

SIXTH EDITION

# Electrical Engineering

PRINCIPLES and APPLICATIONS

Allan R. Hambley



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# Electrical Engineering

## Principles and Applications

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# Electrical Engineering

## Principles and Applications

SIXTH EDITION

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To Judy, Tony, Pam, and Mason



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# Preface

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As in the previous editions, my guiding philosophy in writing this book has three elements. The first element is my belief that in the long run students are best served by learning basic concepts in a general setting. Second, I believe that students need to be motivated by seeing how the principles apply to specific and interesting problems in their own fields. The third element of my philosophy is to take every opportunity to make learning free of frustration for the student.

This book covers circuit analysis, digital systems, electronics, and electromechanics at a level appropriate for either electrical-engineering students in an introductory course or nonmajors in a survey course. The only essential prerequisites are basic physics and single-variable calculus. Teaching a course using this book offers opportunities to develop theoretical and experimental skills and experiences in the following areas:

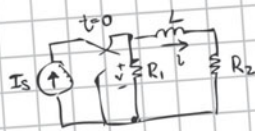
- Basic circuit analysis and measurement
- First- and second-order transients
- Steady-state ac circuits
- Resonance and frequency response
- Digital logic circuits
- Microcontrollers
- Computer-based instrumentation, including LabVIEW
- Diode circuits
- Electronic amplifiers
- Field-effect and bipolar junction transistors
- Operational amplifiers
- Transformers
- Ac and dc machines
- Computer-aided circuit analysis using MATLAB

While the emphasis of this book is on basic concepts, a key feature is the inclusion of short articles scattered throughout showing how electrical-engineering concepts are applied in other fields. The subjects of these articles include anti-knock signal processing for internal combustion engines, a cardiac pacemaker, active noise control, and the use of RFID tags in fisheries research, among others.

I welcome comments from users of this book. Information on how the book could be improved is especially valuable and will be taken to heart in future revisions. My e-mail address is [arhamble@mtu.edu](mailto:arhamble@mtu.edu)

# your work...

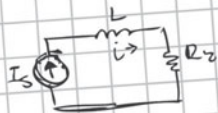
## PART A



Given:

$$I_s = 51.0 \text{ mA}$$
$$R_1 = 54.0 \text{ k}\Omega$$
$$R_2 = 51.0 \text{ k}\Omega$$
$$L = 51.0 \text{ mH}$$

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



$$I_s = i$$
$$i = 51.0 \text{ mA}$$

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



Use Kirchhoff's current law

$$I_s = i + i_R \quad V = iR$$

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

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

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

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

$$i = \frac{51.0 \text{ mA}}{\left( 1 + \frac{54.0 \text{ k}\Omega}{51.0 \text{ k}\Omega} \right)} = 24.77 \text{ mA}$$

# your answer **specific feedback**

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

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

**Submit**

[Hints](#)

[My Answers](#)

[Give Up](#)

[Review Part](#)

**Try Again; 5 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.

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

**Submit**

[Hints](#)

[My Answers](#)

[Give Up](#)

[Review Part](#)

**Try Again; 4 attempts remaining**

It appears you have found the current through the resistor,  $R_1$ . Find the current through the resistor in series with the inductor.



## ON-LINE STUDENT RESOURCES

- **MasteringEngineering.** Tutorial homework problems emulate the instructor's office-hour environment, guiding students through engineering concepts with self-paced individualized coaching. These in-depth tutorial homework problems are designed to coach students with feedback specific to their errors and optional hints that break problems down into simpler steps. Access can be purchased bundled with the textbook or online at [www.masteringengineering.com](http://www.masteringengineering.com).
- **The Companion Website.** Access is included with the purchase of every new book or can be purchased at [www.pearsonhighered.com/hambley](http://www.pearsonhighered.com/hambley) The Companion Website includes:
  - Pearson eText, which is a complete on-line version of the book that includes highlighting, note-taking, and search capabilities.
  - Video Solutions that provide complete, step-by-step solution walkthroughs of representative homework problems from each chapter.
  - A Student Solutions Manual. A PDF file for each chapter includes full solutions for the in-chapter exercises, answers for the end-of-chapter problems that are marked with asterisks, and full solutions for the Practice Tests.
  - A MATLAB folder that contains the m-files discussed in the book.
  - A Multisim folder that contains tutorials on the basic features of Multisim and circuit simulations for a wide variety of circuits from the book.
  - A Virtual Instruments folder, which contains the LabVIEW programs discussed in Section 9.4.

## INSTRUCTOR RESOURCES

Resources for instructors include:

- **MasteringEngineering.** This online Tutorial Homework program allows you to integrate dynamic homework with automatic 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.
- A complete Instructor's Solutions Manual
- PowerPoint slides with all the figures from the book

Instructor Resources are available for download by adopters of this book at the Pearson Higher Education website: [www.pearsonhighered.com](http://www.pearsonhighered.com). If you are in need of a login and password, please contact your local Pearson representative.

## WHAT'S NEW IN THIS EDITION

- We have continued the popular Practice Tests that students can use in preparing for course exams at the end of each chapter. Answers for the Practice Tests appear in Appendix D and complete solutions are included in the on-line Student Solutions Manual files.

- We have updated the coverage of MATLAB and the Symbolic Toolbox for network analysis in Chapters 2 through 6.
- Approximately 200 problems are new to this edition, replacing some of the problems from the previous edition, and many other problems have been modified.
- In Chapter 2, we have added an explanation of how the Wheatstone bridge is used in strain measurements.
- Sections 3.8 and 4.6 have been updated, deleting the coverage of piecewise linear functions which are problematic with recent versions of the Symbolic Toolbox.
- Chapter 8 has been extensively updated and now uses the Freescale Semiconductor HCS12/9S12 family as an example of microcontrollers.
- Section 9.4 has been updated to the most recent version of LabVIEW.
- Relatively minor corrections and improvements appear throughout the book.

## PREREQUISITES

The essential prerequisites for a course from this book are basic physics and single-variable calculus. A prior differential equations course would be helpful but is not essential. Differential equations are encountered in Chapter 4 on transient analysis, but the skills needed are developed from basic calculus.

## PEDAGOGICAL FEATURES

The book includes various pedagogical features designed with the goal of stimulating student interest, eliminating frustration, and engendering an awareness of the relevance of the material to their chosen profession. These features are:

- Statements of learning objectives open each chapter.
- Comments in the margins emphasize and summarize important points or indicate common pitfalls that students need to avoid.
- Short boxed articles demonstrate how electrical-engineering principles are applied in other fields of engineering. For example, see the articles on active noise cancellation (page 287) and electronic pacemakers (starting on page 385).
- Step-by-step problem solving procedures. For example, see the step-by-step summary of node-voltage analysis (on pages 76–77) or the summary of Thévenin equivalents (on page 95).
- A Practice Test at the end of each chapter gives students a chance to test their knowledge. Answers appear in Appendix D.
- Complete solutions to the in-chapter exercises and Practice Tests, included as PDF files on-line, build student confidence and indicate where additional study is needed.
- Summaries of important points at the end of each chapter provide references for students.
- Key equations are highlighted in the book to draw attention to important results.

## MEETING ABET-DIRECTED OUTCOMES

Courses based on this book provide excellent opportunities to meet many of the directed outcomes for accreditation. The Criteria for Accrediting Engineering Programs require that graduates of accredited programs have “an ability to apply knowledge of mathematics, science, and engineering” and “an ability to identify, formulate, and solve engineering problems.” This book, in its entirety, is aimed at developing these abilities.

Also, graduates must have “an ability to design and conduct experiments, as well as analyze and interpret data.” Chapter 9, Computer-Based Instrumentation Systems, helps to develop this ability. If the course includes a laboratory, this ability can be developed even further.

Furthermore, the criteria require “an ability to function on multi-disciplinary teams” and “an ability to communicate effectively.” Courses based on this book contribute to these abilities by giving nonmajors the knowledge and vocabulary to communicate effectively with electrical engineers. The book also helps to inform electrical engineers about applications in other fields of engineering. To aid in communication skills, end-of-chapter problems that ask students to explain electrical-engineering concepts in their own words are included.

## CONTENT AND ORGANIZATION

### Basic Circuit Analysis

Chapter 1 defines current, voltage, power, and energy. Kirchhoff’s laws are introduced. Voltage sources, current sources, and resistance are defined.

Chapter 2 treats resistive circuits. Analysis by network reduction, node voltages, and mesh currents is covered. Thévenin equivalents, superposition, and the Wheatstone bridge are treated.

Capacitance, inductance, and mutual inductance are treated in Chapter 3.

Transients in electrical circuits are discussed in Chapter 4. First-order  $RL$  and  $RC$  circuits and time constants are covered, followed by a discussion of second-order circuits.

Chapter 5 considers sinusoidal steady-state circuit behavior. (A review of complex arithmetic is included in Appendix A.) Power calculations, ac Thévenin and Norton equivalents, and balanced three-phase circuits are treated.

Chapter 6 covers frequency response, Bode plots, resonance, filters, and digital signal processing. The basic concept of Fourier theory (that signals are composed of sinusoidal components having various amplitudes, phases, and frequencies) is qualitatively discussed.

### Digital Systems

Chapter 7 introduces logic gates and the representation of numerical data in binary form. It then proceeds to discuss combinatorial and sequential logic. Boolean algebra, De Morgan’s laws, truth tables, Karnaugh maps, coders, decoders, flip-flops, and registers are discussed.

Chapter 8 treats microcomputers with emphasis on embedded systems using the Freescale Semiconductor HCS12/9S12 as the primary example. Computer organization and memory types are discussed. Digital process control using microcontrollers

is described in general terms. Finally, selected instructions and addressing modes for the CPU12 are described. Assembly language programming is treated very briefly.

Chapter 9 discusses computer-based instrumentation systems including measurement concepts, sensors, signal conditioning, and analog-to-digital conversion. The chapter ends with a discussion of LabVIEW, including an example virtual instrument that students can duplicate using an evaluation version on their own computers.

## Electronic Devices and Circuits

Chapter 10 presents the diode, its various models, load-line analysis, and diode circuits, such as rectifiers, Zener-diode regulators, and wave shapers.

In Chapter 11, the specifications and imperfections of amplifiers that need to be considered in applications are discussed from a users perspective. These include gain, input impedance, output impedance, loading effects, frequency response, pulse response, nonlinear distortion, common-mode rejection, and dc offsets.

Chapter 12 covers the MOS field-effect transistor, its characteristic curves, load-line analysis, large-signal and small-signal models, bias circuits, the common-source amplifier, and the source follower.

Chapter 13 gives a similar treatment for bipolar transistors. If desired, the order of Chapters 12 and 13 can be reversed. Another possibility is to skip most of both chapters so more time can be devoted to other topics.

Chapter 14 treats the operational amplifier and many of its applications. Non-majors can learn enough from this chapter to design and use op-amp circuits for instrumentation applications in their own fields.

## Electromechanics

Chapter 15 reviews basic magnetic field theory, analyzes magnetic circuits, and presents transformers.

DC machines and ac machines are treated in Chapters 16 and 17, respectively. The emphasis is on motors rather than generators because the nonelectrical engineer applies motors much more often than generators. In Chapter 16, an overall view of motors in general is presented before considering DC machines, their equivalent circuits, and performance calculations. The universal motor and its applications are discussed.

Chapter 17 deals with AC motors, starting with the three-phase induction motor. Synchronous motors and their advantages with respect to power-factor correction are analyzed. Small motors including single-phase induction motors are also discussed. A section on stepper motors and brushless dc motors ends the chapter.

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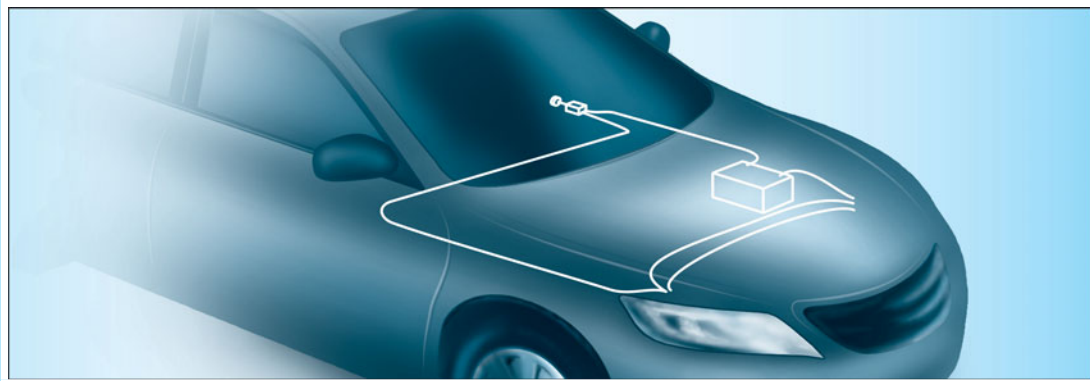
Over the years, many students and faculty using my books at Michigan Technological University and elsewhere have made many excellent suggestions for improving the books and correcting errors. I thank them very much.

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ALLAN R. HAMBLEY



## Chapter 1

# Introduction

### Study of this chapter will enable you to:

- Recognize interrelationships between electrical engineering and other fields of science and engineering.
- List the major subfields of electrical engineering.
- List several important reasons for studying electrical engineering.
- Define current, voltage, and power, including their units.
- Calculate power and energy and determine whether energy is supplied or absorbed by a circuit element.
- State and apply Kirchhoff's current and voltage laws.
- Recognize series and parallel connections.
- Identify and describe the characteristics of voltage and current sources.
- State and apply Ohm's law.
- Solve for currents, voltages, and powers in simple circuits.

### Introduction to this chapter:

In this chapter, we introduce electrical engineering, define circuit variables (current, voltage, power, and energy), study the laws that these circuit

variables obey, and meet several circuit elements (current sources, voltage sources, and resistors).

## 1.1 OVERVIEW OF ELECTRICAL ENGINEERING

Electrical engineers design systems that have two main objectives:

1. To gather, store, process, transport, and present *information*.
2. To distribute, store, and convert *energy* between various forms.

In many electrical systems, the manipulation of energy and the manipulation of information are interdependent.

For example, numerous aspects of electrical engineering relating to information are applied in weather prediction. Data about cloud cover, precipitation, wind speed, and so on are gathered electronically by weather satellites, by land-based radar stations, and by sensors at numerous weather stations. (Sensors are devices that convert physical measurements to electrical signals.) This information is transported by electronic communication systems and processed by computers to yield forecasts that are disseminated and displayed electronically.

In electrical power plants, energy is converted from various sources to electrical form. Electrical distribution systems transport the energy to virtually every factory, home, and business in the world, where it is converted to a multitude of useful forms, such as mechanical energy, heat, and light.

No doubt you can list scores of electrical engineering applications in your daily life. Increasingly, electrical and electronic features are integrated into new products. Automobiles and trucks provide just one example of this trend. The electronic content of the average automobile is growing rapidly in value. Auto designers realize that electronic technology is a good way to provide increased functionality at lower cost. Table 1.1 shows some of the applications of electrical engineering in automobiles.

As another example, we note that many common household appliances contain keypads for operator control, sensors, electronic displays, and computer chips, as well as more conventional switches, heating elements, and motors. Electronics have become so intimately integrated with mechanical systems that the name **mechatronics** is used for the combination.

### Subdivisions of Electrical Engineering

Next, we give you an overall picture of electrical engineering by listing and briefly discussing eight of its major areas.

**1. Communication systems** transport information in electrical form. Cellular phone, radio, satellite television, and the Internet are examples of communication systems. It is possible for virtually any two people (or computers) on the globe to communicate almost instantaneously. A climber on a mountaintop in Nepal can call or send e-mail to friends whether they are hiking in Alaska or sitting in a New York City office. This kind of connectivity affects the way we live, the way we conduct business, and the design of everything we use. For example, communication systems will change the design of highways because traffic and road-condition information collected by roadside sensors can be transmitted to central locations and used to route traffic. When an accident occurs, an electrical signal can be emitted automatically when the airbags deploy, giving the exact location of the vehicle, summoning help, and notifying traffic-control computers.

**2. Computer systems** process and store information in digital form. No doubt you have already encountered computer applications in your own field. Besides the computers of which you are aware, there are many in unobvious places, such as household appliances and automobiles. A typical modern automobile contains several

You may find it interesting to search the web for sites related to “mechatronics.”

Computers that are part of products such as appliances and automobiles are called *embedded computers*.

**Table 1.1. Current and Emerging Electronic/Electrical Applications in Automobiles and Trucks**

---

Safety

- Antiskid brakes
- Inflatable restraints
- Collision warning and avoidance
- Blind-zone vehicle detection (especially for large trucks)
- Infrared night vision systems
- Heads-up displays
- Automatic accident notification
- Rear-view cameras

Communications and entertainment

- AM/FM radio
- Digital audio broadcasting
- CD/DVD player
- Cellular phone
- Computer/e-mail
- Satellite radio

Convenience

- Electronic GPS navigation
- Personalized seat/mirror/radio settings
- Electronic door locks

Emissions, performance, and fuel economy

- Vehicle instrumentation
- Electronic ignition
- Tire inflation sensors
- Computerized performance evaluation and maintenance scheduling
- Adaptable suspension systems

Alternative propulsion systems

- Electric vehicles
- Advanced batteries
- Hybrid vehicles

---

dozen special-purpose computers. Chemical processes and railroad switching yards are routinely controlled through computers.

**3. Control systems** gather information with sensors and use electrical energy to control a physical process. A relatively simple control system is the heating/cooling system in a residence. A sensor (thermostat) compares the temperature with the desired value. Control circuits operate the furnace or air conditioner to achieve the desired temperature. In rolling sheet steel, an electrical control system is used to obtain the desired sheet thickness. If the sheet is too thick (or thin), more (or less) force is applied to the rollers. The temperatures and flow rates in chemical processes are controlled in a similar manner. Control systems have even been installed in tall buildings to reduce their movement due to wind.

**4. Electromagnetics** is the study and application of electric and magnetic fields. The device (known as a magnetron) used to produce microwave energy in an oven is one application. Similar devices, but with much higher power levels, are employed in manufacturing sheets of plywood. Electromagnetic fields heat the glue between



Electronic devices are based on controlling electrons. Photonic devices perform similar functions by controlling photons.

layers of wood so that it will set quickly. Cellular phone and television antennas are also examples of electromagnetic devices.

**5. Electronics** is the study and application of materials, devices, and circuits used in amplifying and switching electrical signals. The most important electronic devices are transistors of various kinds. They are used in nearly all places where electrical information or energy is employed. For example, the cardiac pacemaker is an electronic circuit that senses heart beats, and if a beat does not occur when it should, applies a minute electrical stimulus to the heart, forcing a beat. Electronic instrumentation and electrical sensors are found in every field of science and engineering. Many of the aspects of electronic amplifiers studied later in this book have direct application to the instrumentation used in your field of engineering.

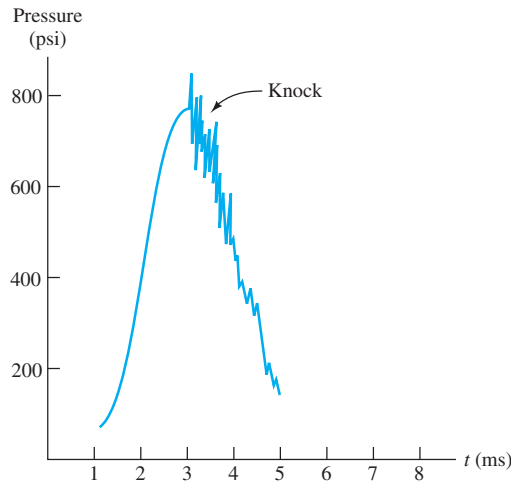
**6. Photonics** is an exciting new field of science and engineering that promises to replace conventional computing, signal-processing, sensing, and communication devices based on manipulating electrons with greatly improved products based on manipulating photons. Photonics includes light generation by lasers and light-emitting diodes, transmission of light through optical components, as well as switching, modulation, amplification, detection, and steering light by electrical, acoustical, and photon-based devices. Current applications include readers for DVD disks, holograms, optical signal processors, and fiber-optic communication systems. Future applications include optical computers, holographic memories, and medical devices. Photonics offers tremendous opportunities for nearly all scientists and engineers.

**7. Power systems** convert energy to and from electrical form and transmit energy over long distances. These systems are composed of generators, transformers, distribution lines, motors, and other elements. Mechanical engineers often utilize electrical motors to empower their designs. The selection of a motor having the proper torque-speed characteristic for a given mechanical application is another example of how you can apply the information in this book.

**8. Signal processing** is concerned with information-bearing electrical signals. Often, the objective is to extract useful information from electrical signals derived from sensors. An application is machine vision for robots in manufacturing. Another application of signal processing is in controlling ignition systems of internal combustion engines. The timing of the ignition spark is critical in achieving good performance and low levels of pollutants. The optimum ignition point relative to crankshaft rotation depends on fuel quality, air temperature, throttle setting, engine speed, and other factors.

If the ignition point is advanced slightly beyond the point of best performance, *engine knock* occurs. Knock can be heard as a sharp metallic noise that is caused by rapid pressure fluctuations during the spontaneous release of chemical energy in the combustion chamber. A combustion-chamber pressure pulse displaying knock is shown in Figure 1.1. At high levels, knock will destroy an engine in a very short time. Prior to the advent of practical signal-processing electronics for this application, engine timing needed to be adjusted for distinctly suboptimum performance to avoid knock under varying combinations of operating conditions.

By connecting a sensor through a tube to the combustion chamber, an electrical signal proportional to pressure is obtained. Electronic circuits process this signal to determine whether the rapid pressure fluctuations characteristic of knock are present. Then electronic circuits continuously adjust ignition timing for optimum performance while avoiding knock.



**Figure 1.1** Pressure versus time for an internal combustion engine experiencing knock. Sensors convert pressure to an electrical signal that is processed to adjust ignition timing for minimum pollution and good performance.

## Why You Need to Study Electrical Engineering

As a reader of this book, you may be majoring in another field of engineering or science and taking a required course in electrical engineering. Your immediate objective is probably to meet the course requirements for a degree in your chosen field. However, there are several other good reasons to learn and retain some basic knowledge of electrical engineering:

1. *To pass the Fundamentals of Engineering (FE) Examination as a first step in becoming a Registered Professional Engineer.* In the United States, before performing engineering services for the public, you will need to become registered as a Professional Engineer (PE). This book gives you the knowledge to answer questions relating to electrical engineering on the registration examinations. Save this book and course notes to review for the FE examination. (See Appendix C for more on the FE exam.)

2. *To have a broad enough knowledge base so that you can lead design projects in your own field.* Increasingly, electrical engineering is interwoven with nearly all scientific experiments and design projects in other fields of engineering. Industry has repeatedly called for engineers who can see the big picture and work effectively in teams. Engineers or scientists who narrow their focus strictly to their own field are destined to be directed by others. (Electrical engineers are somewhat fortunate in this respect because the basics of structures, mechanisms, and chemical processes are familiar from everyday life. On the other hand, electrical engineering concepts are somewhat more abstract and hidden from the casual observer.)

3. *To be able to operate and maintain electrical systems, such as those found in control systems for manufacturing processes.* The vast majority of electrical-circuit malfunctions can be readily solved by the application of basic electrical-engineering principles. You will be a much more versatile and valuable engineer or scientist if you can apply electrical-engineering principles in practical situations.

4. *To be able to communicate with electrical-engineering consultants.* Very likely, you will often need to work closely with electrical engineers in your career. This book will give you the basic knowledge needed to communicate effectively.

Save this book and course notes to review for the FE exam.

Circuit theory is the electrical engineer's fundamental tool.

## Content of This Book

Electrical engineering is too vast to cover in one or two courses. Our objective is to introduce the underlying concepts that you are most likely to need. Circuit theory is the electrical engineer's fundamental tool. That is why the first six chapters of this book are devoted to circuits.

Embedded computers, sensors, and electronic circuits will be an increasingly important part of the products you design and the instrumentation you use as an engineer or scientist. Chapters 7, 8, and 9 treat digital systems with emphasis on embedded computers and instrumentation. Chapters 10 through 14 deal with electronic devices and circuits.

As a mechanical, chemical, civil, industrial, or other engineer, you will very likely need to employ energy-conversion devices. The last three chapters relate to electrical energy systems treating transformers, generators, and motors.

Because this book covers many basic concepts, it is also sometimes used in introductory courses for electrical engineers. Just as it is important for other engineers and scientists to see how electrical engineering can be applied to their fields, it is equally important for electrical engineers to be familiar with these applications.

## 1.2 CIRCUITS, CURRENTS, AND VOLTAGES

### Overview of an Electrical Circuit

Before we carefully define the terminology of electrical circuits, let us gain some basic understanding by considering a simple example: the headlight circuit of an automobile. This circuit consists of a battery, a switch, the headlamps, and wires connecting them in a closed path, as illustrated in Figure 1.2.

The battery voltage is a measure of the energy gained by a unit of charge as it moves through the battery.

Chemical forces in the battery cause electrical charge (electrons) to flow through the circuit. The charge gains energy from the chemicals in the battery and delivers energy to the headlamps. The battery voltage (nominally, 12 volts) is a measure of the energy gained by a unit of charge as it moves through the battery.

Electrons readily move through copper but not through plastic insulation.

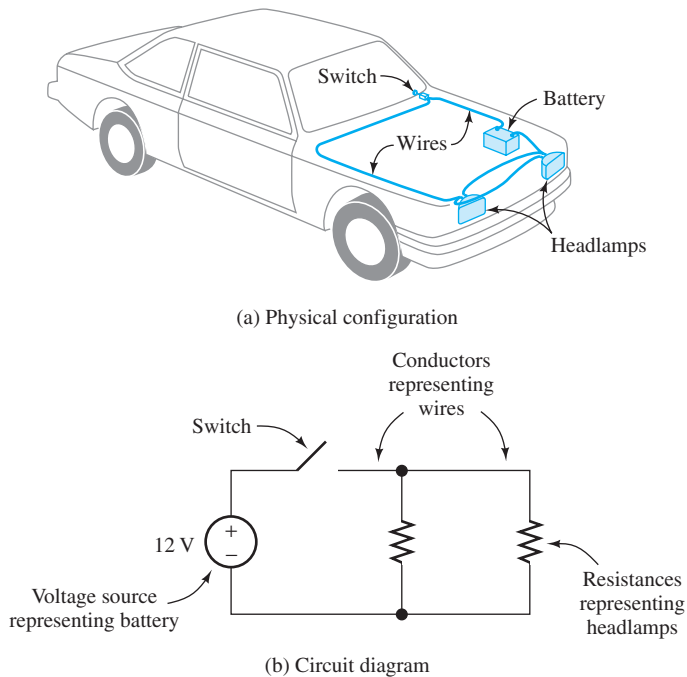
The wires are made of an excellent electrical conductor (copper) and are insulated from one another (and from the metal auto body) by electrical insulation (plastic) coating the wires. Electrons readily move through copper but not through the plastic insulation. Thus, the charge flow (electrical current) is confined to the wires until it reaches the headlamps. Air is also an insulator.

Electrons experience collisions with the atoms of the tungsten wires, resulting in heating of the tungsten.

The switch is used to control the flow of current. When the conducting metallic parts of the switch make contact, we say that the switch is **closed** and current flows through the circuit. On the other hand, when the conducting parts of the switch do not make contact, we say that the switch is **open** and current does not flow.

Energy is transferred by the chemical action in the battery to the electrons and then to the tungsten.

The headlamps contain special tungsten wires that can withstand high temperatures. Tungsten is not as good an electrical conductor as copper, and the electrons experience collisions with the atoms of the tungsten wires, resulting in heating of the tungsten. We say that the tungsten wires have electrical resistance. Thus, energy is transferred by the chemical action in the battery to the electrons and then to the tungsten, where it appears as heat. The tungsten becomes hot enough so that copious light is emitted. We will see that the power transferred is equal to the product of current (rate of flow of charge) and the voltage (also called electrical potential) applied by the battery.



**Figure 1.2** The headlight circuit. (a) The actual physical layout of the circuit. (b) The circuit diagram.

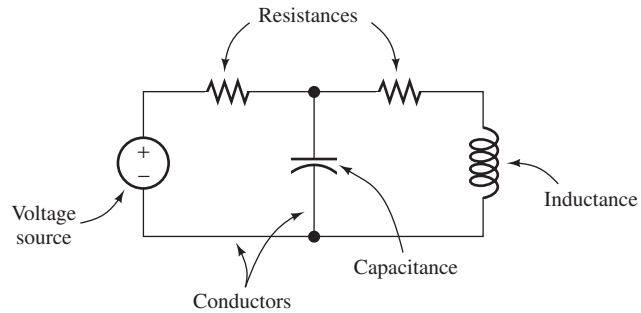
(Actually, the simple description of the headlight circuit we have given is most appropriate for older cars. In more modern automobiles, sensors provide information to an embedded computer about the ambient light level, whether or not the ignition is energized, and whether the transmission is in park or drive. The dashboard switch merely inputs a logic level to the computer, indicating the intention of the operator with regard to the headlights. Depending on these inputs, the computer controls the state of an electronic switch in the headlight circuit. When the ignition is turned off and if it is dark, the computer keeps the lights on for a few minutes so the passengers can see to exit and then turns them off to conserve energy in the battery. This is typical of the trend to use highly sophisticated electronic and computer technology to enhance the capabilities of new designs in all fields of engineering.)

## Fluid-Flow Analogy

Electrical circuits are analogous to fluid-flow systems. The battery is analogous to a pump, and charge is analogous to the fluid. Conductors (usually copper wires) correspond to frictionless pipes through which the fluid flows. Electrical current is the counterpart of the flow rate of the fluid. Voltage corresponds to the pressure differential between points in the fluid circuit. Switches are analogous to valves. Finally, the electrical resistance of a tungsten headlamp is analogous to a constriction in a fluid system that results in turbulence and conversion of energy to heat. Notice that current is a measure of the flow of charge *through* the cross section of a circuit element, whereas voltage is measured *across* the ends of a circuit element or *between* any other two points in a circuit.

Now that we have gained a basic understanding of a simple electrical circuit, we will define the concepts and terminology more carefully.

The fluid-flow analogy can be very helpful initially in understanding electrical circuits.

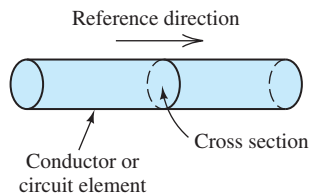


**Figure 1.3** An electrical circuit consists of circuit elements, such as voltage sources, resistances, inductances, and capacitances, connected in closed paths by conductors.

An electrical circuit consists of various types of circuit elements connected in closed paths by conductors.

Charge flows easily through conductors.

Current is the time rate of flow of electrical charge. Its units are amperes (A), which are equivalent to coulombs per second (C/s).



**Figure 1.4** Current is the time rate of charge flow through a cross section of a conductor or circuit element.

Colored shading is used to indicate key equations throughout this book.

## Electrical Circuits

An **electrical circuit** consists of various types of circuit elements connected in closed paths by conductors. An example is illustrated in Figure 1.3. The circuit elements can be resistances, inductances, capacitances, and voltage sources, among others. The symbols for some of these elements are illustrated in the figure. Eventually, we will carefully discuss the characteristics of each type of element.

Charge flows easily through conductors, which are represented by lines connecting circuit elements. Conductors correspond to connecting wires in physical circuits. Voltage sources create forces that cause charge to flow through the conductors and other circuit elements. As a result, energy is transferred between the circuit elements, resulting in a useful function.

## Electrical Current

**Electrical current** is the time rate of flow of electrical charge through a conductor or circuit element. The units are amperes (A), which are equivalent to coulombs per second (C/s). (The charge on an electron is  $-1.602 \times 10^{-19}$  C.)

Conceptually, to find the current for a given circuit element, we first select a cross section of the circuit element roughly perpendicular to the flow of current. Then, we select a **reference direction** along the direction of flow. Thus, the reference direction points from one side of the cross section to the other. This is illustrated in Figure 1.4.

Next, suppose that we keep a record of the net charge flow through the cross section. Positive charge crossing in the reference direction is counted as a positive contribution to net charge. Positive charge crossing opposite to the reference is counted as a negative contribution. Furthermore, negative charge crossing in the reference direction is counted as a negative contribution, and negative charge against the reference direction is a positive contribution to charge.

Thus, in concept, we obtain a record of the net charge in coulombs as a function of time in seconds denoted as  $q(t)$ . The electrical current flowing through the element in the reference direction is given by

$$i(t) = \frac{dq(t)}{dt} \quad (1.1)$$

A constant current of one ampere means that one coulomb of charge passes through the cross section each second.

To find charge given current, we must integrate. Thus, we have

$$q(t) = \int_{t_0}^t i(t) dt + q(t_0) \quad (1.2)$$

in which  $t_0$  is some initial time at which the charge is known. (Throughout this book, we assume that time  $t$  is in seconds unless stated otherwise.)

Current flow is the same for all cross sections of a circuit element. (We reexamine this statement when we introduce the capacitor in Chapter 3.) The current that enters one end flows through the element and exits through the other end.

### Example 1.1 Determining Current Given Charge

Suppose that charge versus time for a given circuit element is given by

$$q(t) = 0 \quad \text{for } t < 0$$

and

$$q(t) = 2 - 2e^{-100t} \text{ C} \quad \text{for } t > 0$$

Sketch  $q(t)$  and  $i(t)$  to scale versus time.

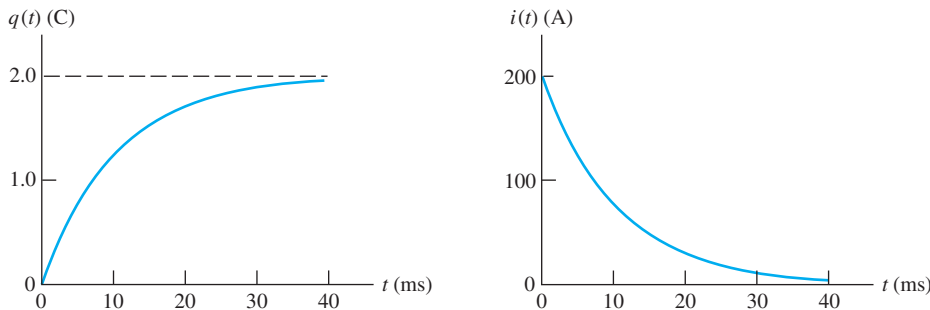
**Solution** First we use Equation 1.1 to find an expression for the current:

$$\begin{aligned} i(t) &= \frac{dq(t)}{dt} \\ &= 0 \quad \text{for } t < 0 \\ &= 200e^{-100t} \text{ A} \quad \text{for } t > 0 \end{aligned}$$

Plots of  $q(t)$  and  $i(t)$  are shown in Figure 1.5. ■

### Reference Directions

In analyzing electrical circuits, we may not initially know the *actual direction* of current flow in a particular circuit element. Therefore, we start by assigning current



**Figure 1.5** Plots of charge and current versus time for Example 1.1. *Note:* The time scale is in milliseconds (ms). One millisecond is equivalent to  $10^{-3}$  seconds.