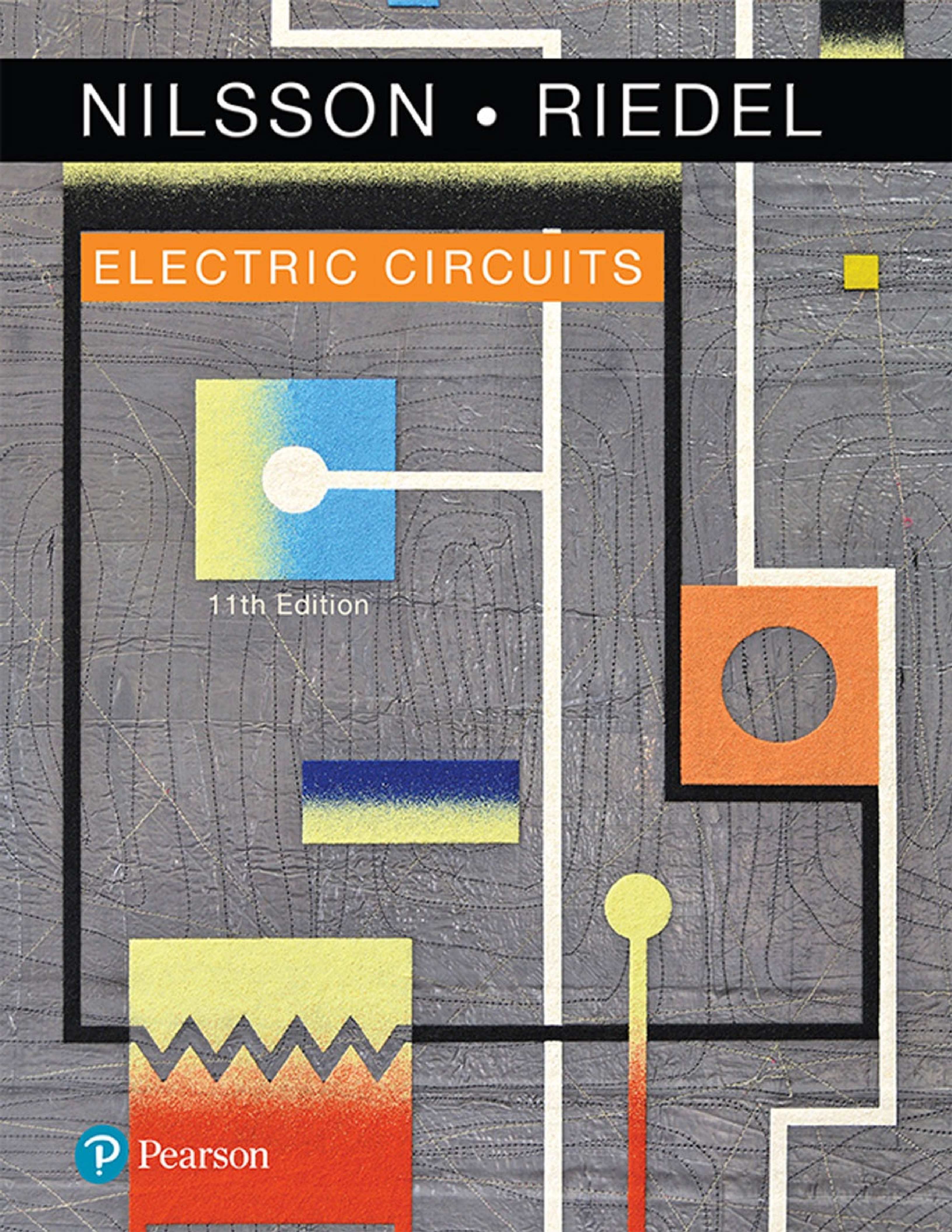

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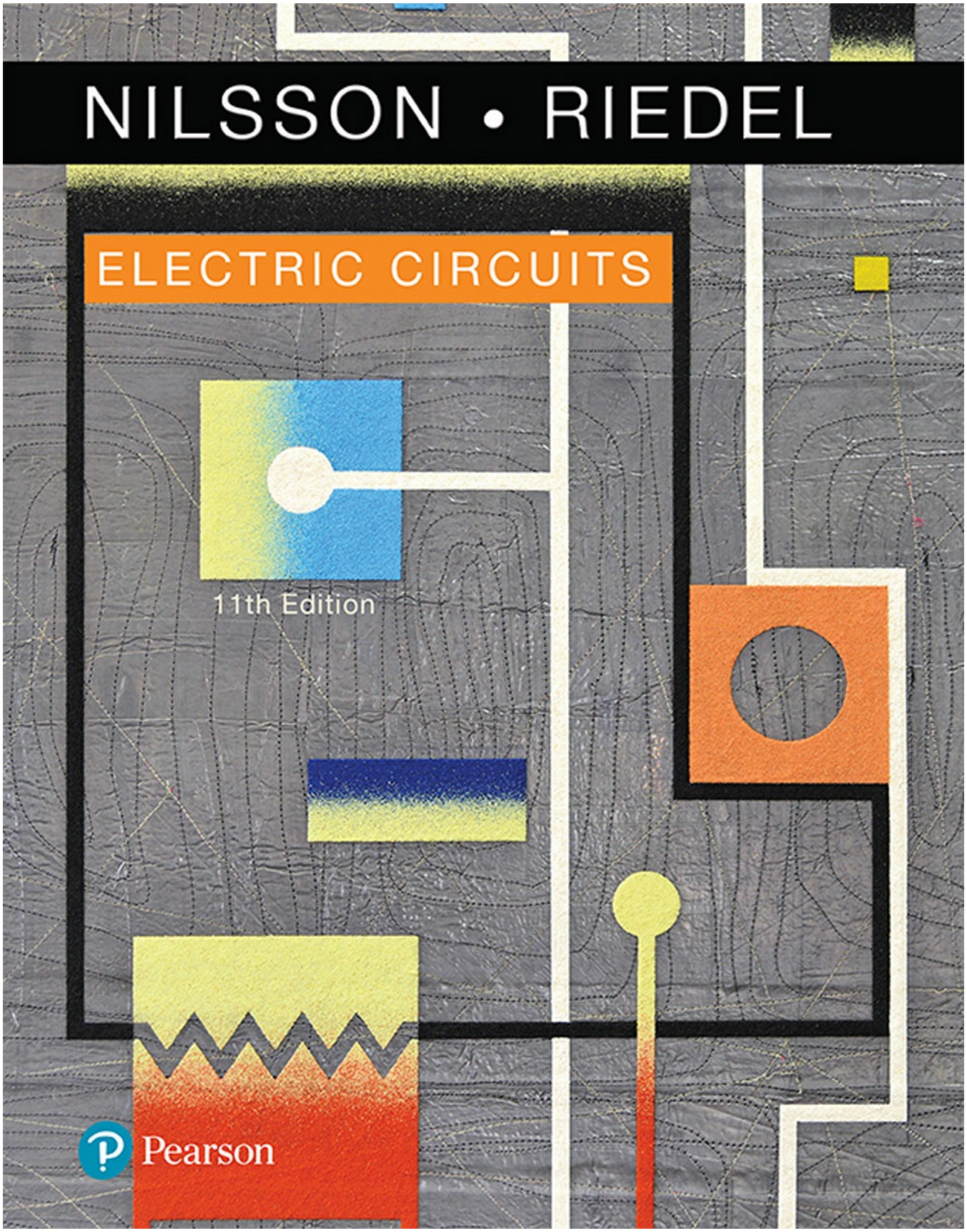

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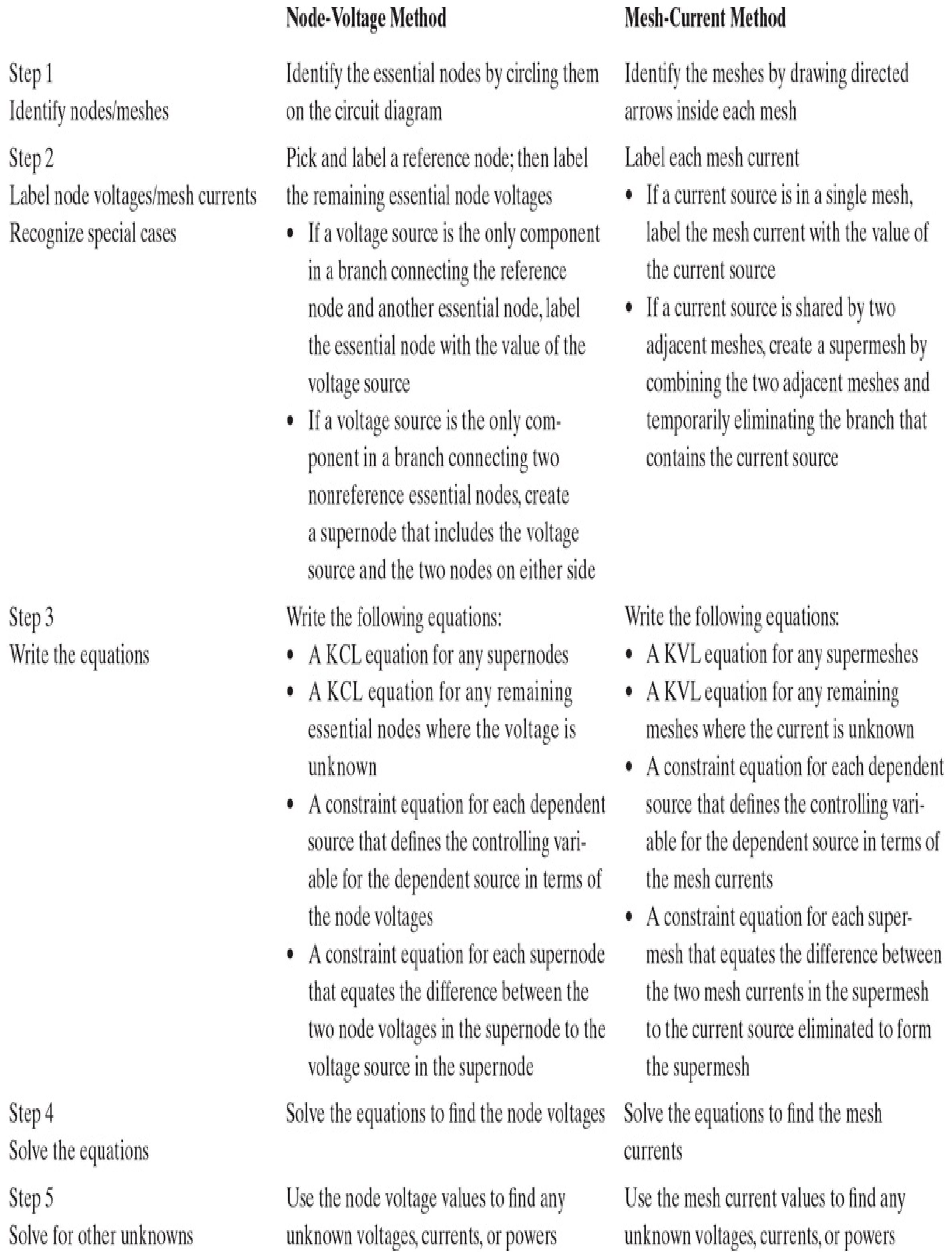
Table 4.3 Steps in the Node-Voltage Method and the Mesh-Current Method



	Node-Voltage Method	Mesh-Current Method
Step 1 Identify nodes/meshes	Identify the essential nodes by circling them on the circuit diagram	Identify the meshes by drawing directed arrows inside each mesh
Step 2 Label node voltages/mesh currents Recognize special cases	Pick and label a reference node; then label the remaining essential node voltages • If a voltage source is the only component in a branch connecting the reference node and another essential node, label the essential node with the value of the voltage source • If a voltage source is the only component in a branch connecting two nonreference essential nodes, create a supernode that includes the voltage source and the two nodes on either side	Label each mesh current • If a current source is in a single mesh, label the mesh current with the value of the current source • If a current source is shared by two adjacent meshes, create a supermesh by combining the two adjacent meshes and temporarily eliminating the branch that contains the current source
Step 3 Write the equations	Write the following equations: • A KCL equation for any supernodes • A KCL equation for any remaining essential nodes where the voltage is unknown • A constraint equation for each dependent source that defines the controlling variable for the dependent source in terms of the node voltages • A constraint equation for each supernode that equates the difference between the two node voltages in the supernode to the voltage source in the supernode	Write the following equations: • A KVL equation for any supermeshes • A KVL equation for any remaining meshes where the current is unknown • A constraint equation for each dependent source that defines the controlling variable for the dependent source in terms of the mesh currents • A constraint equation for each supermesh that equates the difference between the two mesh currents in the supermesh to the current source eliminated to form the supermesh
Step 4 Solve the equations	Solve the equations to find the node voltages	Solve the equations to find the mesh currents
Step 5 Solve for other unknowns	Use the node voltage values to find any unknown voltages, currents, or powers	Use the mesh current values to find any unknown voltages, currents, or powers

Analyzing a Circuit With an Ideal

OP AMP

1. Check for a negative feedback path. If it exists, assume the op amp operates in its linear region.
2. Write a KCL equation at the inverting input terminal.
3. Solve the KCL equation and use the solution to find the op amp's output voltage.
4. Compare the op amp's output voltage to the power supply voltages to determine if the op amp is operating in its linear region or if it is saturated.

General Method for Natural and Step Response of RL and RC Circuits

1. **Identify the variable x(t),** which is the inductor current for RL circuits and capacitor voltage for RC circuits.
2. **Calculate the initial value X0**, by analyzing the circuit to find x(t) for $t<0$
3. **Calculate the time constant** τ; for RL circuits $\tau=L/R$ and for RC circuits $\tau=RC$, where R is the equivalent resistance connected to the inductor or capacitor for $t\geq 0$
4. **Calculate the final value Xf**, by analyzing the circuit to find x(t) as $t\rightarrow\infty$; for the natural response, Xf=0
5. **Write the equation for x(t),** $x(t)=Xf+(X0-Xf)\ e-t/\tau$, for $t\geq 0$.

6. **Calculate other quantities of interest** using $x(t)$.

Natural Response of a Parallel *RLC* Circuit

1. **Determine the initial capacitor voltage ($V0$) and inductor current ($I0$)** from the circuit.

2. **Determine the values of** α **and** $\omega0$ using the equations in Table 8.1.

3. **If** $\alpha2>\omega02$, **the response is overdamped** and $v(t)=A1es1t+A2es2t,t\geq0$

4. **If the response is overdamped, calculate $s1$ and $s2$** using the equations in Table 8.1.

5. **If the response is overdamped, calculate $A1$ and $A2$** by simultaneously solving Eqs. 8.10 and 8.11.

6. **Write the equation for $v(t)$ from Step 3** using the results from Steps 4 and 5; find any desired branch currents.

Table 8.2 Equations for analyzing the natural response of parallel RLC circuits

Characteristic equation	$s^2 + \frac{1}{RC}s + \frac{1}{LC} = 0$
Neper, resonant, and damped frequencies	$\alpha = \frac{1}{2RC} \quad \omega_0 = \sqrt{\frac{1}{LC}} \quad \omega_d = \sqrt{\omega_0^2 - \alpha^2}$
Roots of the characteristic equation	$s_1 = -\alpha + \sqrt{\alpha^2 - \omega_0^2},\ \ s_2 = -\alpha - \sqrt{\alpha^2 - \omega_0^2}$
$\alpha^2 > \omega_0^2$: overdamped	$v(t) = A_1e^{s_1t} + A_2e^{s_2t}, \mathrm{t} \geq 0$ $v(0^+) = A_1 + A_2 = V_0$ $\frac{dv(0^+)}{dt} = s_1A_1 + s_2A_2 = \frac{1}{C}\left(\frac{-V_0}{R} - I_0\right)$
$\alpha^2 < \omega_0^2$: underdamped	$v(t) = B_1e^{-\alpha t}\cos\omega_dt + B_2e^{-\alpha t}\sin\omega_dt, \mathrm{t} \geq 0$ $v(0^+) = B_1 = V_0$ $\frac{dv(0^+)}{dt} = -\alpha B_1 + \omega_dB_2 = \frac{1}{C}\left(\frac{-V_0}{R} - I_0\right)$
$\alpha^2 = \omega_0^2$: critically damped	$v(t) = D_1te^{-\alpha t} + D_2e^{-\alpha t}, \mathrm{t} \geq 0$ $v(0^+) = D_2 = V_0$ $\frac{dv(0^+)}{dt} = D_1 - \alpha D_2 = \frac{1}{C}\left(\frac{-V_0}{R} - I_0\right)$

(Note that the equations in the last three rows assume that the reference direction for the current in every component is in the direction of the reference voltage drop across that component.)

Step Response of a Parallel *RLC*

Circuit

1. **Determine the initial capacitor voltage (V0), the initial inductor current (I0), and the final inductor current (If)** from the circuit.

2. **Determine the values of** α **and** ω0 using the equations in Table 8.3.

3. **If** α2>ω02, **the response is overdamped** and iL(t)=If+A′1es1t+A′2es2t, t≥0+;

   If α2>ω02 **the response is underdamped** and iL(t)=If+B′1e−αtcosωdt+B′2e−αtsinωdt, t≥0+;

   If α2=ω02, **the response is critically damped** and iL(t)=If+D′1te−αt+D′2e−αt, t≥0+

4. **If the response is overdamped, calculate s1 and s2** using the equations in Table 8.3;

   If the response is underdamped, calculate ωd using the equation in Table 8.3.

5. **If the response is overdamped, calculate** A1′ **and** A2′ by simultaneously solving the equations in Table 8.3;

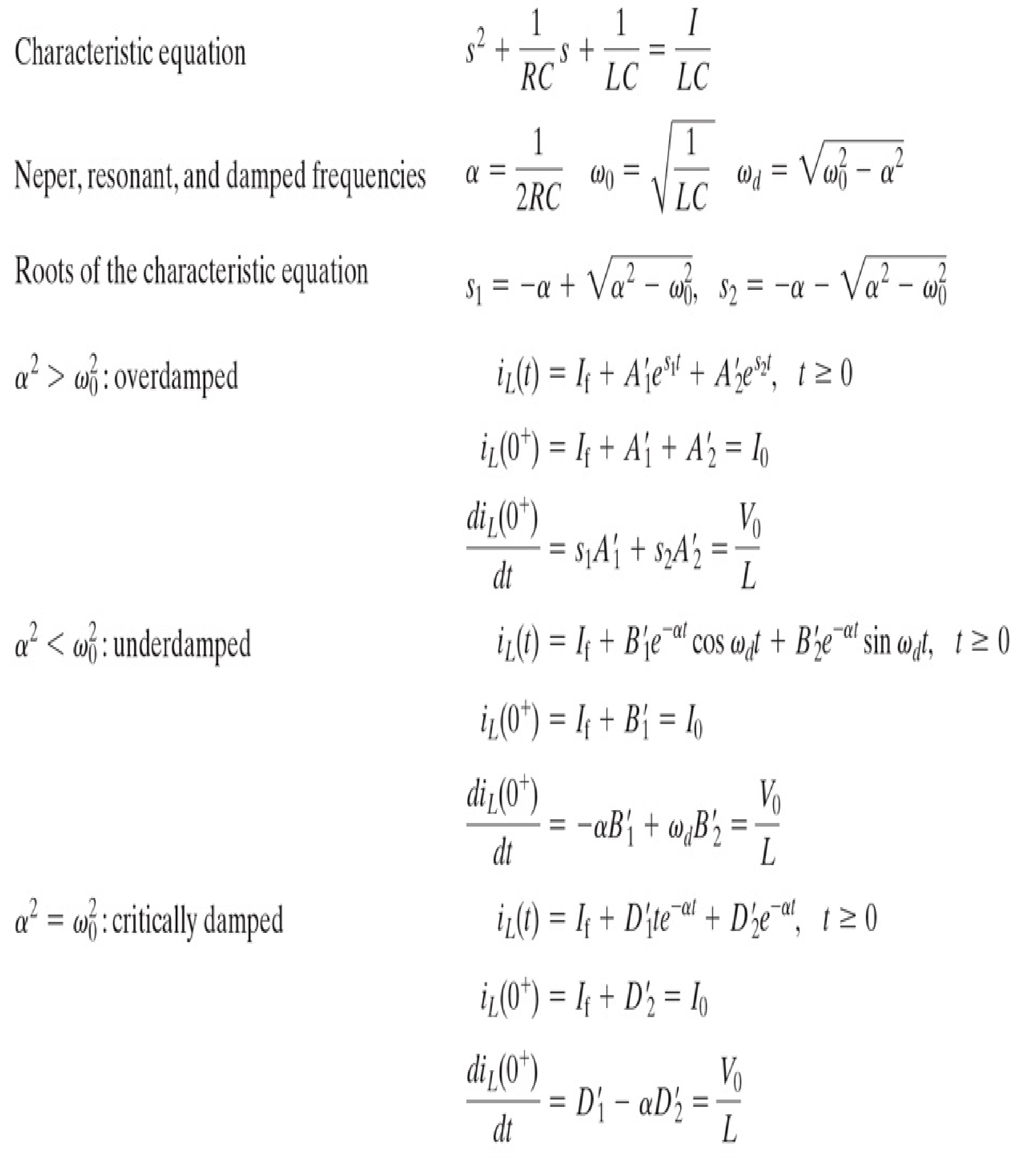
   If the response is underdamped, calculate B1′ **and** B2′ by simultaneously solving the equations in Table 8.3;

   If the response is critically damped, calculate D1′ **and** D2′ by simultaneously solving the equations in Table 8.3.

6. **Write the equation for iL(t) from Step 3** using the results from Steps 4 and 5; find the inductor voltage and any desired branch currents.

Table 8.3 Equations for

analyzing the step response of parallel RLC circuits



Characteristic equation	$s^2 + \frac{1}{RC}s + \frac{1}{LC} = \frac{I}{LC}$
Neper, resonant, and damped frequencies	$\alpha = \frac{1}{2RC} \quad \omega_0 = \sqrt{\frac{1}{LC}} \quad \omega_d = \sqrt{\omega_0^2 - \alpha^2}$
Roots of the characteristic equation	$s_1 = -\alpha + \sqrt{\alpha^2 - \omega_0^2}, \ \ s_2 = -\alpha - \sqrt{\alpha^2 - \omega_0^2}$
$\alpha^2 > \omega_0^2$: overdamped	$i_L(t) = I_f + A_1' e^{s_1 t} + A_2' e^{s_2 t}, \quad t \geq 0$ $i_L(0^+) = I_f + A_1' + A_2' = I_0$ $\frac{di_L(0^+)}{dt} = s_1 A_1' + s_2 A_2' = \frac{V_0}{L}$
$\alpha^2 < \omega_0^2$: underdamped	$i_L(t) = I_f + B_1' e^{-\alpha t} \cos \omega_d t + B_2' e^{-\alpha t} \sin \omega_d t, \quad t \geq 0$ $i_L(0^+) = I_f + B_1' = I_0$ $\frac{di_L(0^+)}{dt} = -\alpha B_1' + \omega_d B_2' = \frac{V_0}{L}$
$\alpha^2 = \omega_0^2$: critically damped	$i_L(t) = I_f + D_1' t e^{-\alpha t} + D_2' e^{-\alpha t}, \quad t \geq 0$ $i_L(0^+) = I_f + D_2' = I_0$ $\frac{di_L(0^+)}{dt} = D_1' - \alpha D_2' = \frac{V_0}{L}$

(Note that the equations in the last three rows assume that the reference direction for the current in every component is in the direction of the reference voltage drop across that component.)

Electric Circuits

Eleventh Edition

Electric Circuits

Eleventh Edition

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Courtesy of Anna Nilsson

In Memoriam

We remember our beloved author, James W. Nilsson, for his lasting legacy to the electrical and computer engineering field.

The first edition of *Electric Circuits* was published in 1983. As this book evolved over the years to better meet the needs of both students and their instructors, the underlying teaching methodologies Jim established remain relevant, even in the Eleventh Edition.

Jim earned his bachelor’s degree at the University of Iowa (1948), and his master’s degree (1952) and Ph.D. (1958) at Iowa State University. He joined the ISU faculty in 1948 and taught electrical engineering there for 39 years.

He became an IEEE fellow in 1990 and earned the prestigious IEEE Undergraduate Teaching Award in 1992.

For Anna

Brief Contents

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List of Examples

3. Chapter 3

4. Chapter 4

5. Chapter 5

6. Chapter 6

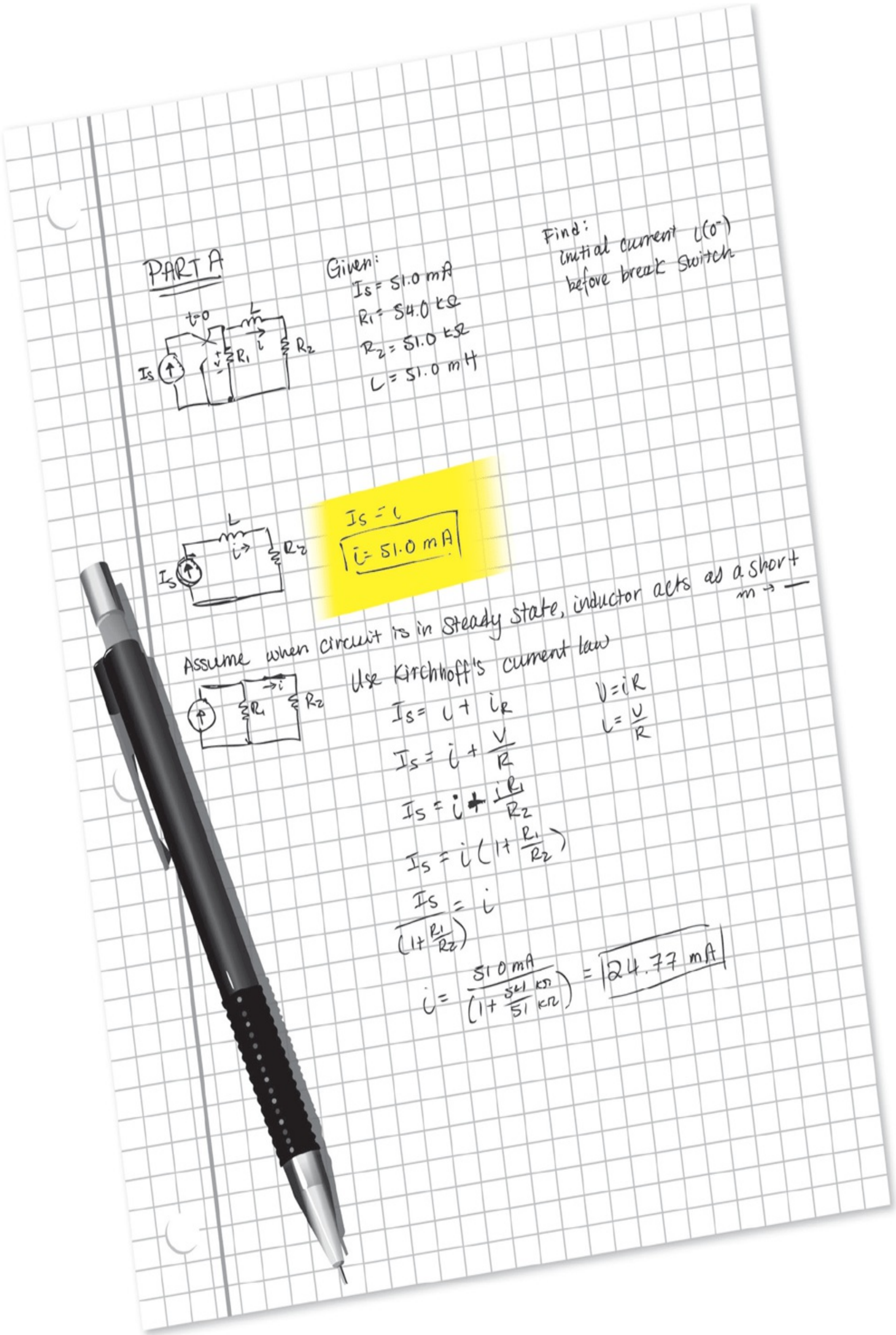
8. Chapter 8

10. Chapter 10

List of Tables

List of Analysis Methods

Combine this...



PART A

Given:
$I_s = 51.0\ mA$
$R_1 = 54.0\ k\Omega$
$R_2 = 51.0\ k\Omega$
$L = 51.0\ mH$

Find:
initial current $i(0^-)$
before break switch

$I_s = i$

$\boxed{i = 51.0\ mA}$

Assume when circuit is in steady state, inductor acts as a short
m → —

Use Kirchhoff's current law

$I_s = i + i_R$

$V = iR$

$i = \frac{V}{R}$

$I_s = i + \frac{V}{R}$

$I_s = i + \frac{iR_1}{R_2}$

$I_s = i\left(1 + \frac{R_1}{R_2}\right)$

$\frac{I_s}{\left(1 + \frac{R_1}{R_2}\right)} = i$

$i = \frac{51.0\ mA}{\left(1 + \frac{54\ k\Omega}{51\ k\Omega}\right)} = \boxed{24.77\ mA}$

With the Power of Mastering Engineering for Electric Circuits 11/e

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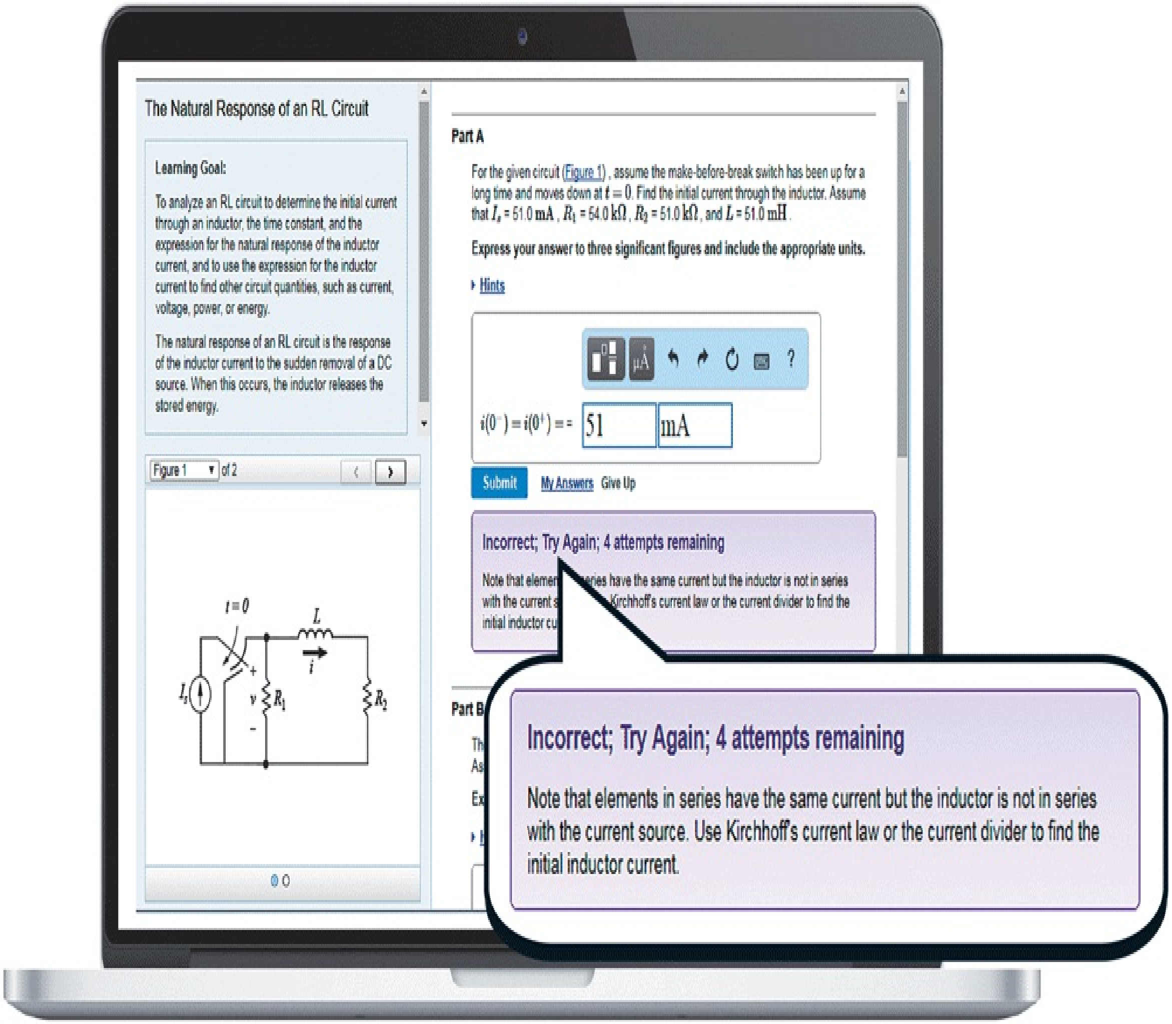

The Natural Response of an RL Circuit

Learning Goal:

To analyze an RL circuit to determine the initial current through an inductor, the time constant, and the expression for the natural response of the inductor current, and to use the expression for the inductor current to find other circuit quantities, such as current, voltage, power, or energy.

The natural response of an RL circuit is the response of the inductor current to the sudden removal of a DC source. When this occurs, the inductor releases the stored energy.

Part A

For the given circuit (Figure 1), assume the make-before-break switch has been up for a long time and moves down at $t=0$. Find the initial current through the inductor. Assume that $I_s = 51.0\ \mathrm{mA}$, $R_1 = 54.0\ \mathrm{k\Omega}$, $R_2 = 51.0\ \mathrm{k\Omega}$, and $L = 51.0\ \mathrm{mH}$.

Express your answer to three significant figures and include the appropriate units.

$i(0^-) = i(0^+) =$ = 51 mA

Incorrect; Try Again; 4 attempts remaining

Note that elements in series have the same current but the inductor is not in series with the current source. Use Kirchhoff's current law or the current divider to find the initial inductor current.

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Preface

The Eleventh Edition of *Electric Circuits* represents the most extensive revision to the text since the Fifth Edition, published in 1996. Every sentence, paragraph, subsection, and chapter has been examined to improve clarity, readability, and pedagogy. Yet the fundamental goals of the text are unchanged. These goals are:

- To build new concepts and ideas on concepts previously presented. This challenges students to see the explicit connections among the many circuit analysis tools and methods.
- To develop problem-solving skills that rely on a solid conceptual foundation. This challenges students to examine many different approaches to solving a problem before writing a single equation.
- To introduce realistic engineering experiences at every opportunity. This challenges students to develop the insights of a practicing engineer and exposes them to practice of engineering.

Why This Edition?

The Eleventh Edition of *Electric Circuits* incorporates the following new and revised elements:

- Analysis Methods – This new feature identifies the steps needed to apply a particular circuit analysis technique. Many students struggle just to get started when analyzing a circuit, and the analysis methods will reduce that struggle. Some of the analysis methods that are used most often can be found inside the book’s covers for easy reference.
- Examples – Many students rely on examples when developing and refining their problem-solving skills. We identified many places in the text that needed additional examples, and as a result the number of

examples has increased by nearly 35% to 200.

- End-of-chapter problems – Problem solving is fundamental to the study of circuit analysis. Having a wide variety of problems to assign and work is a key to success in any circuits course. Therefore, some existing end-of-chapter problems were revised, and some new end-of-chapter problems were added. Approximately 30% of the problems in the Eleventh Edition were rewritten.

- Fundamental equations and concepts – These important elements in the text were previously identified with margin notes. In this edition, the margin notes have been replaced by a second-color background, enlarged fonts, and a descriptive title for each fundamental equation and concept. In additional, many equation numbers have been eliminated to make it easier to distinguish fundamental equations from the many other equations in the text.

- Circuit simulation software – The PSpice® and Multisim® manuals have been revised to include screenshots from the most recent versions of these software simulation applications. Each manual presents the simulation material in the same order as the material is encountered in the text. These manuals include example simulations of circuits from the text. Icons identify end-of-chapter problems that are good candidates for simulation using either PSpice or Multisim.

- Solving simultaneous equations – Most circuit analysis techniques in this text eventually require you to solve two or more simultaneous linear algebraic equations. Appendix A has been extensively revised and includes examples of paper-and-pencil techniques, calculator techniques, and computer software techniques.

- Student workbook – Students who could benefit from additional examples and practice problems can use the Student Workbook, which has been revised for the Eleventh Edition of the text. This workbook has examples and problems covering the following material: balancing power, simple resistive circuits, node voltage method, mesh current method, Thévenin and Norton equivalents, op amp circuits, first-order circuits, second-order circuits, AC steady-state analysis, and Laplace transform circuit analysis.

- The Student Workbook now includes access to Video Solutions, complete, step-by-step solution walkthroughs to representative homework problems.
- Learning Catalytics, a “bring your own device” student engagement, assessment, and classroom intelligence system is available with the Eleventh Edition. With Learning Catalytics you can:
  - Use open-ended questions to get into the minds of students to understand what they do or don’t know and adjust lectures accordingly.
  - Use a wide variety of question types to sketch a graph, annotate a circuit diagram, compose numeric or algebraic answers, and more.
  - Access rich analytics to understand student performance.
  - Use pre-built questions or add your own to make Learning Catalytics fit your course exactly.
- Pearson Mastering Engineering is an online tutorial and assessment program that provides students with personalized feedback and hints and instructors with diagnostics to track students’ progress. With the Eleventh Edition, Mastering Engineering will offer new enhanced end-of-chapter problems with hints and feedback, Coaching Activities, and Adaptive Follow-Up assignments. Visit www.masteringengineering.com for more information.

Hallmark Features

Analysis Methods

Students encountering circuit analysis for the first time can benefit from step-by-step directions that lead them to a problem’s solution. We have compiled these directions in a collection of analysis methods, and revised many of the examples in the text to employ these analysis methods.

Chapter Problems

Users of *Electric Circuits* have consistently rated the Chapter Problems as one of the book’s most attractive features. In the Eleventh Edition, there are 1185 end-of-chapter problems with approximately 30% that have been revised from the previous edition. Problems are organized at the end of each chapter by section.

Practical Perspectives

The Eleventh Edition continues using Practical Perspectives to introduce the chapter. They provide real-world circuit examples, taken from real-world devices. Every chapter begins by describing a practical application of the material that follows. After presenting that material, the chapter revisits the Practical Perspective, performing a quantitative circuit analysis using the newly introduced chapter material. A special icon identifies end-of-chapter problems directly related to the Practical Perspective application. These problems provide additional opportunities for solving real-world problems using the chapter material.

Assessment Problems

Each chapter begins with a set of chapter objectives. At key points in the chapter, you are asked to stop and assess your mastery of a particular objective by solving one or more assessment problems. The answers to all of the assessment problems are given at the conclusion of each problem, so you can check your work. If you are able to solve the assessment problems for a given objective, you have mastered that objective. If you need more practice, several end-of-chapter problems that relate to the objective are suggested at the conclusion of the assessment problems.

Examples

Every chapter includes many examples that illustrate the concepts presented in the text in the form of a numeric example. There are now nearly 200 examples in this text, an increase of about 35% when compared to the previous edition. The examples illustrate the application of a particular concept, often employ an Analysis Method, and exemplify good problem-solving skills.

Fundamental Equations and Concepts

Throughout the text, you will see fundamental equations and concepts set apart from the main text. This is done to help you focus on some of the key principles in electric circuits and to help you navigate through the important topics.

Integration of Computer Tools

Computer tools can assist students in the learning process by providing a visual representation of a circuit's behavior, validating a calculated solution, reducing the computational burden of more complex circuits, and iterating toward a desired solution using parameter variation. This computational support is often invaluable in the design process. The Eleventh Edition supports PSpice and Multisim, both popular computer tools for circuit simulation and analysis. Chapter problems suited for exploration with PSpice and Multisim are marked accordingly.

Design Emphasis

The Eleventh Edition continues to support the emphasis on the design of circuits in many ways. First, many of the Practical Perspective discussions focus on the design aspects of the circuits. The accompanying Chapter Problems continue the discussion of the design issues in these practical examples. Second, design-oriented Chapter Problems have been labeled explicitly, enabling students and instructors to identify those problems with a design focus. Third, the identification of problems suited to exploration with PSpice or Multisim suggests design opportunities using these software tools. Fourth, some problems in nearly every chapter focus on the use of realistic component values in achieving a desired circuit design. Once such a problem has been analyzed, the student can proceed to a laboratory to build and test the circuit, comparing the analysis with the measured performance of the actual circuit.

Accuracy

All text and problems in the Eleventh Edition have undergone our strict hallmark accuracy checking process, to ensure the most error-free book possible.

Resources For Students

Mastering Engineering. Mastering Engineering provides tutorial homework problems designed to emulate the instructor’s office hour environment, guiding students through engineering concepts with self-paced individualized coaching. These in-depth tutorial homework problems provide students with feedback specific to their errors and optional hints that break problems down into simpler steps. Visit www.masteringengineering.com for more information.

Learning Catalytics. Learning Catalytics is an interactive student response tool that encourages team-based learning by using student’s smartphones, tablets, or laptops to engage them in interactive tasks and thinking. Visit www.learningcatalytics.com for more information.

Student Workbook. This resource teaches students techniques for solving problems presented in the text. Organized by concepts, this is a valuable problem-solving resource for all levels of students. The Student Workbook now includes access to Video Solutions, complete, step-by-step solution walkthroughs to representative homework problems.

Introduction to Multisim and Introduction to PSpice Manuals—Updated for the Eleventh Edition, these manuals are excellent resources for those wishing to integrate PSpice or Multisim into their classes.

Resources for Instructors

All instructor resources are available for download at www.pearsonhighered.com. If you are in need of a login and password for this site, please contact your local Pearson representative.

Instructor Solutions Manual—Fully worked-out solutions to Assessment Problems and end-of-chapter problems.

PowerPoint lecture images—All figures from the text are available in PowerPoint for your lecture needs. An additional set of full lecture slides with embedded assessment questions are available upon request.

MasteringEngineering. This online tutorial and assessment program allows you to integrate dynamic homework with automated grading and personalized feedback. MasteringEngineering allows you to easily track the performance of your entire class on an assignment-by-assignment basis, or the detailed work of an individual student. For more information visit www.masteringengineering.com.

Learning Catalytics—This “bring your own device” student engagement, assessment and classroom intelligence system enables you to measure student learning during class, and adjust your lectures accordingly. A wide variety of question and answer types allows you to author your own questions, or you can use questions already authored into the system. For more information visit www.learningcatalytics.com or click on the Learning Catalytics link inside Mastering Engineering.

Prerequisites

In writing the first 12 chapters of the text, we have assumed that the reader has taken a course in elementary differential and integral calculus. We have also assumed that the reader has had an introductory physics course, at either the high school or university level, that introduces the concepts of energy, power, electric charge, electric current, electric potential, and electromagnetic fields. In writing the final six chapters, we have assumed the student has had, or is enrolled in, an introductory course in differential equations.

Course Options

The text has been designed for use in a one-semester, two-semester, or a three-quarter sequence.

- Single-semester course: After covering Chapters 1–4 and Chapters 6–10 (omitting Sections 7.7 and 8.5) the instructor can develop the desired emphasis by covering Chapter 5 (operational amplifiers), Chapter 11 (three-phase circuits), Chapters 13 and 14 (Laplace methods), or Chapter 18 (Two-Port Circuits).

- Two-semester sequence: Assuming three lectures per week, cover the first nine chapters during the first semester, leaving Chapters 10–18 for the second semester.

- Academic quarter schedule: Cover Chapters 1–6 in the first quarter, Chapters 7–12 in the second quarter, and Chapters 13–18 in the third quarter.

Note that the introduction to operational amplifier circuits in Chapter 5 can be omitted with minimal effect on the remaining material. If Chapter 5 is omitted, you should also omit Section 7.7, Section 8.5, Chapter 15, and those assessment problems and end-of-chapter problems that pertain to operational amplifiers.

There are several appendixes at the end of the book to help readers make effective use of their mathematical background. Appendix A presents several different methods for solving simultaneous linear equations; complex numbers are reviewed in Appendix B; Appendix C contains additional material on magnetically coupled coils and ideal transformers; Appendix D contains a brief discussion of the decibel; Appendix E is dedicated to Bode diagrams; Appendix F is devoted to an abbreviated table of trigonometric identities that are useful in circuit analysis; and an abbreviated table of useful integrals is given in Appendix G. Appendix H provides tables of common standard component values for resistors, inductors, and capacitors, to be used in solving many end-of-chapter problems. Selected Answers provides answers to selected end-of-chapter problems.

Acknowledgments

I will be forever grateful to Jim Nilsson for giving me the opportunity to collaborate with him on this textbook. I started by revising the PSpice supplement for the Third Edition, and became a co-author of the Fifth Edition. Jim was a patient and gracious mentor, and I learned so much from him about teaching and writing and hard work. It is a great honor to be associated with him through this textbook, and to impact the education of the thousands of students who use this text.

There were many hard-working people behind the scenes at our publisher who deserve my thanks and gratitude for their efforts on behalf of the Eleventh Edition. At Pearson, I would like to thank Norrin Dias, Erin Ault, Rose Kernan, and Scott Disanno for their continued support and encouragement, their professional demeanor, their willingness to lend an ear, and their months of long hours and no weekends. The author would also like to acknowledge the staff at Integra Software Solutions for their dedication and hard work in typesetting this text.

I am very grateful for the many instructors and students who have done formal reviews of the text or offered positive feedback and suggestions for

improvement more informally. I am pleased to receive email from instructors and students who use the book, even when they are pointing out an error I failed to catch in the review process. I have been contacted by people who use our text from all over the world, and I thank all of you for taking the time to do so. I use as many of your suggestions as possible to continue to improve the content, the pedagogy, and the presentation in this text. I am privileged to have the opportunity to impact the educational experience of the many thousands of future engineers who will use this text.

Susan A. Riedel

Electric Circuits

Eleventh Edition

Chapter 1 Circuit Variables

Chapter Contents

Chapter Objectives

1. Understand and be able to use SI units and the standard prefixes for powers of 10.
2. Know and be able to use the definitions of *voltage* and *current*.
3. Know and be able to use the definitions of *power* and *energy*.
4. Be able to use the passive sign convention to calculate the power for an ideal basic circuit element given its voltage and current.

Electrical engineering is an exciting and challenging profession for anyone who has a genuine interest in, and aptitude for, applied science and mathematics. Electrical engineers play a dominant role in developing systems that change the way people live and work. Satellite communication links, cell phones, computers, televisions, diagnostic and surgical medical equipment, robots, and aircraft represent systems that define a modern technological society. As an electrical engineer, you can participate in this ongoing technological revolution by improving and refining existing systems and by discovering and developing new systems to meet the needs of our ever-changing society.

This text introduces you to electrical engineering using the analysis and design of linear circuits. We begin by presenting an overview of electrical engineering, some ideas about an engineering point of view as it relates to circuit analysis, and a review of the International System of Units. We then describe generally what circuit analysis entails. Next, we introduce the concepts of voltage and current. We continue by discussing the ideal basic element and the need for a polarity reference system. We conclude the chapter by describing how current and voltage relate to power and energy.

Practical Perspective

Balancing Power

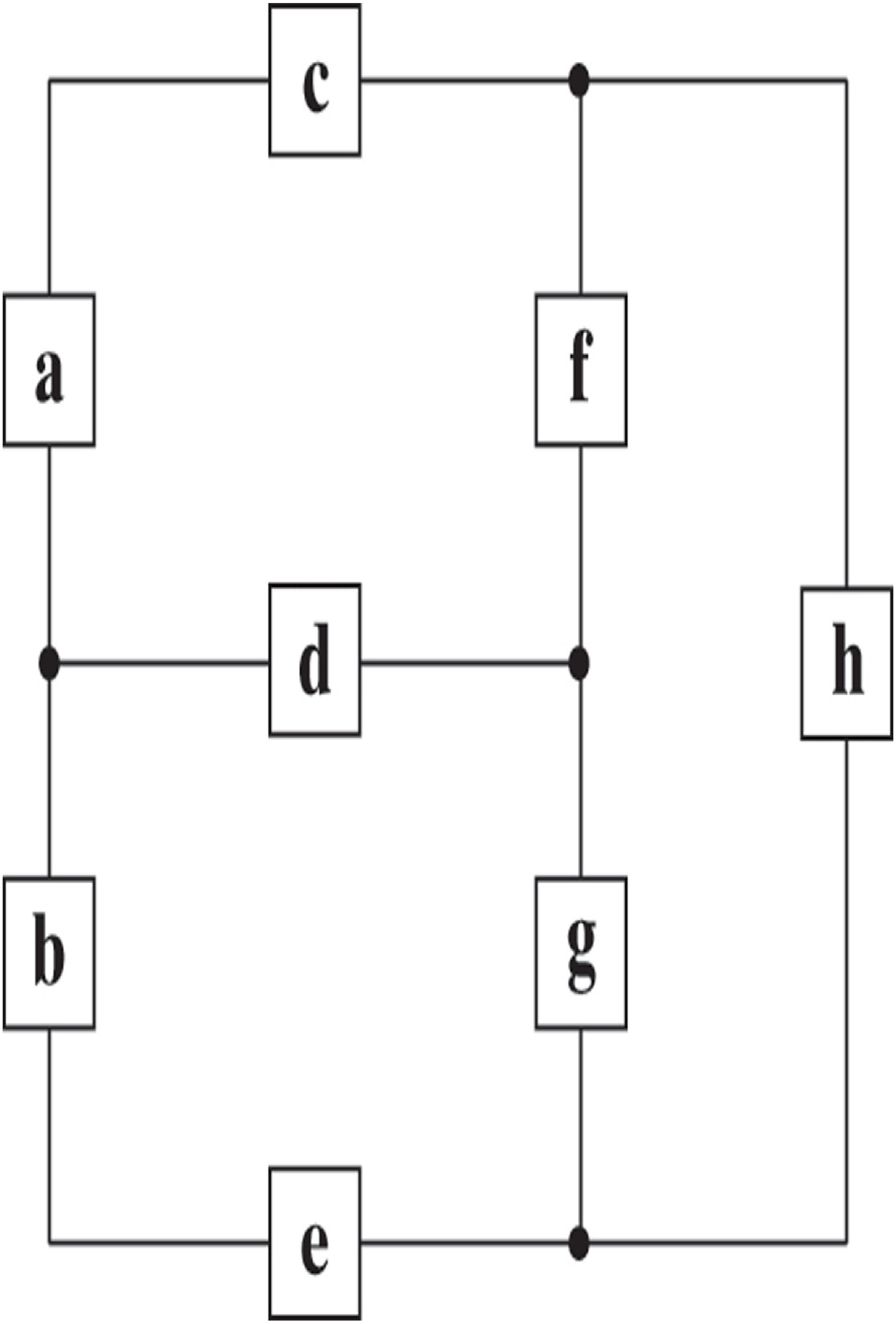
One of the most important skills you will develop is the ability to check your answers for the circuits you design and analyze using the tools developed in this text. A common method used to check for valid answers is to calculate the power in the circuit. The linear circuits we study have no net power, so the sum of the power associated with all circuit components must be zero. If the total power for the circuit is zero, we say that the power balances, but if the total power is not zero, we need to find the errors in our calculation.

As an example, we will consider a simple model for distributing electricity to a typical home. (Note that a more realistic model will be investigated in the Practical Perspective for Chapter 9.) The components labeled a and b represent the source of electrical power for the home. The components labeled c, d, and e represent the wires that carry the electrical current from the source to the devices in the home requiring electrical power. The components labeled f, g, and h represent lamps, televisions, hair dryers, refrigerators, and other devices that require power.

romakoma/Shutterstock

PhotoSerg/Shutterstock

Once we have introduced the concepts of voltage, current, power, and energy, we will examine this circuit model in detail, and use a power balance to determine whether the results of analyzing this circuit are correct.


c
a
f
d
h
b
g
e

1.1-3 Full Alternative Text

AfricaStudio/Shutterstock

1.1 Electrical Engineering: An Overview

The electrical engineering profession focuses on systems that produce, transmit, and measure electric signals. Electrical engineering combines the physicist's models of natural phenomena with the mathematician's tools for manipulating those models to produce systems that meet practical needs. Electrical systems pervade our lives; they are found in homes, schools, workplaces, and transportation vehicles everywhere. We begin by presenting a few examples from each of the five major classifications of electrical systems:

- communication systems
- computer systems
- control systems
- power systems
- signal-processing systems

Then we describe how electrical engineers analyze and design such systems.

Communication systems are electrical systems that generate, transmit, and distribute information. Well-known examples include television equipment, such as cameras, transmitters, receivers, and monitors; radio telescopes, used to explore the universe; satellite systems, which return images of other planets and our own; radar systems, used to coordinate plane flights; and telephone systems.

Figure 1.1 depicts the major components of a modern telephone system that supports mobile phones, landlines, and international calling. Inside a telephone, a microphone turns sound waves into electric signals. These signals are carried to local or mobile exchanges, where they are combined with the signals from tens, hundreds, or thousands of other telephones. The form of the signals can be radio waves traveling through air, electrical signals traveling in underground coaxial cable, light pulses traveling in fiber-optic cable, or microwave signals that travel through space. The combined signals are broadcast from a transmission antenna to a receiving antenna. There the combined signals are separated at an exchange, and each is routed to the appropriate telephone, where an earphone acts as a speaker to convert the received electric signals back into sound waves. At each stage of the process, electric circuits operate on the signals. Imagine the challenge involved in designing, building, and operating each circuit in a way that guarantees that all of the hundreds of thousands of simultaneous calls have high-quality connections.

Figure 1.1 A telephone system.

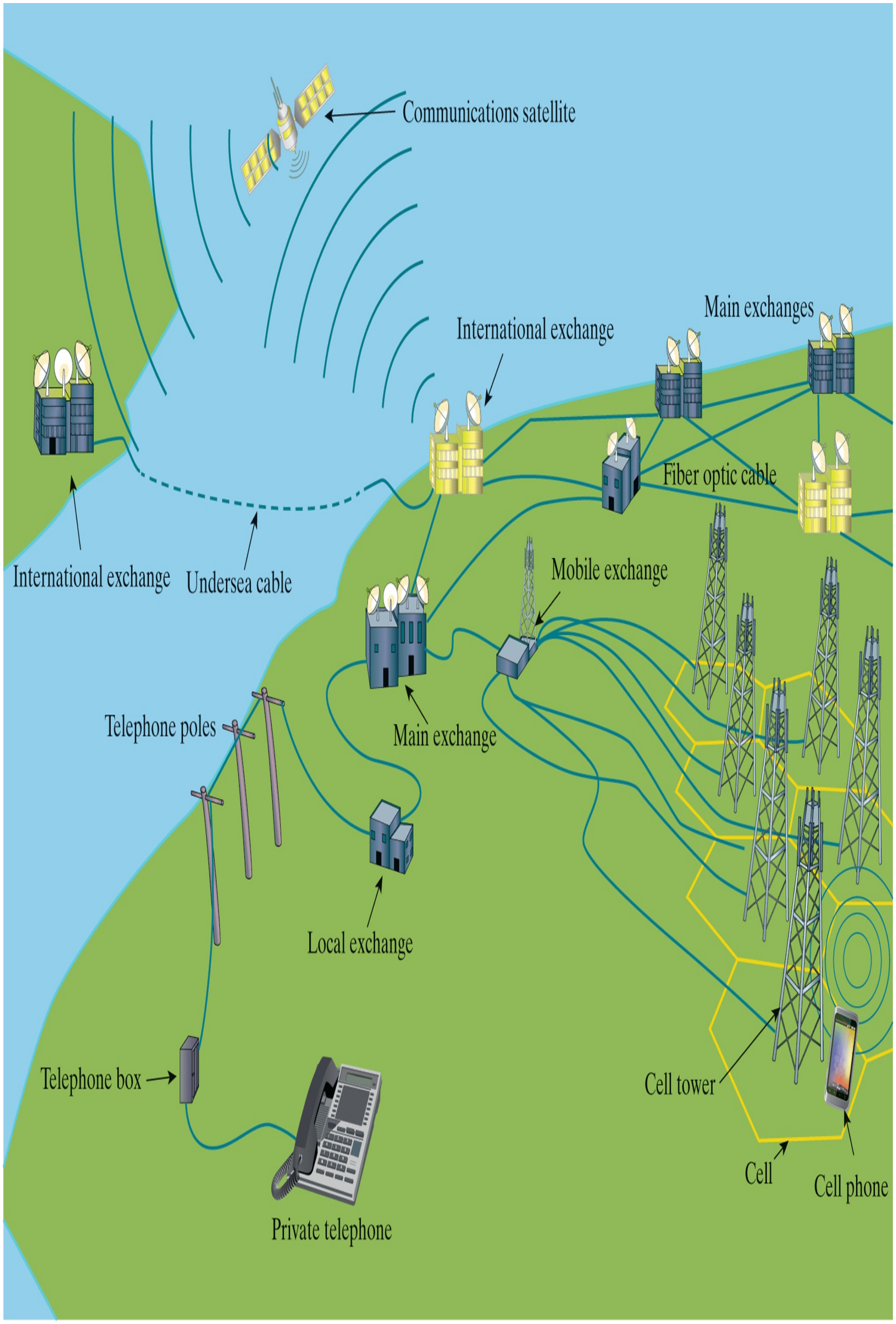

Communications satellite
International exchange
Main exchanges
Fiber optic cable
International exchange
Undersea cable
Mobile exchange
Main exchange
Telephone poles
Local exchange
Telephone box
Private telephone
Cell tower
Cell
Cell phone

Figure 1.1 Full Alternative Text

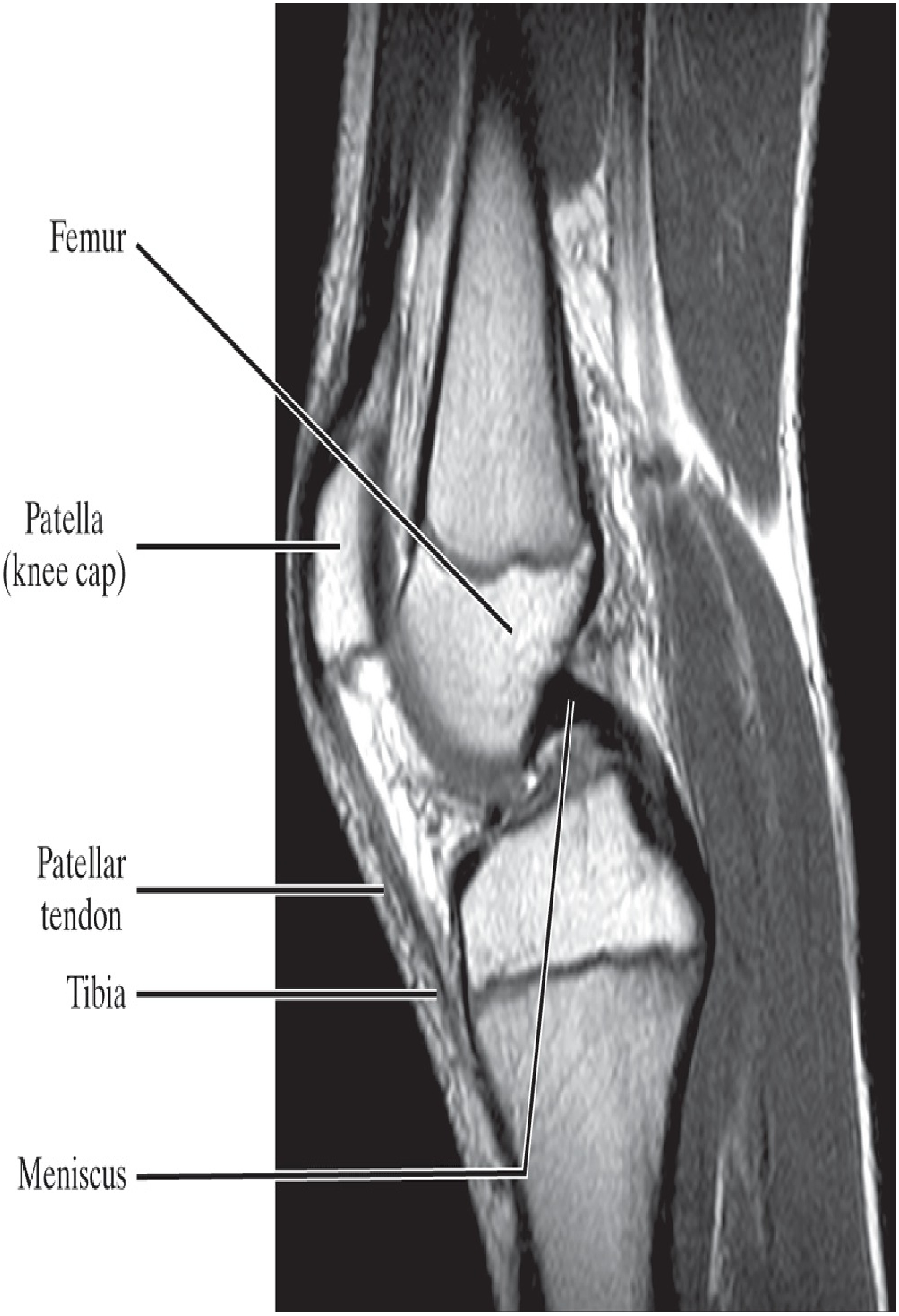
Computer systems use electric signals to process information ranging from word processing to mathematical computations. Systems range in size and power from simple calculators to personal computers to supercomputers that perform such complex tasks as processing weather data and modeling chemical interactions of complex organic molecules. These systems include networks of integrated circuits—miniature assemblies of hundreds, thousands, or millions of electrical components that often operate at speeds and power levels close to fundamental physical limits, including the speed of light and the thermodynamic laws.

Control systems use electric signals to regulate processes. Examples include the control of temperatures, pressures, and flow rates in an oil refinery; the fuel–air mixture in a fuel-injected automobile engine; mechanisms such as the motors, doors, and lights in elevators; and the locks in the Panama Canal. The autopilot and autolanding systems that help to fly and land airplanes are also familiar control systems.

Power systems generate and distribute electric power. Electric power, which is the foundation of our technology-based society, usually is generated in large quantities by nuclear, hydroelectric, solar, and thermal (coal-, oil-, or gas-fired) generators. Power is distributed by a grid of conductors that crisscross the country. A major challenge in designing and operating such a system is to provide sufficient redundancy and control so that failure of any piece of equipment does not leave a city, state, or region completely without power.

Signal-processing systems act on electric signals that represent information. They transform the signals and the information contained in them into a more suitable form. There are many different ways to process the signals and their information. For example, image-processing systems gather massive quantities of data from orbiting weather satellites, reduce the amount of data to a manageable level, and transform the remaining data into a video image for the evening news broadcast. A magnetic resonance imaging (MRI) scan is another example of an image-processing system. It takes signals generated by powerful magnetic fields and radio waves and transforms them into a detailed, three-dimensional image such as the one shown in Fig. 1.2, which can be used to diagnose disease and injury.

Figure 1.2 An MRI scan of an adult knee joint.


Femur
Patella
(knee cap)
Patellar
tendon
Tibia
Meniscus

Neil Borden/Science Source/Getty Images

Figure 1.2 Full Alternative Text

Considerable interaction takes place among the engineering disciplines involved in designing and operating these five classes of systems. Thus, communications engineers use digital computers to control the flow of information. Computers contain control systems, and control systems contain computers. Power systems require extensive communications systems to coordinate safely and reliably the operation of components, which may be spread across a continent. A signal-processing system may involve a communications link, a computer, and a control system.

A good example of the interaction among systems is a commercial airplane, such as the one shown in Fig. 1.3. A sophisticated communications system enables the pilot and the air traffic controller to monitor the plane's location, permitting the air traffic controller to design a safe flight path for all of the nearby aircraft and enabling the pilot to keep the plane on its designated path. An onboard computer system manages engine functions, implements the navigation and flight control systems, and generates video information screens in the cockpit. A complex control system uses cockpit commands to adjust the position and speed of the airplane, producing the appropriate signals to the engines and the control surfaces (such as the wing flaps, ailerons, and rudder) to ensure the plane remains safely airborne and on the desired flight path. The plane must have its own power system to stay aloft and to provide and distribute the electric power needed to keep the cabin lights on, make the coffee, and activate the entertainment system. Signal-processing systems reduce the noise in air traffic communications and transform information about the plane's location into the more meaningful form of a video display in the cockpit. Engineering challenges abound in the design of each of these systems and their integration into a coherent whole. For example, these systems must operate in widely varying and unpredictable environmental conditions. Perhaps the most important engineering challenge is to guarantee that sufficient redundancy is incorporated in the designs, ensuring that passengers arrive safely and on time at their desired destinations.

Figure 1.3 Interacting systems on a commercial aircraft.

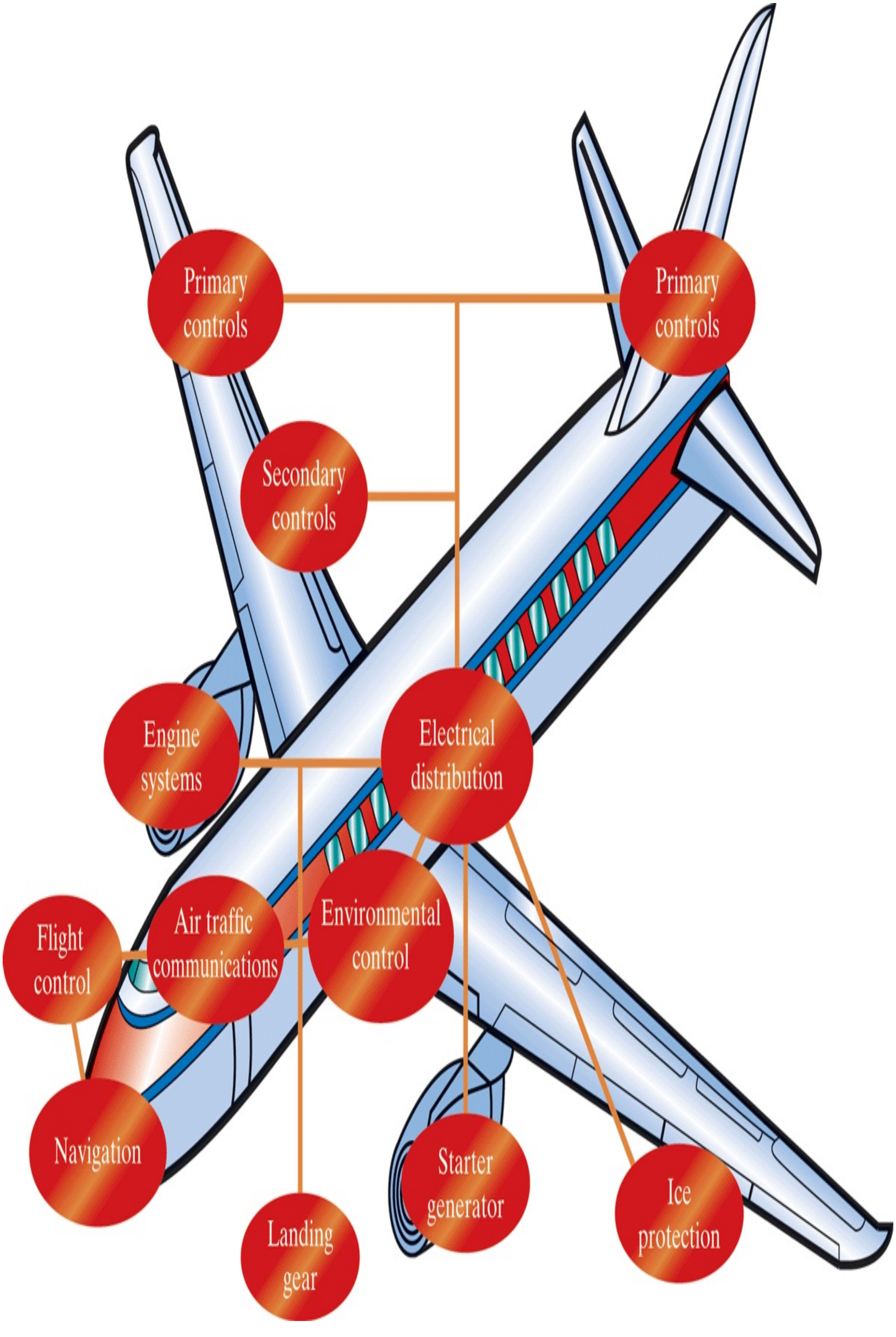

Primary controls
Primary controls
Secondary controls
Engine systems
Electrical distribution
Flight control
Air traffic communications
Environmental control
Navigation
Landing gear
Starter generator
Ice protection

Figure 1.3 Full Alternative Text

Although electrical engineers may be interested primarily in one area, they must also be knowledgeable in other areas that interact with this area of interest. This interaction is part of what makes electrical engineering a challenging and exciting profession. The emphasis in engineering is on making things work, so an engineer is free to acquire and use any technique from any field that helps to get the job done.

Circuit Theory

An **electric circuit** is a mathematical model that approximates the behavior of an actual electrical system. Since electric circuits are found in every branch of electrical engineering, they provide an important foundation for learning how to design and operate systems such as those just described. The models, the mathematical techniques, and the language of circuit theory will form the intellectual framework for your future engineering endeavors.

Note that the term *electric circuit* is commonly used to refer to an actual electrical system as well as to the model that represents it. In this text, when we talk about an electric circuit, we always mean a model, unless otherwise stated. It is the modeling aspect of circuit theory that has broad applications across engineering disciplines.

Circuit theory is a special case of electromagnetic field theory: the study of static and moving electric charges. But applying generalized field theory to the study of electric signals is cumbersome and requires advanced mathematics. Consequently, a course in electromagnetic field theory is not a prerequisite to understanding the material in this book. We do, however, assume that you have had an introductory physics course in which electrical and magnetic phenomena were discussed.

Three basic assumptions permit us to use circuit theory, rather than electromagnetic field theory, to study a physical system represented by an electric circuit.

1. Electrical effects happen instantaneously throughout a system. We can make this assumption because we know that electric signals travel at or near the speed of light. Thus, if the system is physically small, electric signals move through it so quickly that we can consider them to affect every point in the system simultaneously. A system that is small enough so that we can make this assumption is called a **lumped-parameter system**.

2. The net charge on every component in the system is always zero. Thus, no component can collect a net excess of charge, although some components, as you will learn later, can hold equal but opposite separated charges.

3. There is no magnetic coupling between the components in a system. As we demonstrate later, magnetic coupling can occur *within* a component.

That’s it; there are no other assumptions. Using circuit theory provides simple solutions (of sufficient accuracy) to problems that would become hopelessly complicated if we were to use electromagnetic field theory. These benefits are so great that engineers sometimes specifically design electrical systems to ensure that these assumptions are met. The importance of assumptions 2 and 3 becomes apparent after we introduce the basic circuit elements and the rules for analyzing interconnected elements.

Let’s take a closer look at assumption 1. The question is, “How small does a physical system have to be to qualify as a lumped-parameter system?” To get a quantitative answer to this question, remember that electric signals propagate as waves. If the wavelength of the signal is large compared to the physical dimensions of the system, we have a lumped-parameter system. The wavelength λ is the velocity divided by the repetition rate, or **frequency**, of the signal; that is, $\lambda=c/f$. The frequency f is measured in hertz (Hz). For example, power systems in the United States operate at 60 Hz. If we use the speed of light (c=3×108 m/s) as the velocity of propagation, the wavelength is 5×106 m. If the power system of interest is physically smaller than this wavelength, we can represent it as a lumped-parameter system and use circuit theory to analyze its behavior. How do we define *smaller*? A good rule is the *rule of 1/10th*: If the dimension of the system is less than 1/10th the dimension of the wavelength, you have a lumped-parameter system. Thus, as long as the physical dimension of the power system is less than 5×105 m (which is about 310 miles), we can treat it as a lumped-parameter system.

Now consider a communication system that sends and receives radio signals. The propagation frequency of radio signals is on the order of 109 Hz, so the wavelength is 0.3 m. Using the rule of 1N10th, a communication system qualifies as a lumped-parameter system if its dimension is less than 3 cm. Whenever any of the pertinent physical dimensions of a system under study approaches the wavelength of its signals, we must use electromagnetic field theory to analyze that system. Throughout this book we study circuits derived from lumped-parameter systems.

Problem Solving

As a practicing engineer, you will not be asked to solve problems that have already been solved. Whether you are improving the performance of an existing system or designing a new system, you will be working on unsolved problems. As a student, however, you will read and discuss problems with known solutions. Then, by solving related homework and exam problems on your own, you will begin to develop the skills needed to attack the unsolved problems you'll face as a practicing engineer.

Let's review several general problem-solving strategies. Many of these pertain to thinking about and organizing your solution strategy *before* proceeding with calculations.

1. Identify what's given and what's to be found. In problem solving, you need to know your destination before you can select a route for getting there. What is the problem asking you to solve or find? Sometimes the goal of the problem is obvious; other times you may need to paraphrase or make lists or tables of known and unknown information to see your objective.

   On one hand, the problem statement may contain extraneous information that you need to weed out before proceeding. On the other hand, it may offer incomplete information or more complexities than can be handled by the solution methods you know. In that case, you'll need to make assumptions to fill in the missing information or simplify the problem context. Be prepared to circle back and reconsider supposedly extraneous information and/or your assumptions if your calculations get bogged down or produce an answer that doesn't seem to make sense.

2. Sketch a circuit diagram or other visual model. Translating a verbal problem description into a visual model is often a useful step in the solution process. If a circuit diagram is already provided, you may need to add information to it, such as labels, values, or reference directions. You may also want to redraw the circuit in a simpler, but equivalent, form. Later in this text you will learn the methods for developing such simplified equivalent circuits.

3. Think of several solution methods and decide on a way of choosing among them. This course will help you build a collection of analytical tools, several of which may work on a given problem. But one method may produce fewer equations to be solved than another, or it may require only algebra instead of calculus to reach a solution. Such efficiencies, if you can anticipate them, can streamline your calculations considerably. Having an alternative method in mind also gives you a path to pursue if your first solution attempt bogs down.

4. Calculate a solution. Your planning up to this point should have helped you identify a good analytical method and the correct equations for the problem. Now comes the solution of those equations. Paper-and-pencil, calculator, and computer methods are all available for performing the actual calculations of circuit analysis. Efficiency and your instructor's preferences will dictate which tools you should use.

5. Use your creativity. If you suspect that your answer is off base or if the calculations seem to go on and on without moving you toward a solution, you should pause and consider alternatives. You may need to revisit your assumptions or select a different solution method. Or you may need to take a less conventional problem-solving approach, such as working backward from a solution. This text provides answers to all of the Assessment Problems and many of the Chapter Problems so that you may work backward when you get stuck. In the real world, you won't be

given answers in advance, but you may have a desired problem outcome in mind from which you can work backward. Other creative approaches include allowing yourself to see parallels with other types of problems you’ve successfully solved, following your intuition or hunches about how to proceed, and simply setting the problem aside temporarily and coming back to it later.

6. Test your solution. Ask yourself whether the solution you’ve obtained makes sense. Does the magnitude of the answer seem reasonable? Is the solution physically realizable? Are the units correct? You may want to rework the problem using an alternative method to validate your original answer and help you develop your intuition about the most efficient solution methods for various kinds of problems. In the real world, safety-critical designs are always checked by several independent means. Getting into the habit of checking your answers will benefit you both as a student and as a practicing engineer.

These problem-solving steps cannot be used as a recipe to solve every problem in this or any other course. You may need to skip, change the order of, or elaborate on certain steps to solve a particular problem. Use these steps as a guideline to develop a problem-solving style that works for you.

1.2 The International System of Units

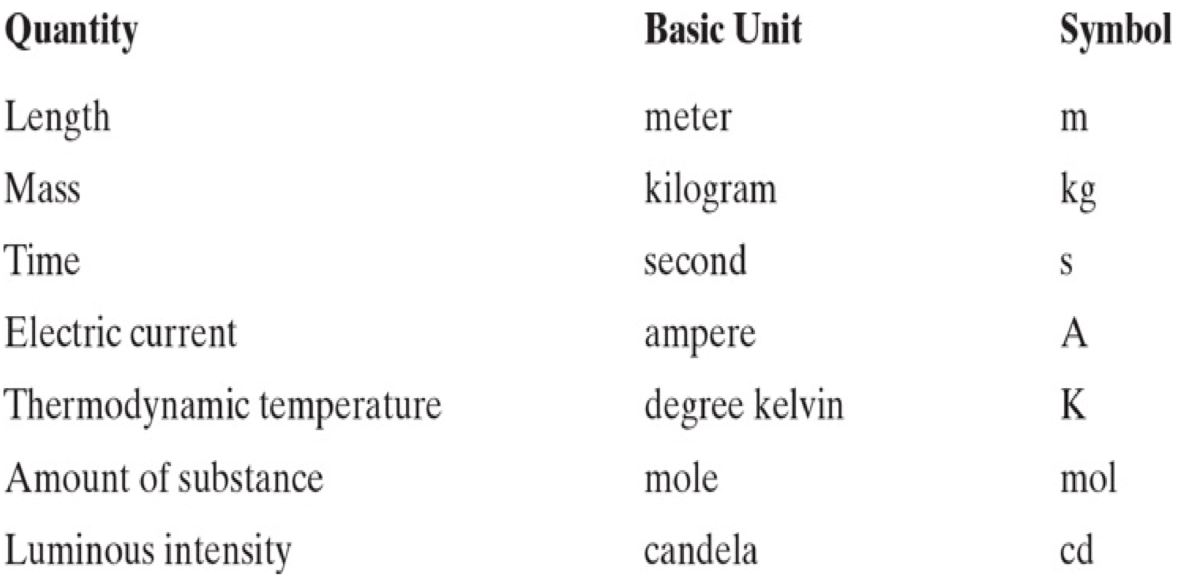
Engineers use quantitative measures to compare theoretical results to experimental results and compare competing engineering designs. Modern engineering is a multidisciplinary profession in which teams of engineers work together on projects, and they can communicate their results in a meaningful way only if they all use the same units of measure. The International System of Units (abbreviated SI) is used by all the major engineering societies and most engineers throughout the world; hence we use it in this book.

The SI units are based on seven *defined* quantities:

- length
- mass
- time
- electric current
- thermodynamic temperature
- amount of substance
- luminous intensity

These quantities, along with the basic unit and symbol for each, are listed in Table 1.1. Although not strictly SI units, the familiar time units of minute (60 s), hour (3600 s), and so on are often used in engineering calculations. In addition, defined quantities are combined to form **derived** units. Some quantities, such as force, energy, power, and electric charge, you already know through previous physics courses. Table 1.2 lists the derived units used in this book.

Table 1.1 The International System of Units (SI)

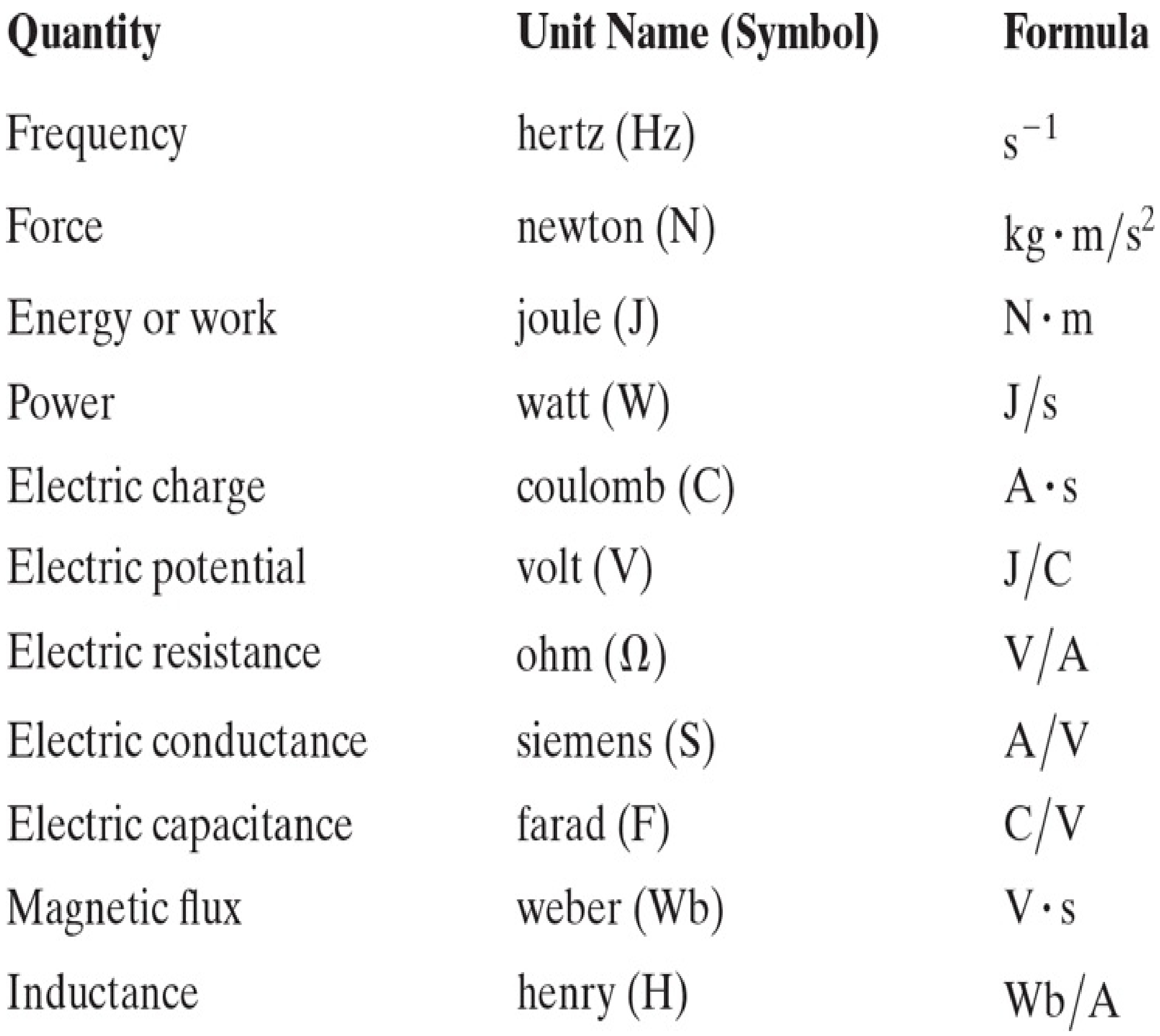


Quantity	Basic Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	degree kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

National Institute of Standards and Technology Special Publication 330, 2008 Edition, Natl. Inst. Stand. Technol. Spec. Pub. 330, 2008 Ed., 96 pages (March 2008)

Table 1.1 Full Alternative Text

Table 1.2 Derived Units in SI



Quantity	Unit Name (Symbol)	Formula
Frequency	hertz (Hz)	s^{-1}
Force	newton (N)	$kg \cdot m/s^2$
Energy or work	joule (J)	$N \cdot m$
Power	watt (W)	J/s
Electric charge	coulomb (C)	$A \cdot s$
Electric potential	volt (V)	J/C
Electric resistance	ohm (Ω)	V/A
Electric conductance	siemens (S)	A/V
Electric capacitance	farad (F)	C/V
Magnetic flux	weber (Wb)	$V \cdot s$
Inductance	henry (H)	Wb/A

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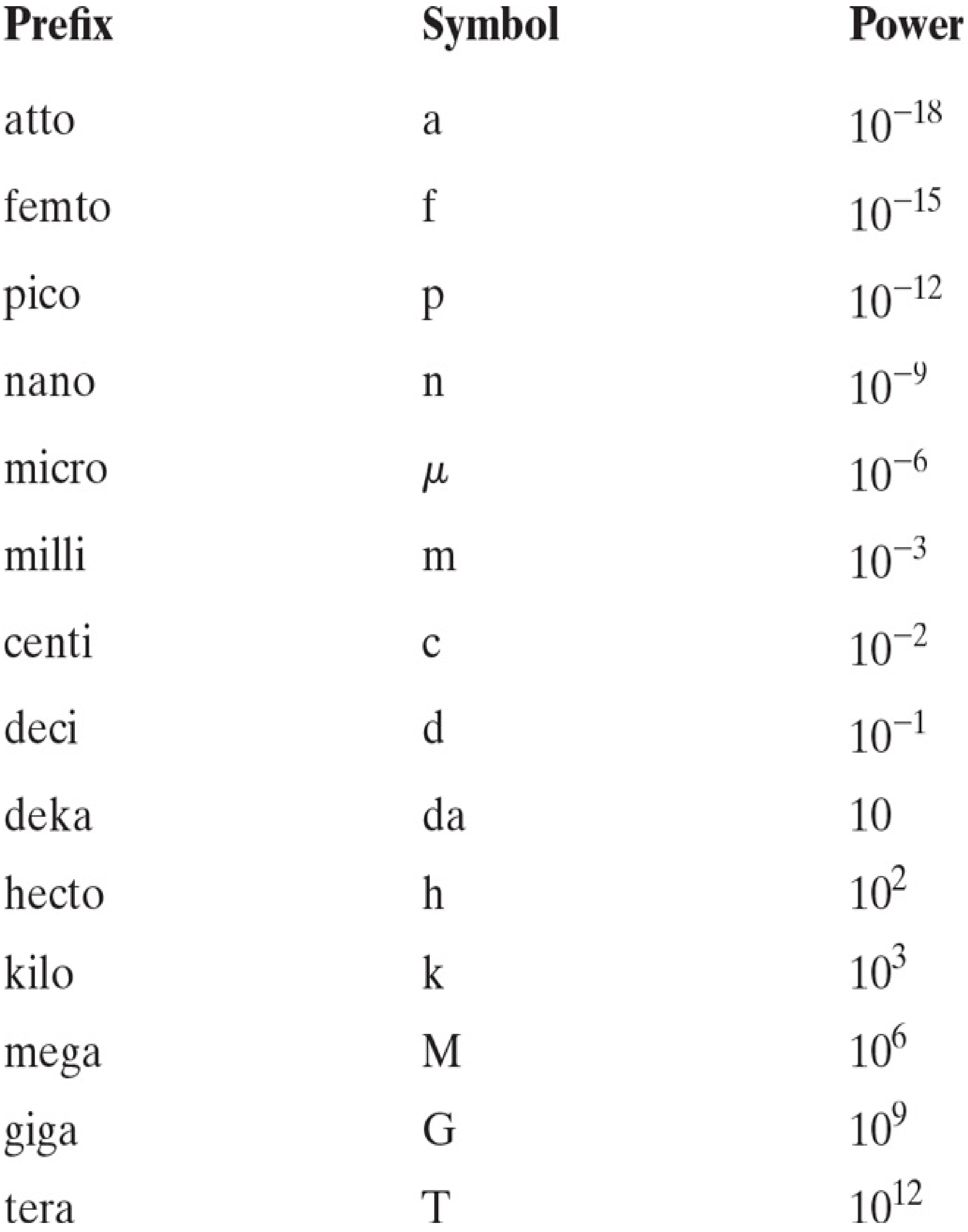
Table 1.2 Full Alternative Text

In many cases, the SI unit is either too small or too large to use conveniently. Standard prefixes corresponding to powers of 10, as listed in Table 1.3, are then applied to the basic unit. Engineers often use only the prefixes for powers divisible by 3; thus centi, deci, deka, and hecto are used rarely. Also, engineers often select the prefix that places the base number in the range between 1 and 1000. Suppose that a time calculation yields a result of 10−5 s, that is, 0.00001 s. Most engineers would describe this quantity as 10 μs, that is, 10−5=10×10−6 s, rather than as 0.01 ms or 10,000 ns.

Table 1.3 Standardized Prefixes to Signify Powers of 10



Prefix	Symbol	Power
atto	a	10^{-18}
femto	f	10^{-15}
pico	p	10^{-12}
nano	n	10^{-9}
micro	μ	10^{-6}
milli	m	10^{-3}
centi	c	10^{-2}
deci	d	10^{-1}
deka	da	10
hecto	h	10^{2}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}
tera	T	10^{12}

> National Institute of Standards and Technology Special Publication 330, 2008 Edition, Natl. Inst. Stand. Technol. Spec. Pub. 330, 2008 Ed., 96 pages (March 2008)

Table 1.3 Full Alternative Text

Example 1.1 illustrates a method for converting from one set of units to another and also uses power-of-10 prefixes.

Example 1.1 Using SI Units and Prefixes for Powers of 10

If a signal can travel in a cable at 80% of the speed of light, what length of cable, in inches, represents 1 ns?

Solution

First, note that 1 ns=10−9 s. Also, recall that the speed of light c=3×108 m/s. Then, 80% of the speed of light is 0.8c=(0.8)(3×108)=2.4×108 m/s. Using a product of ratios, we can convert 80% of the speed of light from meters per second to inches per nanosecond. The result is the distance in inches traveled in 1 nanosecond:

2.4× 10 8 meters 1 second · 1 second 10 9 nanoseconds · 100 centimeters 1 meter · 1 inch 2.54 centimeters =9.45 inches/nanosecond.

Therefore, a signal traveling at 80% of the speed of light will cover 9.45 inches of cable in 1 nanosecond.

Assessment Problems

Objective 1—Understand and be able to use SI units and the standard

prefixes for powers of 10

1. 1.1 Assume a telephone signal travels through a cable at two-thirds the speed of light. How long does it take the signal to get from New York City to Miami if the distance is approximately 1100 miles?

   Answer: 8.85 ms.

2. 1.2 How many dollars per millisecond would the federal government have to collect to retire a deficit of $100 billion in one year?

   Answer: $3.17/ms.

SELF-CHECK: Also try Chapter Problems 1.2, 1.3, and 1.6.

1.3 Circuit Analysis: An Overview

We look broadly at engineering design, specifically the design of electric circuits, before becoming involved in the details of circuit analysis. This overview provides you with a perspective on where circuit analysis fits within the whole of circuit design. Even though this book focuses on circuit analysis, we try to provide opportunities for circuit design where appropriate.

All engineering designs begin with a need 1, as shown in Fig. 1.4. This need may come from the desire to improve on an existing design, or it may be something brand new. A careful assessment of the need results in design specifications, which are measurable characteristics of a proposed design. Once a design is proposed, the design specifications 2 allow us to assess whether or not the design actually meets the need.

Figure 1.4 A conceptual model for electrical engineering design.

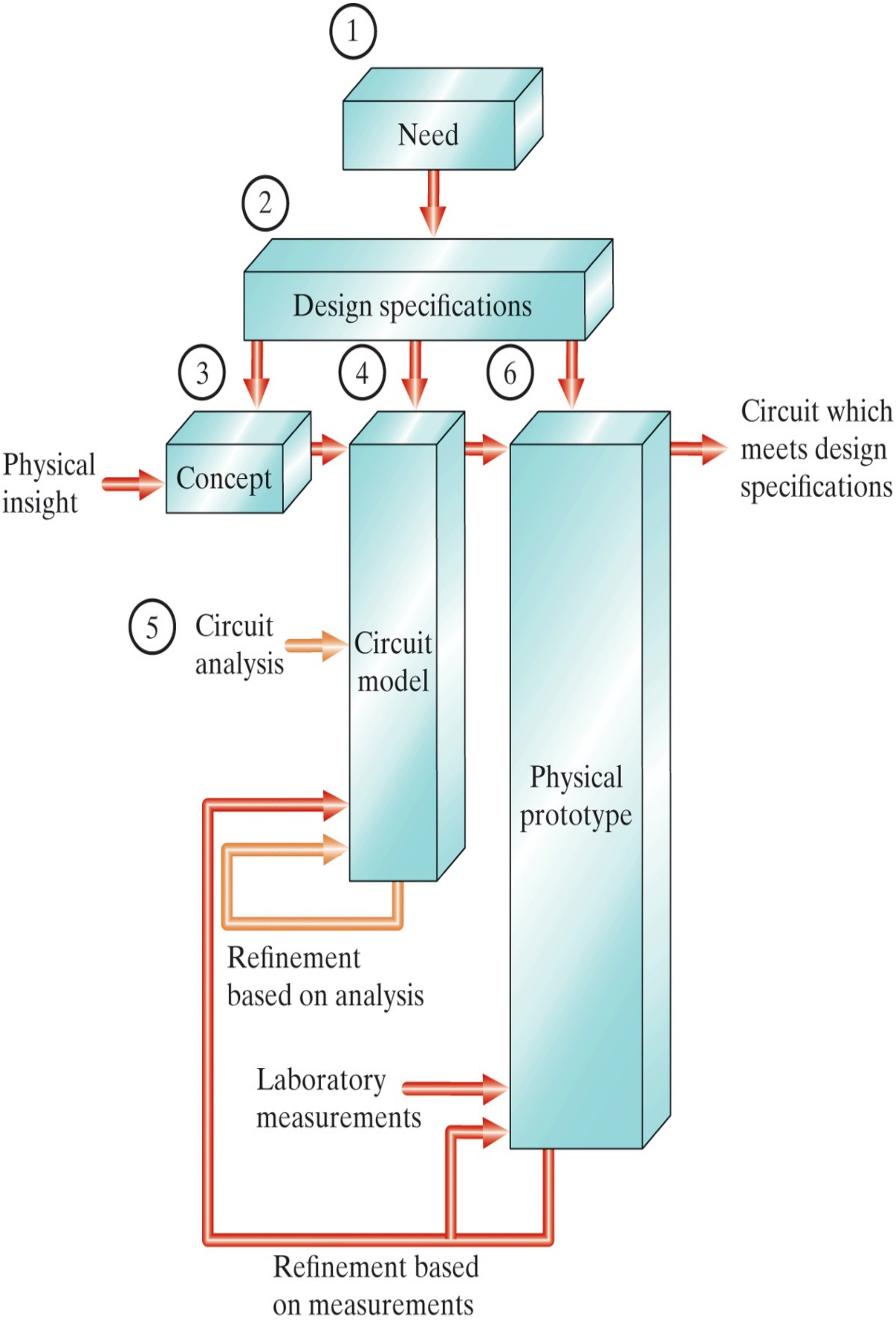

①
Need
②
Design specifications
③
④
⑥
Physical insight
Concept
Circuit model
Physical prototype
Circuit which meets design specifications
⑤
Circuit analysis
Refinement based on analysis
Laboratory measurements
Refinement based on measurements

Figure 1.4 Full Alternative Text

A concept 3 for the design comes next. The concept derives from a complete understanding of the design specifications coupled with an insight into the need, which comes from education and experience. The concept may be realized as a sketch, as a written description, or as some other form. Often the next step is to translate the concept into a mathematical model. A commonly used mathematical model for electrical systems is a circuit model 4.

The elements that make up the circuit model are called ideal circuit components. An **ideal circuit component** is a mathematical model of an actual electrical component, like a battery or a light bulb. The ideal circuit components used in a circuit model should represent the behavior of the actual electrical components to an acceptable degree of accuracy. The tools of circuit analysis 5, the focus of this book, are then applied to the circuit. **Circuit analysis** uses mathematical techniques to predict the behavior of the circuit model and its ideal circuit components. A comparison between the desired behavior, from the design specifications, and the predicted behavior, from circuit analysis, may lead to refinements in the circuit model and its ideal circuit elements. Once the desired and predicted behaviors are in agreement, a physical prototype 6 can be constructed.

The **physical prototype** is an actual electrical system, constructed from actual electrical components. Measurements determine the quantitative behavior of the physical system. This actual behavior is compared with the desired behavior from the design specifications and the predicted behavior from circuit analysis. The comparisons may result in refinements to the physical prototype, the circuit model, or both. This iterative process, in which models, components, and systems are continually refined, usually produces a design that accurately satisfies the design specifications and thus meets the need.

Circuit analysis clearly plays a very important role in the design process. Because circuit analysis is applied to circuit models, practicing engineers try to use mature circuit models so that the resulting designs will meet the design specifications in the first iteration. In this book, we use models that have been tested for at least 40 years; you can assume that they are mature. The ability to model actual electrical systems with ideal circuit elements makes circuit theory extremely useful to engineers.

Saying that the interconnection of ideal circuit elements can be used to quantitatively predict the behavior of a system implies that we can describe the interconnection with mathematical equations. For the mathematical equations to be useful, we must write them in terms of measurable quantities. In the case of circuits, these quantities are voltage and current, which we discuss in Section 1.4. The study of circuit analysis involves understanding the behavior of each ideal circuit element in terms of its voltage and current and understanding the constraints imposed on the voltage and current as a result of interconnecting the ideal elements.

1.4 Voltage and Current

The concept of electric charge is the basis for describing all electrical phenomena. Let’s review some important characteristics of electric charge.

- Electric charge is bipolar, meaning that electrical effects are described in terms of positive and negative charges.
- Electric charge exists in discrete quantities, which are integer multiples of the electronic charge, 1.6022×10−19 C.
- Electrical effects are attributed to both the separation of charge and charges in motion.

In circuit theory, the separation of charge creates an electric force (voltage), and the motion of charge creates an electric fluid (current).

The concepts of voltage and current are useful from an engineering point of view because they can be expressed quantitatively. Whenever positive and negative charges are separated, energy is expended. **Voltage** is the energy per unit charge created by the separation. We express this ratio in differential form as

Definition of Voltage

v=dwdq, (1.1)

where

v=the voltage in volts,w=the energy in joules,q=the charge in coulombs.

The electrical effects caused by charges in motion depend on the rate of charge flow. The rate of charge flow is known as the **electric current**, which is expressed as

Definition of Current

$i=dqdt$, (1.2)

where

i=the current in amperes,q=the charge in coulombs,t=the time in seconds.

Equations 1.1 and 1.2 define the magnitude of voltage and current, respectively. The bipolar nature of electric charge requires that we assign polarity references to these variables. We will do so in Section 1.5.

Although current is made up of discrete moving electrons, we do not need to consider them individually because of the enormous number of them. Rather, we can think of electrons and their corresponding charge as one smoothly flowing entity. Thus, i is treated as a continuous variable.

One advantage of using *circuit models* is that we can model a component strictly in terms of the voltage and current at its terminals. Thus, two physically different components could have the same relationship between the terminal voltage and terminal current. If they do, for purposes of circuit analysis, they are identical. Once we know how a component behaves at its terminals, we can analyze its behavior in a circuit. However, when developing *component models,* we are interested in a component’s internal behavior. We might want to know, for example, whether charge conduction is taking place because of free electrons moving through the crystal lattice structure of a metal or whether it is because of electrons moving within the covalent bonds of a semiconductor material. These concerns are beyond the realm of circuit theory, so in this book we use component models that have already been developed.

1.5 The Ideal Basic Circuit Element

An **ideal basic circuit element** has three attributes.

1. It has only two terminals, which are points of connection to other circuit components.
2. It is described mathematically in terms of current and/or voltage.
3. It cannot be subdivided into other elements.

Using the word *ideal* implies that a basic circuit element does not exist as a realizable physical component. Ideal elements can be connected in order to model actual devices and systems, as we discussed in Section 1.3. Using the word *basic* implies that the circuit element cannot be further reduced or subdivided into other elements. Thus, the basic circuit elements form the building blocks for constructing circuit models, but they themselves cannot be modeled with any other type of element.

Figure 1.5 represents an ideal basic circuit element. The box is blank because we are making no commitment at this time as to the type of circuit element it is. In Fig. 1.5, the voltage across the terminals of the box is denoted by v, and the current in the circuit element is denoted by i. The plus and minus signs indicate the polarity reference for the voltage, and the arrow placed alongside the current indicates its reference direction. Table 1.4 interprets the voltage polarity and current direction, given positive or negative numerical values of v and i. Note that algebraically the notion of positive charge flowing in one direction is equivalent to the notion of negative charge flowing in the opposite direction.

Figure 1.5 An ideal basic circuit element.