements 69
- 2-8 Electrical Safety 75
- Application Activity 78

3 Ohm's Law 92

- 3-1 The Relationship of Current, Voltage, and Resistance 93
- 3-2 Current Calculations 97
- 3-3 Voltage Calculations 100
- 3-4 Resistance Calculations 102
- 3-5 Introduction to Troubleshooting 104
- Application Activity 107

4 Energy and Power 118

- 4-1 Energy and Power 119
- 4-2 Power in an Electric Circuit 121
- 4-3 Resistor Power Ratings 123
- 4-4 Energy Conversion and Voltage Drop in Resistance 128
- 4-5 Power Supplies and Batteries 129
- Application Activity 132

5 Series Circuits 141

- 5-1 Resistors in Series 142
- 5-2 Total Series Resistance 144

- 5-3 Current in a Series Circuit 148
- 5-4 Application of Ohm's Law 150
- 5-5 Voltage Sources in Series 154
- 5-6 Kirchhoff's Voltage Law 157
- 5-7 Voltage Dividers 161
- 5-8 Power in Series Circuits 168
- 5-9 Voltage Measurements 170
- 5-10 Troubleshooting 175
- Application Activity 179

6 Parallel Circuits 197

- 6-1 Resistors in Parallel 198
- 6-2 Voltage in a Parallel Circuit 201
- 6-3 Kirchhoff's Current Law 203
- 6-4 Total Parallel Resistance 207
- 6-5 Application of Ohm's Law 213
- 6-6 Current Sources in Parallel 216
- 6-7 Current Dividers 218
- 6-8 Power in Parallel Circuits 222
- 6-9 Parallel Circuit Applications 224
- 6-10 Troubleshooting 228
- Application Activity 233

7 Series-Parallel Circuits 251

- 7-1 Identifying Series-Parallel Relationships 252
- 7-2 Analysis of Series-Parallel Resistive Circuits 257
- 7-3 Voltage Dividers with Resistive Loads 265
- 7-4 Loading Effect of a Voltmeter 270
- 7-5 Ladder Networks 273
- 7-6 The Wheatstone Bridge 279
- 7-7 Troubleshooting 284
- Application Activity 288

8 Circuit Theorems and Conversions 306

- 8-1 The DC Voltage Source 307
- 8-2 The Current Source 310
- 8-3 Source Conversions 312
- 8-4 The Superposition Theorem 315
- 8-5 Thevenin's Theorem 323
- 8-6 Norton's Theorem 335
- 8-7 Maximum Power Transfer Theorem 339

- 8–8 Delta-to-Wye (Δ -to-Y) and Wye-to-Delta (Y-to- Δ) Conversions 343
Application Activity 349

9 Branch, Loop, and Node Analyses 365

- 9–1 Simultaneous Equations in Circuit Analysis 366
9–2 Branch Current Method 377
9–3 Loop Current Method 381
9–4 Node Voltage Method 388
Application Activity 395

10 Magnetism and Electromagnetism 406

- 10–1 The Magnetic Field 407
10–2 Electromagnetism 413
10–3 Electromagnetic Devices 419
10–4 Magnetic Hysteresis 426
10–5 Electromagnetic Induction 429
10–6 The DC Generator 434
10–7 The DC Motor 439
Application Activity 443

11 Introduction to Alternating Current and Voltage 453

- 11–1 The Sinusoidal Waveform 454
11–2 Sinusoidal Voltage and Current Values 459
11–3 Angular Measurement of a Sine Wave 463
11–4 The Sine Wave Formula 467
11–5 Introduction to Phasors 469
11–6 Analysis of AC Circuits 475
11–7 The Alternator (AC Generator) 480
11–8 The AC Motor 484
11–9 Nonsinusoidal Waveforms 487
11–10 The Oscilloscope 493
Application Activity 500

12 Capacitors 518

- 12–1 The Basic Capacitor 519
12–2 Types of Capacitors 525
12–3 Series Capacitors 531
12–4 Parallel Capacitors 535
12–5 Capacitors in DC Circuits 537
12–6 Capacitors in AC Circuits 549
12–7 Capacitor Applications 557
12–8 Switched-Capacitor Circuits 561
Application Activity 564

13 RC Circuits 580

- 13–1 The Complex Number System 581
Part 1: Series Circuits 592
13–2 Sinusoidal Response of Series RC Circuits 592

- 13–3 Impedance of Series RC Circuits 593

- 13–4 Analysis of Series RC Circuits 596

Part 2: Parallel Circuits 609

- 13–5 Impedance and Admittance of Parallel RC Circuits 609

- 13–6 Analysis of Parallel RC Circuits 612

Part 3: Series-Parallel Circuits 618

- 13–7 Analysis of Series-Parallel RC Circuits 618

Part 4: Special Topics 625

- 13–8 Power in RC Circuits 625

- 13–9 Basic Applications 629

- 13–10 Troubleshooting 635
Application Activity 641

14 Inductors 661

- 14–1 The Basic Inductor 662

- 14–2 Types of Inductors 668

- 14–3 Series and Parallel Inductors 669

- 14–4 Inductors in DC Circuits 671

- 14–5 Inductors in AC Circuits 683

- 14–6 Inductor Applications 690
Application Activity 692

15 RL Circuits 704

Part 1: Series Circuits 705

- 15–1 Sinusoidal Response of Series RL Circuits 705

- 15–2 Impedance of Series RL Circuits 706

- 15–3 Analysis of Series RL Circuits 708

Part 2: Parallel Circuits 718

- 15–4 Impedance and Admittance of Parallel RL Circuits 718

- 15–5 Analysis of Parallel RL Circuits 721

Part 3: Series-Parallel Circuits 727

- 15–6 Analysis of Series-Parallel RL Circuits 727

Part 4: Special Topics 731

- 15–7 Power in RL Circuits 731

- 15–8 Basic Applications 734

- 15–9 Troubleshooting 739
Application Activity 743

16 Transformers 757

- 16–1 Mutual Inductance 758

- 16–2 The Basic Transformer 759

- 16–3 Step-Up and Step-Down Transformers 763

- 16–4 Loading the Secondary 766

- 16–5 Reflected Load 768

- 16–6 Impedance Matching 770

- 16–7 Transformer Ratings and Characteristics 773

- 16–8 Tapped and Multiple-Winding Transformers 776

- 16–9 Troubleshooting 782

- Application Activity 784

17 RLC Circuits and Resonance 797**Part 1: Series Circuits 798**

- 17-1 Impedance of Series *RLC* Circuits 798
- 17-2 Analysis of Series *RLC* Circuits 800
- 17-3 Series Resonance 805
- Part 2: Parallel Circuits 812**
- 17-4 Impedance of Parallel *RLC* Circuits 812
- 17-5 Analysis of Parallel *RLC* Circuits 816
- 17-6 Parallel Resonance 818
- Part 3: Series-Parallel Circuits 823**
- 17-7 Analysis of Series-Parallel *RLC* Circuits 823
- Part 4: Special Topics 831**
- 17-8 Bandwidth of Resonant Circuits 831
- 17-9 Applications 835
 - Application Activity 839

18 Passive Filters 853

- 18-1 Low-Pass Filters 854
- 18-2 High-Pass Filters 862
- 18-3 Band-Pass Filters 867
- 18-4 Band-Stop Filters 871
 - Application Activity 876

19 Circuit Theorems in AC Analysis 887

- 19-1 The Superposition Theorem 888
- 19-2 Thevenin's Theorem 893
- 19-3 Norton's Theorem 903
- 19-4 Maximum Power Transfer Theorem 907
 - Application Activity 912

20 Time Response of Reactive Circuits 921

- 20-1 The *RC* Integrator 922
- 20-2 Response of an *RC* Integrator to a Single Pulse 923

- 20-3 Response of *RC* Integrators to Repetitive Pulses 928
- 20-4 Response of an *RC* Differentiator to a Single Pulse 933
- 20-5 Response of *RC* Differentiators to Repetitive Pulses 938
- 20-6 Response of *RL* Integrators to Pulse Inputs 940
- 20-7 Response of *RL* Differentiators to Pulse Inputs 945
- 20-8 Relationship of Time Response to Frequency Response 949
- 20-9 Troubleshooting 952
 - Application Activity 955

21 Three-Phase Systems in Power Applications 967

- 21-1 Generators in Power Applications 968
- 21-2 Types of Three-Phase Generators 971
- 21-3 Three-Phase Source/Load Analysis 976
- 21-4 Three-Phase Power 983

APPENDICES

- A** Table of Standard Resistor Values 991
- B** Derivations 992
- C** Capacitor Label Coding 997
- D** NI Multisim for Circuit Simulation 1001

Answers to Odd-Numbered Problems 1005

Glossary 1019

Index 1025

QUANTITIES AND UNITS

1

CHAPTER OUTLINE

- 1-1 Units of Measurement
- 1-2 Scientific Notation
- 1-3 Engineering Notation and Metric Prefixes
- 1-4 Metric Unit Conversions
- 1-5 Measured Numbers

CHAPTER OBJECTIVES

- ▶ Discuss the SI standard
- ▶ Use scientific notation (powers of ten) to represent quantities
- ▶ Use engineering notation and metric prefixes to represent large and small quantities
- ▶ Convert from one unit with a metric prefix to another
- ▶ Express measured data with the proper number of significant digits

KEY TERMS

- ▶ SI
- ▶ Scientific notation
- ▶ Power of ten
- ▶ Exponent
- ▶ Engineering notation
- ▶ Metric prefix
- ▶ Error
- ▶ Accuracy
- ▶ Precision
- ▶ Significant digits
- ▶ Round off

VISIT THE COMPANION WEBSITE

Study aids for this chapter are available at www.pearsonglobaleditions.com

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.



SAFETY NOTE

- ▶ When you work with electricity, you must always consider safety first. Safety notes throughout the book remind you of the importance of safety and provide tips for a safe workplace. Basic safety precautions are introduced in Chapter 2.

1-1 UNITS OF MEASUREMENT

In the 19th century, the principal weight and measurement units dealt with commerce. As technology advanced, scientists and engineers saw the need for international standard measurement units. In 1875, at a conference called by the French, representatives from 18 nations signed a treaty that established international standards. Today, all engineering and scientific work use an improved international system of units, Le Système International d'Unités, abbreviated **SI***.

After completing this section, you should be able to

- ◆ **Discuss the SI standard**
 - ◆ Specify the base (fundamental) SI units
 - ◆ Specify the supplementary units
 - ◆ Explain what derived units are

Base and Derived Units

The SI system is based on seven base units (sometimes called *fundamental units*) and two supplementary units. All measurements can be expressed as some combination of base and supplementary units. Table 1-1 lists the base units, and Table 1-2 lists the supplementary units.

The base electrical unit, the ampere, is the unit for electrical current. Current is abbreviated with the letter I (for intensity) and uses the symbol A (for ampere). The ampere is unique in that it uses the base unit of time (t) in its definition (second). All other electrical and magnetic units (such as voltage, power, and magnetic flux) use various combinations of base units in their definitions and are called *derived units*.

For example, the derived unit of voltage, which is the volt (V), is defined in terms of base units as $\text{m}^2 \cdot \text{kg} \cdot \text{s}^{-3} \cdot \text{A}^{-1}$. As you can see, this combination of base units is very cumbersome and impractical. Therefore, the volt is used as the derived unit.

▶ **TABLE 1-1**

SI base units.

QUANTITY	UNIT	SYMBOL
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electric current	Ampere	A
Temperature	Kelvin	K
Luminous intensity	Candela	cd
Amount of substance	Mole	mol

▶ **TABLE 1-2**

SI supplementary units.

QUANTITY	UNIT	SYMBOL
Plane angle	Radian	r
Solid angle	Steradian	sr

*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.

Letter symbols are used to represent both quantities and their units. One symbol is used to represent the name of the quantity, and another symbol is used to represent the unit of measurement of that quantity. For example, italic P stands for *power*, and nonitalic W stands for *watt*, which is the unit of power. Another example is voltage, where the same letter stands for both the quantity and its unit. Italic V represents voltage and nonitalic V represents *volt*, which is the unit of voltage. As a rule, italic letters stand for the quantity and nonitalic (roman) letters represent the unit of that quantity.

Table 1–3 lists the most important electrical quantities, along with their derived SI units and symbols. Table 1–4 lists magnetic quantities, along with their derived SI units and symbols.

QUANTITY	SYMBOL	SI UNIT	SYMBOL
Capacitance	C	Farad	F
Charge	Q	Coulomb	C
Conductance	G	Siemens	S
Energy (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 1–3

Electrical quantities and derived units with SI symbols.

QUANTITY	SYMBOL	SI UNIT	SYMBOL
Magnetic field intensity	H	Ampere-turns/meter	At/m
Magnetic flux	ϕ	Weber	Wb
Magnetic flux density	B	Tesla	T
Magnetomotive force	F_m	Ampere-turn	At
Permeability	μ	Webers/ampere-turn · meter	Wb/At · m
Reluctance	\mathcal{R}	Ampere-turns/weber	At/Wb

TABLE 1–4

Magnetic quantities and derived units with SI symbols.

In addition to the common electrical units shown in Table 1–3, the SI system has many other units that are defined in terms of certain base 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*). The mole (abbreviated *mol*) was added in 1971. Three base units form the basis of the mks (for meter-kilogram-second) units that are used for derived quantities in engineering and basic physics and have become the preferred units for nearly all scientific and engineering work. 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.

SECTION 1-1 CHECKUP

Answers are at the end of the chapter.

1. How does a base unit differ from a derived unit?
2. What is the base electrical unit?
3. What does *SI* stand for?
4. Without referring to Table 1-3, list as many electrical quantities as possible, including their symbols, units, and unit symbols.
5. Without referring to Table 1-4, list as many magnetic quantities as possible, including their symbols, units, and unit symbols.

1-2 SCIENTIFIC NOTATION

In electrical and electronics fields, both very small and very large quantities are commonly used. For example, it is common to have electrical current values of only a few thousandths or even a few millionths of an ampere and to have resistance values ranging up to several thousand or several million ohms.

After completing this section, you should be able to

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

Scientific notation provides a convenient method to represent large and small numbers and to perform calculations involving such numbers. In scientific notation, a quantity is expressed as a product of a number between 1 and 10 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 1-5 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 (10^x). An **exponent** is a number to which a base number is raised. It indicates the number of places that the decimal point is moved to the right or left to produce the

▼ **TABLE 1-5**

Some positive and negative powers of ten.

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

decimal number. For a positive power of ten, move the decimal point to the right to get the equivalent decimal number. For example, for an exponent of 4,

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

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

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

EXAMPLE 1–1

Express each number in scientific notation.

- (a) 200 (b) 5,000 (c) 85,000 (d) 3,000,000

Solution In each case, move the decimal point an appropriate number of places to the left to determine the positive power of ten. Notice that the result is always a number between 1 and 10 times a power of ten.

- (a) $200 = 2 \times 10^2$ (b) $5,000 = 5 \times 10^3$
 (c) $85,000 = 8.5 \times 10^4$ (d) $3,000,000 = 3 \times 10^6$

Related Problem* Express 4,750 in scientific notation.

*Answers are at the end of the chapter.

EXAMPLE 1–2

Express each number in scientific notation.

- (a) 0.2 (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) $0.2 = 2 \times 10^{-1}$ (b) $0.005 = 5 \times 10^{-3}$
 (c) $0.00063 = 6.3 \times 10^{-4}$ (d) $0.000015 = 1.5 \times 10^{-5}$

Related Problem Express 0.00738 in scientific notation.

EXAMPLE 1–3

Express each of the following as a regular decimal number:

- (a) 1×10^5 (b) 2×10^3 (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) $1 \times 10^5 = 100,000$ (b) $2 \times 10^3 = 2,000$
 (c) $3.2 \times 10^{-2} = 0.032$ (d) $2.5 \times 10^{-6} = 0.0000025$

Related Problem Express 9.12×10^3 as a regular decimal number.

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 is the power of ten of the sum.

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 $52 \times 10^6 = \mathbf{5.2 \times 10^7}$.

Related Problem Add 3.1×10^3 and 5.5×10^4 .

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 is the power of ten of the difference.

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} .

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 5×10^{12} and 3×10^{-6} and express the result in scientific notation.

Solution Multiply the numbers, and algebraically add the powers.

$$(5 \times 10^{12})(3 \times 10^{-6}) = (5)(3) \times 10^{12+(-6)} = 15 \times 10^6 = \mathbf{1.5 \times 10^7}$$

Related Problem Multiply 3.2×10^6 and 1.5×10^{-3} .

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 (the exponent) in the denominator from the power of ten in the numerator (the powers 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 as

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

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

$$\frac{5.0 \times 10^8}{2.5 \times 10^3} = 2 \times 10^{8-3} = 2 \times 10^5$$

Related Problem Divide 8×10^{-6} by 2×10^{-10} .

SECTION 1–2 CHECKUP

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) 4,350 (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) $(1 \times 10^5) + (2 \times 10^5)$ (b) $(3 \times 10^6)(2 \times 10^4)$
(c) $(8 \times 10^3) \div (4 \times 10^2)$ (d) $(2.5 \times 10^{-6}) - (1.3 \times 10^{-7})$

1–3 ENGINEERING NOTATION AND METRIC PREFIXES

Engineering notation, a specialized form of scientific notation, is used widely in technical fields to represent large and small quantities. In electronics, engineering notation is used to represent values of voltage, current, power, resistance, capacitance, inductance, and time, to name a few. Metric prefixes are used in conjunction with engineering notation as a “short hand” for the certain powers of ten that are multiples of three.

After completing this section, you should be able to

- ◆ Use engineering notation and metric prefixes to represent large and small quantities
 - ◆ List the metric prefixes
 - ◆ Change a power of ten in engineering notation to a metric prefix
 - ◆ Use metric prefixes to express electrical quantities
 - ◆ Convert one metric prefix to another

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 expressed in engineering notation is 45×10^{-3} . In scientific notation, it is expressed as 4.5×10^{-2} .

EXAMPLE 1–8

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 82×10^3 .
 (b) 243,000 is expressed as 243×10^3 .
 (c) 1,956,000 is expressed as 1.956×10^6 .

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

EXAMPLE 1–9

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 2.2×10^{-3} .
 (b) 0.000000047 is expressed as 47×10^{-9} .
 (c) 0.00033 is expressed as 330×10^{-6} .

Related Problem Express 0.000000000056 in engineering notation.

Metric Prefixes

A metric prefix is an affix that precedes a measured quantity and represents a multiple or power of 10 multiple of the quantity. In engineering notation **metric prefixes** represent each of the most commonly used powers of ten in electronics and electrical work. The most commonly used metric prefixes are listed in Table 1–6 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 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 milliamperes. Note that the metric prefix *milli* has replaced 10^{-3} . As another example, 10,000,000 ohms can be expressed as 10×10^6 Ω . This quantity expressed using a metric prefix is 10 M Ω , which is read 10 megohms. The metric prefix *mega* has replaced 10^6 .

METRIC PREFIX	SYMBOL	POWER OF TEN	VALUE
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

TABLE 1-6

Common metric prefixes used in electronics and electrical work with their symbols and corresponding powers of ten and values.

EXAMPLE 1-10

Express each quantity using a metric prefix:

- (a) 50,000 V (b) 5,000,000 Ω (c) 0.000036 A

- Solution* (a) $50,000 \text{ V} = 50 \times 10^3 \text{ V} = \mathbf{50 \text{ kV}}$
 (b) $5,000,000 \Omega = 5 \times 10^6 \Omega = \mathbf{5 \text{ M}\Omega}$
 (c) $0.000036 \text{ A} = 36 \times 10^{-6} \text{ A} = \mathbf{36 \mu\text{A}}$

Related Problem Express using metric prefixes:

- (a) 56,000 Ω (b) 0.000470 A

Calculator Tip

All scientific and graphing calculators provide features for entering and displaying numbers in various formats. Scientific and engineering notation are special cases of exponential (power of ten) notation. Most calculators have a key labeled EE (or EXP) that is used to enter the exponent of numbers. To enter a number in exponential notation, enter the base number first, including the sign, and then press the EE key, followed by the exponent, including the sign.

Scientific and graphing calculators have displays for showing the power of ten. Some calculators display the exponent as a small raised number on the right side of the display.

47.0⁰³

Other calculators display the number with a small E followed by the exponent.

47.0E03

Notice that the base 10 is not generally shown, but it is implied or represented by the E. When you write out the number, you need to include the base 10. The displayed number shown above is written out as 47.0×10^3 in engineering notation.

Some calculators are placed in the scientific or engineering notation mode using a secondary or tertiary function, such as SCI or ENG. Then numbers are entered in regular decimal form. The calculator automatically converts them to the proper format. Other calculators provide for mode selection using a menu.

Always check the owner's manual for your particular calculator to determine how to use the exponential notation features.

SECTION 1-3
CHECKUP

- Express the following numbers in engineering notation:
(a) 0.0056 (b) 0.000000283 (c) 950,000 (d) 375,000,000,000
- 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}
- Use an appropriate metric prefix to express 0.000001 A.
- Use an appropriate metric prefix to express 250,000 W.

1-4 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 rules apply to metric unit conversions:

- When converting from a larger unit to a smaller unit, move the decimal point to the right.
- When converting from a smaller unit to a larger unit, move the decimal point to the left.
- 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). Notice that when the unit is made smaller, the number is made larger by a corresponding amount and vice versa. The following examples illustrate a few conversions.

EXAMPLE 1-11

Convert 0.15 milliamperes (0.15 mA) to microamperes (μA).

Solution Move the decimal point three places to the right.

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

Related Problem Convert 1 mA to microamperes.

EXAMPLE 1-12

Convert 4,500 microvolts (4,500 μV) to millivolts (mV).

Solution Move the decimal point three places to the left.

$$4,500 \mu\text{V} = 4,500 \times 10^{-6} \text{ V} = 4.5 \times 10^{-3} \text{ V} = \mathbf{4.5 \text{ mV}}$$

Related Problem Convert 1,000 μV to millivolts.

EXAMPLE 1–13Convert 5,000 nanoamperes (5,000 nA) to microamperes (μA).*Solution* Move the decimal point three places to the left.

$$5,000 \text{ nA} = 5,000 \times 10^{-9} \text{ A} = 5 \times 10^{-6} \text{ A} = \mathbf{5 \mu\text{A}}$$

Related Problem Convert 893 nA to microamperes.**EXAMPLE 1–14**Convert 47,000 picofarads (47,000 pF) to microfarads (μF).*Solution* Move the decimal point six places to the left.

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

Related Problem Convert 10,000 pF to microfarads.**EXAMPLE 1–15**Convert 0.00022 microfarad (0.00022 μF) to picofarads (pF).*Solution* Move the decimal point six places to the right.

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

Related Problem Convert 0.0022 μF to picofarads.**EXAMPLE 1–16**Convert 1,800 kilohms (1,800 k Ω) to megohms (M Ω).*Solution* Move the decimal point three places to the left.

$$1,800 \text{ k}\Omega = 1,800 \times 10^3 \Omega = 1.8 \times 10^6 \Omega = \mathbf{1.8 \text{ M}\Omega}$$

Related Problem Convert 2.2 k Ω to megohms.

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

EXAMPLE 1–17Add 15 mA and 8,000 μA and express the sum in milliamperes.*Solution* Convert 8,000 μA to 8 mA and add.

$$\begin{aligned} 15 \text{ mA} + 8,000 \mu\text{A} &= 15 \times 10^{-3} \text{ A} + 8,000 \times 10^{-6} \text{ A} \\ &= 15 \times 10^{-3} \text{ A} + 8 \times 10^{-3} \text{ A} = 15 \text{ mA} + 8 \text{ mA} = \mathbf{23 \text{ mA}} \end{aligned}$$

Related Problem Add 2,873 mA to 10,000 μA ; express the sum in milliamperes.**SECTION 1–4
CHECKUP**

- Convert 0.01 MV to kilovolts (kV).
- Convert 250,000 pA to milliamperes (mA).
- Add 0.05 MW and 75 kW and express the result in kW.
- Add 50 mV and 25,000 μV and express the result in mV.
- Which is larger: 2000 pF or 0.02 μF ?

1–5 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. It is a measure of how well a given measurement agrees with a standard. 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*. 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 two 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 three, four, or five significant digits. To clarify the significant digits, scientific notation (or a metric prefix) should be used. For example, 12.10 k Ω has four 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 not significant. To avoid confusion, numbers should be shown using scientific or engineering notation if it is necessary to show the significant zeros.

EXAMPLE 1–18

Express the measured number 4,300 with two, three, and four significant digits.

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

$$4.3 \times 10^3$$

To show three significant digits, write

$$4.30 \times 10^3$$

To show four significant digits, write

$$4.300 \times 10^3$$

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

EXAMPLE 1–19

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 $\times 10^5$ 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 1–18.
 (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 1–20

Round off the following numbers to three significant digits:

(a) 10.071 (b) 29.961 (c) 6.3948 (d) 123.52 (e) 122.5 (f) 328.52

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**. (f) 328.52 rounds to **329**.

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 one part in 1,000. 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 1–5
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 1,000 Ω resistor listed as 1.0 k Ω . 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?

SUMMARY

- SI is an abbreviation for Le Système International d’Unités and is a standardized system of units.
- A base unit is an SI unit from which other SI units are derived. There are seven base units and two supplementary units.
- Scientific notation is a method for representing 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 modified form of scientific notation in which quantities are represented with one, two, or three digits to the left of the decimal point times a power of ten that is a multiple of three.