ELECTRICAL ENGINEERING

Principles and Applications

Allan R. Hambley

Seventh Edition

Pearson

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Electrical Engineering

Principles and Applications

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Pearson

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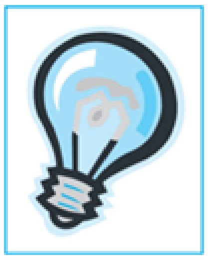
To my family Judy, Tony, Pam, and Mason and to my special friend, Carol

Contents

Practical Applications of Electrical Engineering Principles



Preface

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:

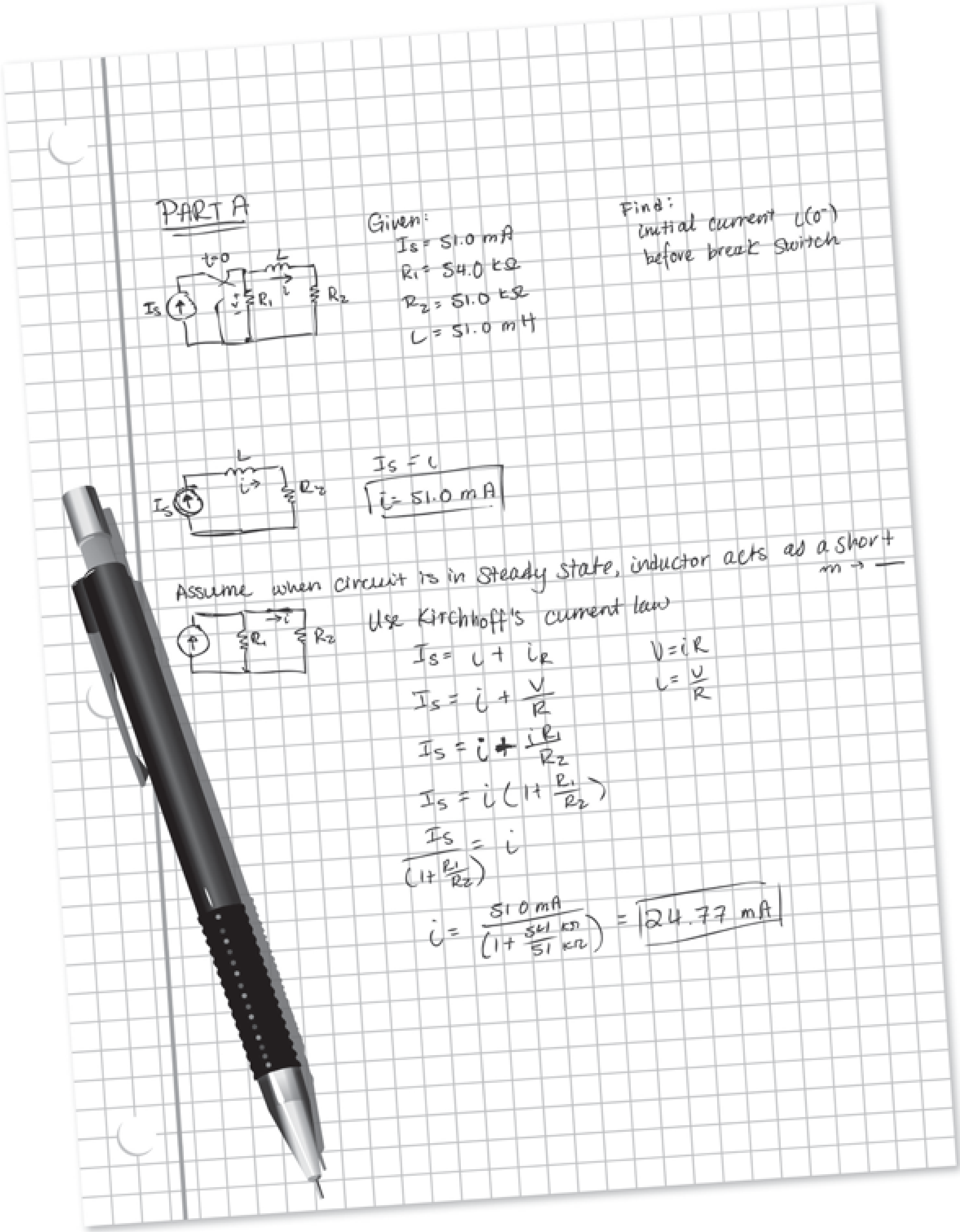
- Basic circuit analysis and measurement
- First- and second-order transients
- Steady-state ac circuits
- Resonance and frequency response
- Digital logic circuits
- Microcontrollers
- Computer-based instrumentation
- Diode circuits
- Electronic amplifiers
- Field-effect and bipolar junction transistors
- 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

your work...



your answer specific feedback

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

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

Submit | Hints | My Answers | Give Up | Review Part

Incorrect; 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.

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

$i(0^-) = i(0^+) = =$ 24.7 mA

Submit | Hints | My Answers | Give Up | Review Part

Incorrect; 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.

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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. Video Solutions and coaching activities also provide complete, step-by-step solution walkthroughs of representative homework problems from each chapter. Access can be purchased bundled with the textbook or online at **www.masteringengineering.com**.

- Pearson eText, which is a complete on-line version of the book that includes highlighting, note-taking, and search capabilities is also available through MasteringEngineering.
- **Resource Website.** An open access website is available at **www.pearsonhighered.com/engineering-resources.** Resources include:
  - 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.

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**. 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 and added items to 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.
- New examples have been added in **Chapters 1** through **7**.
- Approximately half of the end-of-chapter problems have been replaced or modified.
- Coverage of computers, microcontrollers and computer-based instrumentation has been merged

from two chapters into **Chapter 8** for this edition.

- **Appendix C** has been modified to keep up with new developments in the Fundamentals of Engineering Exam.
- We have updated the coverage of MATLAB and the Symbolic Toolbox for network analysis in **Chapters 2** through **6**.
- 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 **296**) and electronic pacemakers (starting on page **394**).
- Step-by-step problem solving procedures. For example, see the step-by-step summary of node-voltage analysis (on pages 76–80) or the summary of Thévenin equivalents (on page **252**).
- 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.

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. Selected instructions and addressing modes for the CPU12 are described. Assembly language programming is treated very briefly. Finally, computer-based instrumentation systems including measurement concepts, sensors, signal conditioning, and analog-to-digital conversion are discussed.

Electronic Devices and Circuits

Chapter 9 presents the diode, its various models, load-line analysis, and diode circuits, such as rectifiers, Zener-diode regulators, and wave shapers.

In **Chapter 10**, 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 11 covers the MOS field-effect transistor, its characteristic curves, loadline analysis, large-signal and small-signal models, bias circuits, the common-source amplifier, and the source follower.

Chapter 12 gives a similar treatment for bipolar transistors. If desired, the order of **Chapters 11** and **12** can be reversed. Another possibility is to skip most of both chapters so more time can be devoted to other topics.

Chapter 13 treats the operational amplifier and many of its applications. Nonmajors can learn enough from this chapter to design and use op-amp circuits for instrumentation applications in their own fields.

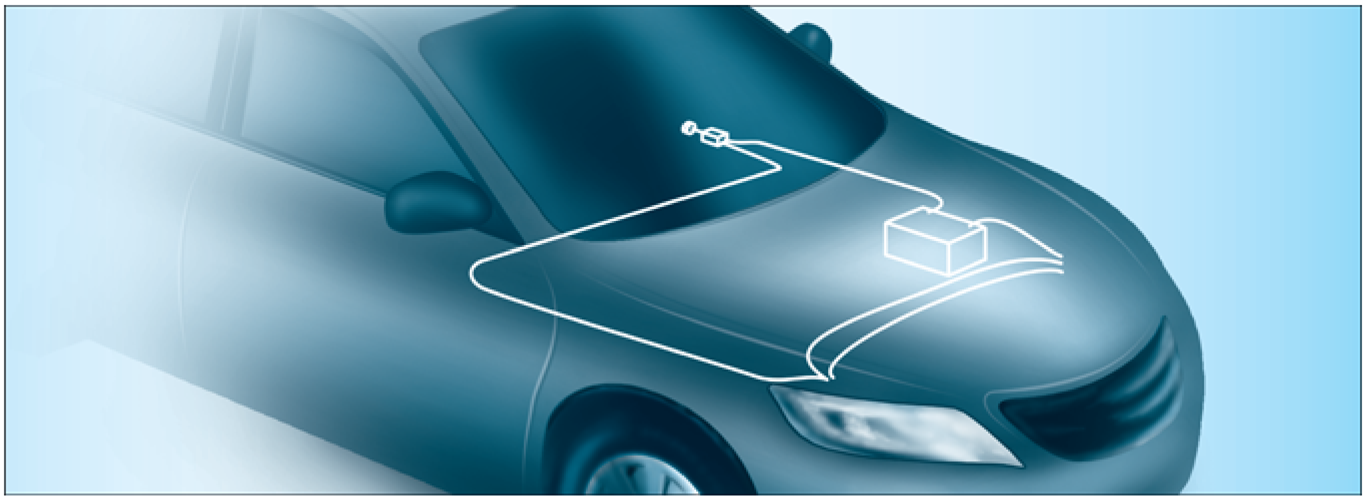
Electromechanics

Chapter 14 reviews basic magnetic field theory, analyzes magnetic circuits, and presents transformers.

DC machines and ac machines are treated in **Chapters 15** and **16**, respectively. The emphasis is on motors rather than generators because the nonelectrical engineer applies motors much more often than generators. In **Chapter 15**, 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 16 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.

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. Self-driving vehicles are in rapid development and will eventually become the norm. 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.

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

As another example, we note that many common household appliances contain keypads or touch screens 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.

> You may find it interesting to search the web for sites related to "mechatronics."

Subdivisions of Electrical Engineering

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

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

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** 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 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 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.

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

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.

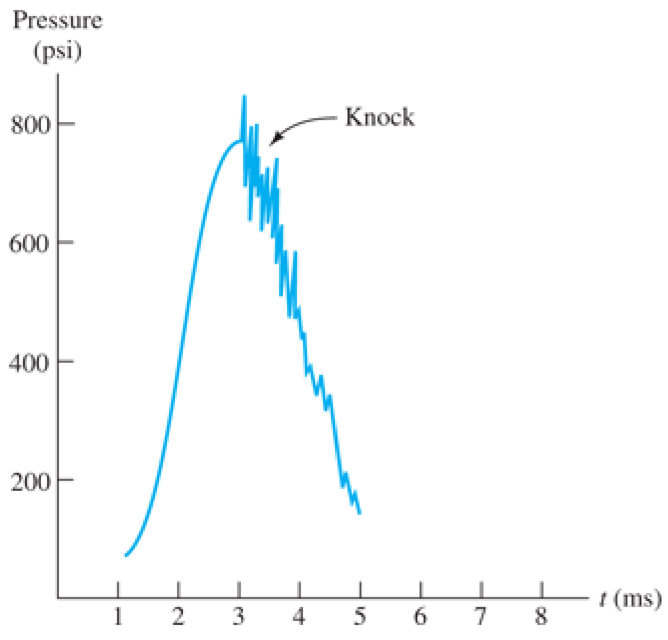


Figure 1.1
Pressure versus time for an internal combustion engine experiencing knock. Sensors convert pressure to an electrical signal that is processed to adjust ignition timing for minimum pollution and good performance.

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.

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.)

Save this book and course notes to review for 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.

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.

Circuit theory is the electrical engineer's fundamental tool.

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** and **8** treat digital systems with emphasis on embedded computers and instrumentation. **Chapters 9** through **13** 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**.

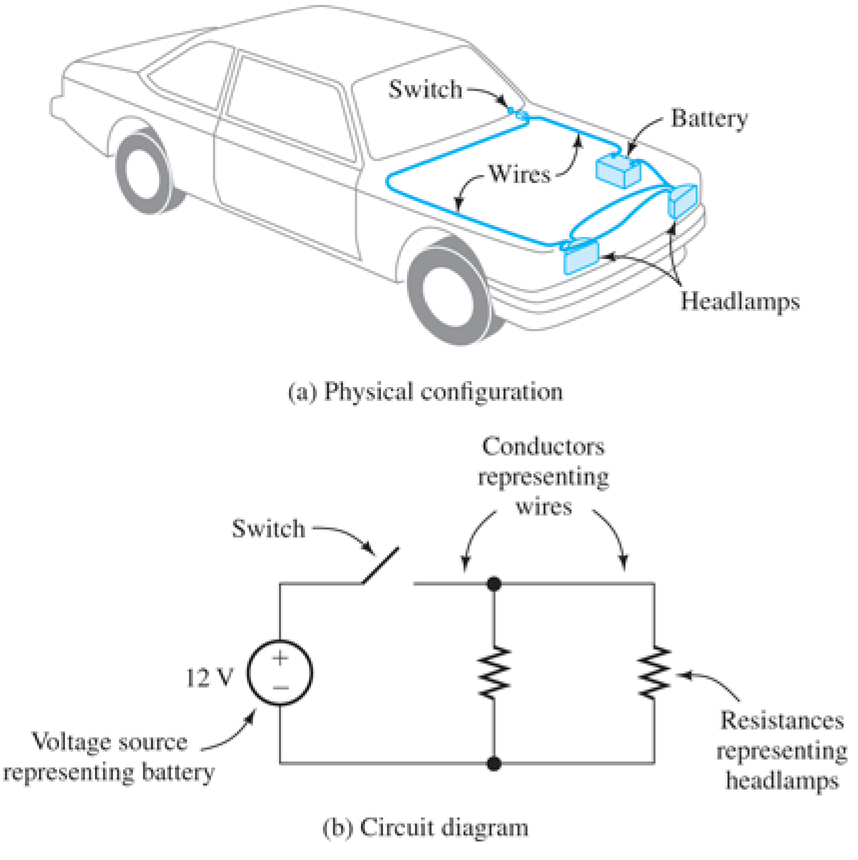


Figure 1.2

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

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.

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

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 readily move through copper but not through plastic insulation.

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** switch 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.

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

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

(Actually, the simple description of the headlight circuit we have given is most appropriate for older cars. In more modern automobiles, light emitting diodes (LEDs) are used in place of the tungsten filaments. Furthermore, 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.

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

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

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.

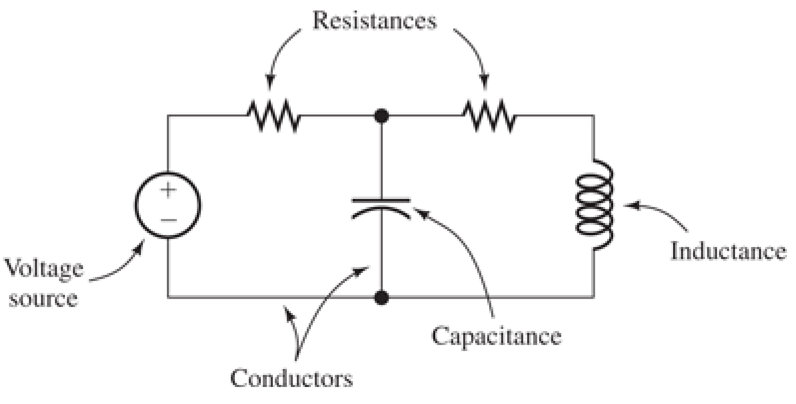


Figure 1.3
An electrical circuit consists of circuit elements, such as voltage sources, resistances, inductances, and capacitances, connected in closed paths by conductors.

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

Charge flows easily through conductors, 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.

Charge flows easily through conductors.

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 -1.602×10^{-19} C.)

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

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**.

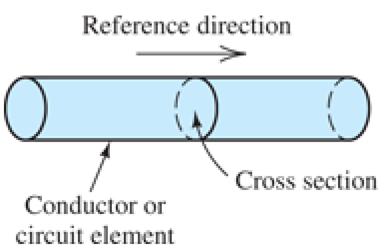


Figure 1.4
Current is the time rate of charge flow through a cross section of a conductor or circuit element.

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

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

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

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

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

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

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

and

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

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

Solution

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

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

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

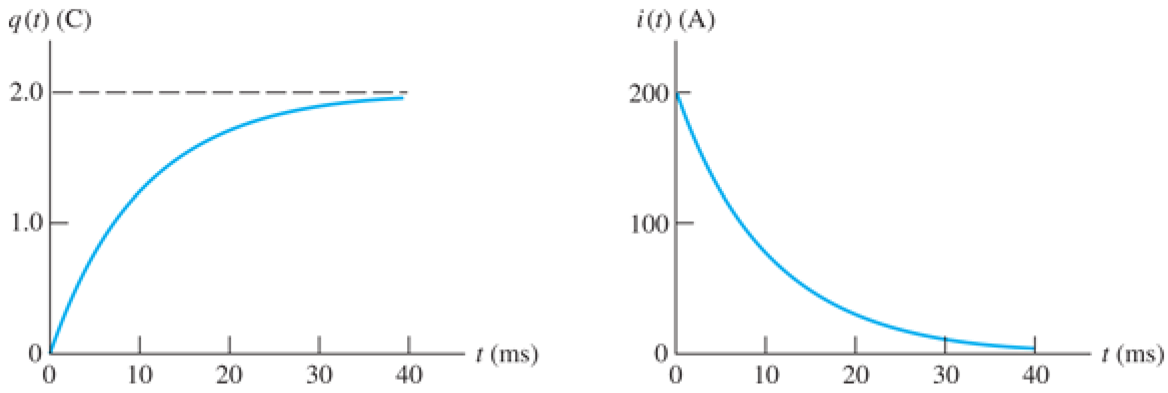


Figure 1.5

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.

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 variables and arbitrarily selecting a *reference direction* for each current of interest. It is customary to use the letter *i* for currents and subscripts to distinguish different currents. This is illustrated by the example in **Figure 1.6**, in which the boxes labeled *A*, *B*, and so on represent circuit elements. After we solve for the current values, we may find that some currents have negative values. For example, suppose that $i_1 = -2$ A in the circuit of **Figure 1.6**. Because i_1 has a negative value, we know that current actually flows in the direction opposite to the reference initially selected for i_1. Thus, the actual current is 2 A flowing downward through element *A*.

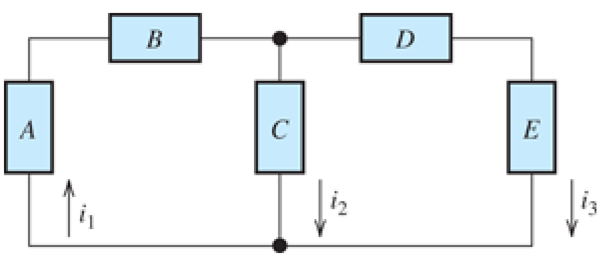


Figure 1.6

In analyzing circuits, we frequently start by assigning current variables i_1, i_2, i_3, and so forth.

Direct Current and Alternating Current

Dc currents are constant with respect to time, whereas ac currents vary with time.

When a current is constant with time, we say that we have **direct current**, abbreviated as dc. On the other hand, a current that varies with time, reversing direction periodically, is called **alternating current**, abbreviated as ac. **Figure 1.7** shows the values of a dc current and a sinusoidal ac current versus time. When $i_b(t)$ takes a negative value, the actual current direction is opposite to the reference direction for $i_b(t)$. The designation ac is used for other types of time-varying currents, such as the triangular and square waveforms shown in **Figure 1.8**.

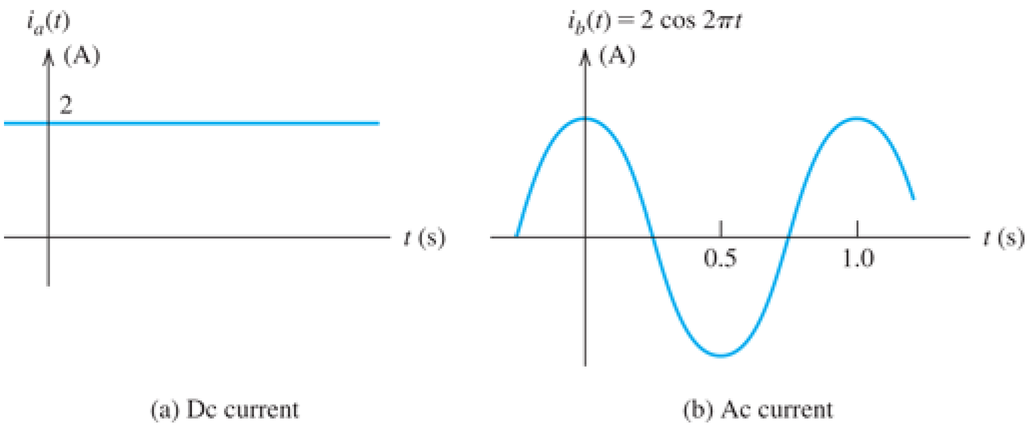


Figure 1.7
Examples of dc and ac currents versus time.

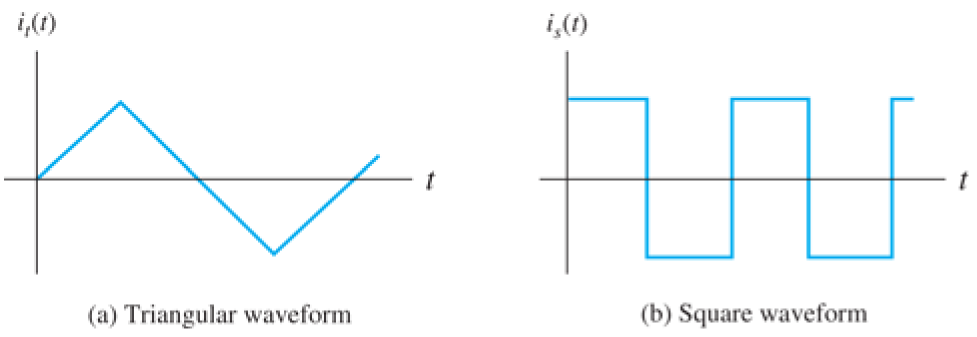


Figure 1.8
Ac currents can have various waveforms.

Double-Subscript Notation for Currents

So far we have used arrows alongside circuit elements or conductors to indicate reference directions for currents. Another way to indicate the current and reference direction for a circuit element is to label the ends of the element and use double subscripts to define the reference direction for the current. For example, consider the resistance of **Figure 1.9**. The current denoted by i_{ab} is the current through the element with its reference direction pointing from *a* to *b*. Similarly, i_{ba} is the current with its reference directed from *b* to *a*. Of course, i_{ab} and i_{ba} are the same in magnitude and opposite in sign, because they denote the same current but with opposite reference directions. Thus, we have

$$i_{ab} = -i_{ba}$$

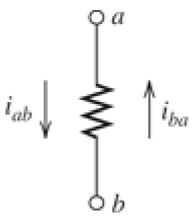


Figure 1.9
Reference directions can be indicated by labeling the ends of circuit elements and using double subscripts on current variables. The reference direction for i_{ab} points from *a* to *b*. On the other hand, the reference direction for i_{ba} points from *b* to *a*.

Exercise 1.1

A constant current of 2 A flows through a circuit element. In 10 seconds (s), how much net charge passes through the element?

Answer 20 C.

Exercise 1.2

The charge that passes through a circuit element is given by $q(t) = 0.01 \sin(200t)$ C, in which the angle is in radians. Find the current as a function of time.

Answer $i(t) = 2 \cos(200t)$ A.

Exercise 1.3

In **Figure 1.6**, suppose that $i_2 = 1$ A and $i_3 = -3$ A. Assuming that the current consists of positive charge, in which direction (upward or downward) is charge moving in element *C*? In element *E*?

Answer Downward in element *C* and upward in element *E*.

Voltages

When charge moves through circuit elements, energy can be transferred. In the case of automobile headlights, stored chemical energy is supplied by the battery and absorbed by the headlights where it appears as heat and light. The **voltage** associated with a circuit element is the energy transferred per unit of charge that flows through the element. The units of voltage are volts (V), which are equivalent to joules per coulomb (J/C).

> Voltage is a measure of the energy transferred per unit of charge when charge moves from one point in an electrical circuit to a second point.

For example, consider the storage battery in an automobile. The voltage across its terminals is (nominally) 12 V. This means that 12 J are transferred to or from the battery for each coulomb that flows through it. When charge flows in one direction, energy is supplied by the battery, appearing elsewhere in the circuit as heat or light or perhaps as mechanical energy at the starter motor. If charge moves through the battery in the opposite direction, energy is absorbed by the battery, where it appears as stored chemical energy.

> Notice that voltage is measured across the ends of a circuit element, whereas current is a measure of charge flow through the element.

Voltages are assigned polarities that indicate the direction of energy flow. If positive charge moves from the positive polarity through the element toward the negative polarity, the element absorbs energy that appears as heat, mechanical energy, stored chemical energy, or as some other form. On the other hand, if positive charge moves from the negative polarity toward the positive polarity, the element supplies energy. This is illustrated in **Figure 1.10**. For negative charge, the direction of energy transfer is reversed.

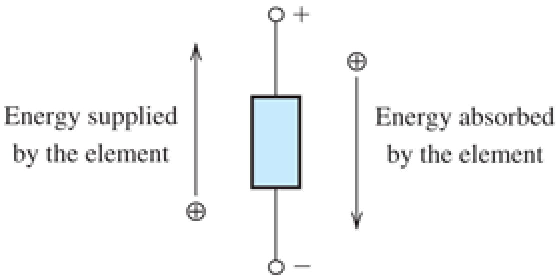


Figure 1.10
Energy is transferred when charge flows through an element having a voltage across it.

Reference Polarities

When we begin to analyze a circuit, we often do not know the actual polarities of some of the voltages of interest in the circuit. Then, we simply assign voltage variables choosing *reference* polarities arbitrarily. (Of course, the *actual* polarities are not arbitrary.) This is illustrated in **Figure 1.11**. Next, we apply circuit principles (discussed later), obtaining equations that are solved for the voltages. If a given voltage has an actual polarity opposite to our arbitrary choice for the reference polarity, we obtain a negative value for the voltage. For example, if we find that $v_3 = -5$ V in **Figure 1.11**, we know that the voltage across element 3 is 5 V in magnitude and its actual polarity is opposite to that shown in the figure (i.e., the actual polarity is positive at the bottom end of element 3 and negative at the top).

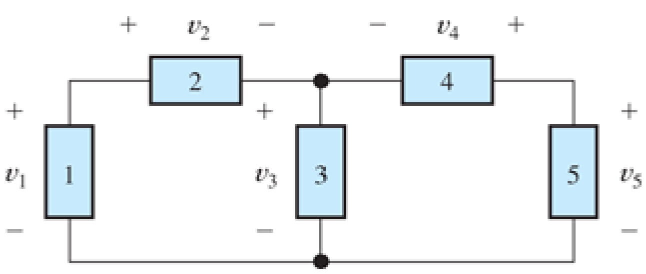


Figure 1.11
If we do not know the voltage values and polarities in a circuit, we can start by assigning voltage variables choosing the reference polarities arbitrarily. (The boxes represent unspecified circuit elements.)

In circuit analysis, we frequently assign reference polarities for voltages arbitrarily. If we find at the end of the analysis that the value of a voltage is negative, then we know that the true polarity is opposite of the polarity selected initially.

We usually do not put much effort into trying to assign "correct" references for current directions or voltage polarities. If we have doubt about them, we make arbitrary choices and use circuit analysis to determine true directions and polarities (as well as the magnitudes of the currents and voltages).

Voltages can be constant with time or they can vary. Constant voltages are called **dc voltages**. On the other hand, voltages that change in magnitude and alternate in polarity with time are said to be **ac voltages**. For example,

$$v_1(t) = 10 \text{ V}$$

is a dc voltage. It has the same magnitude and polarity for all time. On the other hand,

$$v_2(t) = 10\cos(200\pi t) \text{ V}$$

is an ac voltage that varies in magnitude and polarity. When $v_2(t)$ assumes a negative value, the actual polarity is opposite the reference polarity. (We study sinusoidal ac currents and voltages in **Chapter 5**.)

Double-Subscript Notation for Voltages

Another way to indicate the reference polarity of a voltage is to use double subscripts on the voltage variable. We use letters or numbers to label the terminals between which the voltage appears, as illustrated in **Figure 1.12**. For the resistance shown in the figure, v_{ab} represents the voltage between points *a* and *b* with the positive reference at point *a*. The two subscripts identify the points between which the voltage appears, and the first subscript is the positive reference. Similarly, v_{ba} is the voltage between *a* and *b* with the positive reference at point *b*. Thus, we can write

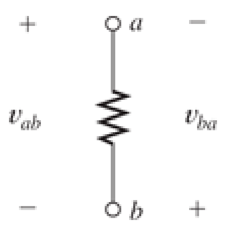


Figure 1.12

The voltage v_{ab} has a reference polarity that is positive at point *a* and negative at point *b*.

$$v_{ab} = -v_{ba} \tag{1.3}$$

because v_{ba} has the same magnitude as v_{ab} but has opposite polarity.

Still another way to indicate a voltage and its reference polarity is to use an arrow, as shown in **Figure 1.13**. The positive reference corresponds to the head of the arrow.

Figure 1.13

The positive reference for *v* is at the head of the arrow.

Switches

Switches control the currents in circuits. When an ideal switch is open, the current through it is zero and the voltage across it is determined by the remainder of the circuit. When an ideal switch is closed, the voltage across it is zero and the current through it is determined by the remainder of the circuit.

Exercise 1.4

The voltage across a given circuit element is $v_{ab} = 20$ V. A positive charge of 2 C moves through the circuit element from terminal *b* to terminal *a*. How much energy is transferred? Is the energy supplied by the circuit element or absorbed by it?

Answer 40 J are supplied by the circuit element.

1.3 Power and Energy

Consider the circuit element shown in **Figure 1.14**. Because the current *i* is the rate of flow of charge and the voltage *v* is a measure of the energy transferred per unit of charge, the product of the current and the voltage is the rate of energy transfer. In other words, the product of current and voltage is power:

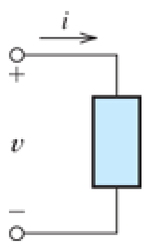


Figure 1.14
When current flows through an element and voltage appears across the element, energy is transferred. The rate of energy transfer is $p=vi$

$$p=vi. \tag{1.4}$$

The physical units of the quantities on the right-hand side of this equation are

$$\text{volts}\times\text{amperes}=\left(\text{joules/coulomb}\right)\times\left(\text{coulombs/second}\right)=\text{joules/second}=\text{watts}$$

Passive Reference Configuration

Now we may ask whether the power calculated by **Equation 1.4** represents energy supplied by or absorbed by the element. Refer to **Figure 1.14** and notice that the current reference enters the positive polarity of the voltage. We call this arrangement the **passive reference configuration**. Provided that the references are picked in this manner, a positive result for the power calculation implies that energy is being absorbed by the element. On the other hand, a negative result means that the element is supplying energy to other parts of the circuit.

If the current reference enters the negative end of the reference polarity, we compute the power as

(1.5)

$p = -vi$

Then, as before, a positive value for *p* indicates that energy is absorbed by the element, and a negative value shows that energy is supplied by the element.

If the circuit element happens to be an electrochemical battery, positive power means that the battery is being charged. In other words, the energy absorbed by the battery is being stored as chemical energy. On the other hand, negative power indicates that the battery is being discharged. Then the energy supplied by the battery is delivered to some other element in the circuit.

Sometimes currents, voltages, and powers are functions of time. To emphasize this fact, we can write **Equation 1.4** as

$$p(t) = v(t)i(t) \tag{1.6}$$

Example 1.2 Power Calculations

Consider the circuit elements shown in **Figure 1.15**. Calculate the power for each element. If each element is a battery, is it being charged or discharged?

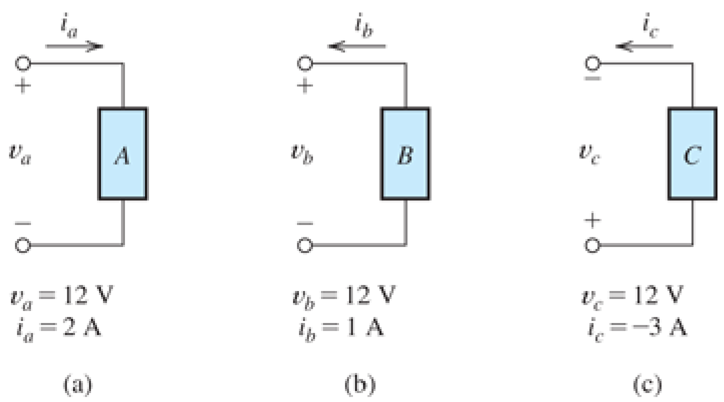


Figure 1.15
Circuit elements for **Example 1.2**.

Solution

In element *A*, the current reference enters the positive reference polarity. This is the passive reference configuration. Thus, power is computed as

$$p_a = v_a i_a = 12\ \text{V} \times 2\ \text{A} = 24\ \text{W}$$

Because the power is positive, energy is absorbed by the device. If it is a battery, it is being charged.

In element *B*, the current reference enters the negative reference polarity. (Recall that the current that enters one end of a circuit element must exit from the other end, and vice versa.) This is opposite to the passive reference configuration. Hence, power is computed as

$$p_b = -v_b i_b = -(12\ V) \times 1\ A = -12\ W$$

Since the power is negative, energy is supplied by the device. If it is a battery, it is being discharged.

In element *C*, the current reference enters the positive reference polarity. This is the passive reference configuration. Thus, we compute power as

$$p_c = v_c i_c = 12\ V \times (-3\ A) = -36\ W$$

Since the result is negative, energy is supplied by the element. If it is a battery, it is being discharged. (Notice that since i_c takes a negative value, current actually flows downward through element *C*.) ■

Energy Calculations

To calculate the energy *w* delivered to a circuit element between time instants t_1 and t_2, we integrate power:

$$w = \int_{t_1}^{t_2} p(t)\, dt \qquad (1.7)$$

Here we have explicitly indicated that power can be a function of time by using the notation *p*(*t*).

Example 1.3 Energy Calculation

Find an expression for the power for the voltage source shown in **Figure 1.16**. Compute the energy for the interval from $t_1 = 0$ to $t_2 = \infty$.

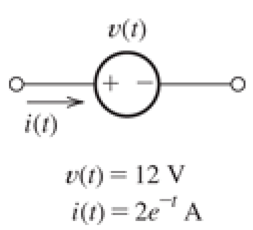


Figure 1.16 Circuit element for Example 1.3.

Solution

The current reference enters the positive reference polarity. Thus, we compute power as

$$p(t) = v(t)i(t) = 12 \times 2e^{-t} = 24e^{-t} \text{ W}$$

Subsequently, the energy transferred is given by

$$w = \int_0^\infty p(t)\,dt = \int_0^\infty 24e^{-t}\,dt = \left[-24e^{-t}\right]_0^\infty = -24e^{-\infty} - (-24e^0) = 24 \text{ J}$$

Because the energy is positive, it is absorbed by the source. ■

Prefixes

In electrical engineering, we encounter a tremendous range of values for currents, voltages, powers, and other quantities. We use the prefixes shown in **Table 1.2** when working with very large or small quantities. For example, 1 milliampere (1 mA) is equivalent to 10^{-3} A, 1 kilovolt (1 kV) is equivalent to 1000 V, and so on.

Table 1.2 Prefixes Used for Large or Small Physical Quantities

Prefix	Abbreviation	Scale Factor
giga-	G	10^9
meg- or mega-	M	10^6
kilo-	k	10^3
milli-	m	10^{-3}
micro-	μ	10^{-6}
nano-		10^{-9}
pico-	p	10^{-12}
femto-	f	10^{-15}

Exercise 1.5

The ends of a circuit element are labeled *a* and *b*, respectively. Are the references for i_{ab} and v_{ab} related by the passive reference configuration? Explain.

Answer The reference direction for i_{ab} enters terminal *a*, which is also the positive reference for v_{ab}. Therefore, the current reference direction enters the positive reference polarity, so we have the passive reference configuration.

Exercise 1.6

Compute the power as a function of time for each of the elements shown in **Figure 1.17**. Find the energy transferred between $t_1=0$ and $t_2=10$ s. In each case is energy supplied or absorbed by the element?

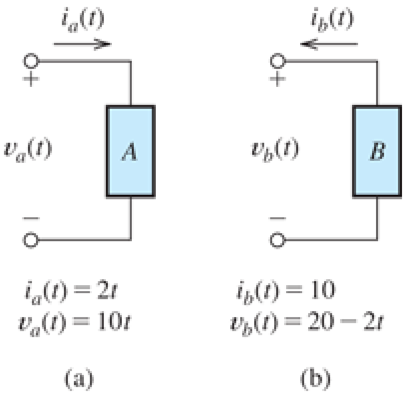


Figure 1.17
See **Exercise 1.6**.

Answer

a. $p_a(t)=20t^2$ W, $w_a=6667$ J; since w_a is positive, energy is absorbed by element *A*.

b. $p_b(t)=20t-200$ W, $w_b=-1000$ J; since w_b is negative, energy is supplied by element *B*.

1.4 Kirchhoff's Current Law

A **node** in an electrical circuit is a point at which two or more circuit elements are joined together. Examples of nodes are shown in **Figure 1.18**.

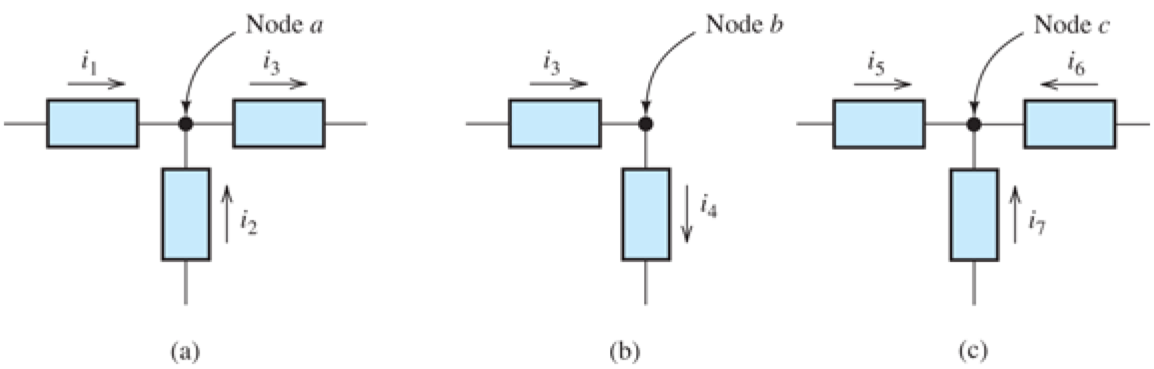


Figure 1.18
Partial circuits showing one node each to illustrate Kirchhoff's current law.

> Kirchhoff's current law states that the net current entering a node is zero.

An important principle of electrical circuits is **Kirchhoff's current law**: *The net current entering a node is zero.* To compute the *net* current entering a node, we add the currents entering and subtract the currents leaving. For illustration, consider the nodes of **Figure 1.18**. Then, we can write:

Node a: $i_1 + i_2 - i_3 = 0$ Node b: $i_3 - i_4 = 0$ Node c: $i_5 + i_6 + i_7 = 0$

Notice that for node *b*, Kirchhoff's current law requires that $i_3 = i_4$. In general, if only two circuit elements are connected at a node, their currents must be equal. The current flows into the node through one element and out through the other. Usually, we will recognize this fact and assign a single current variable for both circuit elements.

For node *c*, either all of the currents are zero or some are positive while others are negative.

We abbreviate Kirchhoff's current law as KCL. There are two other equivalent ways to state KCL. One way is: *The net current leaving a node is zero.* To compute the net current leaving a node, we add the currents leaving and subtract the currents entering. For the nodes of **Figure 1.18**, this yields the following:

Node a: $-i_1 - i_2 + i_3 = 0$ Node b: $-i_3 + i_4 = 0$ Node c: $-i_5 - i_6 - i_7 = 0$

Of course, these equations are equivalent to those obtained earlier.

Another way to state KCL is: *The sum of the currents entering a node equals the sum of the currents leaving a node.* Applying this statement to **Figure 1.18**, we obtain the following set of equations:

> An alternative way to state Kirchhoff's current law is that the sum of the currents entering a node is equal to the sum of the currents leaving a node.

Node a: $i_1 + i_2 = i_3$ Node b: $i_3 = i_4$ Node c: $i_5 + i_6 + i_7 = 0$

Again, these equations are equivalent to those obtained earlier.

Physical Basis for Kirchhoff's Current Law

An appreciation of why KCL is true can be obtained by considering what would happen if it were violated. Suppose that we could have the situation shown in **Figure 1.18(a)**, with $i_1 = 3$ A, $i_2 = 2$ A, and $i_3 = 4$ A. Then, the net current entering the node would be

$$i_1 + i_2 - i_3 = 1 \text{ A} = 1 \text{ C/s}$$

In this case, 1 C of charge would accumulate at the node during each second. After 1 s, we would have +1 C of charge at the node, and −1 C of charge somewhere else in the circuit.

Suppose that these charges are separated by a distance of one meter (m). Recall that unlike charges experience a force of attraction. The resulting force turns out to be approximately 8.99×10^9 newtons (N) (equivalent to 2.02×10^9 pounds). Very large forces are generated when charges of this magnitude are separated by moderate distances. In effect, KCL states that such forces prevent charge from accumulating at the nodes of a circuit.

All points in a circuit that are connected directly by conductors can be considered to be a single node. For example, in **Figure 1.19**, elements *A*, *B*, *C*, and *D* are connected to a common node. Applying KCL, we can write

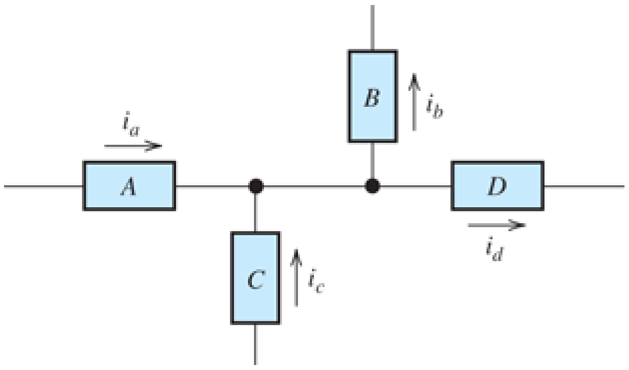


Figure 1.19

Elements *A, B, C,* and *D* can be considered to be connected to a common node, because all points in a circuit that are connected directly by conductors are electrically equivalent to a single point.

$$i_a + i_c = i_b + i_d$$

> All points in a circuit that are connected directly by conductors can be considered to be a single node.

Series Circuits

We make frequent use of KCL in analyzing circuits. For example, consider the elements *A*, *B*, and C shown in **Figure 1.20**. When elements are connected end to end, we say that they are connected in **series**. *In order for elements A and B to be in series, no other path for current can be connected to the node joining A and B. Thus, all elements in a series circuit have identical currents.* For example, writing Kirchhoff's current law at node 1 for the circuit of **Figure 1.20**, we have

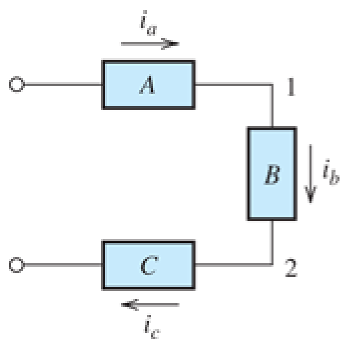


Figure 1.20

Elements *A*, *B*, and *C* are connected in series.

$i_a = i_b$

At node 2, we have

$i_b = i_c$

Thus, we have

$i_a = i_b = i_c$

The current that enters a series circuit must flow through each element in the circuit.

Example 1.4 Kirchhoff's Current Law

Consider the circuit shown in **Figure 1.21**.

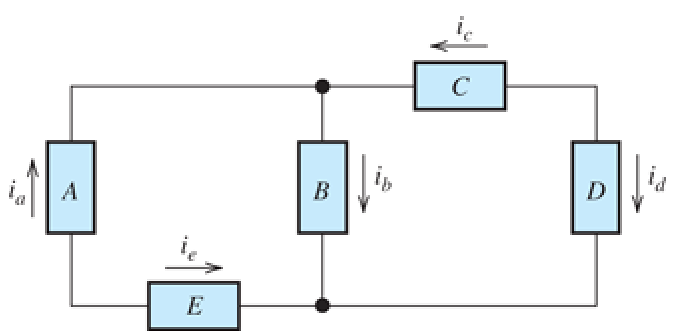


Figure 1.21

Circuit for **Example 1.4**.

a. Which elements are in series?
b. What is the relationship between i_d and i_c?

c. Given that $i_a = 6$ A and $i_c = -2$ A, determine the values of i_b and i_d.

Solution

a. Elements *A* and *E* are in series, and elements *C* and *D* are in series.
b. Because elements *C* and *D* are in series, the currents are equal in magnitude. However, because the reference directions are opposite, the algebraic signs of the current values are opposite. Thus, we have $i_c = -i_d$.
c. At the node joining elements *A, B,* and *C,* we can write the KCL equation $i_b = i_a + i_c = 6 - 2 = 4$ A. Also, we found earlier that $i_d = -i_c = 2$ A.

Exercise 1.7

Use KCL to determine the values of the unknown currents shown in **Figure 1.22**.

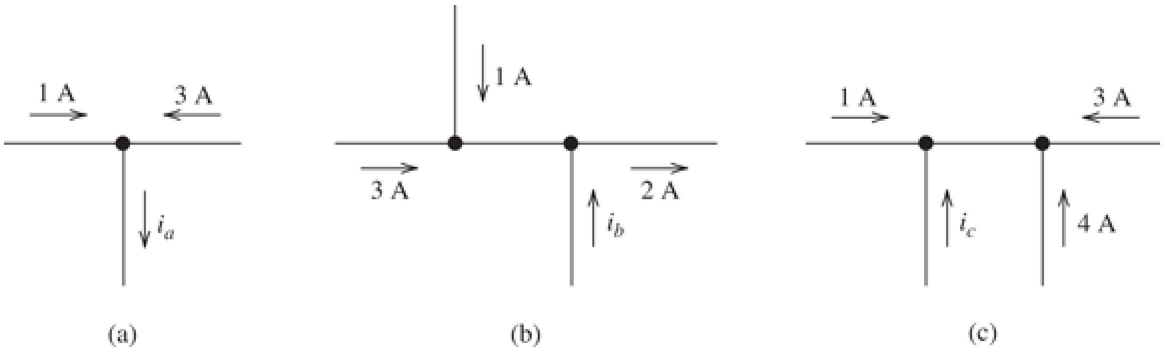


Figure 1.22
See **Exercise 1.7**.

Answer $i_a = 4$ A, $i_b = -2$ A, $i_c = -8$ A.

Exercise 1.8

Consider the circuit of **Figure 1.23**. Identify the groups of circuit elements that are connected in series.

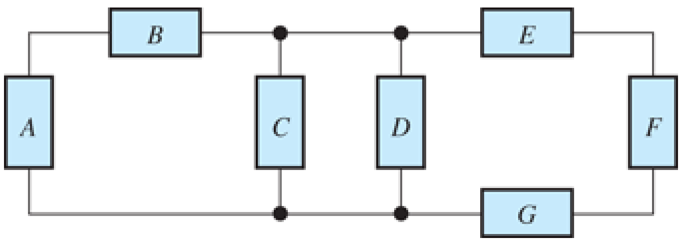


Figure 1.23
Circuit for **Exercise 1.8**.

Answer Elements A and B are in series; elements E, F, and G form another series combination.

1.5 Kirchhoff's Voltage Law

> Kirchhoff's voltage law (KVL) states that the algebraic sum of the voltages equals zero for any closed path (loop) in an electrical circuit.

A **loop** in an electrical circuit is a closed path starting at a node and proceeding through circuit elements, eventually returning to the starting node. Frequently, several loops can be identified for a given circuit. For example, in **Figure 1.23**, one loop consists of the path starting at the top end of element *A* and proceeding clockwise through elements *B* and *C*, returning through *A* to the starting point. Another loop starts at the top of element *D* and proceeds clockwise through *E*, *F*, and *G*, returning to the start through *D*. Still another loop exists through elements *A*, *B*, *E*, *F*, and *G* around the periphery of the circuit.

Kirchhoff's voltage law (KVL) states: *The algebraic sum of the voltages equals zero for any closed path (loop) in an electrical circuit.* In traveling around a loop, we encounter various voltages, some of which carry a positive sign while others carry a negative sign in the algebraic sum. A convenient convention is to use the first polarity mark encountered for each voltage to decide if it should be added or subtracted in the algebraic sum. If we go through the voltage from the positive polarity reference to the negative reference, it carries a plus sign. If the polarity marks are encountered in the opposite direction (minus to plus), the voltage carries a negative sign. This is illustrated in **Figure 1.24**.

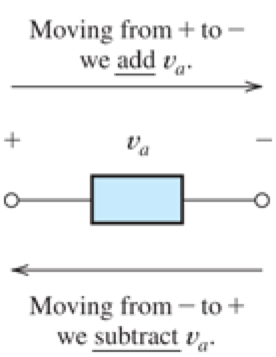


Figure 1.24
In applying KVL to a loop, voltages are added or subtracted depending on their reference polarities relative to the direction of travel around the loop.

For the circuit of **Figure 1.25**, we obtain the following equations:

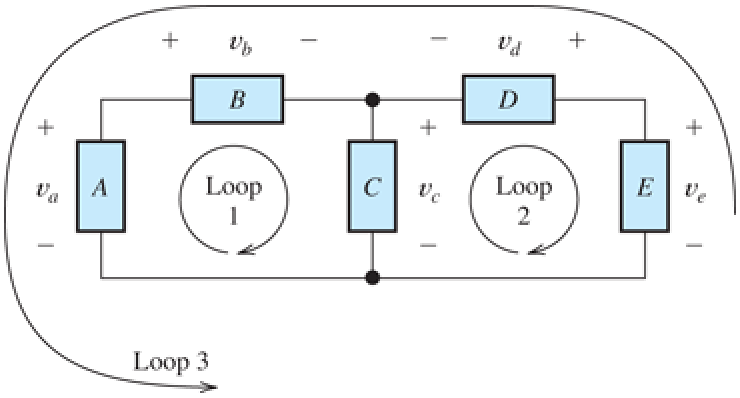


Figure 1.25
Circuit used for illustration of Kirchhoff's voltage law.

Loop 1: $-v_a + v_b + v_c = 0$ Loop 2: $-v_c - v_d + v_e = 0$ Loop 3: $v_a - v_b + v_d - v_e = 0$

Notice that v_a is subtracted for loop 1, but it is added for loop 3, because the direction of travel is different for the two loops. Similarly, v_c is added for loop 1 and subtracted for loop 2.

Kirchhoff's Voltage Law Related to Conservation of Energy

KVL is a consequence of the law of energy conservation. Consider the circuit shown in **Figure 1.26**. This circuit consists of three elements connected in series. Thus, the same current *i* flows through all three elements. The power for each of the elements is given by

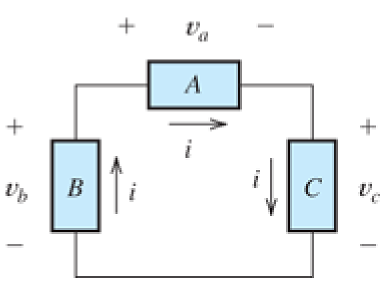


Figure 1.26
In this circuit, conservation of energy requires that $v_b = v_a + v_c$.

Element A: $p_a = v_a i$ Element B: $p_b = -v_b i$ Element C: $p_c = v_c i$

Notice that the current and voltage references have the passive configuration (the current reference enters the plus polarity mark) for elements *A* and *C*. For element *B*, the relationship is opposite to the passive reference configuration. That is why we have a negative sign in the calculation of p_b.

At a given instant, the sum of the powers for all of the elements in a circuit must be zero. Otherwise, for an increment of time taken at that instant, more energy would be absorbed than is supplied by the circuit elements (or vice versa):

$$p_a + p_b + p_c = 0$$

Substituting for the powers, we have

$$v_a i - v_b i + v_c i = 0$$

Canceling the current *i*, we obtain

$$v_a - v_b + v_c = 0$$

This is exactly the same equation that is obtained by adding the voltages around the loop and setting the sum to zero for a clockwise loop in the circuit of **Figure 1.26**.

One way to check our results after solving for the currents and voltages in a circuit is the check to see that the power adds to zero for all of the elements.

Parallel Circuits

We say that two circuit elements are connected in **parallel** if both ends of one element are connected directly (i.e., by conductors) to corresponding ends of the other. For example, in **Figure 1.27**, elements *A* and *B* are in parallel. Similarly, we say that the three circuit elements *D*, *E*, and *F* are in parallel. Element *B* is *not* in parallel with *D* because the top end of *B* is not *directly* connected to the top end of *D*.

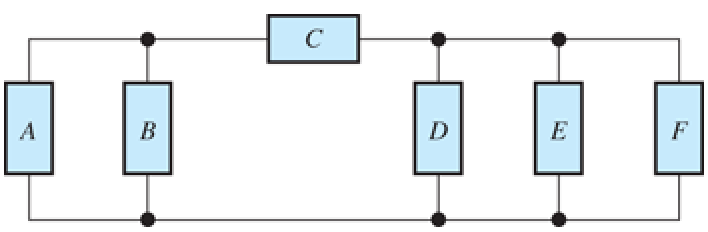


Figure 1.27
In this circuit, elements *A* and *B* are in parallel. Elements *D*, *E*, and *F* form another parallel combination.

Two circuit elements are connected in parallel if both ends of one element are connected directly (i.e., by conductors) to corresponding ends of the other.

The voltages across parallel elements are equal in magnitude and have the same polarity. For illustration, consider the partial circuit shown in **Figure 1.28**. Here elements *A*, *B*, and *C* are connected in parallel. Consider a loop from the bottom end of *A* upward and then down through element *B* back to the bottom of *A*. For this clockwise loop, we have $-v_a + v_b = 0$. Thus, KVL requires that

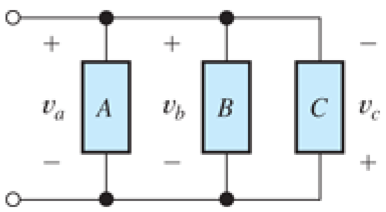


Figure 1.28

For this circuit, we can show that $v_a = v_b = -v_c$. Thus, the magnitudes and *actual* polarities of all three voltages are the same.

$$v_a = v_b$$

Next, consider a clockwise loop through elements *A* and *C*. For this loop, KVL requires that

$$-v_a - v_c = 0$$

This implies that $v_a = -v_c$. In other words, v_a and v_c have opposite algebraic signs. Furthermore, one or the other of the two voltages must be negative (unless both are zero). Therefore, one of the voltages has an actual polarity opposite to the reference polarity shown in the figure. Thus, the actual polarities of the voltages are the same (either both are positive at the top of the circuit or both are positive at the bottom).

Usually, when we have a parallel circuit, we simply use the same voltage variable for all of the elements as illustrated in **Figure 1.29**.

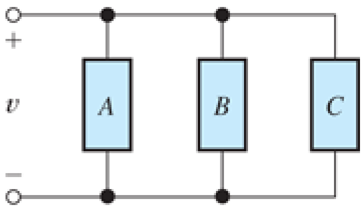


Figure 1.29
Analysis is simplified by using the same voltage variable and reference polarity for elements that are in parallel.

Example 1.5 Kirchhoff's Voltage Law

Consider the circuit shown in **Figure 1.30**.

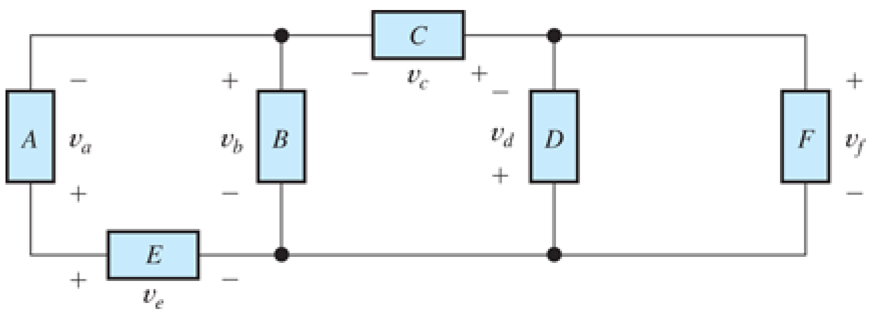


Figure 1.30
Circuit for **Example 1.5**.

a. Which elements are in parallel?
b. Which elements are in series?
c. What is the relationship between v_d and v_f?
d. Given that $v_a = 10$ V, $v_c = 15$ V and $v_e = 20$ V, determine the values of v_b and v_f.

Solution

a. Elements *D* and *F* are in parallel.
b. Elements *A* and *E* are in series.
c. Because elements *D* and *F* are in parallel, v_d and v_f are equal in magnitude. However, because the reference directions are opposite, the algebraic signs of their values are opposite. Thus, we have $v_d = -v_f$.
d. Applying KVL to the loop formed by elements *A, B,* and *E,* we have:

   $$v_a + v_b - v_e = 0$$

   Solving for v_b and substituting values, we find that $v_b = 10$ V.

Applying KVL to the loop around the outer perimeter of the circuit, we have:

$v_a - v_c + v_f = 0$

Solving for v_b and substituting values, we find that $v_b = 10$ V. $v_f = 5$ V. ■

Exercise 1.9

Use repeated application of KVL to find the values of v_c and v_e for the circuit of **Figure 1.31**.

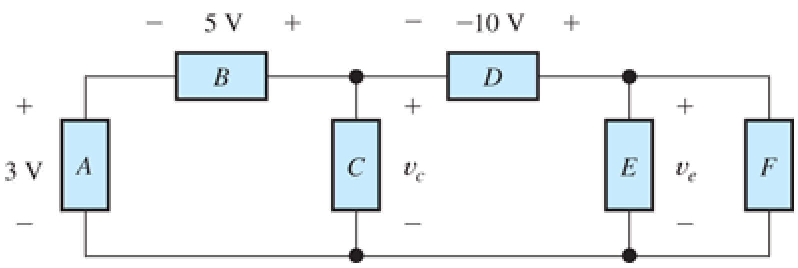


Figure 1.31 Circuit for Exercises 1.9 and 1.10.

Answer $v_c = 8$ V, $v_e = -2$ V.

Exercise 1.10

Identify elements that are in parallel in **Figure 1.31**. Identify elements in series.

Answer Elements *E* and *F* are in parallel; elements *A* and *B* are in series.

1.6 Introduction to Circuit Elements

In this section, we carefully define several types of ideal circuit elements:

Conductors

Voltage sources

Current sources

Resistors

Later in the book, we will encounter additional elements, including inductors and capacitors. Eventually, we will be able to use these idealized circuit elements to describe (model) complex real-world electrical devices.

Conductors

We have already encountered conductors. Ideal conductors are represented in circuit diagrams by unbroken lines between the ends of other circuit elements. We define ideal circuit elements in terms of the relationship between the voltage across the element and the current through it.

> The voltage between the ends of an ideal conductor is zero regardless of the current flowing through the conductor.

The voltage between the ends of an ideal conductor is zero regardless of the current flowing through the conductor. When two points in a circuit are connected together by an ideal conductor, we say that the points are **shorted** together. Another term for an ideal conductor is **short circuit**. All points in a circuit that are connected by ideal conductors can be considered as a single node.

All points in a circuit that are connected by ideal conductors can be considered as a single node.

If no conductors or other circuit elements are connected between two parts of a circuit, we say that an **open circuit** exists between the two parts of the circuit. No current can flow through an ideal open circuit.

Independent Voltage Sources

An **ideal independent voltage source** maintains a specified voltage across its terminals. The voltage across the source is independent of other elements that are connected to it and of the current flowing through it. We use a circle enclosing the reference polarity marks to represent independent voltage sources. The value of the voltage is indicated alongside the symbol. The voltage can be constant or it can be a function of time. Several voltage sources are shown in Figure 1.32.

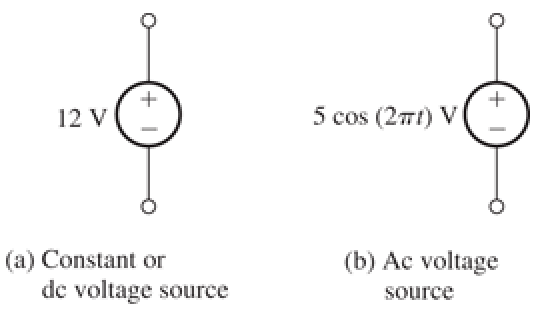


Figure 1.32
Independent voltage sources.

An ideal independent voltage source maintains a specified voltage across its terminals.

In Figure 1.32(a), the voltage across the source is constant. Thus, we have a dc voltage source. On the