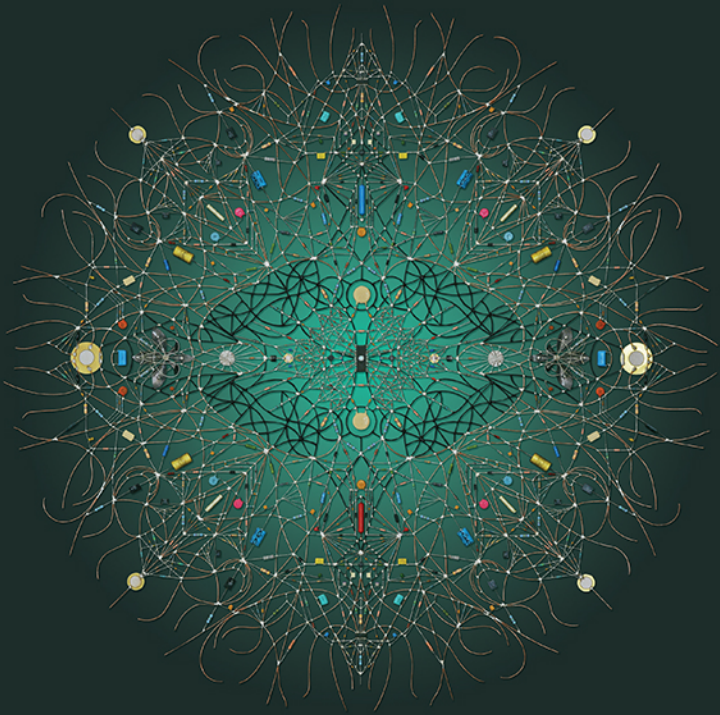
# ELECTRIC CIRCUITS



NILSSON • RIEDEL

12th Edition

# ELECTRIC CIRCUITS

TWELFTH EDITION

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# ELECTRIC CIRCUITS

TWELFTH EDITION

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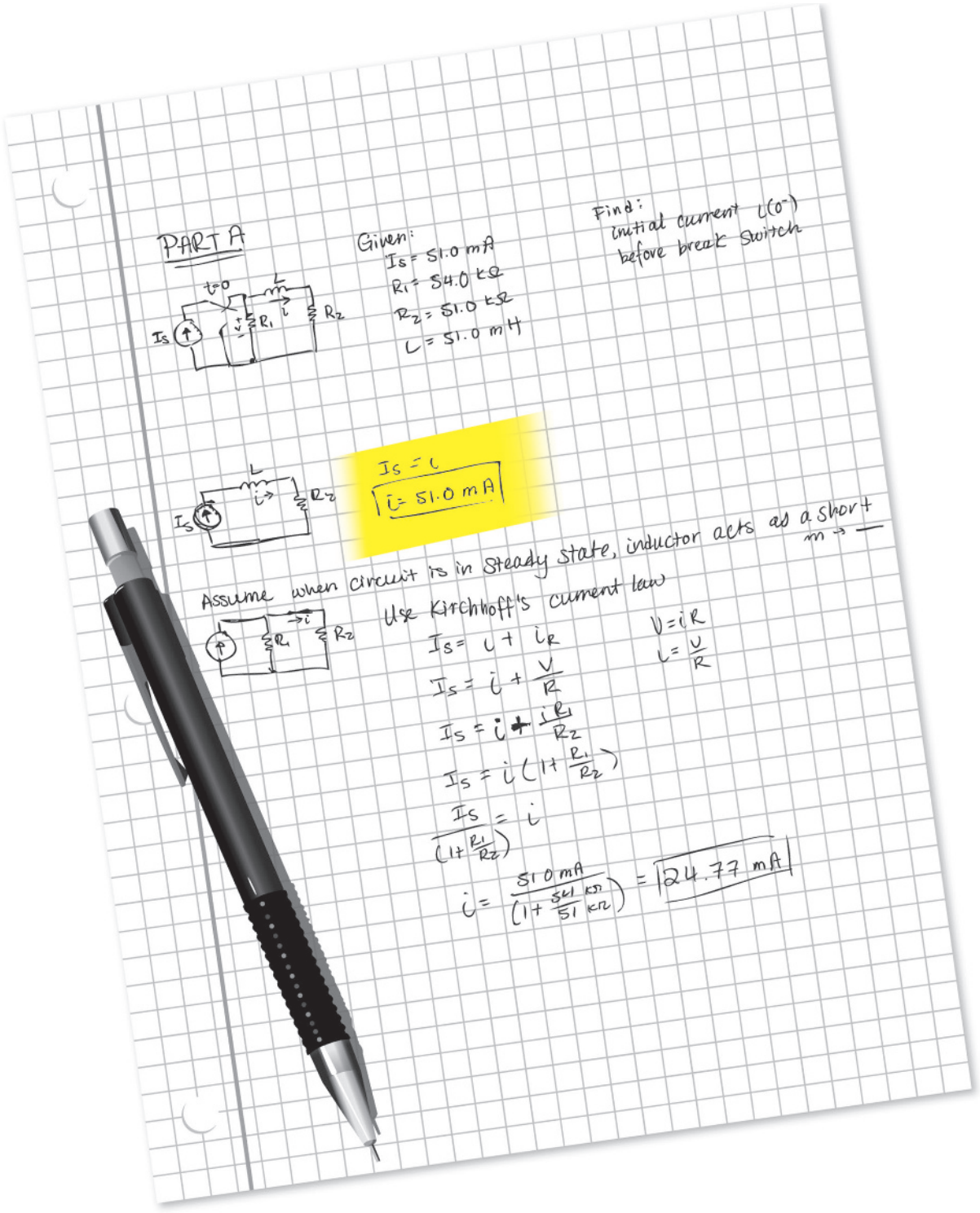

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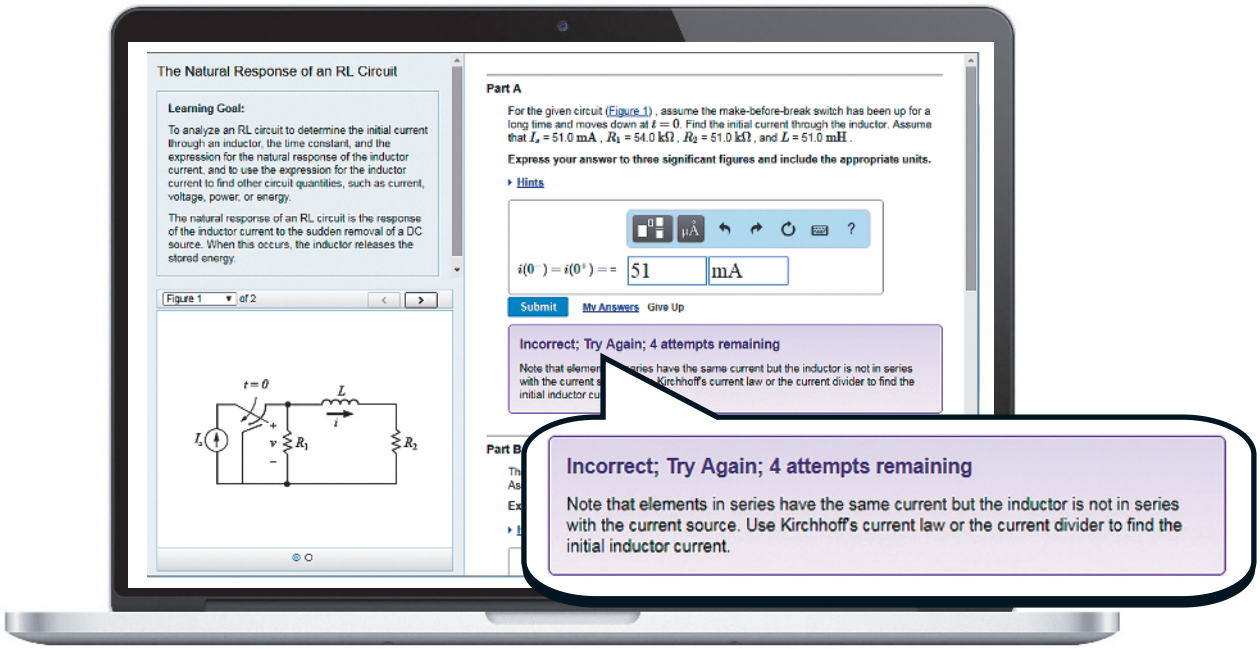


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# Preface

The Twelfth Edition of *Electric Circuits* represents a planned, incremental revision focusing on the Assessment Problems and the end-of-chapter Problems. 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 Twelfth Edition of *Electric Circuits* incorporates the following new and revised elements:

- 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, nearly all of the existing existing end-of-chapter problems were revised, and some new end-of-chapter problems were added. The only problems that were not altered are those asking you to derive or prove a particular result.
- Assessment Problems—After most subsections in a chapter, one or two assessment problems give you a chance to reflect on the new material and apply it to solve a problem. Every assessment problem is new to the Twelfth Edition and comes with answers to all parts of the problem posed. Many of the assessment problems have interactive video solutions available in Mastering, which guide you through the solution and ask you to participate in the problem-solving process.
- 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 Twelfth 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.
- We have eliminated the Selected Answers appendix that has appeared in previous editions. Some instructors may not wish to assign problems whose solutions are readily available to students at the back of the text. Since instructors have the complete solutions available to them, they are free to supply answers to select problems they assign if they wish. Providing the reader with answers to problems discourages them from checking their own answers using an alternate analysis technique or comparing their answers to known circuit behavior.

# 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. These directions are compiled into a collection of analysis methods, and many of the examples in the text use these analysis methods. Some of the analysis methods that are used most often can be found inside the book's covers for easy reference.

## Chapter Problems

Users of *Electric Circuits* have consistently praised the breadth, depth, variety, and sheer number of Chapter Problems. In the Twelfth Edition, there are nearly 1200 end-of-chapter problems, organized at the end of each chapter by section.

## Practical Perspectives

The Twelfth 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. End-of-chapter problems directly related to the Practical Perspective application are identified for easy reference. 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 the assessment problems are given at the conclusion of each problem, so you can check your work. If you can solve the assessment problems for a given objective, you have mastered that objective. The Student Study area of Mastering includes interactive video solutions for many of the assessment problems. If you want 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 numeric examples illustrating the concepts presented in the text. There are nearly 200 examples in this text that apply a particular concept, often employ an Analysis Method, and exemplify good problem-solving skills.

## Checking the Results of Analysis

You are encouraged to check analysis results to verify that they make sense. There are many different ways to check results and examples of these checks are included throughout the text, the assessment problems, and the end-of-chapter problems. Don't rely on comparing your results with some known answer, and instead check your own answer by solving the problem in a different way or comparing your answer with known circuit behavior.

## 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 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 Twelfth 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 Twelfth Edition emphasizes 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 discussing 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, identifying problems suited to PSpice or Multisim exploration suggests design opportunities using these software tools. Fourth, some problems in nearly every chapter ask you to choose realistic circuit component values in achieving a desired circuit design. Once such a problem has been analyzed, the student can build and test the circuit in a laboratory, comparing the analysis with the measured performance of the actual circuit.

### Accuracy

All text and problems in the Twelfth 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.pearson.com/mastering/engineering for more information.

**Learning Catalytics**—Learning Catalytics is an interactive student response tool that encourages team-based learning by using students' 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 students. The Student Workbook is available in Mastering.

**Introduction to Multisim and Introduction to PSpice Manuals**—There are several powerful circuit simulators available free or at low cost to students. Circuit simulation is an excellent tool for exploring a circuit in depth and for visualizing the behavior of a circuit. The Multisim and PSpice manuals introduce these two popular simulators using examples tied directly to the main text. These manuals are available in Mastering.

# 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.

**Mastering Engineering**—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 from a library available in the system. For more information visit www.learningcatalytics.com or click on the Learning Catalytics link inside Mastering Engineering.

**Introduction to Multisim and Introduction to PSpice Manuals**—These manuals, available in Mastering, are excellent resources for those wishing to integrate PSpice or Multisim into their classes.

# 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.

## Acknowledgments

Jim Nilsson has my eternal gratitude for inviting me to collaborate with him on this textbook. I learned so much from him about teaching and writing and hard work. It is a gift to be associated with him through this textbook, and to impact the education of the thousands of students who use this text.

The Eleventh Edition was a year-long undertaking to examine every word, sentence, paragraph, and chapter of this text to streamline, clarify, and modernize the writing and the presentation. Much to my horror, I forgot to thank the incredible Matt Walker, who served as the developmental editor on that project and made countless suggestions for improving both the content and the design. He was a great collaborator and I'm so very sorry for failing to catch this error before the Eleventh Edition was published.

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 Twelfth Edition. A special shout-out to the amazing Rose Kernan, who has helped guide these revisions since the Seventh Edition, which first appeared in 2005. Rose is so easy to work with, does her very best to keep me on top of the production schedule, and is an endless source of encouragement. I would also like to thank Erin Ault, Erin Sullivan, Holly Stark, Sandra Rodriguez, and Scott Disanno at Pearson for their continued support, encouragement, and hard work. I thank the staff at Integra Software Solutions for their dedication and attention to detail 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 that I failed to catch in the review process. Thank you for taking the time to contact Pearson or me with your comments and suggestions. I use as many of them 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*

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# ELECTRIC CIRCUITS

TWELFTH EDITION

CHAPTER

# 1

# Circuit Variables

## CHAPTER CONTENTS


1.1 **Electrical Engineering: An Overview** *p. 4*
1.2 **The International System of Units** *p. 9*
1.3 **Circuit Analysis: An Overview** *p. 11*
1.4 **Voltage and Current** *p. 12*
1.5 **The Ideal Basic Circuit Element** *p. 14*
1.6 **Power and Energy** *p. 15*


## 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 this chapter 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.

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.

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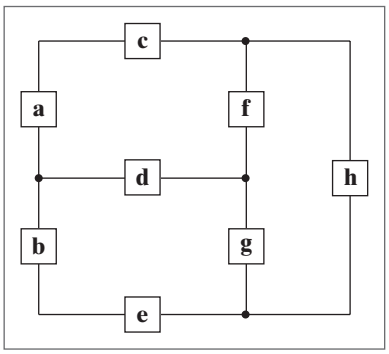

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## 1.1 Electrical Engineering: An Overview

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

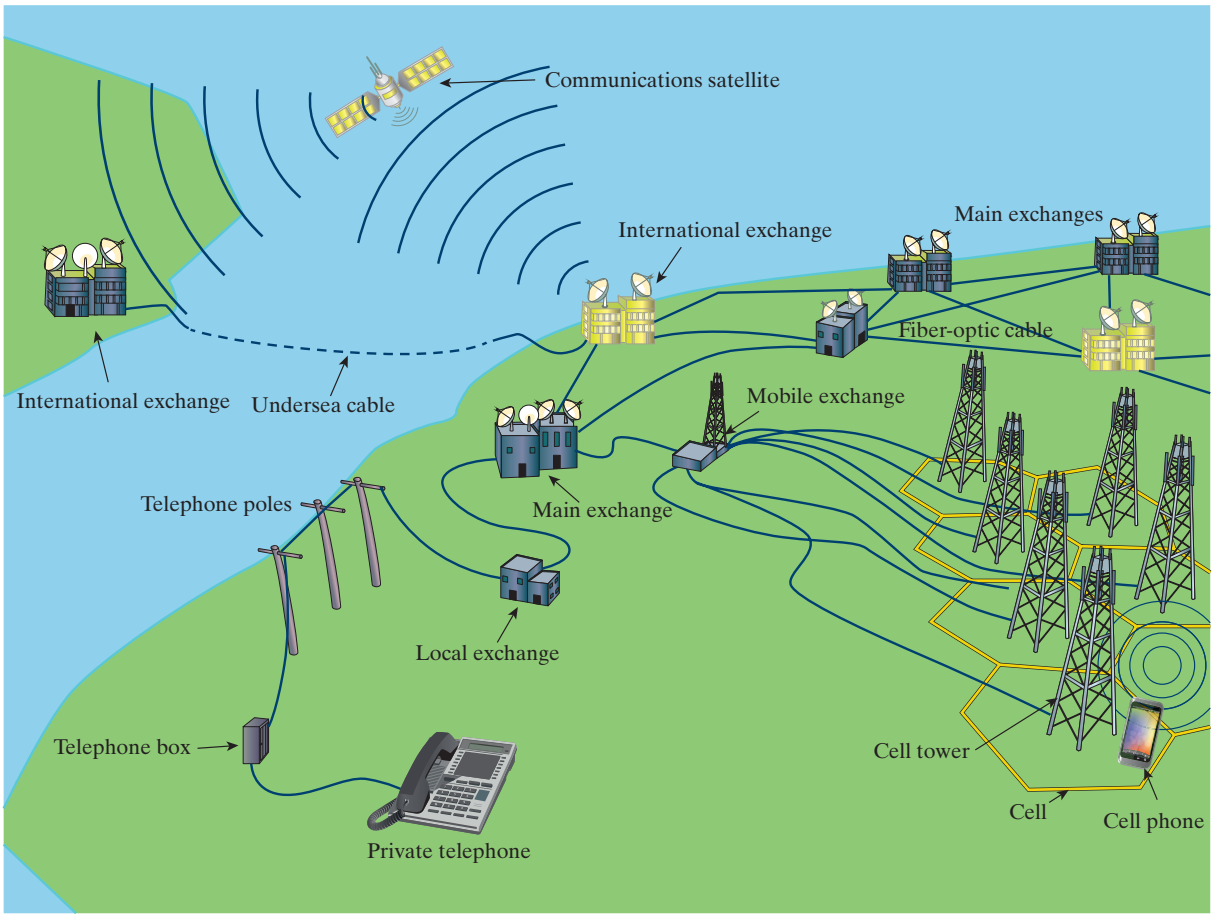


**Figure 1.1** ▲ A telephone system.

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.

**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.

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

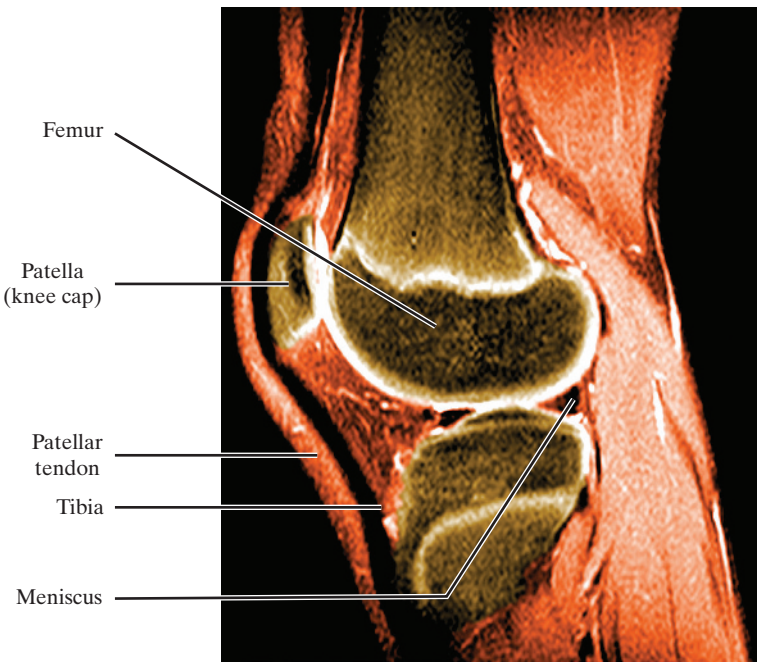


**Figure 1.2** ▲ An MRI scan of an adult knee joint.
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coordinate safely and reliably the operation of components, which may be spread across a continent. A signal-processing system may involve a communications link, a computer, and a control system.

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.

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.

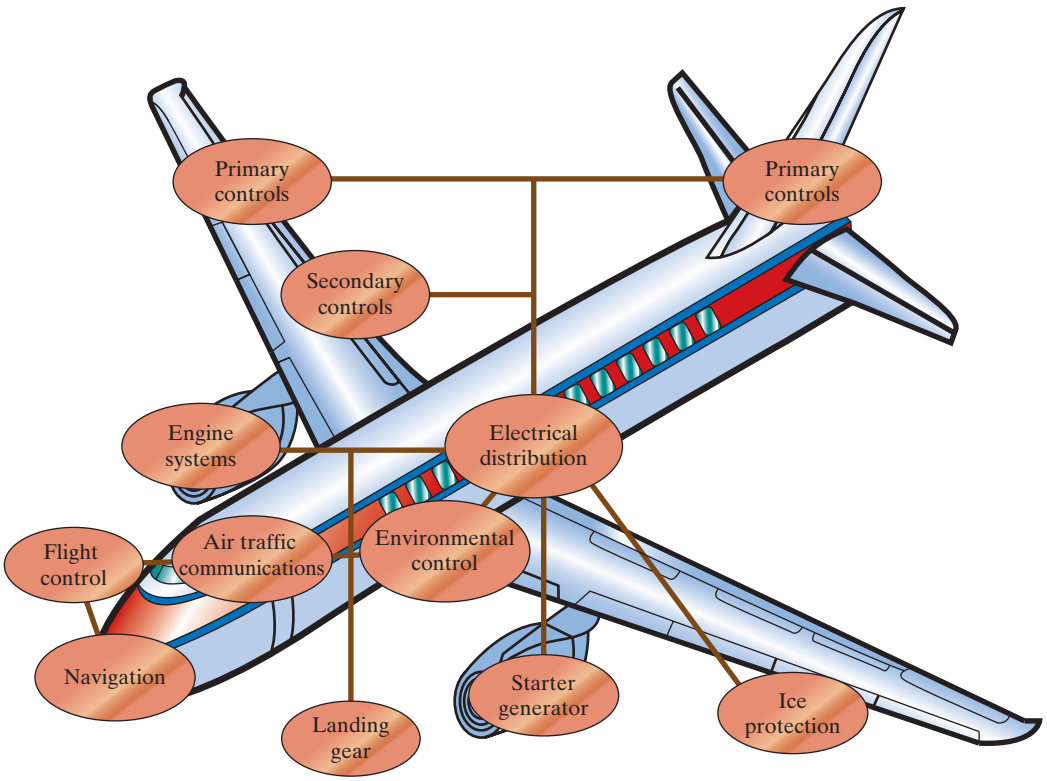


**Figure 1.3 ▲** Interacting systems on a commercial aircraft.

## 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 text. 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 $\lambda$ 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 ($c = 3 \times 10^8$ m/s) as the velocity of propagation, the wavelength is $5 \times 10^6$ 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 $5 \times 10^5$ 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 $10^9$ Hz, so the wavelength is 0.3 m. Using the rule of 1/10th, 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 text 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 text.

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