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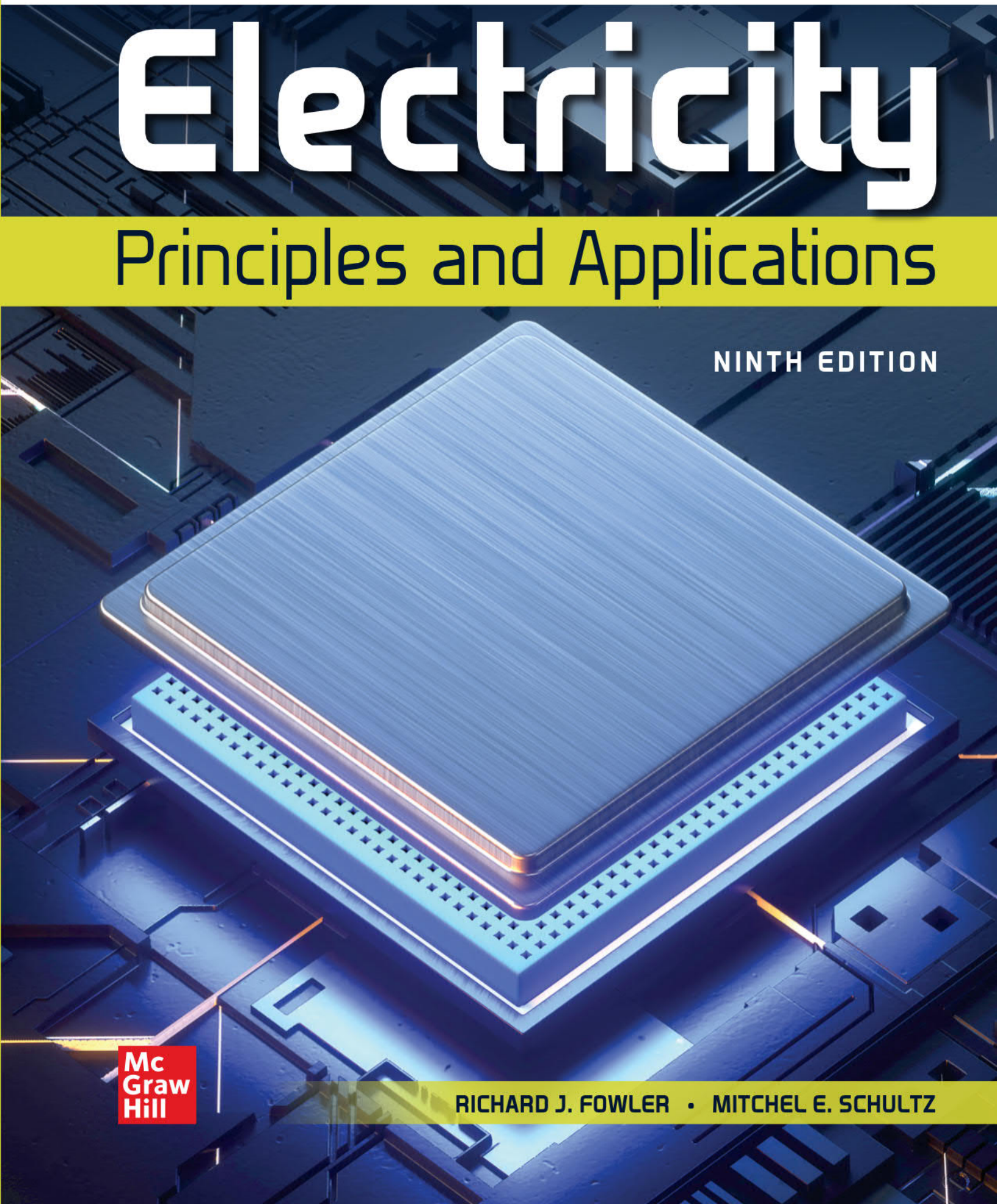
Electricity

Principles and Applications

NINTH EDITION



RICHARD J. FOWLER • MITCHEL E. SCHULTZ

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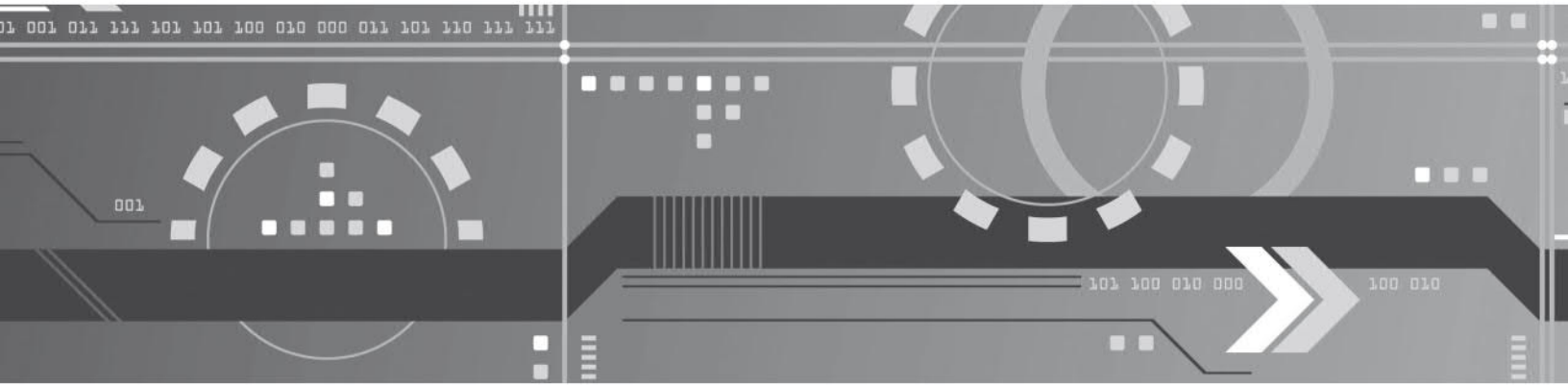

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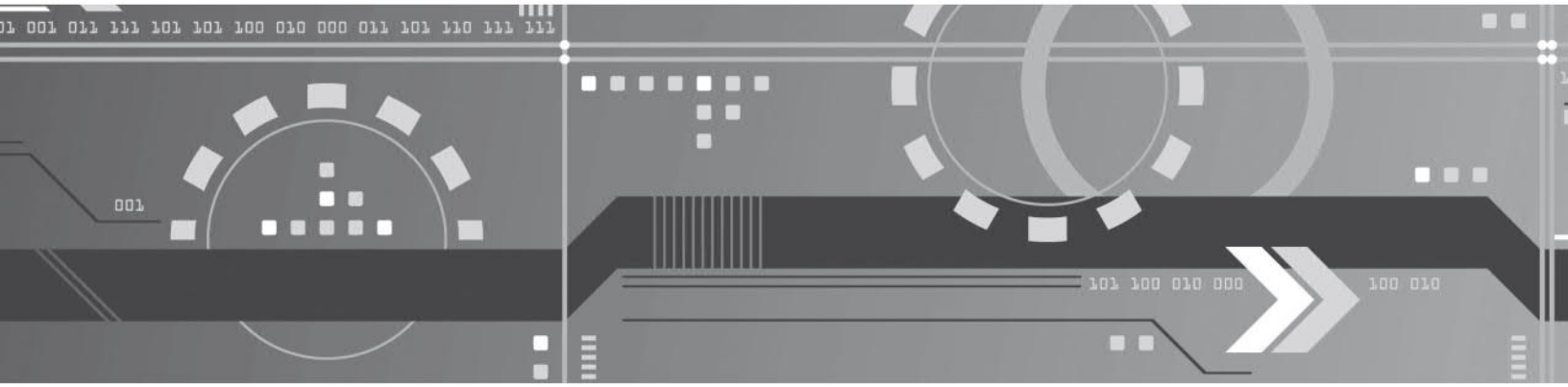

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Preface

The ninth edition of *Electricity: Principles and Applications* utilizes the same philosophy of learning and teaching as was used in the previous editions. It assumes that the student has very limited or no knowledge of electrical theory and principles. Mastery of the material in this text will aid the student desiring an entry-level job in an occupation requiring an understanding of electricity. Mastering this material will also provide the student with the knowledge and skills needed to pursue further education in electricity and electronics.

This text has been written so that students with limited math and reading skills can gain a clear understanding of electricity and electronic devices. Concepts are explained and developed by using a number of short, simple sentences rather than one long, complicated, convoluted sentence. It is never assumed that something is intuitively obvious.

Any mathematics beyond simple arithmetic is carefully explained and illustrated with examples before it is used to solve more advanced circuit problems. Although simultaneous equations, matrixes, and determinants are introduced in Chap. 6, they are defined and explained in some detail before actually being used. Similarly, the elements of trigonometry used with ac circuits are fully explained and illustrated with examples before being applied to ac circuit problems.

Chapters 1 through 6 of this text are devoted, in general, to the fundamentals of direct current, and Chaps. 8 through 13 focus on subjects usually associated with alternating current. Chapter 14 provides comprehensive coverage of electric motors, including motor classifications, motor ratings, and motor types. Chapter 15 covers the most common test instruments, such as analog and digital multimeters. This chapter also includes the topic of voltmeter loading. Chapter 16 introduces students to the concepts and practices involved with residential house wiring. This arrangement provides students with balanced coverage of basic concepts. The transition from direct current to alternating current through the study of magnetism and electromagnetism is distinct enough to allow use of the material in a traditional dc/ac sequence. However, all the material is structured to provide a unified introduction to the broad subject area called *electricity*.

What's New in the Ninth Edition of *Electricity: Principles and Applications*

The ninth edition of *Electricity: Principles and Applications* provides complete and thorough coverage of the basics of electricity without overwhelming the student with the unnecessary details and rigor of a more advanced course in electricity. This book assumes that the learner has no previous knowledge of electricity. It therefore introduces the basic concepts in a gradual manner, which allows the student to transition from one topic to another without being overwhelmed or inundated with little-known facts. The information is carefully laid out so as not to distract the reader from learning the basic concepts presented.

In this edition, changes have been made in every chapter to help clarify or add to the topics being presented. Additional Chapter Review Questions have been added to some chapters to cover new material.

Brand-new to this edition is a chapter called ***"Introduction to Powers of 10."*** This chapter, which appears at the front of the book, introduces and prepares students to work with both very small and very large numbers expressed in both *scientific* and *engineering notation*. The ***"Introduction to Powers of 10"*** chapter is placed before the chapters covering voltage, current, power, resistance, etc., so that the student is prepared to deal with the very large and very small units encountered in these topical areas. Not only are scientific and engineering notation covered in this chapter, but so are the metric prefixes associated with the basic units of measure that are so common in electricity. Students learn how to add, subtract, multiply, divide, square, and take the square root of numbers expressed in any form of powers of 10 notation.

Also new to this edition are ***homework problems*** that appear at the end of every chapter. Instructors can assign all of the homework problems for a chapter or hand-pick certain problems based on the concepts they want to emphasize.

Appendix B—Solder and the Soldering Process provides new information involving the use of lead-free solder.

Appendix I—The Oscilloscope has been completely rewritten for this edition. This appendix now provides much more extensive coverage of menu-driven oscilloscopes and, oscilloscope probes and the measurement of voltage, time, frequency, and phase.

Additional Resources

An ***Experiments Manual*** designed specifically for this textbook is available. It contains a comprehensive test, a wide variety of lab exercises and experiments, and additional problems for each chapter in the textbook. Some experiments must be done with physical (real) components, some must be done with electronic-circuit simulation software (Multisim), and some can be done with either.

The Instructor Resources provides a wide selection of information for the instructor. It contains the following features:

- An Instructor's Manual that includes a list of the parts and equipment needed to perform lab experiments,

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Learning Outcomes for each chapter, and answers to chapter review questions

- Instructor PowerPoint slide show for each chapter
- Multisim files for experiments that can be completed with simulation software

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About the Author

Mitchel E. Schultz was the program chair of Electronic and Computer Engineering Technology at Western Technical College in La Crosse, Wisconsin, where he taught for 31 years before retiring at the end of 2020. Prior to teaching at Western, he taught electronics for eight years at Riverland Community College in Austin, Minnesota. He has also done extensive industry training over the past 39 years. Before he began teaching, he worked as an electronics technician in the field of land mobile communications systems. Mitchel graduated from Minnesota State Southeast Technical College in 1978, where he earned an associate's degree in Electronics Technology. He also attended Winona State University, Mankato State University, and the University of Minnesota. Mitchel is the author of *Grob's Basic Electronics* and the Problems Manual that accompanies it.

Richard J. Fowler spent four years in the United States Air Force testing, repairing, and maintaining radio and navigation equipment. He taught electricity and electronics for 30 years–one year in a public high school and 29 years in three universities. He earned his Ed.D from Texas A&M University (1965) and published two textbooks, two laboratory manuals, and one chapter in a professional yearbook.

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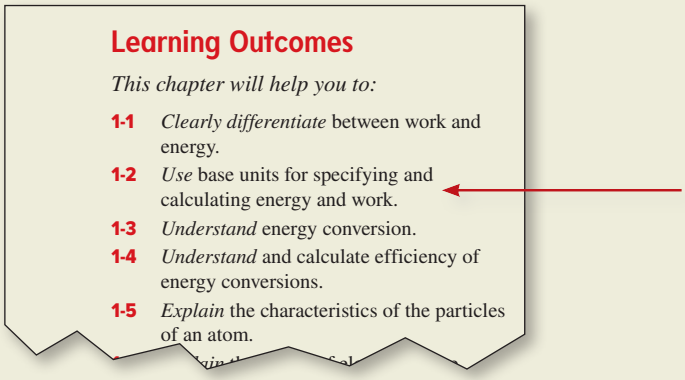
Walkthrough

Electricity: Principles and Applications was written to be a concise and practical introduction to this subject. The textbook's easy-to-read style, color illustrations, clear explanations, and simple math problems make it ideal for students who want to learn the essentials of electricity and apply them to real job-related situations.



Each chapter starts with ***Learning Outcomes*** that give the reader an idea of what to expect in the following pages, and what he or she should be able to accomplish by the end of the chapter. These outcomes are now distinctly linked to the chapter subsections.

The text contains numerous worked-out ***Examples*** that emphasize the importance of using a systematic, step-by-step approach to problem solving. Students should make rough approximations of the answer to a problem before doing the detailed math necessary to find the exact answer. This can reveal major mathematical errors that are sometimes overlooked.

EXAMPLE 1-1

If it requires a steady force of 150 newtons to pull a boat, how much work is required to pull a boat 8 meters?

Given: Force = 150 newtons
Distance = 8 meters

Find: Work

Known: Work (W) = force × distance
1 newton-meter = 1 joule (J)

Solution: Work = 150 newtons
× 8 meters
= 1200 newton-meters
= 1200 joules

Answer: Work = 1200 joules
W = 1200 J

EXAMPLE 1-2

It requires 500 joules of energy and 100 newtons of force to move an object from point A to point B. What is the distance between point A and point B?

Given: Energy = 500 joules
Force = 100 newtons

Find: Distance

Known: W = force × distance, and by rearranging

$$\text{Distance} = \frac{W}{\text{force}}$$

1 newton-meter = 1 joule

Solution:

$$\text{Distance} = \frac{500 \text{ newton-meters}}{100 \text{ newtons}}$$

= 5 meters

Self-Test

Answer the following questions.

1. Define work and energy.
2. What is a base unit?
3. What is the base unit of energy?
4. How much energy does it take to push a car 120 meters with a steady force of 360 newtons?

Answers to Self-Tests

1. Work is a force moving through a distance; energy is the ability to do work.
2. A base unit is a term that is used to specify the amount of something.
3. joule (J)
4. **Given:** Distance = 120 meters
   Force = 360 newtons
   Find: Work
   Known: Work = force × distance
   Solution: Work = 360 newtons × 120 meters
   Answer: Work = 43,200 joules

Self-Tests serve as positive reinforcement for material that students already know, and they help students identify areas that need further study. Students may check their responses in the ***Answers to Self-Tests*** sections at the end of each chapter.

Key Terms are carefully defined and explained in the text and listed in the margins so students can easily find them.

Electron
Atoms
Proton
Neutron
Nucleus
Molecule

I-5 Structure of Matter

All matter is composed of *atoms*. Atoms are the basic building blocks of nature. Regardless of their physical characteristics, glass, chalk, rock, and wood are all made from atoms. Rock is different from wood because of the type of atoms of which it is composed.

The smallest particle of a substance that still has all of its characteristics is called a *molecule*. A molecule consists of two or more atoms. If a molecule of chalk is divided into smaller parts, it is no longer chalk.

There are more than 100 different types of atoms. Matter composed of a single type of

HISTORY OF ELECTRONICS

James Prescott Joule

The SI (*Système Internationale*) unit of measure for electric energy is the joule (J), named for James Prescott Joule (1 joule is equal to 1 volt-coulomb).

Roscoe, Henry E. *The Life & Experiences of Sir Henry Enfield Roscoe, D.C.L., LL.D., F.R.S.*, London, New York: Macmillan, 1906.

History of Electronics features add historical depth to the topics

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You May Recall

. . . that static electricity, which produces voltage, was discussed in Chap. 1. The mechanical energy required to rub a glass rod against a silk cloth is converted to electric energy. The silk cloth becomes the negative terminal, and the glass rod becomes the positive terminal of this voltage source.

You May Recall sections connect the text on the page with concepts that were previously introduced in the textbook.

Critical facts and principles are reviewed in the ***Summary and Review*** section at the end of each chapter.

Chapter 1 Summary and Review

Summary

1. Energy is the ability to do work.
2. The symbol for energy is *W*.
3. Electricity is a form of energy.
4. Work equals force times distance.
5. The joule is the base unit of energy.
6. The joule is the base unit of work.
7. The symbol for the joule is J.
8. Under ordinary conditions, energy is neither created nor destroyed.
9. All matter is made up of atoms.
10. Hydrogen has only one electron and one proton. All other atoms contain electrons, protons, and neutrons.
11. Protons and neutrons are found in the nucleus of the atom.
12. Electrons have a negative electric charge.
13. Protons have a positive electric charge.
14. Neutrons do not have an electric charge.
15. Atoms have an equal number of protons and electrons.
16. Valence electrons are found in the outermost shell of the atom.
17. Valence electrons can become free electrons when their energy level is raised.
18. Negative ions are atoms that have attracted and captured an extra (free) electron.
19. Positive ions are atoms that have given up an electron.
20. Static charges are the result of an object's possessing either more or fewer electrons than protons.
21. A positive charge means a deficiency of electrons.
22. A negative charge means an excess of electrons.
23. Like charges repel each other.
24. Unlike charges attract each other.
25. A charged object can attract an uncharged object.
26. When an uncharged object touches a charged object, it becomes charged.

All of the important chapter formulas are summarized at the end of each chapter in ***Related Formulas***. ***Chapter Review Questions*** are also found at the end of each chapter, as are ***Chapter Review Problems, Critical Thinking Questions*** and homework problems, which are new to this edition.

Related Formulas

$$\text{Percent efficient} = \frac{W_{out}}{W_{in}} \times 100$$

$$\text{Work} = \text{force} \times \text{distance}$$

Chapter Review Questions

For questions 1-1 to 1-7, determine whether each statement is true or false.

1-1. Opposite electric charges repel each other. (1-6)
1-2. Free electrons are at a higher energy level than valence electrons are. (1-8)
1-3. The same base unit is used for both work and energy. (1-2)
1-4. Atoms have twice as many protons as electrons. (1-6)
1-5. An object that has a static charge can possess either more or fewer electrons than protons. (1-10)
1-6. The second shell, or orbit, of an atom can contain any number of electrons. (1-5)
1-7. If an electric device is less than 100 percent efficient, part of the energy provided to it is destroyed. (1-3)

For questions 1-8 to 1-14, choose the letter that best completes each sentence.

1-8. The symbol for energy is (1-1)
a. *D*
b. *W*

Chapter Review Problems

1-1. What is the efficiency of a motor which requires 914 base units of electric energy to produce 585 joules of mechanical energy? (1-4)
1-2. How much work is done when an object is moved 3 meters by applying a force of 80 newtons? (1-2)
1-3. How much energy is involved in problem 1-2? (1-2)
1-4. How much energy is required by an electric lamp that is 18 percent efficient and provides 5463 J of light energy? (1-4)
1-5. A motor is 70 percent efficient and requires 1200 base units of energy. How much energy does it provide? (1-4)
1- 6 How much heat energy is produced by a light bulb that requires 400 joules of electric energy to produce 125 joules of light energy? (1-3)

Critical Thinking Questions

1-1. Discuss the probable changes in your lifestyle if the electric service to your home is disconnected for one week.
1-2. In addition to decreasing costs, why is it important to increase the efficiency of electric devices as much as is practical?
1-3. Why are large, continuously operated motors designed to be more efficient than small, intermittently operated motors?
1-4. Is the low efficiency of the lights in our homes a greater disadvantage during the winter months or the summer months? Why?
1-5. Many electric devices could be designed and constructed to operate more efficiently. Why aren't they?

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Safety

Electric and electronic circuits can be dangerous. Safe practices are necessary to prevent electrical shock, fires, explosions, mechanical damage, and injuries resulting from the improper use of tools.

Perhaps the greatest hazard is electrical shock. A current through the human body in excess of 10 milliamperes can paralyze the victim and make it impossible to let go of a "live" conductor or component. Ten milliamperes is a rather small amount of current flow: it is only *ten one-thousandths* of an ampere. An ordinary flashlight can provide more than 40 times that amount of current!

Flashlight cells and batteries are safe to handle because the resistance of human skin is normally high enough to keep the current flow very small. For example, touching an ordinary 1.5-V cell produces a current flow in the microampere range (a microampere is one-millionth of an ampere). This amount of current is too small to be noticed.

High voltage, on the other hand, can force enough current through the skin to produce a shock. If the current approaches 100 milliamperes or more, the shock can be fatal. Thus, the danger of shock increases with voltage. Those who work with high voltage must be properly trained and equipped.

When human skin is moist or cut, its resistance to the flow of electricity can drop drastically. When this happens, even moderate voltages may cause a serious shock. Experienced technicians know this, and they also know that so-called low-voltage equipment may have a high-voltage section or two. In other words, they do not practice two methods of working with circuits: one for high voltage and one for low voltage. They follow safe procedures at all times. They do not assume protective devices are working. They do not assume a circuit is off even though the switch is in the off position. They know the switch could be defective.

Even a low-voltage, high-current-capacity system like an automotive electrical system can be quite dangerous. Short-circuiting such a system with a ring or metal watchband can cause very severe burns—especially when the ring or band welds to the points being shorted.

As your knowledge and experience grow, you will learn many specific safe procedures for dealing with electricity and electronics. In the meantime:

1. Always follow recommended safety procedures.
2. Use service manuals as often as possible. They often contain specific safety information. Read, and comply with, all appropriate material safety data sheets. Material safety data sheets (MSDS) are provided with many products, and they discuss any hazards associated with the product as well as the safe use, storage, and disposal of the product.
3. Investigate before you act.
4. When in doubt, *do not act*. Ask your instructor or supervisor.

General Safety Rules for Electricity and Electronics

Safe practices will protect you and your fellow workers. Study the following rules. Discuss them with others, and ask your instructor about any you do not understand.

1. Do not work when you are tired or taking medicine that makes you drowsy.
2. Do not work in poor light.
3. Do not work in damp areas or with wet shoes or clothing.
4. Use approved tools, equipment, and protective devices.
5. Avoid wearing rings, bracelets, and similar metal items when working around exposed electric circuits.
6. Never assume that a circuit is off. Double-check it with an instrument that you are sure is operational.
7. Always use the lockout/tagout (LO/TO) procedure, which is locking power OFF and tagging. If not possible, then use the "buddy system" to guarantee that power will not be turned on while a technician is still working on a circuit.
8. Never tamper with or try to override safety devices such as an interlock (a type of switch that automatically removes power when a door is opened or a panel removed).

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9. Keep tools and test equipment clean and in good working condition. Replace insulated probes and leads at the first sign of deterioration.
10. Some devices, such as capacitors, can store a *lethal* charge. They may store this charge for long periods of time. You must be certain these devices are discharged before working around them.
11. Do not remove grounds and do not use adaptors that defeat the equipment ground.
12. Use only an approved fire extinguisher for electrical and electronic equipment. Water can conduct electricity and may severely damage equipment. Carbon dioxide (CO_2) or halogenated-type extinguishers are usually preferred. Foam-type extinguishers may also be desired in *some* cases. Commercial fire extinguishers are rated for the types of fires for which they are effective. Use only those rated for the proper working conditions.
13. Follow directions when using solvents and other chemicals. They may be toxic or flammable, or they may damage certain materials such as plastics. Always read and follow the appropriate material safety data sheets.
14. A few materials used in electronic equipment are toxic. Examples include tantalum capacitors and beryllium oxide transistor cases. These devices should not be crushed or abraded, and you should wash your hands thoroughly after handling them. Other materials (such as heat shrink tubing) may produce irritating fumes if overheated. Always read and follow the appropriate material safety data sheets.
15. Certain circuit components affect the safe performance of equipment and systems. Use only exact or approved replacement parts.
16. Use protective clothing and safety glasses when handling high-vacuum devices such as picture tubes and cathode-ray tubes.
17. Don't work on equipment before you know proper procedures and are aware of any potential safety hazards. Material safety data sheets warn users of any hazard associated with the product.
18. Many accidents have been caused by people rushing and cutting corners. Take the time required to protect yourself and others. Running, horseplay, and practical jokes are strictly forbidden in shops and laboratories.

Circuits and equipment must be treated with respect. Learn how they work and the proper way of working on them. Always practice safety: Your health and life depend on it.

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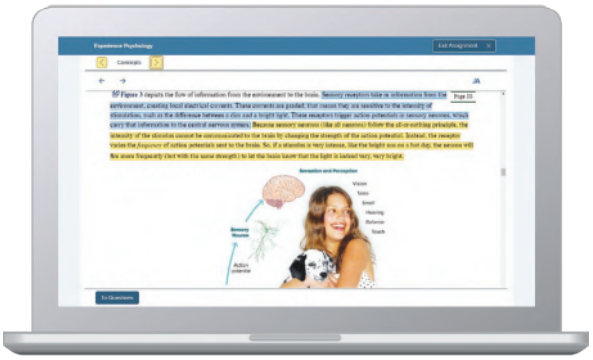

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INTRODUCTION

Introduction to Powers of 10

Learning Outcomes

This chapter will help you to:

I-1 *Express* any number in scientific or engineering notation.

I-2 *List* the metric prefixes and their corresponding powers of 10.

I-3 *Change* a power of 10 in engineering notation to its corresponding metric prefix.

I-4 *Convert* between metric prefixes.

I-5 *Add* and *subtract* numbers expressed in powers of 10 notation.

I-6 *Multiply* and *divide* numbers expressed in powers of 10 notation.

I-7 *Determine* the reciprocal of a power of 10.

I-8 *Find* the square of a number expressed in powers of 10 notation.

I-9 *Find* the square root of a number expressed in powers of 10 notation.

I-10 *Enter* numbers written in scientific and engineering notation into your calculator.

The electrical quantities you will encounter while working in the field of electronics are often extremely small or extremely large. For example, it is not at all uncommon to work with extremely small decimal numbers such as 0.000000000027 or extremely large numbers such as 15,500,000,000. To enable us to work conveniently with both very small and very large numbers, powers of 10 notation is used. With powers of 10 notation, any number, no matter how small or large, can be expressed as a decimal number multiplied by a power of 10. A power of 10 is an exponent written above and to the right of 10, which is called the base. The power of 10 indicates how many times the base is to be multiplied by itself. For example, 10^3 means $10 \times 10 \times 10$ and 10^6 means $10 \times 10 \times 10 \times 10 \times 10 \times 10$. In electronics, the base 10 is common because multiples of 10 are used in the metric system of units.

Scientific and engineering notation are the two most common forms of powers of 10 notation. In electronics, engineering notation is generally more common than scientific notation because it ties in directly with the metric prefixes so often used. When a number is written in standard form without using any form of powers of 10 notation, it is said to be written in decimal notation (sometimes referred to as floating decimal notation). When selecting a calculator for solving problems in electronics, be sure to choose one that can display the answers in decimal, scientific, and engineering notation.

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I–1 Scientific Notation

Before jumping directly into **scientific notation**, let's take a closer look at **powers of 10**. A power of 10 is an exponent of the base 10 and can be either positive or negative.

Base ⟶ 10^X ⟵ Exponent

Positive powers of 10 are used to indicate numbers greater than 1, whereas negative powers of 10 are used to indicate numbers less than 1. Table I-1 shows the powers of 10 ranging from 10^{-12} to 10^9 and their equivalent decimal values. In electronics, you will seldom work with powers of 10 outside this range. From Table I-1, notice that $10^0 = 1$ and that $10^1 = 10$. In the case of $10^0 = 1$, it is important to realize that any number raised to the zero power equals 1. In the case of $10^1 = 10$, it is important to note that any number written without a power is assumed to have a power of 1.

Table I-1 Powers of 10

$1{,}000{,}000{,}000 = 10^9$
$100{,}000{,}000 = 10^8$
$10{,}000{,}000 = 10^7$
$1{,}000{,}000 = 10^6$
$100{,}000 = 10^5$
$10{,}000 = 10^4$
$1{,}000 = 10^3$
$100 = 10^2$
$10 = 10^1$
$1 = 10^0$
$0.1 = 10^{-1}$
$0.01 = 10^{-2}$
$0.001 = 10^{-3}$
$0.0001 = 10^{-4}$
$0.00001 = 10^{-5}$
$0.000001 = 10^{-6}$
$0.0000001 = 10^{-7}$
$0.00000001 = 10^{-8}$
$0.000000001 = 10^{-9}$
$0.0000000001 = 10^{-10}$
$0.00000000001 = 10^{-11}$
$0.000000000001 = 10^{-12}$

Expressing a Number in Scientific Notation

The procedure for using any form of powers of 10 notation is to write the original number as two separate factors. Scientific notation is a form of powers of 10 notation in which a number is expressed as a number between 1 and 10 times a power of 10. The power of 10 is used to place the decimal point correctly. The power of 10 indicates the number of places by which the decimal point has been moved to the left or right in the original number. If the decimal point is moved to the left in the original number, then the power of 10 will increase or become more positive. Conversely, if the decimal point is moved to the right in the original number then the power of 10 will decrease or become more negative. Let's take a look at an example.

EXAMPLE I-1

Express the following numbers in scientific notation: (a) 4700 (b) 0.0000018

Answer: (a) To express 4700 in scientific notation, write the number as a number between 1 and 10, which is 4.7 in this case, times a power of 10. To do this, the decimal point must be shifted three places to the left. The number of places by which the decimal point is shifted to the left indicates the positive power of 10. Therefore, $4700 = 4.7 \times 10^3$ in scientific notation.

(b) To express 0.0000018 in scientific notation, write the number as a number between 1 and 10, which is 1.8 in this case, times a power of 10. To do this, the decimal point must be shifted six places to the right. The number of places by which the decimal point is shifted to the right indicates the negative power of 10. Therefore, $0.0000018 = 1.8 \times 10^{-6}$ in scientific notation.

When expressing a number in scientific notation, remember the following rules:

Rule 1: Express the number as a number between 1 and 10 times a power of 10.

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Rule 2: If the decimal point is moved to the left in the original number, make the power of 10 positive. If the decimal point is moved to the right in the original number, make the power of 10 negative.

Rule 3: The power of 10 always equals the number of places by which the decimal point has been shifted to the left or right in the original number.

Let's try another example.

EXAMPLE I-2

Express the following numbers in scientific notation: (a) 667,000 (b) 791,000,000 (c) 0.000275 (d) 0.00000000000055.

Answer: (a) To express the number 667,000 in scientific notation, move the decimal point five places to the left, which gives us a number of 6.67. Next, multiply this number by 10^5. Notice that the power of 10 is a positive 5 because the decimal point was shifted five places to the left in the original number. Therefore, $667{,}000 = 6.67 \times 10^5$ in scientific notation.

(b) To express 791,000,000 in scientific notation, move the decimal point eight places to the left, which gives us a number of 7.91. Next, multiply this number by 10^8. Notice that the power of 10 is a positive 8 because the decimal point was shifted eight places to the left in the original number. Therefore, $791{,}000{,}000 = 7.91 \times 10^8$ in scientific notation.

(c) To express 0.000275 in scientific notation, move the decimal point four places to the right, which gives us a number of 2.75. Next, multiply this number by 10^{-4}. Notice that the power of 10 is a negative 4 because the decimal point was shifted four places to the right in the original number. Therefore, $0.000275 = 2.75 \times 10^{-4}$.

(d) To express 0.00000000000055 in scientific notation, move the decimal point 13 places to the right, which gives us a number of 5.5. Next, multiply this number by 10^{-13}. Notice that the power of 10 is a negative 13 because the decimal point was shifted 13 places to the right in the original number. Therefore, $0.00000000000055 = 5.5 \times 10^{-13}$ in scientific notation.

Decimal Notation

Numbers written in standard form without using any form of powers of 10 notation are said to be written in **decimal notation**, sometimes called floating decimal notation. In some cases, it may be necessary or desirable to change a number written in scientific notation into decimal notation. When converting from scientific to decimal notation, observe the following rules.

Rule 4: If the exponent or power of 10 is positive, move the decimal point to the right, the same number of places as the exponent.

Rule 5: If the exponent or power of 10 is negative, move the decimal point to the left, the same number of places as the exponent.

EXAMPLE I-3

Convert the following numbers written in scientific notation into decimal notation: (a) 8.32×10^2 (b) 9.3×10^{-5}.

Answer: (a) To convert 8.32×10^2 into decimal notation, the decimal point must be shifted two places to the right. The decimal point is shifted to the right because the power of 10, which is 2 in this case, is positive. Therefore, $8.32 \times 10^2 = 832$ in decimal notation.

(b) To convert 9.3×10^{-5} into decimal notation, the decimal point must be shifted five places to the left. The decimal point is shifted to the left because the power of 10, which is -5 in this case, is negative. Therefore, $9.3 \times 10^{-5} = 0.000093$ in decimal notation.

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Self-Test

Answer the following questions.

1. Are positive or negative powers of 10 used to indicate numbers less than 1?
2. Are positive or negative powers of 10 used to indicate numbers greater than 1?
3. $10^0 = 1$. (True/False)
4. Express the following numbers in scientific notation: (a) 13,500 (b) 0.00825 (c) 95,600,000 (d) 0.104.
5. Convert the following numbers written in scientific notation into decimal notation: (a) 4.6×10^{-7} (b) 3.33×10^{3} (c) 5.4×10^{8} (d) 2.54×10^{-2}.

I–2 Engineering Notation and Metric Prefixes

Engineering notation is another form of powers of 10 notation. Engineering notation is similar to scientific notation except that in engineering notation, the powers of 10 are always multiples of 3 such as 10^{-12}, 10^{-9}, 10^{-6}, 10^{-3}, 10^{3}, 10^{6}, 10^{9}, 10^{12}, etc. More specifically, a number expressed in engineering notation is always expressed as a number between 1 and 1000 times a power of 10 that is a multiple of 3.

EXAMPLE I-4

Express the following numbers in engineering notation: (a) 27,000 (b) 0.00047.

Answer: (a) To express the number 27,000 in engineering notation, it must be written as a number between 1 and 1000 times a power of 10 that is a multiple of 3. It is often helpful to begin by expressing the number in scientific notation: $27{,}000 = 2.7 \times 10^{4}$. Next, examine the power of 10 to see if it should be increased to 10^{6} or decreased to 10^{3}. If the power of 10 is increased to 10^{6}, then the decimal point in the number 2.7 would have to be shifted two places to the left. Because 0.027 is not a number between 1 and 1000, the answer of 0.027×10^{6} is not representative of engineering notation. If the power of 10 were decreased to 10^{3}, however, then the decimal point in the number 2.7 would have to be shifted one place to the right and the answer would be 27×10^{3}, which is representative of engineering notation. In summary, $27{,}000 = 2.7 \times 10^{4} = 27 \times 10^{3}$ in engineering notation.

(b) To express the number 0.00047 in engineering notation, it must be written as a number between 1 and 1000 times a power of 10 that is a multiple of 3. Begin by expressing the number in scientific notation: $0.00047 = 4.7 \times 10^{-4}$. Next, examine the power of 10 to see if it should be increased to 10^{-3} or decreased to 10^{-6}. If the power of 10 were increased to 10^{-3}, then the decimal point in the number 4.7 would have to be shifted one place to the left. Because 0.47 is not a number between 1 and 1000, the answer 0.47×10^{-3} is not representative of engineering notation. If the power of 10 were decreased to 10^{-6}, however, then the decimal point in the number 4.7 would have to be shifted two places to the right and the answer would be 470×10^{-6}, which is representative of engineering notation. In summary, $0.00047 = 4.7 \times 10^{-4} = 470 \times 10^{-6}$ in engineering notation.

When expressing a number in engineering notation, remember the following rules:

> **Rule 6:** Express the original number in scientific notation first. If the power of 10 is a multiple of 3, the number appears the same in both scientific and engineering notation.

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Rule 7: If the original number expressed in scientific notation does not use a power of 10 that is a multiple of 3, the power of 10 must be either increased or decreased until it is a multiple of 3. The decimal point in the numerical part of the expression must be adjusted accordingly to compensate for the change in the power of 10.

Rule 8: Each time the power of 10 is increased by 1, the decimal point in the numerical part of the expression must be moved one place to the left. Each time the power of 10 is decreased by 1, the decimal point in the numerical part of the expression must be moved one place to the right.

You know that a quantity is expressed in engineering notation when the original number is written as a number between 1 and 1000 times a power of 10 that is a multiple of 3.

Metric Prefixes

The **metric prefixes** represent those powers of 10 that are multiples of 3. In the field of electronics, engineering notation is much more common than scientific notation because most values of voltage, current, resistance, power, and so on are specified in terms of the metric prefixes. Once a number is expressed in engineering notation, its power of 10 can be replaced directly with its corresponding metric prefix. Table I-2 lists the most common metric prefixes and their corresponding powers of 10. Notice that uppercase letters are used for the abbreviations of the prefixes involving positive powers of 10, whereas lowercase letters are used for negative powers of 10. There is one exception to the rule however; the lowercase letter "k" is used for kilo corresponding to 10^3. The uppercase letter K is not used for the metric prefix kilo because its use is reserved for the kelvin unit of absolute temperature. Because the metric prefixes are used so often in electronics, it is common practice to express the value of a given quantity in engineering notation first so that the power of 10, which is a multiple of 3, can be replaced directly with its corresponding metric prefix. For example, a resistor whose value is 33,000 Ω can be expressed in engineering notation as 33×10^3 Ω. In Table I-2, we see that the metric prefix kilo (k) corresponds to 10^3. Therefore, 33,000 Ω or 33×10^3 Ω can be expressed as 33 kΩ. (Note that the unit of resistance is the ohm abbreviated Ω.) As another example, a current of 0.0000075 A can be expressed in engineering notation as 7.5×10^{-6} A. In Table I-2, we see that the metric prefix micro (μ) corresponds to 10^{-6}. Therefore, 0.0000075 A or 7.5×10^{-6} A can be expressed as 7.5 μA. (The unit of current is the ampere, abbreviated A.)

In general, when using metric prefixes to express the value of a given quantity, write the original number in engineering notation first and then substitute the appropriate metric prefix corresponding to the power of 10 involved. As this technique shows, metric prefixes are direct substitutes for the powers of 10 used in engineering notation.

Table I-3 lists many of the electrical quantities that you will encounter in your study of electronics. For each electrical quantity listed in Table I-3, take special note of the unit and symbol shown. In the examples and problems that follow, we will use several numerical values with various symbols and units from this table. Let's take a look at a few examples.

Table I-2 Metric Prefixes

Power of 10	Prefix	Abbreviation
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

Table I-3 Electrical Quantities with Their Units and Symbols

Quantity	Unit	Symbol
Current	Ampere (A)	*I*
Voltage	Volt (V)	*V*
Resistance	Ohm (Ω)	*R*
Frequency	Hertz (Hz)	*f*
Capacitance	Farad (F)	*C*
Inductance	Henry (H)	*L*
Power	Watt (W)	*P*

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EXAMPLE I-5

Express the resistance of 1,000,000 Ω using the appropriate metric prefix from Table I-2.

Answer: First, express 1,000,000 Ω in engineering notation: 1,000,000 Ω = 1.0×10^6 Ω. Next, replace 10^6 with its corresponding metric prefix. Because the metric prefix mega (M) corresponds to 10^6, the value of 1,000,000 Ω can be expressed as 1 MΩ. In summary, 1,000,000 Ω = 1.0×10^6 Ω = 1 MΩ.

EXAMPLE I-6

Express the voltage value of 0.015 V using the appropriate metric prefix from Table I-2.

Answer: First, express 0.015 V in engineering notation: 0.015 V = 15×10^{-3} V. Next, replace 10^{-3} with its corresponding metric prefix. Because the metric prefix milli (m) corresponds to 10^{-3}, the value 0.015 V can be expressed as 15 mV. In summary, 0.015 V = 15×10^{-3} V = 15 mV.

EXAMPLE I-7

Express the power value of 250 W using the appropriate metric prefix from Table I-2.

Answer: In this case, it is not necessary or desirable to use any of the metric prefixes listed in Table I-2. The reason is that 250 W cannot be expressed as a number between 1 and 1000 times a power of 10 that is a multiple of 3. In other words, 250 W cannot be expressed in engineering notation. The closest we can come is 0.25×10^3 W, which is not representative of engineering notation. Although 10^3 can be replaced with the metric prefix kilo (k), it is usually preferable to express the power as 250 W and not as 0.25 kW.

In summary, whenever the value of a quantity lies between 1 and 1000, only the basic unit of measure should be used for the answer. As another example, 75 V should be expressed as 75 V and not as 0.075 kV or 75,000 mV, and so forth.

Self-Test

Answer the following questions.

6. Express the following numbers in engineering notation: (a) 36,000,000 (b) 0.085 (c) 39,300 (d) 0.000093.
7. List the metric prefixes for each of the powers of 10 listed: (a) 10^{-9} (b) 10^6 (c) 10^{-12} (d) 10^3 (e) 10^4.
8. Express the following values using the appropriate metric prefixes: (a) 0.000010 A (b) 2,200,000 Ω (c) 0.000000045 V (d) 5600 Ω (e) 18 W.

I–3 Converting between Metric Prefixes

As you have seen in the previous section, metric prefixes can be substituted for powers of 10 that are multiples of 3. This is true even when the value of the original quantity is not expressed in proper engineering notation. For example, a capacitance value of 0.047×10^{-6} F could be expressed as 0.047 μF. Also, a frequency of 1510×10^3 Hz could be expressed as 1510 kHz. Furthermore, the values of like quantities in a given circuit may be specified using different metric prefixes such as 22 kΩ and 1.5 MΩ or 0.001 μF and 3300 pF, as examples. In some cases, therefore, it may be necessary or

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desirable to convert from one metric prefix to another when combining values. Converting from one metric prefix to another is actually a change in the power of 10. When the power of 10 is changed, however, care must be taken to make sure that the numerical part of the expression is also changed so that the value of the original number remains the same. When converting from one metric prefix to another, observe the following rule:

Rule 9: When converting from a larger metric prefix to a smaller one, increase the numerical part of the expression by the same factor by which the metric prefix has been decreased. Conversely, when converting from a smaller metric prefix to a larger one, decrease the numerical part of the expression by the same factor by which the metric prefix has been increased.

EXAMPLE I-8

Make the following conversions: (a) convert 25 mA to μA (b) convert 2700 kΩ to MΩ.

Answer: (a) To convert 25 mA to μA, recall that the metric prefix milli (m) corresponds to 10^{-3} and that metric prefix micro (μ) corresponds to 10^{-6}. Since 10^{-6} is less than 10^{-3} by a factor of 1000 (10^3), the numerical part of the expression must be increased by a factor of 1000 (10^3). Therefore, $25\text{ mA} = 25 \times 10^{-3}\text{ A} = 25{,}000 \times 10^{-6}\text{ A} = 25{,}000\ \mu\text{A}$.

(b) To convert 2700 kΩ to MΩ, recall that the metric prefix kilo (k) corresponds to 10^3 and that the metric prefix mega (M) corresponds to 10^6. Since 10^6 is larger than 10^3 by a factor of 1000 (10^3), the numerical part of the expression must be decreased by a factor of 1000 (10^3). Therefore, $2700\ \text{k}\Omega = 2700 \times 10^3\ \Omega = 2.7 \times 10^6\ \Omega = 2.7\ \text{M}\Omega$.

Self-Test

Answer the following questions.

9. Converting from one metric prefix to another is actually a change in the power of 10. (True/False)

10. Make the following conversions: (a) convert 2.2 MΩ to kΩ (b) convert 47,000 pF to nF (c) convert 2500 μA to mA (d) convert 6.25 mW to μW.

I–4 Addition and Subtraction Involving Powers of 10 Notation

When adding or subtracting numbers expressed in powers of 10 notation, observe the following rule:

Rule 10: Before numbers expressed in powers of 10 notation can be added or subtracted, both terms must be expressed using the same power of 10. When both terms have the same power of 10, just add or subtract the numerical parts of each term and multiply the sum or difference by the power of 10 common to both terms. Express the final answer in the desired form of powers of 10 notation.

Let's take a look at a couple of examples.

EXAMPLE I-9

Add 170×10^3 and 23×10^4. Express the final answer in scientific notation.

Answer: First, express both terms using either 10^3 or 10^4 as the common power of 10. Either one can be used. In this example, we will use 10^3 as the common power of 10 for both terms. Rewriting 23×10^4 using 10^3 as the power of 10 gives us 230×10^3. Notice that because the power of 10 was decreased by a factor of 10, the numerical part of the expression was increased by a factor of 10. Next, add the numerical parts of each term and multiply the sum by 10^3, which is the power of 10 common to both terms. This gives us $(170 + 230) \times 10^3$ or

(continued)

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400×10^3. Expressing the final answer in scientific notation gives us 4.0×10^5. In summary, $(170 \times 10^3) + (23 \times 10^4) = (170 \times 10^3) + (230 \times 10^3) = (170 + 230) \times 10^3 = 400 \times 10^3 = 4.0 \times 10^5$.

EXAMPLE I-10

Subtract 250×10^3 from 1.5×10^6. Express the final answer in scientific notation.

Answer: First, express both terms using either 10^3 or 10^6 as the common power of 10. Again, either one can be used. In this example, we will use 10^6 as the common power of 10 for both terms. Rewriting 250×10^3 using 10^6 as the power of 10 gives us 0.25×10^6. Notice that because the power of 10 was increased by a factor 1000 (10^3), the numerical part of the expression was decreased by a factor of 1000 (10^3). Next, subtract 0.25 from 1.5 and multiply the difference by 10^6, which is the power of 10 common to both terms. This gives us $(1.5 - 0.25) \times 10^6$ or 1.25×10^6. Notice that the final answer is already in scientific notation. In summary, $(1.5 \times 10^6) - (250 \times 10^3) = (1.5 \times 10^6) - (0.25 \times 10^6) = (1.5 - 0.25) \times 10^6 = 1.25 \times 10^6$.

Self-Test

Answer the following questions.

11. Add the following terms expressed in powers of 10 notation. Express the answers in scientific notation. (a) $(470 \times 10^4) + (55 \times 10^6)$ (b) $(3.5 \times 10^{-2}) + (1500 \times 10^{-5})$.
12. Subtract the following terms expressed in powers of 10 notation. Express the answers in scientific notation.
(a) $(65 \times 10^4) - (200 \times 10^3)$
(b) $(850 \times 10^{-3}) - (3500 \times 10^{-4})$.

I–5 Multiplication and Division Involving Powers of 10 Notation

When multiplying or dividing numbers expressed in powers of 10 notation, observe the following rules:

Rule 11: When multiplying numbers expressed in powers of 10 notation, multiply the numerical parts and powers of 10 separately. When multiplying powers of 10, simply add the exponents to obtain the new power of 10. Express the final answer in the desired form of powers of 10 notation.

Rule 12: When dividing numbers expressed in powers of 10 notation, divide the numerical parts and powers of 10 separately. When dividing powers of 10, subtract the power of 10 in the denominator from the power of 10 in the numerator. Express the final answer in the desired form of powers of 10 notation.

Let's take a look at a few examples.

EXAMPLE I-11

Multiply (3×10^6) by (150×10^2). Express the final answer in scientific notation.

Answer: First, multiply 3×150 to obtain 450. Next, multiply 10^6 by 10^2 to obtain $10^6 \times 10^2 = 10^{6+2} = 10^8$. To review, $(3 \times 10^6) \times (150 \times 10^2) = (3 \times 150) \times (10^6 \times 10^2) = 450 \times 10^{6+2} = 450 \times 10^8$. The final answer expressed in scientific notation is 4.5×10^{10}.

EXAMPLE I-12

Divide (5.0×10^7) by (2.0×10^4). Express the final answer in scientific notation.

Answer: First, divide 5 by 2 to obtain 2.5. Next, divide 10^7 by 10^4 to obtain $10^{7-4} = 10^3$. To review, $\frac{5.0 \times 10^7}{2.0 \times 10^4} = \frac{5}{2} \times \frac{10^7}{10^4} = 2.5 \times 10^3$. Notice that the final answer is already in scientific notation.

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Self-Test

Answer the following questions.

13. Multiply the following numbers expressed in powers of 10 notation. Express your answers in scientific notation.
(a) $(3.3 \times 10^{-2}) \times (4.0 \times 10^{-3})$
(b) $(2.7 \times 10^{2}) \times (3 \times 10^{-5})$.

14. Divide the following numbers expressed in powers of 10 notation. Express your answers in scientific notation.
(a) $(7.5 \times 10^{8}) \div (3.0 \times 10^{4})$
(b) $(15 \times 10^{-6}) \div (5 \times 10^{-3})$.

I–6 Reciprocals with Powers of 10

Taking the reciprocal of a power of 10 is really just a special case of division using powers of 10 because 1 in the numerator can be written as 10^0 since $10^0 = 1$. With zero as the power of 10 in the numerator, taking the reciprocal results in a sign change for the power of 10 in the denominator. Let's take a look at an example to clarify this point.

EXAMPLE I-13

Find the reciprocals for the following powers of 10: (a) 10^5 (b) 10^{-3}.

Answer: (a) $\frac{1}{10^5} = \frac{10^0}{10^5} = 10^{0-5} = 10^{-5}$;
therefore, $\frac{1}{10^5} = 10^{-5}$.

(b) $\frac{1}{10^{-3}} = \frac{10^0}{10^{-3}} = 10^{0-(-3)} = 10^3$;
therefore, $\frac{1}{10^{-3}} = 10^3$.

Notice that in both (a) and (b), the power of 10 in the denominator is subtracted from zero, which is the power of 10 in the numerator.

Here's a simple rule for reciprocals of powers of 10.

Rule 13: When taking the reciprocal of a power of 10, simply change the sign of the exponent or power of 10.

Negative Powers of 10

Recall that a power of 10 indicates how many times the base, 10, is to be multiplied by itself. For example, $10^4 = 10 \times 10 \times 10 \times 10$. But you might ask how this definition fits with negative powers of 10. The answer is that negative powers of 10 are just reciprocals of positive powers of 10. For example, $10^{-4} = \frac{1}{10^4} = \frac{1}{10 \times 10 \times 10 \times 10}$.

Self-Test

Answer the following questions.

15. Take the reciprocals of each of the powers of 10 listed. (a) 10^{-4} (b) 10^9 (c) 10^{-18} (d) 10^0.

I–7 Squaring Numbers Expressed in Powers of 10 Notation

When squaring a number expressed in powers of 10 notation, observe the following rule:

Rule 14: To square a number expressed in powers of 10 notation, square the numerical part of the expression and double the power of 10. Express the answer in the desired form of powers of 10 notation.

EXAMPLE I-14

Square 3.0×10^4. Express the answer in scientific notation.

Answer: First, square 3.0 to obtain 9.0. Next, square 10^4 to obtain $(10^4)^2 = 10^8$. Therefore, $(3.0 \times 10^4)^2 = 9.0 \times 10^8$.

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