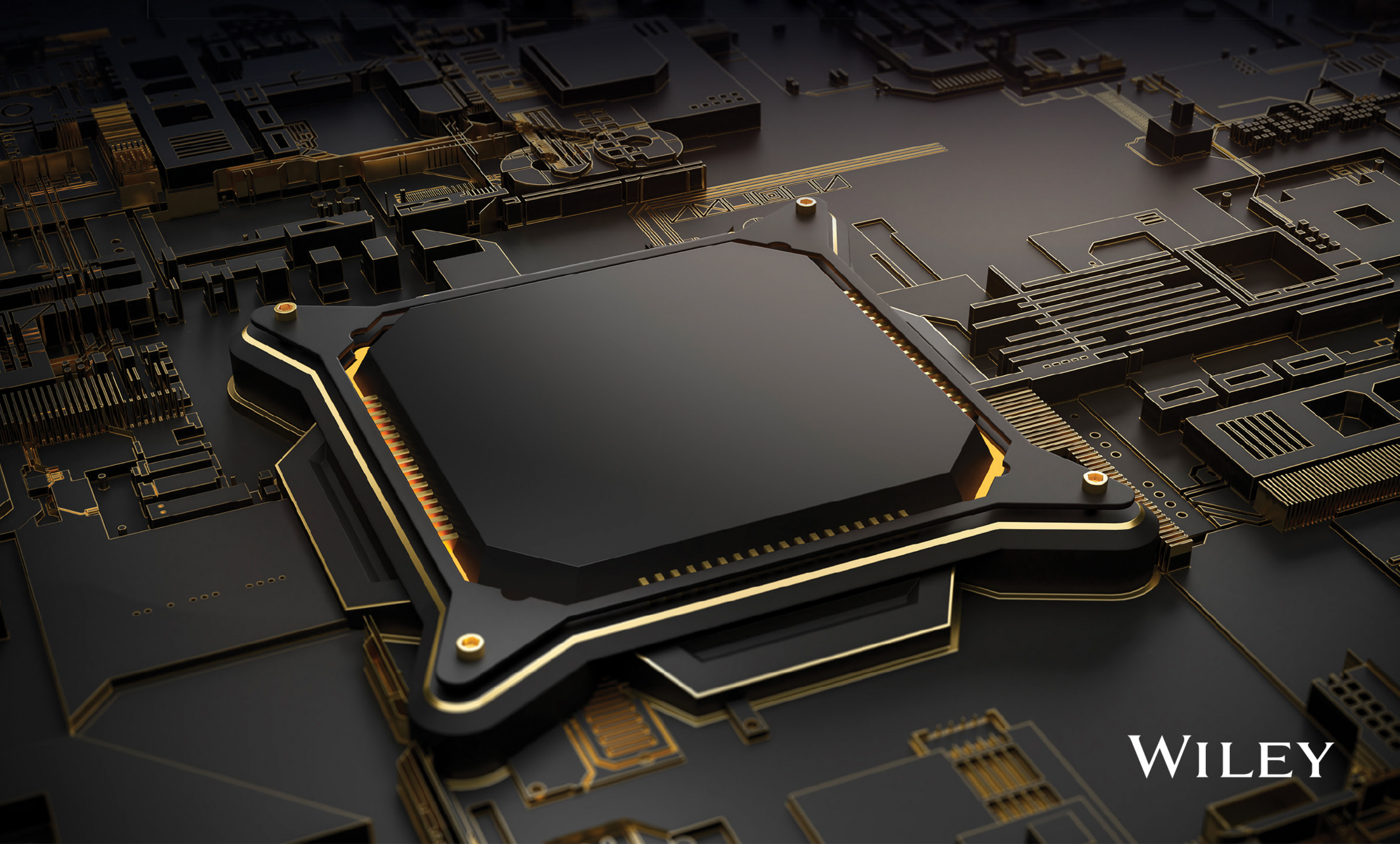
J. DAVID IRWIN • R. MARK NELMS

BASIC ENGINEERING CIRCUIT ANALYSIS

TWELFTH EDITION



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Basic Engineering Circuit Analysis

12th Edition

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Auburn University

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WILEY

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In Loving Memory of My Grandson

Ryan Watson Frazier (1995-2015)

To my parents:

Robert and Elizabeth Nelms

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Preface

To the Student

Circuit analysis is not only fundamental to the entire breadth of electrical and computer engineering—the concepts studied here extend far beyond those boundaries. For this reason, it remains the starting point for many future engineers who wish to work in this field. The text and all the supplementary materials associated with it will aid you in reaching this goal. We strongly recommend while you are here to read the Preface closely and view all the resources available to you as a learner. One last piece of advice: Learning to analyze electric circuits is like learning to play a musical instrument. Most people take music lessons as a starting point. Then, they become proficient through practice, practice, and more practice. Lessons on circuit analysis are provided by your instructor and this textbook. Proficiency in circuit analysis can only be obtained through practice. Take advantage of the many opportunities throughout this textbook to practice, practice, and practice. In the end, you'll be thankful you did.

To the instructor

The Twelfth Edition has been prepared based on a careful examination of feedback received from instructors and students. The revisions and changes made should appeal to a wide variety of instructors. We are aware of significant changes taking place in the way this material is being taught and learned. Consequently, the authors and the publisher have created a formidable array of traditional and nontraditional learning resources to meet the needs of students and teachers of modern circuit analysis.

By design, this book contains a bank of reserve assessment problems not available to students. As a time-saving measure, the instructor can use this bank of problems for exam questions, term after term, without repetition. These problems are organized by chapter section and categorized as easy, medium, and hard. The end-of-chapter problems have been arranged in the same manner. Dedicated students will find these problems an excellent resource for testing their understanding on a range of problems.

Flipping the classroom has risen recently as an alternative mode of instruction, which attempts to help the student grasp the material quicker. Studies to date have shown that this mode also tends to minimize instructor office time. This book, with its combination of Learning Assessments and problem-solving videos, is an ideal vehicle for teaching in this format. These resources provide the instructor with the tools necessary to modify the format of the presentation in the hope of enhancing the student's rapid understanding of the material.

In accordance with the earlier editions, the book contains a plethora of examples that are designed to help the student grasp the salient features of the material quickly. New examples have been introduced, and MATLAB® has been employed, where appropriate, to provide a quick and easy software solution as a means of comparison, as well as to check other solution techniques. Application and Design Examples have returned to this edition. These help students answer questions such as, "Why is this important" or "How am I going to use what I learn from this course?"

Highlights of the Twelfth Edition

- A crisp, clean new interior design aimed at enhancing, clarifying, and unifying the text as well as increasing accessibility for all.
- End-of-chapter homework problems have been substantially revised and augmented. There are now approximately 2400 problems in the Twelfth Edition, of which over 800 are new! Multiple-choice Fundamentals of Engineering (FE) Exam problems also appear at the end of each chapter.
- This course offers Reserve Assessment Bank Problems, which are not available to students unless they are assigned. This allows you, as the instructor, to regulate who sees these questions and the solutions. We now publish new Reserve Assessment Bank Problems on an ongoing basis so you'll frequently have fresh material to work with without needing to move to a whole new edition, and you'll have a constant source of problems to use for higher-stakes assessment. Recognizing that third-party solutions become readily available online as soon as a new edition is published, we now offer whole sets of problems for every chapter that are visible only to the instructor, hindering cheating and allowing instructors to choose which problems to assign as homework, and when and whether to provide solutions.
- Problem-Solving Videos (PSVs) have been created, showing students step-by-step how to solve all Learning Assessment problems within each chapter. This is a special feature that should significantly enhance the learning experience for each subsection in a chapter.
- In order to provide maximum flexibility, online supplements contain solutions to examples in the book using MATLAB, PSpice®, or MultiSim®. The worked examples can be supplied to students as digital files, or one or more of them can be incorporated into custom print editions of the text, depending on the instructor's preference.

- Problem-Solving Strategies have been retained in the Twelfth Edition. They are utilized as a guide for the solutions contained in the PSVs.

Organization

This text is suitable for a one-semester, a two-semester, or a three-quarter course sequence. The first seven chapters are concerned with the analysis of dc circuits. An introduction to operational amplifiers is presented in Chapter 4. This chapter may be omitted without any loss of continuity; a few examples and homework problems in later chapters must be skipped. Chapters 8–12 are focused on the analysis of ac circuits beginning with the analysis of single-frequency circuits (single-phase and three-phase) and ending with variable-frequency circuit operation. Calculation of power in single-phase and three-phase ac circuits is also presented. The important topics of the Laplace transform, Fourier transform, and two-port networks are covered in Chapters 13–16.

The organization of the text provides instructors maximum flexibility in designing their courses. One instructor may choose to cover the first seven chapters in a single semester, while another may omit Chapter 4 and cover Chapters 1–3 and 5–8. Other instructors have chosen to cover Chapters 1–3, 5–6, and sections 7.1 and 7.2 and then cover Chapters 8 and 9. The remaining chapters can be covered in a second semester course.

Text Pedagogy

The pedagogy of this text is rich and varied. It includes print and media, and much thought has been put into integrating its use. To gain the most from this pedagogy, please review the following elements commonly available in most chapters of this book.

Learning Objectives are provided at the outset of each chapter. This tabular list tells the reader what is important and what will be gained from studying the material in the chapter.

Examples are the mainstay of any circuit analysis text, and numerous examples have always been a trademark of this textbook. These examples provide a more graduated level of presentation with simple, medium, and challenging examples. Besides regular examples, numerous **Application Examples** and **Design Examples** are found throughout the text.

Hints can often be found in the page margins. They facilitate understanding and serve as reminders of key issues.

Learning Assessments are a critical learning tool in this text. These exercises test the cumulative concepts to that point in a given section or sections. Not only is the answer provided, but a problem-solving video accompanies each of these exercises, demonstrating the solution in step-by-step detail. The student who masters these is ready to move forward.

Problem-Solving Strategies are step-by-step problem-solving techniques that many students find particularly useful. They answer the frequently asked question, “Where do I begin?” Nearly every chapter has one or more of these strategies, which are a kind of summation on problem solving for concepts presented.

Problems have been greatly revised for the Twelfth Edition. This edition has over 800 new problems of varying depth and level. Any instructor will find numerous problems appropriate for any level class. There are approximately 2400 problems in the Twelfth Edition! Included with the Problems are FE Exam Problems for each chapter. If you plan on taking the FE Exam, these problems closely match problems you will typically find on the FE Exam. Reserve Assessment Bank Problems, not available to students, have been added to this edition for the instructor to utilize as exam questions.

Circuit Simulation and Analysis Software represents a fundamental part of engineering circuit design today. Software such as **PSpice**, **MultiSim**, and **MATLAB** allow engineers to design and simulate circuits quickly and efficiently. As an enhancement with enormous flexibility, all three of these software packages can be employed in the Twelfth Edition. In each case, online supplements are available that contain the solutions to numerous examples in each of these software programs. Instructors can opt to make this material available online or as part of a customized print edition, making this software an integral and effective part of the presentation of course material.

The rich collection of material that is provided for this edition offers a distinctive and helpful way for exploring the book’s examples and exercises from a variety of simulation techniques.

Supplements

The supplements list is extensive and provides instructors and students with a wealth of traditional and modern resources to match different learning needs.

Problem-Solving Videos are offered again in the Twelfth Edition in an iOS-compatible format. The videos provide step-by-step solutions to Learning Assessments. Videos for Learning Assessments will directly follow a chapter feature called *Problem-Solving Strategy*. Students who have used these videos with past editions have found them to be very helpful.

The **Solutions Manual** for the Twelfth Edition has been completely redone, checked, and double-checked for accuracy. It is the most accurate solutions manual ever created for this textbook.

Acknowledgments

Over the more than three decades that this text has been in existence, we estimate that more than one thousand instructors have used our book in teaching circuit analysis to hundreds of thousands of students. As authors, there is no greater reward than having your work used by so many. We are grateful for the confidence shown in our text and for the numerous evaluations and suggestions from professors and their students over the years. This feedback has helped us continuously improve the presentation. For this Twelfth Edition, we especially thank Elizabeth Devore, Tanner Grider, Markus Kreitzer, and Austin Taylor with Auburn University for their assistance with the solutions manual.

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J. DAVID IRWIN AND R. MARK NELMS

CHAPTER 1

Basic Concepts

LEARNING OBJECTIVES

The learning goals for this chapter are that students should be able to:

- Use appropriate SI units and standard prefixes when calculating voltages, currents, resistances, and powers.
- Explain the relationships between basic electrical quantities: voltage, current, and power.
- Use the appropriate symbols for independent and dependent voltage and current sources.
- Calculate the value of the dependent sources when analyzing a circuit that contain independent and dependent sources.
- Calculate the power absorbed by a circuit element using the passive sign convention.

1.1 System of Units

The system of units we employ is the international system of units, the *Système international d'unités*, which is normally referred to as the SI standard system. This system, which is composed of the basic units meter (m), kilogram (kg), second (s), ampere (A), kelvin (K), and candela (cd), is defined in all modern physics texts and therefore will not be defined here. However, we will discuss the units in some detail as we encounter them in our subsequent analyses.

The standard prefixes that are employed in SI are shown in **Fig. 1.1**. Note the decimal relationship between these prefixes. These standard prefixes are employed throughout our study of electric circuits.

Circuit technology has changed drastically over the years. For example, in the early 1960s, the space on a circuit board occupied by the base of a single vacuum tube was about the size of a quarter (25-cent coin). Today that same space could be occupied by an Intel Core i7 integrated circuit chip containing 1.75 billion transistors. These chips are the engine for a host of electronic equipment.

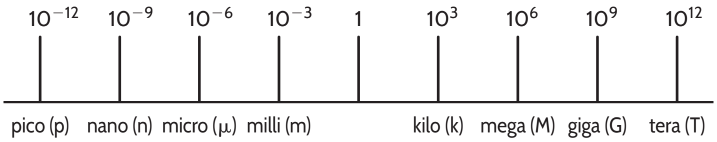


FIGURE 1.1 Standard SI prefixes.

1.2 Basic Quantities

Before we begin our analysis of electric circuits, we must define terms that we will employ. However, in this chapter and throughout the book, our definitions and explanations will be as simple as possible to foster an understanding of the use of the material. No attempt will be made to give complete definitions of many of the quantities because such definitions are not only unnecessary at this level but are often confusing. Although most of us have an intuitive concept of what is meant by a circuit, we will simply refer to an *electric circuit* as an interconnection of electrical components, each of which we will describe with a mathematical model.

The most elementary quantity in an analysis of electric circuits is the electric *charge*. Our interest in electric charge is centered around its motion, since charge in motion results in an energy transfer. Of particular interest to us are those situations in which the motion is confined to a definite closed path.

An electric circuit is essentially a pipeline that facilitates the transfer of charge from one point to another. The time rate of change of charge constitutes an electric *current*. Mathematically, the relationship is expressed as

$$i(t) = \frac{dq(t)}{dt} \qquad \text{or} \qquad q(t) = \int_{-\infty}^{t} i(x)\,dx \tag{1.1}$$

where i and q represent current and charge, respectively (lowercase letters represent time dependency, and capital letters are reserved for constant quantities). The basic unit of current is the ampere (A), and 1 ampere is 1 coulomb (C) per second.

Although we know that current flow in metallic conductors results from electron motion, the conventional current flow, which is universally adopted, represents the movement of positive charges. It is important that the reader think of current flow as the movement of positive charge regardless of the physical phenomena that take place. The symbolism that will be used to represent current flow is shown in **Fig. 1.2**. In **Fig. 1.2a**, $I_1 = 2$ A indicates that at any point in the wire shown, 2 C of charge pass from left to right each second. In **Fig. 1.2b**, $I_2 = -3$ A indicates that at any point in the wire shown, 3 C of charge pass from right to left each second. Therefore, it is important to specify not only the magnitude of the variable representing the current but also its direction.

The two types of current that we encounter often in our daily lives, alternating current (ac) and direct current (dc), are shown as a function of time in **Fig. 1.3**. *Alternating current* is the common current found in every household and is used to run the refrigerator, stove, washing machine, and so on. Batteries, which are used in automobiles and flashlights, are one source of *direct current*. In addition to these two types of currents, which have a wide variety of uses, we can generate many other types of currents. We will examine some of these other types later in the book. In the meantime, it is interesting to note that the magnitude of currents in elements familiar to us ranges from soup to nuts, as shown in **Fig. 1.4**.

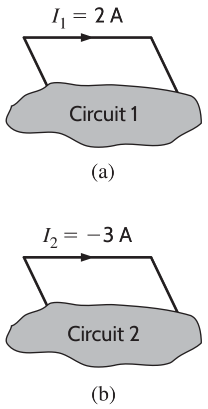


FIGURE 1.2 Conventional current flow: (a) positive current flow; (b) negative current flow.

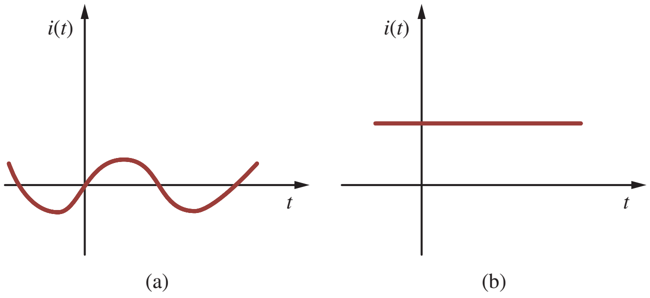


FIGURE 1.3 Two common types of current: (a) alternating current (ac); (b) direct current (dc).

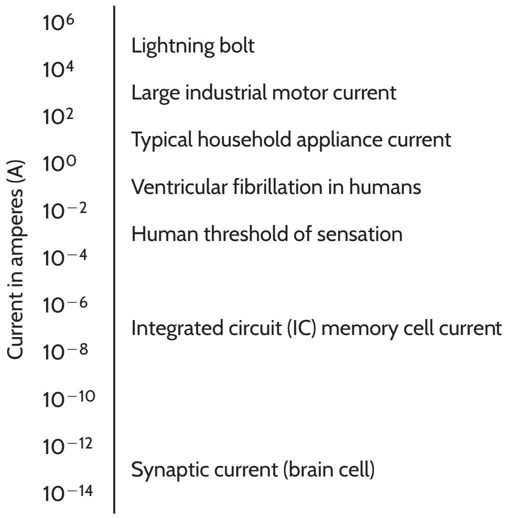


FIGURE 1.4 Typical current magnitudes.

We have indicated that charges in motion yield an energy transfer. Now we define the *voltage* (also called the *electromotive force*, or *potential*) between two points in a circuit as the difference in energy level of a unit charge located at each of the two points. Voltage is very similar to a gravitational force. Think about a bowling ball being dropped from a ladder into a tank of water. As soon as the ball is released, the force of gravity pulls it toward the bottom of the tank. The potential energy of the bowling ball decreases as it approaches the bottom. The gravitational force is pushing the bowling ball through the water. Think of the bowling ball as a charge and the voltage as the force pushing the charge through a circuit. Charges in motion represent a current, so the motion of the bowling ball could be thought of as a current. The water in the tank will resist the motion of the bowling ball. The motion of charges in an electric circuit will be impeded or resisted as well. We will introduce the concept of resistance in Chapter 2 to describe this effect.

Work or energy, $w(t)$ or W, is measured in joules (J); 1 joule is 1 newton meter (N·m). Hence, voltage [$v(t)$ or V] is measured in volts (V), and 1 volt is 1 joule per coulomb; that is, 1 volt = 1 joule per coulomb = 1 newton meter per coulomb. If a unit positive charge is moved between two points, the energy required to move it is the difference in energy level between the two points and is the defined voltage. It is extremely important that the variables used to represent voltage between two points be defined in such a way that the solution will let us interpret which point is at the higher potential with respect to the other.

In **Fig. 1.5a**, the variable that represents the voltage between points A and B has been defined as V_1, and it is assumed that point A is at a higher potential than point B, as indicated by the + and − signs associated with the variable and defined in the figure. The + and − signs define a reference direction for V_1. If $V_1 = 2$ V, then the difference in potential of points A and B is 2 V, and point A is at the higher potential. If a unit positive charge is moved from point A through the circuit to point B, it will give up energy to the circuit and have 2 J less energy when it reaches point B. If a unit positive charge is moved from point B to point A, extra energy must be added to the charge by the circuit, and hence the charge will end up with 2 J more energy at point A than it started with at point B.

For the circuit in **Fig. 1.5b**, $V_2 = -5$ V means that the potential between points A and B is 5 V and point B is at the higher potential. The voltage in Fig. 1.5b can be expressed as shown in **Fig. 1.5c**. In this equivalent case, the difference in potential between points A and B is $V_2 = 5$ V, and point B is at the higher potential.

Note that it is important to define a variable with a reference direction so that the answer can be interpreted to give the physical condition in the circuit. We will find that it is not possible in many cases to define the variable so that the answer is positive, and we will also find that it is not necessary to do so.

As demonstrated in Figs. 1.5b and 1.5c, a negative number for a given variable, for example, V_2 in Fig. 1.5b, gives exactly the same information as a positive number; that is, V_2 in

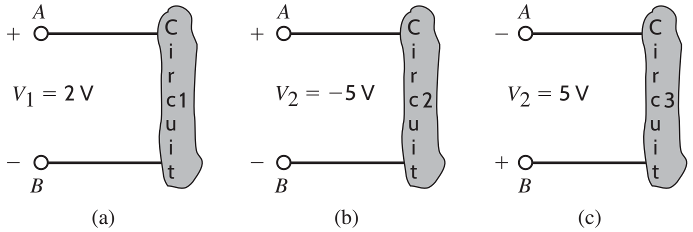


FIGURE 1.5 Voltage representations.

Fig. 1.5c, except that it has an opposite reference direction. Hence, when we define either current or voltage, it is absolutely necessary that we specify both magnitude and direction. Therefore, it is incomplete to say that the voltage between two points is 10 V or the current in a line is 2 A, since only the magnitude and not the direction for the variables has been defined.

The range of magnitudes for voltage, equivalent to that for currents in Fig. 1.4, is shown in **Fig. 1.6**. Once again, note that this range spans many orders of magnitude.

At this point, we have presented the conventions that we employ in our discussions of current and voltage. *Energy* is yet another important term of basic significance. Let's investigate the voltage–current relationships for energy transfer using the flashlight shown in **Fig. 1.7**. The basic elements of a flashlight are a battery, a switch, a light bulb, and connecting wires. Assuming a good battery, we all know that the light bulb will glow when the switch is closed. A current now flows in this closed circuit as charges flow out of the positive terminal of the battery through the switch and light bulb and back into the negative terminal of the battery. The current heats up the filament in the bulb, causing it to glow and emit light. The light bulb converts electrical energy to thermal energy; as a result, charges passing through the bulb lose energy. These charges acquire energy as they pass through the battery as chemical energy is converted to electrical energy. An energy conversion process is occurring in the flashlight as the chemical energy in the battery is converted to electrical energy, which is then converted to thermal energy in the light bulb.

Let's redraw the flashlight as shown in **Fig. 1.8**. There is a current *I* flowing in this diagram. Since we know that the light bulb uses energy, the charges coming out of the bulb have less energy than those entering the light bulb. In other words, the charges expend energy as they move through the bulb. This is indicated by the voltage shown across the bulb. The charges gain energy as they pass through the battery, which is indicated by the voltage across

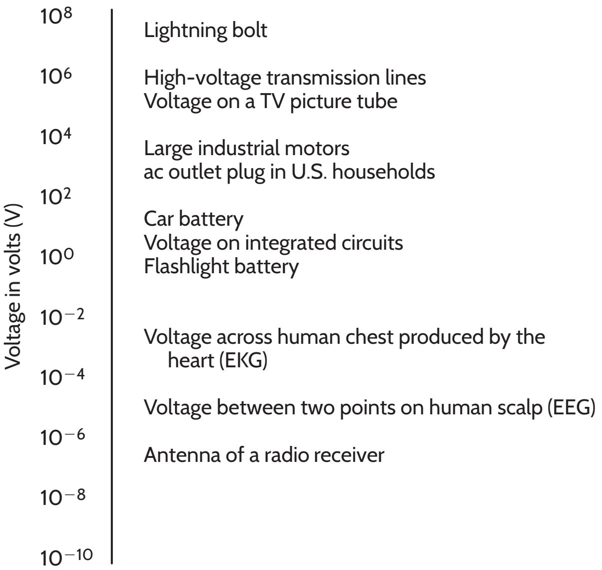


FIGURE 1.6 Typical voltage magnitudes.

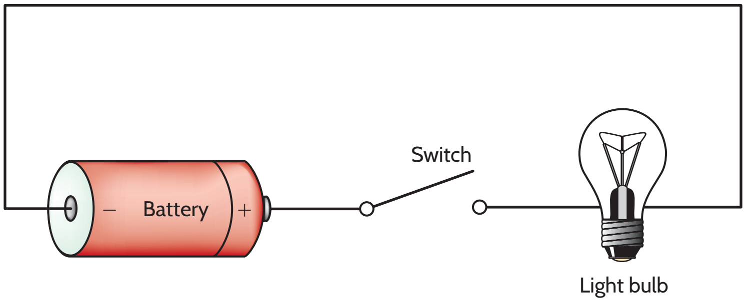


FIGURE 1.7 Flashlight circuit.

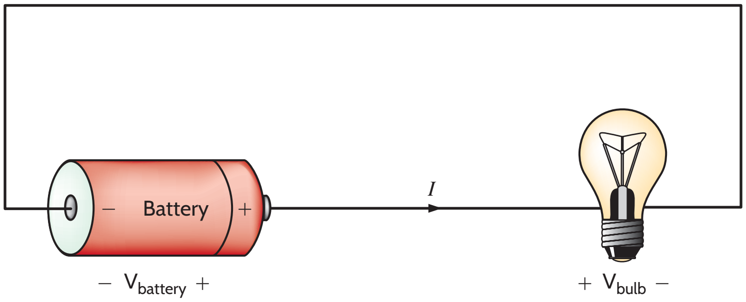


FIGURE 1.8 Flashlight circuit with voltages and current.

the battery. Note the voltage–current relationships for the battery and bulb. We know that the bulb is absorbing energy; the current is entering the positive terminal of the voltage. For the battery, the current is leaving the positive terminal, which indicates that energy is being supplied.

This is further illustrated in **Fig. 1.9**, where a circuit element has been extracted from a larger circuit for examination. In **Fig. 1.9a**, energy is being supplied *to* the element by whatever is attached to the terminals. Note that 2 A—that is, 2 C of charge—are moving from point *A* to point *B* through the element each second. Each coulomb loses 3 J of energy as it passes through the element from point *A* to point *B*. Therefore, the element is absorbing 6 J of energy per second. Note that when the element is *absorbing* energy, a positive current enters the positive terminal. In **Fig. 1.9b**, energy is being supplied *by* the element to whatever is connected to terminals *A-B*. In this case, note that when the element is *supplying* energy, a positive current enters the negative terminal and leaves via the positive terminal. In this convention, a negative current in one direction is equivalent to a positive current in the opposite direction, and vice versa. Similarly, a negative voltage in one direction is equivalent to a positive voltage in the opposite direction.

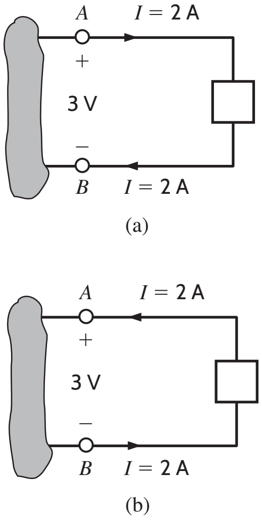


FIGURE 1.9 Voltage–current relationships for (a) energy absorbed and (b) energy supplied.

EXAMPLE 1.1

Suppose that your car will not start. To determine whether the battery is faulty, you turn on the light switch and find that the lights are very dim, indicating a weak battery. You borrow a friend's car and a set of jumper cables. However, how do you connect his car's battery to yours? What do you want his battery to do?

Solution Essentially, his car's battery must supply energy to yours, and therefore it should be connected in the manner shown in **Fig. 1.10**. Note that the positive current leaves the positive terminal of the good battery (supplying energy) and enters the positive terminal of the weak battery (absorbing energy). Note that the same connections are used when charging a battery.

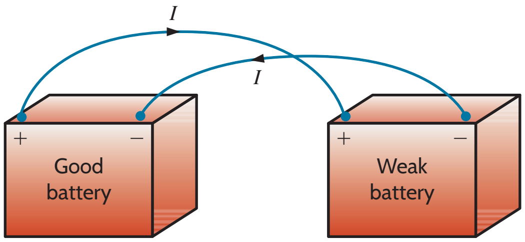


FIGURE 1.10 Diagram for Example 1.1.

In practical applications, there are often considerations other than simply the electrical relations (e.g., safety). Such is the case with jump-starting an automobile. Automobile batteries produce explosive gases that can be ignited accidentally, causing severe physical injury. Be safe—follow the procedure described in your auto owner's manual.

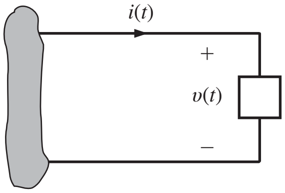


FIGURE 1.11 Sign convention for power.

We have defined voltage in joules per coulomb as the energy required to move a positive charge of 1 C through an element. If we assume that we are dealing with a differential amount of charge and energy, then

$$v = \frac{dw}{dq} \qquad 1.2$$

Multiplying this quantity by the current in the element yields

$$vi = \frac{dw}{dq}\left(\frac{dq}{dt}\right) = \frac{dw}{dt} = p \qquad 1.3$$

which is the time rate of change of energy or power measured in joules per second, or watts (W). Since, in general, both v and i are functions of time, p is also a time-varying quantity. Therefore, the change in energy from time t_1 to time t_2 can be found by integrating Eq. (1.3); that is,

$$\Delta w = \int_{t_1}^{t_2} p\,dt = \int_{t_1}^{t_2} v\,i\,dt \qquad 1.4$$

HINT 1.1

The passive sign convention is used to determine whether power is being absorbed or supplied.

At this point, let us summarize our sign convention for power. To determine the sign of any of the quantities involved, the variables for the current and voltage should be arranged as shown in **Fig. 1.11**. The variable for the voltage $v(t)$ is defined as the voltage across the element with the positive reference at the same terminal that the current variable $i(t)$ is entering. This convention is called the *passive sign convention* and will be so noted in the remainder of this book. The product of v and i, with their attendant signs, will determine the magnitude and sign of the power (see **HINT 1.1**). If the sign of the power is positive, power is being absorbed by the element; if the sign is negative, power is being supplied by the element.

EXAMPLE 1.2

Given the two diagrams shown in **Fig. 1.12**, determine whether the element is absorbing or supplying power and how much.

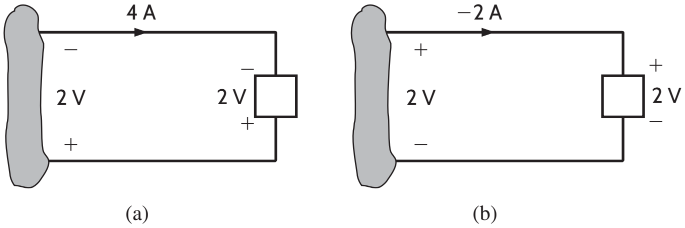


FIGURE 1.12 Elements for Example 1.2.

Solution In **Fig. 1.12a**, the power is $P = (2\text{ V})(-4\text{ A}) = -8$ W. Therefore, the element is supplying power. In **Fig. 1.12b**, the power is $P = (2\text{ V})(-2\text{ A}) = -4$ W. Therefore, the element is supplying power.

Learning Assessment

E1.1 Determine the amount of power absorbed or supplied by the elements in Fig. E1.1.

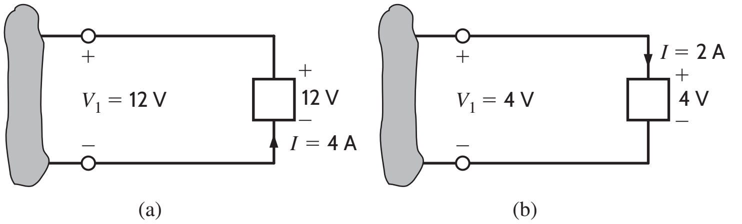


FIGURE E1.1

Answer:

(a) $P = -48$ W;

(b) $P = 8$ W.

EXAMPLE 1.3

We wish to determine the unknown voltage or current in **Fig. 1.13**.

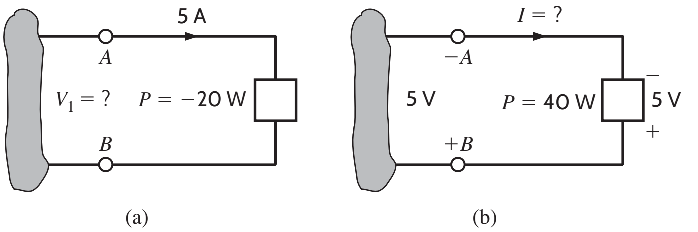


FIGURE 1.13 Elements for Example 1.3.

Solution In **Fig. 1.13a**, a power of −20 W indicates that the element is delivering power. Therefore, the current enters the negative terminal (terminal A), and from Eq. (1.3) the voltage is 4 V. Thus, B is the positive terminal, A is the negative terminal, and the voltage between them is 4 V.

In **Fig. 1.13b**, a power of +40 W indicates that the element is absorbing power and, therefore, the current should enter the positive terminal B. The current thus has a value of −8 A, as shown in the figure.

Learning Assessment

E1.2 Determine the unknown variables in Fig. E1.2.

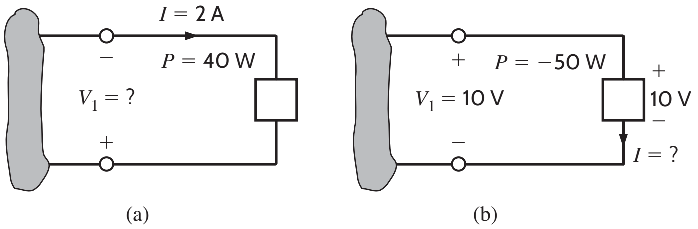


FIGURE E1.2

Answer:

(a) $V_1 = -20$ V;

(b) $I = -5$ A.

Finally, it is important to note that our electrical networks satisfy the principle of conservation of energy. Because of the relationship between energy and power, it can be implied that power is also conserved in an electrical network. This result was formally stated in 1952 by B. D. H. Tellegen and is known as Tellegen's theorem—the sum of the powers absorbed by all elements in an electrical network is zero. Another statement of this theorem is that the power supplied in a network is exactly equal to the power absorbed. Checking to verify that Tellegen's theorem is satisfied for a particular network is one way to check our calculations when analyzing electrical networks.

1.3 Circuit Elements

Thus far, we have defined voltage, current, and power. In the remainder of this chapter we will define both independent and dependent current and voltage sources. Although we will assume ideal elements, we will try to indicate the shortcomings of these assumptions as we proceed with the discussion.

In general, the elements we will define are terminal devices that are completely characterized by the current through the element and/or the voltage across it. These elements, which we will employ in constructing electric circuits, will be broadly classified as being either active or passive. The distinction between these two classifications depends essentially on one thing—whether they supply or absorb energy. As the words themselves imply, an *active* element is capable of generating energy and a *passive* element cannot generate energy.

However, later we will show that some passive elements are capable of storing energy. Typical active elements are batteries and generators. The three common passive elements are resistors, capacitors, and inductors.

In Chapter 2, we will launch an examination of passive elements by discussing the resistor in detail. Before proceeding with that element, we first present some very important active elements.

1. Independent voltage source
2. Independent current source
3. Two dependent voltage sources
4. Two dependent current sources

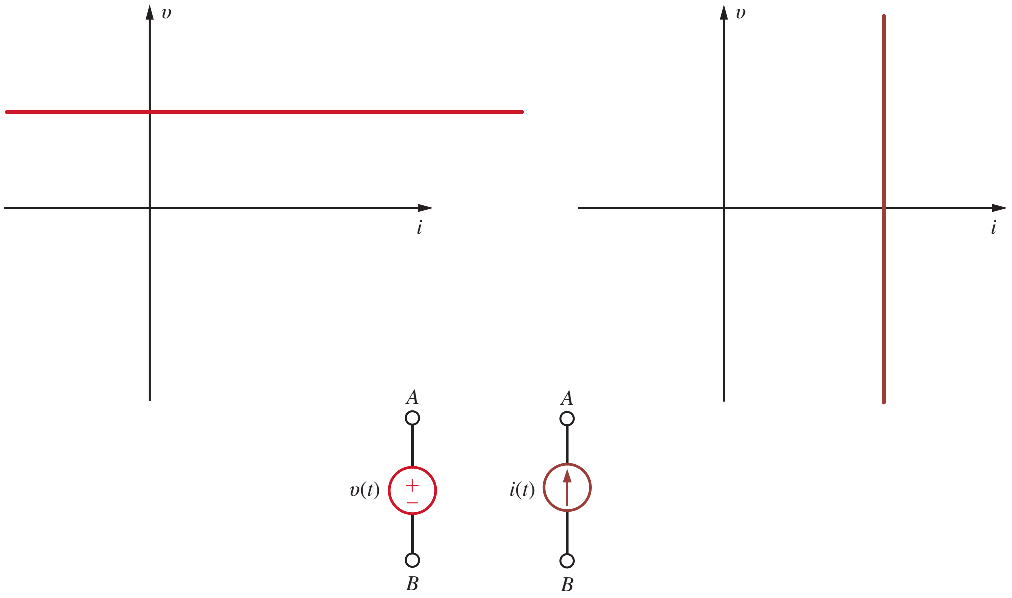
Independent Sources

An *independent voltage source* is a two-terminal element that maintains a specified voltage between its terminals *regardless of the current through it,* as shown by the v-i plot in **Fig. 1.14a**. The general symbol for an independent source, a circle, is also shown in Fig. 1.14a. As the figure indicates, terminal A is $v(t)$ volts positive with respect to terminal B.

In contrast to the independent voltage source, the *independent current source* is a two-terminal element that maintains a specified current *regardless of the voltage across its terminals*, as illustrated by the v-i plot in **Fig. 1.14b**. The general symbol for an independent current source is also shown in Fig. 1.14b, where $i(t)$ is the specified current and the arrow indicates the positive direction of current flow.

In their normal mode of operation, independent sources supply power to the remainder of the circuit. However, they may also be connected into a circuit in such a way that they absorb power. A simple example of this latter case is a battery-charging circuit, such as that shown in Example 1.1.

It is important that we pause here to interject a comment concerning a shortcoming of the models. In general, mathematical models approximate actual physical systems only under a certain range of conditions. Rarely does a model accurately represent a physical system under every set of conditions. To illustrate this point, consider the model for the voltage source in Fig. 1.14a. We assume that the voltage source delivers v volts regardless of what is connected to its terminals. Theoretically, we could adjust the external circuit so that an infinite amount of current would flow, and therefore the voltage source would deliver an infinite amount of power. This is, of course, physically impossible. A similar argument could be made for the independent current source. Hence, the reader is cautioned to keep in mind that models have limitations and thus are valid representations of physical systems only under certain conditions.



(a) (b)

FIGURE 1.14 Symbols for (a) independent voltage source and (b) independent current source.

For example, can the independent voltage source be utilized to model the battery in an automobile under all operating conditions? With the headlights on, turn on the radio. Do the headlights dim with the radio on? They probably won't if the sound system in your automobile was installed at the factory. If you try to crank your car with the headlights on, you will notice that the lights dim. The starter in your car draws considerable current, thus causing the voltage at the battery terminals to drop and dimming the headlights. The independent voltage source is a good model for the battery with the radio turned on; however, an improved model is needed for your battery to predict its performance under cranking conditions.

EXAMPLE 1.4

Determine the power absorbed or supplied by the elements in the network in **Fig. 1.15**.

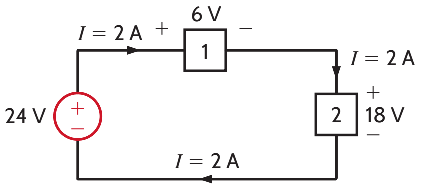


FIGURE 1.15 Network for Example 1.4.

Solution The current flow is out of the positive terminal of the 24-V source, and therefore this element is supplying (2)(24) = 48 W of power. The current is into the positive terminals of elements 1 and 2, and therefore elements 1 and 2 are absorbing (2)(6) = 12 W and (2)(18) = 36 W, respectively. Note that the power supplied is equal to the power absorbed. Also note that the same 2 A current flows through all elements in this circuit (see **HINT 1.2**).

HINT 1.2

Elements that are connected in series have the same current.

Learning Assessment

E1.3 Find the power that is absorbed or supplied by the elements in Fig. E1.3.

Answer:

Current source supplies 36 W, element 1 absorbs 54 W, and element 2 supplies 18 W.

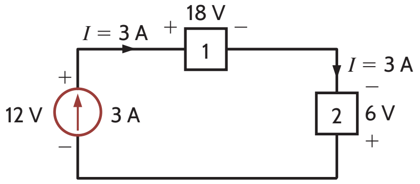


FIGURE E1.3

Dependent Sources

In contrast to the independent sources, which produce a particular voltage or current completely unaffected by what is happening in the remainder of the circuit, dependent sources generate a voltage or current that is determined by a voltage or current at a specified location in the circuit. These sources are very important because they are an integral part of the mathematical models used to describe the behavior of many electronic circuit elements.

For example, metal-oxide-semiconductor field-effect transistors (MOSFETs) and bipolar transistors, both of which are commonly found in a host of electronic equipment, are modeled with dependent sources, and therefore the analysis of electronic circuits involves the use of these controlled elements.

In contrast to the circle used to represent independent sources, a diamond is used to represent a dependent or controlled source. **Fig. 1.16** illustrates the four types of dependent sources. The input terminals on the left represent the voltage or current that controls the dependent source, and the output terminals on the right represent the output current or voltage of the controlled source. Note that in **Figs. 1.16a** and **d**, the quantities μ and β are dimensionless constants because we are transforming voltage to voltage and current to current. This is not the case in **Figs. 1.16b** and **c**; hence, when we employ these elements a short time later, we must describe the units of the factors *r* and *g*.

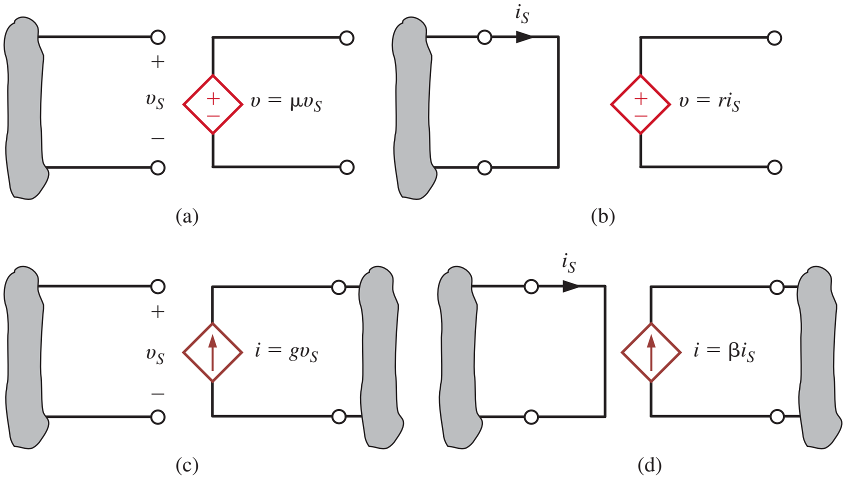


FIGURE 1.16 Four different types of dependent sources.

EXAMPLE 1.5

Given the two networks shown in **Fig. 1.17**, we wish to determine the outputs.

Solution In **Fig. 1.17a**, the output voltage is $V_o = \mu V_S$ or $V_o = 20\ V_S = (20)(2\text{ V}) = 40$ V. Note that the output voltage has been amplified from 2 V at the input terminals to 40 V at the output terminals; that is, the circuit is a voltage amplifier with an amplification factor of 20.

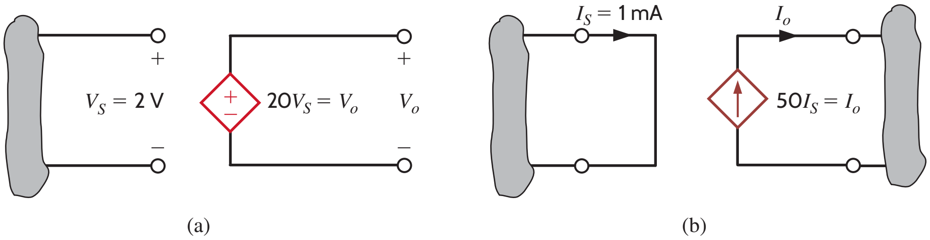


FIGURE 1.17 Circuits for Example 1.5.

In **Fig. 1.17b**, the output current is $I_o = \beta I_S = (50)(1\text{ mA}) = 50$ mA; that is, the circuit has a current gain of 50, meaning that the output current is 50 times greater than the input current.

Learning Assessment

E1.4 Determine the power supplied by the dependent sources in Fig. E1.4.

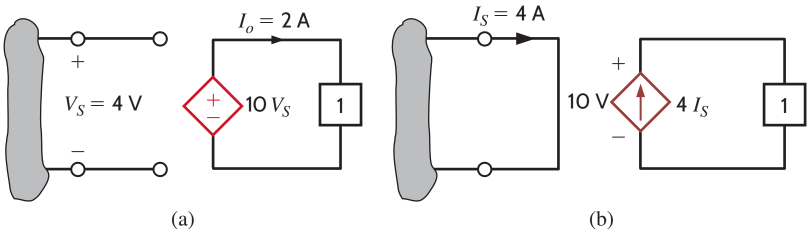


FIGURE E1.4

Answer:

(a) Power supplied = 80 W;

(b) Power supplied = 160 W.

EXAMPLE 1.6

Calculate the power absorbed by each element in the network of **Fig. 1.18**. Also verify that Tellegen's theorem is satisfied by this network.

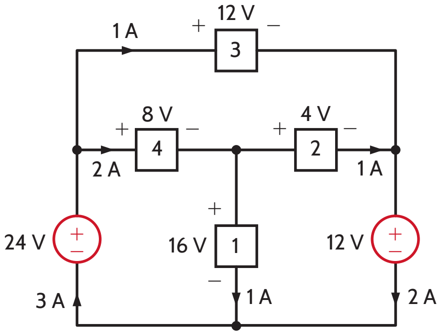


FIGURE 1.18 Circuit used in Example 1.6.

Solution Let's calculate the power absorbed by each element using the sign convention for power.

$$P_1 = (16)(1) = 16\text{ W}$$
$$P_2 = (4)(1) = 4\text{ W}$$
$$P_3 = (12)(1) = 12\text{ W}$$
$$P_4 = (8)(2) = 16\text{ W}$$
$$P_{12\text{ V}} = (12)(2) = 24\text{ W}$$
$$P_{24\text{ V}} = (24)(-3) = -72\text{ W}$$

Note that to calculate the power absorbed by the 24-V source, the current of 3 A flowing up through the source was changed to a current −3 A flowing down through the 24-V source.

Let's sum up the power absorbed by all elements: $16 + 4 + 12 + 16 + 24 - 72 = 0$

This sum is zero, which verifies that Tellegen's theorem is satisfied.

EXAMPLE 1.7

Use Tellegen's theorem to find the current I_o in the network in **Fig. 1.19**.

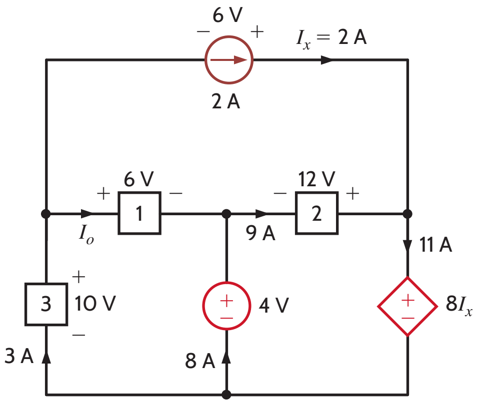


FIGURE 1.19 Circuit used in Example 1.7.

Solution First, we must determine the power absorbed by each element in the network. Using the sign convention for power, we find

$$P_{2\text{ A}} = (6)(-2) = -12\text{ W}$$
$$P_1 = (6)(I_o) = 6I_o\text{ W}$$
$$P_2 = (12)(-9) = -108\text{ W}$$
$$P_3 = (10)(-3) = -30\text{ W}$$
$$P_{4\text{ V}} = (4)(-8) = -32\text{ W}$$
$$P_{DS} = (8I_x)(11) = (16)\,(11) = 176\text{ W}$$

Applying Tellegen's theorem yields

$$-12 + 6I_o - 108 - 30 - 32 + 176 = 0$$

or

$$6I_o + 176 = 12 + 108 + 30 + 32$$

Hence,

$$I_o = 1\text{ A}$$

Learning Assessments

E1.5 Find the power that is absorbed or supplied by the circuit elements in the network in Fig. E1.5.

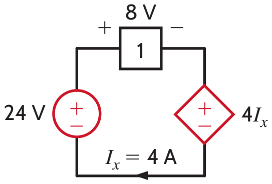


FIGURE E1.5

Answer:

$P_{24\text{ V}} = 96$ W supplied;

$P_1 = 32$ W absorbed;

$P_{4I_x} = 64$ W absorbed.

E1.6 Find the power that is absorbed or supplied by the network elements in Fig. E1.6.

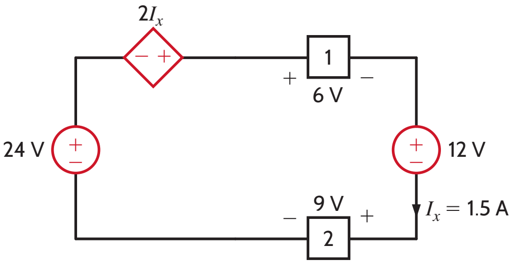


FIGURE E1.6

Answer:

$P_{24\text{ V}} = 36$ W supplied;

$P_{12\text{ V}} = 18$ W absorbed;

$P_{2I_x} = 4.5$ W supplied;

$P_1 = 9$ W absorbed;

$P_2 = 13.5$ W absorbed.

E1.7 Find I_x in Fig. E1.7 using Tellegen's theorem.

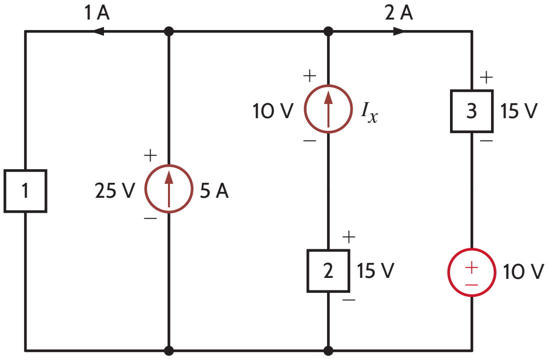


FIGURE E1.7

Answer:

$I_x = -2$ A.

EXAMPLE 1.8

The charge that enters the BOX is shown in **Fig. 1.20**. Calculate and sketch the current flowing into and the power absorbed by the BOX between 0 and 10 milliseconds.

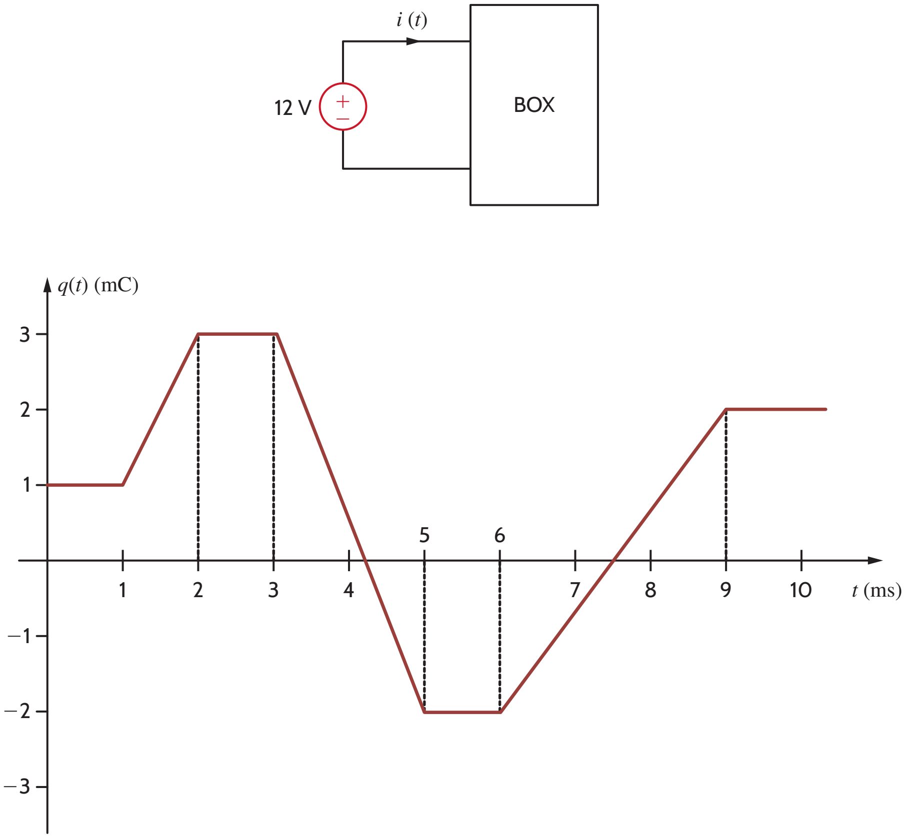


FIGURE 1.20 Diagrams for Example 1.8.

Solution Recall that current is related to charge by $i(t) = \dfrac{dq(t)}{dt}$. The current is equal to the slope of the charge waveform.

$$
\begin{aligned}
&i(t) = 0 && 0 \le t \le 1 \text{ ms}\\
&i(t) = \frac{3\times10^{-3} - 1\times10^{-3}}{2\times10^{-3} - 1\times10^{-3}} = 2 \text{ A} && 1 \le t \le 2 \text{ ms}\\
&i(t) = 0 && 2 \le t \le 3 \text{ ms}\\
&i(t) = \frac{-2\times10^{-3} - 3\times10^{-3}}{5\times10^{-3} - 3\times10^{-3}} = -2.5 \text{ A} && 3 \le t \le 5 \text{ ms}\\
&i(t) = 0 && 5 \le t \le 6 \text{ ms}\\
&i(t) = \frac{2\times10^{-3} - (-2\times10^{-3})}{9\times10^{-3} - 6\times10^{-3}} = 1.33 \text{ A} && 6 \le t \le 9 \text{ ms}\\
&i(t) = 0 && t \ge 9 \text{ ms}
\end{aligned}
$$

The current is plotted with the charge waveform in **Fig. 1.21**. Note that the current is zero during times when the charge is a constant value. When the charge is increasing, the current is positive, and when the charge is decreasing, the current is negative.

The power absorbed by the BOX is $12 \times i(t)$.

$$
\begin{aligned}
&p(t) = 12(0) = 0 && 0 \le t \le 1 \text{ ms}\\
&p(t) = 12(2) = 24 \text{ W} && 1 \le t \le 2 \text{ ms}\\
&p(t) = 12(0) = 0 && 2 \le t \le 3 \text{ ms}\\
&p(t) = 12(-2.5) = -30 \text{ W} && 3 \le t \le 5 \text{ ms}
\end{aligned}
$$

$$p(t) = 12(0) = 0 \qquad 5 \le t \le 6 \text{ ms}$$

$$p(t) = 12(1.33) = 16 \text{ W} \qquad 6 \le t \le 9 \text{ ms}$$

$$p(t) = 12(0) = 0 \qquad t \ge 9 \text{ ms}$$

The power absorbed by the BOX is plotted in **Fig. 1.22**. For the time intervals, $1 \le t \le 2$ ms and $6 \le t \le 9$ ms, the BOX is absorbing power. During the time interval $3 \le t \le 5$ ms, the power absorbed by the BOX is negative, which indicates that the BOX is supplying power to the 12-V source.

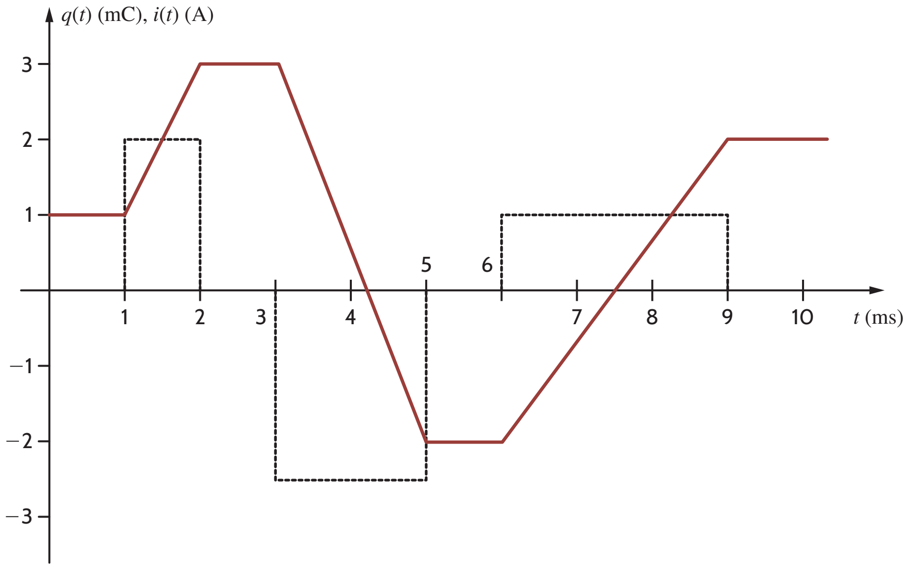


FIGURE 1.21 Charge and current waveforms for Example 1.8.

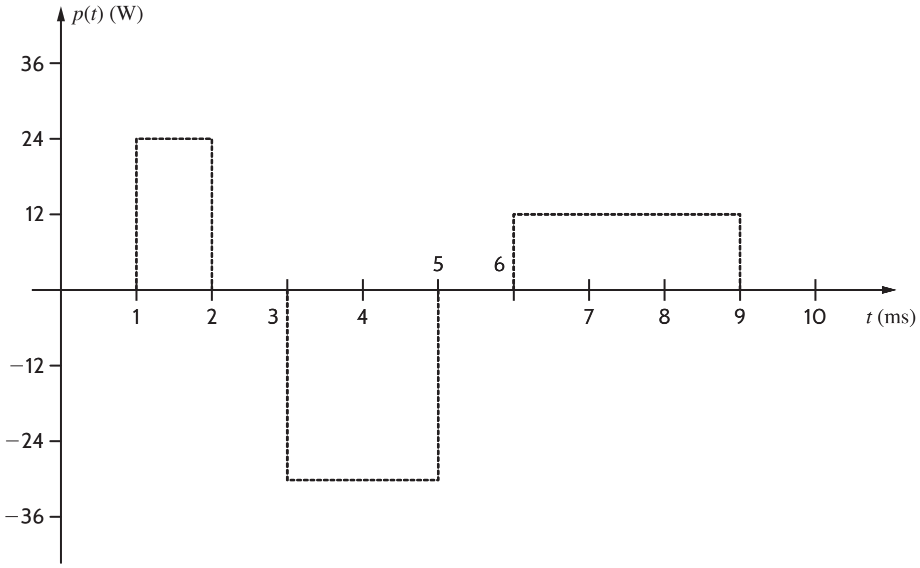


FIGURE 1.22 Power waveform for Example 1.8.

Learning Assessments

E1.8 The power absorbed by the BOX in Fig. E1.8 is $p(t) = 2.5e^{-4t}$ W. Compute the energy and charge delivered to the BOX in the time interval $0 < t < 250$ ms.

Answer:

395.1 mJ; 8.8 mC.

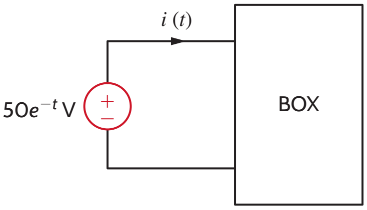


FIGURE E1.8

E1.9 The energy absorbed by the BOX is shown in Fig. E1.9. Calculate and sketch the current flowing into the BOX. Also calculate the charge that enters the BOX between 0 and 12 seconds.

Answer:

$Q = 0$.

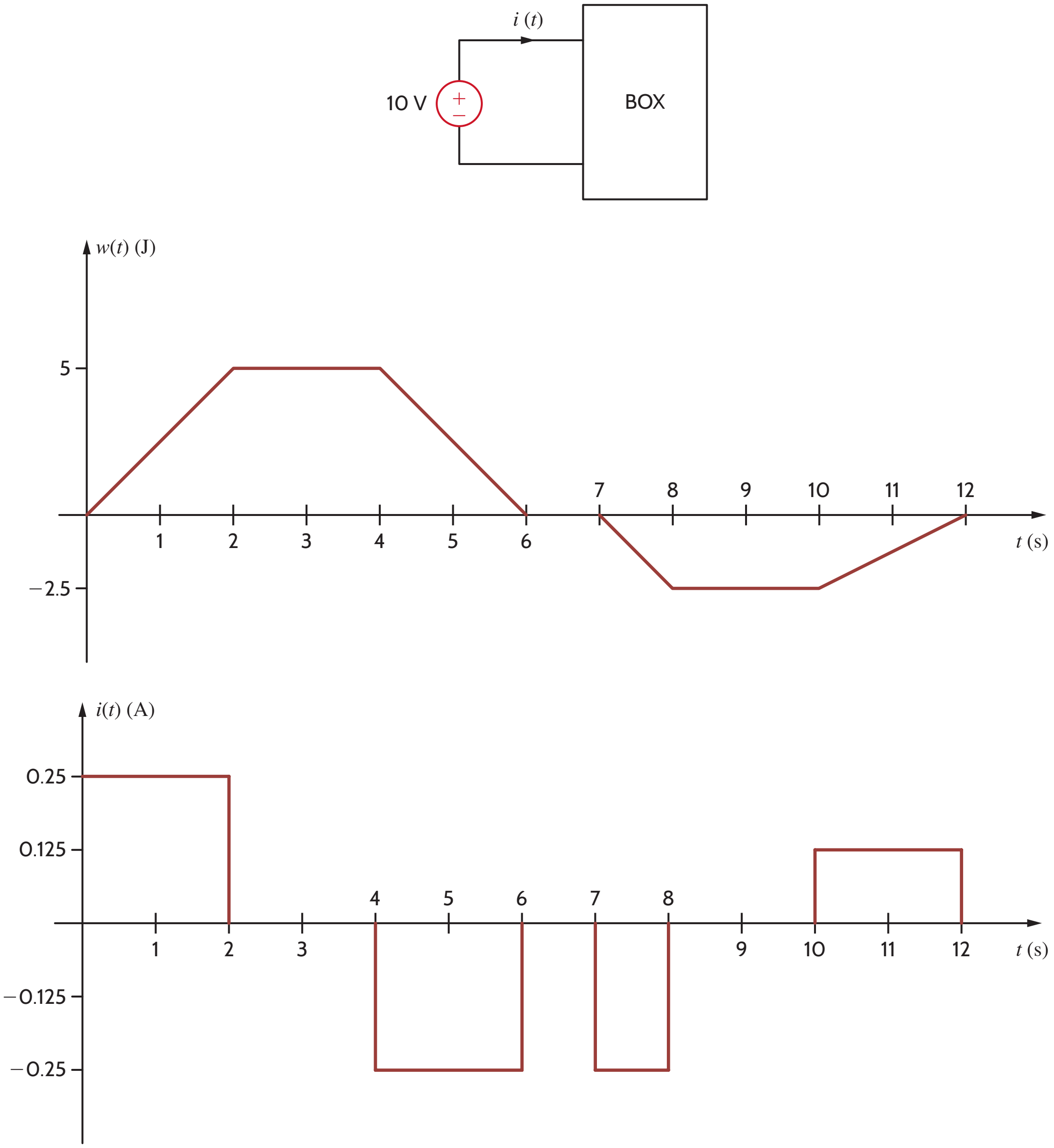


FIGURE E1.9