CIRCUIT ANALYSIS

THEORY AND PRACTICE

FIFTH EDITION

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INTRODUCTION

CHAPTER PREVIEW

An electrical circuit is a system of interconnected components such as resistors, capacitors, inductors, voltage sources, and so on. The electrical behavior of these components is described by a few basic experimental laws. These laws and the principles, concepts, mathematical relationships, and methods of analysis that have evolved from them are known as **circuit theory.**

Much of circuit theory deals with problem solving and numerical analysis. When you analyze a problem or design a circuit, for example, you are typically required to compute values for voltage, current, and power. In addition to a numerical value, your answer must include a unit. The system of units used for this purpose is the SI system (Systéme International). The SI system is a unified system of metric measurement; it encompasses not only the familiar MKS (meters, kilograms, seconds) units for length, mass, and time, but also units for electrical and magnetic quantities as well.

Quite frequently, however, the SI units yield numbers that are either too large or too small for convenient use. To handle these, engineering notation and a set of standard prefixes have been developed. Their use in representation and computation is described and illustrated.

Since circuit theory is somewhat abstract, diagrams are used to help present ideas. We look at several types—schematic, pictorial, and block diagrams—and show how to use them to represent circuits and systems.

We conclude the chapter with a brief look at computer and calculator usage in circuit analysis. Two popular software simulation packages are described, Multisim® (from National Instruments Corporation) and Orcad PSpice® (from Cadence Design Systems Inc.). These two packages are used throughout the book to illustrate ideas, to show how computers may be used to solve problems, and to help you understand the principles of circuit theory. ■

Putting It in Perspective

Hints on Problem Solving

During the analysis of electrical and electronic circuits, you will find yourself solving quite a few problems. An organized approach helps. Listed below are some useful guidelines:

1. Make a sketch (e.g., a circuit diagram), mark on it what you know, then identify what it is that you are trying to determine. Watch for "implied data" such as the phrase "the capacitor is initially uncharged." (As you will find out later, this means that the initial voltage on the capacitor is zero.) Be sure to convert all implied data to explicit data, for example, $V_0 = 0V$.
2. Think through the problem to identify the principles involved, then look for relationships that tie together the unknown and known quantities.
3. Substitute the known information into the selected equation(s) and solve for the unknown. (For complex problems, the solution may require a series of steps involving several concepts. If you cannot identify the complete set of steps before you start, start anyway. As each piece of the solution emerges, you are one step closer to the answer. You may make false starts. However, even experienced people do not get it right on the first try every time. Note also that there is seldom one "right" way to solve a problem. You may therefore come up with an entirely different correct solution method than the authors do.)
4. Check the answer to see that it is sensible—that is, is it in the "right ballpark?" Does it have the correct sign? Do the units match?

1.1 Introduction

NOTES...

1. These examples are chosen to give you a concept of the scope of the application of electrical and electronic technology and its integration with other technical disciplines. To illustrate this breadth, we have chosen illustrative applications from the fields of home entertainment, health care, and industrial manufacturing processes.
2. As you go through the examples here, you will see components, devices and electrical quantities that have not yet been discussed. You will learn about these later. For the moment, just concentrate on the general ideas.

Technology has dramatically changed the way we do things; we now have Internet-connected computers and sophisticated electronic entertainment systems in our homes, electronic control systems in our cars, cell phones that can be used just about anywhere, robots that assemble products on production lines, and so on.

A first step to understanding these technologies is electric circuit theory. Circuit theory provides you with the knowledge of basic principles that you need to understand the behavior of electric and electronic devices, circuits, and systems. In this book, we develop and explore its basic ideas.

Examples of the Technology at Work

Before we begin, let us look at a few more examples of the technology at work (see Notes 1 and 2).

First, consider Figure 1–1, which shows a home theater system. This system relies on electrical and electronic circuits, magnetic circuits, and laser technology for its operation. For example, resistors, capacitors, and integrated circuits are used to control the voltages and currents that operate its motors and to amplify its audio and video signals, while laser circuitry is used to read data from the disks. The speaker system relies on magnetic circuits for its operation, while other magnetic circuits (the power transformers) drop the ac voltage from the 120-volt wall outlet voltage to the lower levels required to power the system.

iStockphoto/shippee

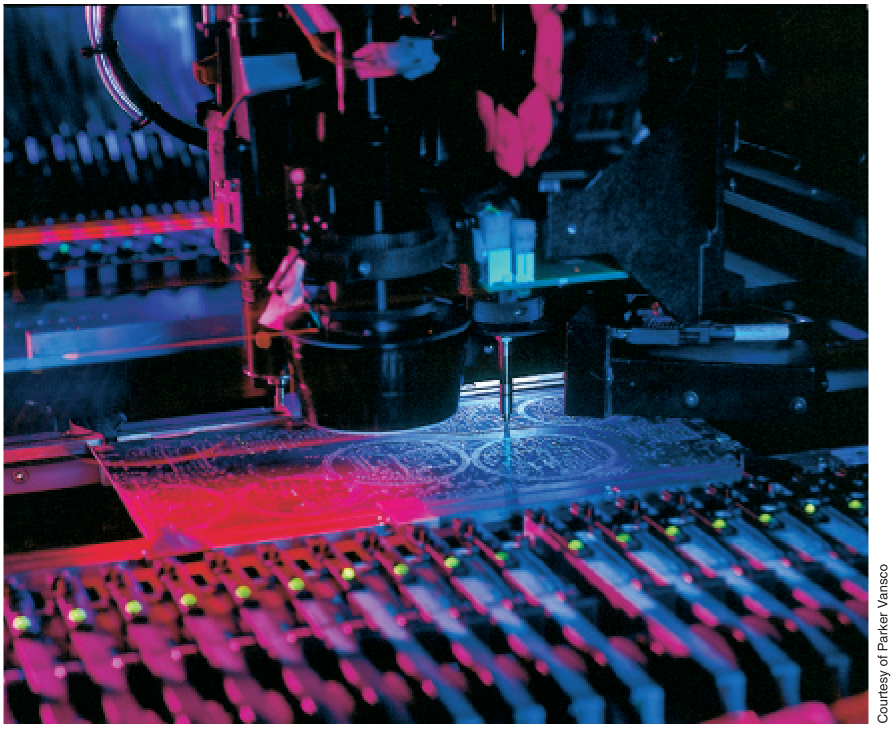
FIGURE 1–1 A home theater installation. This system incorporates many aspects of electrical and electronic technology.

Photo courtesy of IMRIS

FIGURE 1–2 An innovative Magnetic Resonance Imaging (MRI) suite. This suite features a movable high field MR machine, a surgical information management system, a data display system, and more. The suite is engineered to permit image-guided therapy without having to move the patient between machines during the process.

Figure 1–2 shows another example, a Magnetic Resonance Imaging (MRI) suite. The heart of the suite is an MRI machine, a noninvasive medical diagnostic machine that helps physicians diagnose and treat medical conditions. The suite employs a sophisticated array of electrical, electronic, computer, mechanical, and magnetic systems to permit its use in image-guided therapy.

Figure 1–3 shows another application, a manufacturing facility where fine pitch surface-mount (SMT) components are placed on printed circuit boards at high speed using laser centering and optical verification. The bottom row of Figure 1–4 shows how small many of these components are. Computer control provides the high precision needed to accurately position parts as tiny as these.



Courtesy of Parker Vansco

FIGURE 1–3 Laser centering and optical verification in a manufacturing process. This machine is installing surface mount components of the type seen in Figure 10–30(a), Chapter 10.

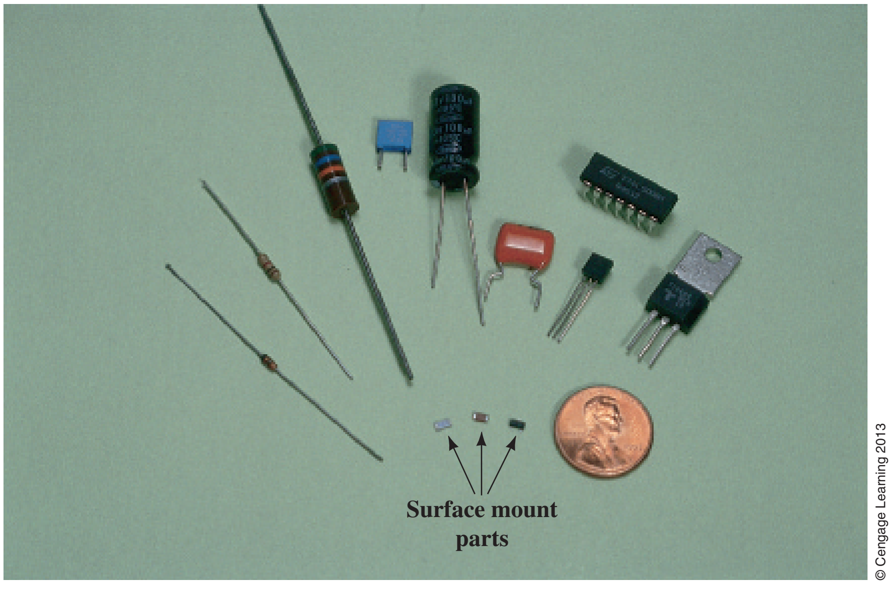


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FIGURE 1–4 Some typical electronic components. The part with 7 pins visible is an integrated circuit, the small parts at the bottom are "surface mount parts," and the rest are "discrete components"—see Notes.

NOTES...

While most manufacturers now use surface mount components in their products, such parts are too small for general use in introductory electronics laboratories, so you will mostly encounter discrete components and integrated circuits in your basic studies.

1.2 The SI System of Units

The solution of technical problems requires the use of units. At present, two major systems—the English (US Customary) and the metric—are in everyday use. For scientific and technical purposes, however, the English system has been almost totally superseded. In its place the **SI system** is used. Table 1–1 shows a few frequently encountered quantities with units expressed in both systems.

The SI system combines the MKS metric units and the electrical units into one unified system: See Table 1–2 and Table 1–3. (Do not worry about the electrical units yet. We define them later, starting in Chapter 2.) Note that some symbols and abbreviations use capital letters while others use lowercase letters.

A few non-SI units are still in use. For example, electric motors are commonly rated in horsepower, and wires are frequently specified in AWG sizes (American Wire Gage, Section 3.2). On occasion, you will need to convert non-SI units to SI units. Table 1–4 may be used for this purpose.

TABLE 1–1 Common Quantities

1 meter = 100 centimeters
 = 39.37 inches
1 millimeter = 39.37 mils
1 inch = 2.54 centimeters
1 foot = 0.3048 meter
1 yard = 0.9144 meter
1 mile = 1.609 kilometers
1 kilogram = 1000 grams
 = 2.2 pounds
1 gallon (US) = 3.785 liters

Definition of Units

When the metric system came into being in 1792, the meter was defined as one ten-millionth of the distance from the north pole to the equator and the second as $\frac{1}{60} \times \frac{1}{60} \times \frac{1}{24}$ of the mean solar day. Later, more accurate definitions based on

TABLE 1–2 Some SI Base Units

Quantity	Symbol	Unit	Abbreviation
Length	*l*	meter	m
Mass	*m*	kilogram	kg
Time	*t*	second	s
Electric current	*I*, *i*	ampere	A
Temperature	*T*	kelvin	K

TABLE 1–3 Some SI Derived Units*

Quantity	Symbol	Unit	Abbreviation
Force	*F*	newton	N
Energy	*W*	joule	J
Power	*P*, *p*	watt	W
Voltage	*V*, *v*, *E*, *e*	volt	V
Charge	*Q*, *q*	coulomb	C
Resistance	*R*	ohm	Ω
Capacitance	*C*	farad	F
Inductance	*L*	henry	H
Frequency	*f*	hertz	Hz
Magnetic flux	Φ	weber	Wb
Magnetic flux density	*B*	tesla	T

*Electrical and magnetic quantities will be explained as you progress through the book. As in Table 1–2, the distinction between capitalized and lowercase letters is important.

TABLE 1–4 Conversions

	When You Know	Multiply By	To Find
Length	inches (in.)	0.0254	meters (m)
	feet (ft)	0.3048	meters (m)
	miles (mi)	1.609	kilometers (km)
Force	pounds (lb)	4.448	newtons (N)
Power	horsepower (hp)	746	watts (W)
Energy	kilowatthour (kWh)	3.6×10^6	joules† (J)
	foot-pound (ft-lb)	1.356	joules† (J)

†1 joule = 1 newton-meter.

physical laws of nature were adopted. The meter is now defined as the distance travelled by light in a vacuum in 1/299 792 458 of a second, while the second is defined in terms of the period of a cesium-based atomic clock. The definition of the kilogram is the mass of a specific platinum-iridium cylinder (the international prototype), preserved at the International Bureau of Weights and Measures in France (although this is under review at the time of writing and may be changed).

Relative Size of the Units*

To gain a feel for the SI units and their relative size, refer to Table 1–1 and Table 1–4. Note that 1 meter is equal to 39.37 inches; thus, 1 inch equals $1/39.37 = 0.0254$ meter or 2.54 centimeters. A force of one pound is equal to 4.448 newtons; thus, 1 **newton** is equal to $1/4.448 = 0.225$ pound of force, which is about the force required to lift a quarter-pound weight. One **joule** is the work done in moving a distance of one meter against a force of one newton. This is about equal to the work required to raise a quarter-pound weight one meter. Raising the weight one meter in one second requires about one **watt** of power.

The watt is also the SI unit for electrical power. A typical electric lamp, for example, dissipates power at the rate of 60 watts, and a toaster at a rate of about 1000 watts.

The link between electrical and mechanical units can be easily established. Consider an electrical generator. Mechanical power input produces electrical power output. If the generator were 100% efficient, then one watt of mechanical power input would yield one watt of electrical power output. This clearly ties the electrical and mechanical systems of units together.

However, just how big is a watt? While the preceding examples suggest that the watt is quite small, in terms of the rate at which a human can work, it is actually quite large. For example, a person can do manual labor at a rate of about 60 watts when averaged over an 8-hour day—just enough to power a standard 60-watt electric lamp continuously over this time! A horse can do considerably better. Based on experiment, James Watt determined that a strong dray horse could average 746 watts. From this, he defined the **horsepower (hp)** as 1 horsepower = 746 watts. This is the figure that we still use today.

1.3 Converting Units

Sometimes quantities expressed in one unit must be converted to another. For example, suppose you want to determine how many kilometers there are in 10 miles. Given that 1 mile is equal to 1.609 kilometers (Table 1–1), you can write 1 mi = 1.609 km, using the abbreviations in Table 1–4. Now multiply both sides by 10. Thus, 10 mi = 16.09 km.

This procedure is quite adequate for simple conversions. However, for complex conversions, it may be difficult to keep track of units. The procedure outlined next helps. It involves writing units into the conversion sequence, cancelling where applicable, then gathering up the remaining units to ensure that the final result has the correct units.

To get at the idea, suppose you want to convert 12 centimeters to inches. From Table 1–1, 2.54 cm = 1 in. From this, you can write

$$\frac{2.54\ \text{cm}}{1\ \text{in}} = 1 \quad \text{or} \quad \frac{1\ \text{in}}{2.54\ \text{cm}} = 1 \tag{1–1}$$

*Paraphrased from Edward C. Jordan and Keith Balmain, *Electromagnetic Waves and Radiating Systems,* Second Edition. (Englewood Cliffs, New Jersey: Prentice-Hall, Inc, 1968).

The quantities in Equation 1–1 are called **conversion factors.** As you can see, conversion factors have a value of 1, and thus you can multiply them times any expression without changing the value of that expression. For example, to complete the conversion of 12 cm to inches, choose the second ratio (so that units cancel), then multiply. Thus,

$$12 \text{ cm} = 12 \cancel{\text{cm}} \times \frac{1 \text{ in}}{2.54 \cancel{\text{cm}}} = 4.72 \text{ in}$$

When you have a chain of conversions, select factors so that all unwanted units cancel. This provides an automatic check on the final result as illustrated in part (b) of Example 1–1.

EXAMPLE 1–1

Given a speed of 60 miles per hour (mph),

a. convert it to kilometers per hour,
b. convert it to meters per second.

Solution

a. Recall, 1 mi = 1.609 km. Thus,

$$1 = \frac{1.609 \text{ km}}{1 \text{ mi}}$$

Now multiply both sides by 60 mi/h and cancel units:

$$60 \text{ mi/h} = \frac{60 \cancel{\text{mi}}}{\text{h}} \times \frac{1.609 \text{ km}}{1 \cancel{\text{mi}}} = 96.54 \text{ km/h}$$

b. Given that 1 mi = 1.609 km, 1 km = 1000 m, 1 h = 60 min, and 1 min = 60 s, choose conversion factors as follows:

$$1 = \frac{1.609 \text{ km}}{1 \text{ mi}}, \quad 1 = \frac{1000 \text{ m}}{1 \text{ km}}, \quad 1 = \frac{1 \text{ h}}{60 \text{ min}}, \quad \text{and} \quad 1 = \frac{1 \text{ min}}{60 \text{ s}}$$

Thus,

$$\frac{60 \text{ mi}}{\text{h}} = \frac{60 \cancel{\text{mi}}}{\cancel{\text{h}}} \times \frac{1.609 \cancel{\text{km}}}{1 \cancel{\text{mi}}} \times \frac{1000 \text{ m}}{1 \cancel{\text{km}}} \times \frac{1 \cancel{\text{h}}}{60 \cancel{\text{min}}} \times \frac{1 \cancel{\text{min}}}{60 \text{ s}} = 26.8 \text{ m/s}$$

You can also solve this problem by treating the numerator and denominator separately. For example, you can convert miles to meters and hours to seconds, then divide (see Example 1–2). In the final analysis, both methods are equivalent.

EXAMPLE 1–2

Do Example 1–1(b) by expanding the top and bottom separately.

Solution

$$60 \text{ mi} = 60 \cancel{\text{mi}} \times \frac{1.609 \cancel{\text{km}}}{1 \cancel{\text{mi}}} \times \frac{1000 \text{ m}}{1 \cancel{\text{km}}} = 96\,540 \text{ m}$$

$$1 \text{ h} = 1 \cancel{\text{h}} \times \frac{60 \cancel{\text{min}}}{1 \cancel{\text{h}}} \times \frac{60 \text{ s}}{1 \cancel{\text{min}}} = 3600 \text{ s}$$

Thus, velocity = 96 540 m/3600 s = 26.8 m/s as above.

PRACTICE PROBLEMS 1

1. Area $= \pi r^2$. Given $r = 8$ inches, determine area in square meters (m^2).
2. A car travels 60 feet in 2 seconds. Determine
   a. its speed in meters per second,
   b. its speed in kilometers per hour.

For part (b), use the method of Example 1–1, then check using the method of Example 1–2.

Answers
1. 0.130 m^2; 2. a. 9.14 m/s, b. 32.9 km/h

1.4 Power of Ten Notation

Electrical values vary tremendously in size. In electronic systems, for example, voltages may range from a few millionths of a volt to several thousand volts, while in power systems, voltages of up to several hundred thousand are common. To handle this large range, the **power of ten notation** (Table 1–5) is used—see Note.

To express a number in the power of ten notation, move the decimal point to where you want it, then multiply the result by the power of ten needed to restore the number to its original value. Thus, 247 000 $= 2.47 \times 10^5$. (The number 10 is called the **base,** and its power is called the **exponent.**) An easy way to determine the exponent is to count the number of places (right or left) that you moved the decimal point. Thus,

$$247\ 000 = 2\underbrace{4\,7\,0\,0\,0}_{5\;4\;3\;2\;1} = 2.47 \times 10^5$$

Similarly, the number 0.003 69 may be expressed as 3.69×10^{-3} as illustrated below.

$$0.003\ 69 = 0.\underbrace{0\,0\,3}_{1\;2\;3}\,6\,9 = 3.69 \times 10^{-3}$$

Multiplication and Division Using Powers of Ten

To multiply numbers in power of ten notation, multiply their base numbers, then add their exponents. Thus,

$$(1.2 \times 10^3)(1.5 \times 10^4) = (1.2)(1.5) \times 10^{(3+4)} = 1.8 \times 10^7$$

For division, subtract the exponents in the denominator from those in the numerator. Thus,

$$\frac{4.5 \times 10^2}{3 \times 10^{-2}} = \frac{4.5}{3} \times 10^{2-(-2)} = 1.5 \times 10^4$$

NOTES...

The complete range of powers of ten defined in the SI system includes twenty members. However, only those powers of common interest to us in circuit theory are shown in Table 1–5.

TABLE 1–5 Common Power of Ten Multipliers

$1\ 000\ 000 = 10^6$	$0.000001 = 10^{-6}$
$100\ 000 = 10^5$	$0.00001 = 10^{-5}$
$10\ 000 = 10^4$	$0.0001 = 10^{-4}$
$1\ 000 = 10^3$	$0.001 = 10^{-3}$
$100 = 10^2$	$0.01 = 10^{-2}$
$10 = 10^1$	$0.1 = 10^{-1}$
$1 = 10^0$	$1 = 10^0$

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EXAMPLE 1–3

Convert the following numbers to power of ten notation, then perform the operation indicated:

a. 276×0.009,
b. 98 200/20.

Solution

a. $276 \times 0.009 = (2.76 \times 10^2)(9 \times 10^{-3}) = 24.8 \times 10^{-1} = 2.48$

b. $\dfrac{98\,200}{20} = \dfrac{9.82 \times 10^4}{2 \times 10^1} = 4.91 \times 10^3$

Addition and Subtraction Using Powers of Ten

To add or subtract, first adjust all numbers to the same power of ten. It does not matter what exponent you choose, as long as all are the same.

EXAMPLE 1–4

Add 3.25×10^2 and 5×10^3

a. using 10^2 representation,
b. using 10^3 representation.

Solution

a. $5 \times 10^3 = 50 \times 10^2$. Thus, $3.25 \times 10^2 + 50 \times 10^2 = 53.25 \times 10^2$.
b. $3.25 \times 10^2 = 0.325 \times 10^3$. Thus, $0.325 \times 10^3 + 5 \times 10^3 = 5.325 \times 10^3$, which is the same as 53.25×10^2 as found in part (a).

Powers

Raising a number to a power is a form of multiplication (or division if the exponent is negative). For example,

$$(2 \times 10^3)^2 = (2 \times 10^3)(2 \times 10^3) = 4 \times 10^6$$

In general, $(N \times 10^n)^m = N^m \times 10^{nm}$. In this notation, $(2 \times 10^3)^2 = 2^2 \times 10^{3\times 2} = 4 \times 10^6$ as before.

Integer fractional powers represent roots. Thus, $4^{1/2} = \sqrt{4} = 2$ and $27^{1/3} = \sqrt[3]{27} = 3$.

NOTES...

Use common sense when handling numbers. With calculators, for example, it is often easier to work directly with numbers in their original form than to convert them to power of ten notation. [As an example, it is more sensible to multiply 276×0.009 directly than to convert to power of ten notation as we did in Example 1–3(a).] If the final result is needed as a power of ten, you can convert as a last step.

EXAMPLE 1–5

Expand the following:

a. $(250)^3$ b. $(0.0056)^2$ c. $(141)^{-2}$ d. $(60)^{1/3}$

Solution

a. $(250)^3 = (2.5 \times 10^2)^3 = (2.5)^3 \times 10^{2\times3} = 15.625 \times 10^6$
b. $(0.0056)^2 = (5.6 \times 10^{-3})^2 = (5.6)^2 \times 10^{-6} = 31.36 \times 10^{-6}$
c. $(141)^{-2} = (1.41 \times 10^2)^{-2} = (1.41)^{-2} \times (10^2)^{-2} = 0.503 \times 10^{-4}$
d. $(60)^{1/3} = \sqrt[3]{60} = 3.915$

PRACTICE PROBLEMS 2

Determine the following:

a. $(6.9 \times 10^5)(0.392 \times 10^{-2})$
b. $(23.9 \times 10^{11})/(8.15 \times 10^5)$
c. $14.6 \times 10^2 + 11.2 \times 10^1$ (Express in 10^2 and 10^1 notation.)
d. $(29.6)^3$
e. $(0.385)^{-2}$

Answers
a. 2.70×10^3; b. 2.93×10^6; c. $15.72 \times 10^2 = 157.2 \times 10^1$; d. 25.9×10^3; e. 6.75

1.5 Prefixes, Engineering Notation, and Numerical Results

In scientific work, it is common to find very large and very small numbers expressed in power of ten notation. However, in engineering, certain elements of style and standard practices have evolved, giving rise to what is referred to as **engineering notation.** In engineering notation, it is more common to use **prefixes** than powers of ten. The most common prefixes (along with their symbols) are listed in Table 1–6. (Note: In this notation, powers of ten must be multiples of three.) As an example, while a current of 0.0045 A (amperes) may be expressed as 4.5×10^{-3} A, it is preferable to express it as 4.5 mA or as 4.5 milliamps. Note also that there are often several equally acceptable choices. For example, a time interval of 15×10^{-5} s may be expressed as 150 μs, or as 150 microseconds, or as 0.15 ms, or as 0.15 milliseconds. Note also that it is not wrong to express the number as 15×10^{-5}; it is simply not common engineering practice. From here onward, we will use engineering notation almost exclusively.

TABLE 1–6 Engineering Prefixes

Power of 10	Prefix	Symbol
10^{12}	tera	T
10^9	giga	G
10^6	mega	M
10^3	kilo	k
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

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EXAMPLE 1–6

Express the following in engineering notation:

a. 10×10^4 volts b. 0.1×10^{-3} watts c. 250×10^{-7} seconds

Solution

a. $10 \times 10^4\ \text{V} = 100 \times 10^3\ \text{V} = 100$ kilovolts $= 100$ kV
b. $0.1 \times 10^{-3}\ \text{W} = 0.1$ milliwatts $= 0.1$ mW
c. $250 \times 10^{-7}\ \text{s} = 25 \times 10^{-6}\ \text{s} = 25$ microseconds $= 25\ \mu\text{s}$

EXAMPLE 1–7

Convert 0.1 MV to kilovolts (kV).

Solution

$$0.1\ \text{MV} = 0.1 \times 10^6\ \text{V} = (0.1 \times 10^3) \times 10^3\ \text{V} = 100\ \text{kV}$$

Remember that a prefix represents a power of ten, and thus the rules for power of ten computation apply. For example, when adding or subtracting, adjust to a common base, as illustrated in Example 1–8.

EXAMPLE 1–8

Compute the sum of 1 ampere (amp) and 100 milliamperes.

Solution Adjust to a common base, either amps (A) or milliamps (mA). Thus,

$$1\ \text{A} + 100\ \text{mA} = 1\ \text{A} + 100 \times 10^{-3}\ \text{A} = 1\ \text{A} + 0.1\ \text{A} = 1.1\ \text{A}$$

Alternatively, $1\ \text{A} + 100\ \text{mA} = 1000\ \text{mA} + 100\ \text{mA}$
$= 1100\ \text{mA} = 1.1\ \text{A}$ as above.

PRACTICE PROBLEMS 3

1. Convert 1800 kV to megavolts (MV).
2. In Chapter 4, we show that voltage is the product of current times resistance—that is, $V = I \times R$, where V is in volts, I is in amperes, and R is in ohms. Given $I = 25$ mA and $R = 4\ \text{k}\Omega$, convert these to power of ten notation, then determine V.
3. If $I_1 = 520\ \mu\text{A}$, $I_2 = 0.157$ mA, and $I_3 = 2.75 \times 10^{-4}$ A, what is $I_1 + I_2 + I_3$ in mA? In microamps?

Answers
1. 1.8 MV; 2. 100 V; 3. 0.952 mA, 952 μA

Numerical Results

While computers and calculators typically display many digits, the question is how many should you actually retain in your answer? While it is tempting to write them all down, a closer inspection shows that this may not be sensible. To see why, note that much of engineering is based on measurement. In practice, for example, voltage is measured with a voltmeter and current with an ammeter. Such measured values are approximate since it is impossible to measure anything exactly. Since measured values have an element of uncertainty, computations based on them also have an element of uncertainty—see Notes. To illustrate, suppose you want to know the area of a garden and you measure the length and width as $L = 5.76$ m and $W = 3.72$ m. Assume an uncertainty of 1 in the last digit of each—that is, $L = 5.76 \pm 0.01$ and $W = 3.72 \pm 0.01$. This means that L can be as small as 5.75 and as large as 5.77, while W can range between 3.71 and 3.73. The area can thus be as small as $5.75 \text{ m} \times 3.71 \text{ m} = 21.3 \text{ m}^2$ or as large as $5.77 \text{ m} \times 3.73 \text{ m} = 21.5 \text{ m}^2$. Note that we aren't even sure what the first digit is after the decimal place in this result. Now you can see why it doesn't make sense to write down all the digits that your calculator shows, since you would get $5.76 \text{ m} \times 3.72 \text{ m} = 21.4272 \text{ m}^2$ on a six-digit display—and it is clearly senseless to claim that you know what the four digits following the decimal point are when in fact, you don't even know what the first digit is.

So what do we do? A practical solution is to carry all the digits throughout the solution of the problem (your calculator will probably do this anyway), then round the answer to a suitable number of digits. As a useful guideline, you should round your final answer to three digits unless it makes sense to do otherwise. For the preceding example, this would yield an answer of 21.4 m^2 which, as you can see, is the average of the high and low computed values. When performing a chain calculation, make sure that you carry enough digits all the way through—that is, do not write down three-digit intermediate answers, then reenter them to continue the calculation—this will lead to more uncertainty in the final answers.

NOTES...

1. Numbers may be exact or they may be approximate. Exact numbers are typically obtained by a process of counting or by definition—for example, 1 hour is defined as 60 minutes. Here, 60 is exact (i.e., it is not 59.99 or 60.01). Computations based solely on exact numbers contain no uncertainty. However, computations involving both exact and approximate numbers carry the uncertainty of the approximate numbers.
2. In this book, **unless otherwise noted, all numbers in examples and problems are to be taken as exact.** Thus, there will be no uncertainty in the computed answers.
3. We may show more than three digits in the answers in this book since the process of solution is usually of primary importance and it can be obscured by dropping digits too soon.
4. The topic of significant digits, numerical accuracy, and working with approximate numbers has only been touched upon here. For additional information, please visit our Web site at www.cengagebrain.com. In the search box at the top of the page, key in Robbins and Miller. (This will take you to the product page where your resources can be found.) Follow the links to *For Further Investigation,* then select *Significant Digits and Numerical Accuracy* to access it.

IN-PROCESS LEARNING CHECK 1

(Answers are at the end of the chapter.)

1. All conversion factors have a value of what?
2. Convert 14 yards to centimeters.
3. What units does the following reduce to?

$$\frac{\text{km}}{\text{h}} \times \frac{\text{m}}{\text{km}} \times \frac{\text{h}}{\text{min}} \times \frac{\text{min}}{\text{s}}$$

4. Express the following in engineering notation:
   a. 4270 ms b. 0.001 53 V c. 12.3×10^{-4} s
5. Express the result of each of the following computations as a number times 10 to the power indicated:
   a. 150×120 as a value times 10^4; as a value times 10^3.
   b. $300 \times 6/0.005$ as a value times 10^4; as a value times 10^5; as a value times 10^6.
   c. $430 + 15$ as a value times 10^2; as a value times 10^1.
   d. $(3 \times 10^{-2})^3$ as a value times 10^{-6}; as a value times 10^{-5}.
6. Express each of the following as indicated.
   a. 752 μA in mA.
   b. 0.98 mV in μV.
   c. 270 μs + 0.13 ms in μs and in ms.

1.6 Circuit Diagrams

Electrical and electronic circuits are constructed using components such as batteries, switches, resistors, capacitors, transistors, and interconnecting wires. To represent these circuits on paper, diagrams are used. In this book, we use three types: block diagrams, schematic diagrams, and pictorials.

Block Diagrams

Block diagrams describe a circuit or system in simplified form. The overall problem is broken into blocks, each representing a portion of the system or circuit. Blocks are labelled to indicate what they do or what they contain, then interconnected to show their relationship to each other. General signal flow is usually from left to right and top to bottom. Figure 1–5, for example, represents an audio amplifier. Although you have not covered any of its circuits yet, you should be able to follow the general idea quite easily—sound is picked up by

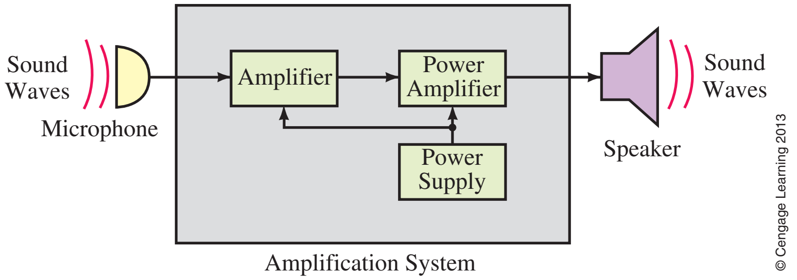


FIGURE 1–5 An example block diagram. Pictured is a simplified representation of an audio amplification system.

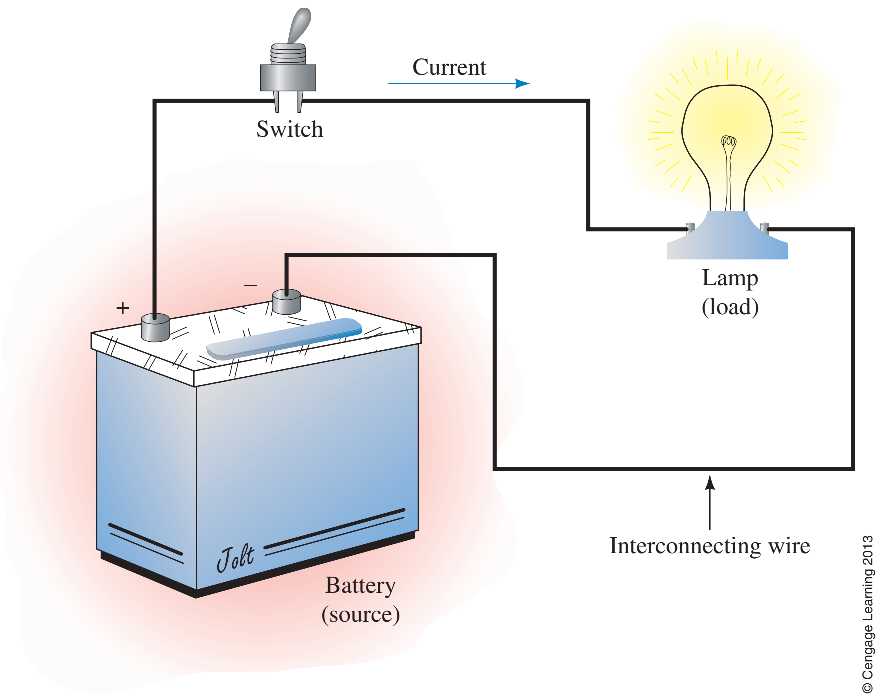


FIGURE 1–6 A pictorial diagram. The battery is referred to as a *source* while the lamp is referred to as a *load*. (The + and − on the battery are discussed in Chapter 2.)

the microphone, converted to an electrical signal, amplified by a pair of amplifiers, then output to the speaker, where it is converted back to sound. A power supply energizes the system. The advantage of a block diagram is that it gives you the overall picture and helps you understand the general nature of a problem. However, it does not provide detail.

Pictorial Diagrams

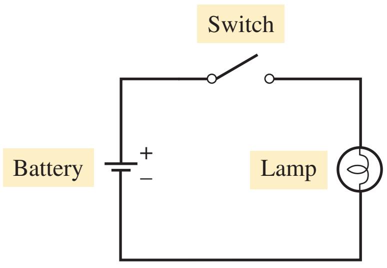
Pictorial diagrams provide detail. They help you visualize circuits and their operation by showing components as they actually look physically. For example, the circuit of Figure 1–6 consists of a battery, a switch, and an electric lamp, all interconnected by wire. Operation is easy to visualize—when the switch is closed, the battery causes current in the circuit, which lights the lamp. The battery is referred to as the source and the lamp as the load.

Schematic Diagrams

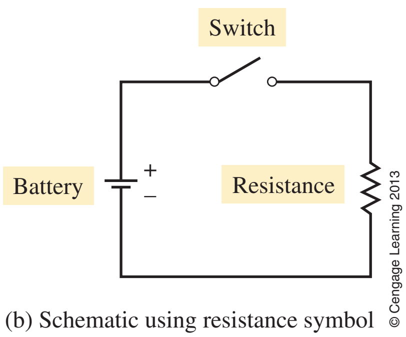
While pictorial diagrams help you visualize circuits, they are cumbersome to draw. **Schematic diagrams** get around this by using simplified, standard symbols to represent components; see Table 1–7. (The meaning of these symbols will be made clear as you progress through the book.) In Figure 1–7(a), for example, we have used some of these symbols to create a schematic for the circuit of Figure 1–6. Each component has been replaced by its corresponding circuit symbol.

When choosing symbols, choose those that are appropriate to the occasion. Consider the lamp of Figure 1–7(a). As we will show later, the lamp possesses a property called **resistance.** When you wish to emphasize this property, use the resistance symbol rather than the lamp symbol, as in Figure 1–7(b).

When we draw schematic diagrams, we usually draw them with horizontal and vertical lines joined at right angles as in Figure 1–7. This is standard practice. (At this point you should glance through some later chapters, e.g., Chapter 7, and study additional examples.)



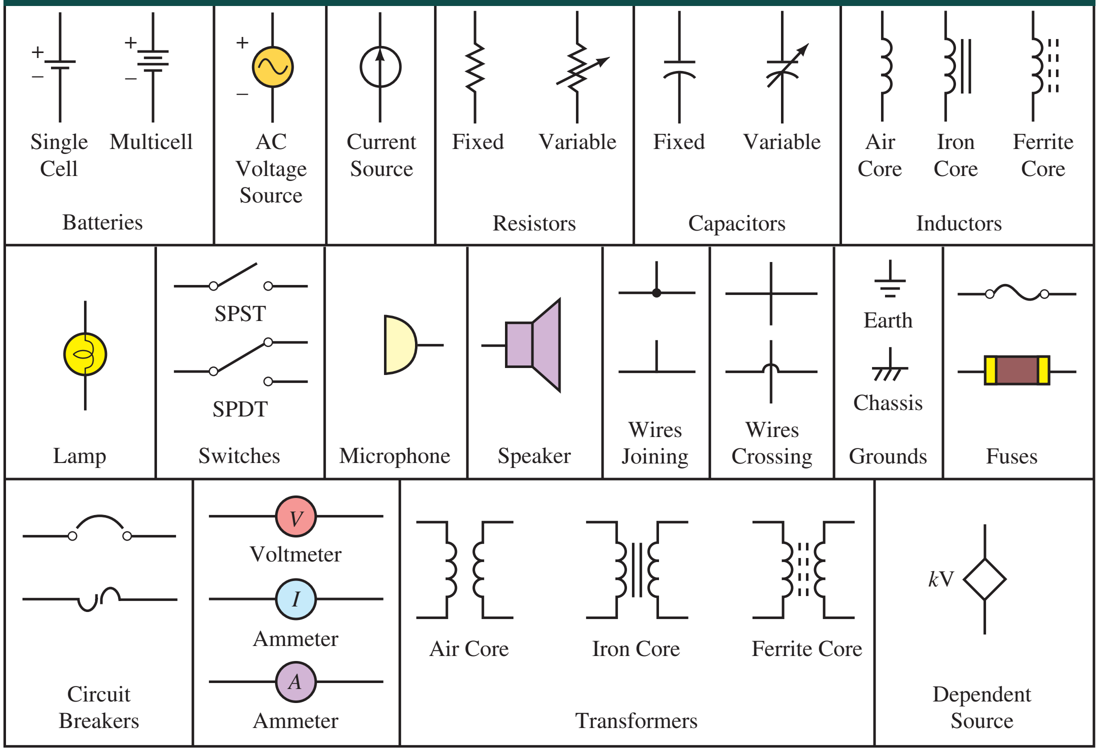
(a) Schematic using lamp symbol



(b) Schematic using resistance symbol

FIGURE 1–7 Schematic representation of Figure 1–6. The lamp has a circuit property called resistance (discussed in Chapter 3).

TABLE 1–7 Schematic Circuit Symbols



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1.7 Circuit Analysis Using Computers and Calculators

Computers and calculators are widely used for circuit analysis and design. Software commonly employed for this purpose includes simulation software (such as **Multisim** and **PSpice**) and numerical analysis software such as Mathcad and Matlab—see Notes. We begin with simulation software.

NOTES...

1. Software for technical use falls into two broad categories—**application software** (such as Multisim and PSpice) and programming languages (such as Java and C++). Application software is designed to solve problems without requiring programming on the part of the user, whereas programming languages require that you write code for each type of problem to be solved. In this book, we do not consider programming languages.
2. Software tools should always be used wisely. Before you use Multisim or PSpice, for example, be sure you understand the basics of the subject that you are studying, as the uninformed use of such software can result in answers that make no sense—and you need to be able to recognize this fact. This is why you should solve many problems manually with your calculator first—to develop both an understanding of the theory and a "feel" for what is right.
3. Computer software is frequently updated, and the versions used in this book are the versions current at the time of writing—see Appendix A.
4. Multisim® is a trademark of National Instruments Company; OrCAD®, OrCAD Capture®, and PSpice® are registered trademarks of Cadence Design Systems Inc.; Matlab is a trademark of MathWorks; and Mathcad® is a trademark of Parametric Technology Corporation.

Circuit Simulation Software

Simulation software solves problems by simulating the behavior of electrical and electronic circuits rather than by solving sets of equations. To analyze a circuit, you "build" it on your screen by selecting components (resistors, capacitors, transistors, etc.) from a list of parts, which you then position and interconnect to form the desired circuit. You can change component values, connections, and analysis options instantly with the click of a mouse. Figures 1–8 and 1–9 show two examples. Software products such as these permit you to set up and test your circuit on the computer screen without the need to build a hardware prototype.

Most simulation packages use a software engine called SPICE, an acronym for *Simulation Program with Integrated Circuit Emphasis.* Two of the most popular products are PSpice and Multisim, the simulation tools used in this book. Each has its strong points. Multisim, for instance, more closely models an actual workbench (complete with realistic meters) than does PSpice, but PSpice has other advantages, as you will see throughout this book.

FIGURE 1–8 Multisim simulation of the time delay alarm circuit featured in Chapter 11. Not only does the software analyze the circuit, it displays the results graphically as color-coded waveforms.

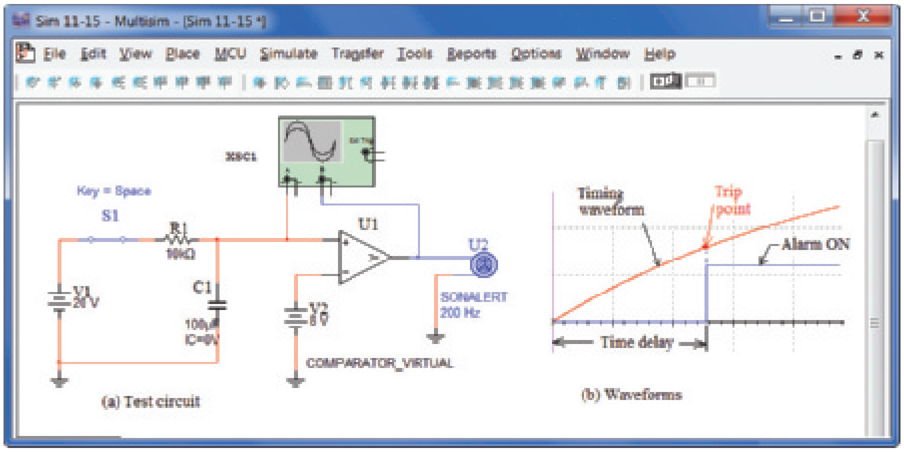
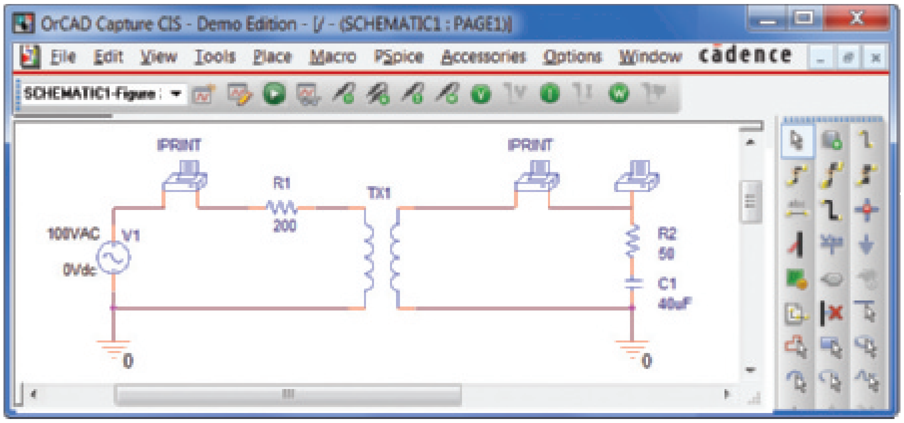


FIGURE 1–9 PSpice simulation of a transformer coupled circuit from Chapter 23. The meters measure circuit variables and show results in numerical form.



Prepackaged Math Software

Another useful category of software includes mathematics packages such as Mathcad and Matlab. These programs (which use numerical analysis techniques to solve equations, plot data, etc.) also require no programming—you simply enter the data and let the computer do the work. Generally, they use standard mathematical notation (or very close to it) and are great aids for solving simultaneous equations such as those encountered in mesh and nodal analysis, which will be discussed in Chapter 8 and Chapter 19.

Calculators in Circuit Analysis

While the preceding software programs can be very useful, a calculator will be your primary tool for learning circuit analysis. You will need one that is able to work with complex numbers in both rectangular and polar forms. Such a calculator saves a great deal of time and effort and cuts down dramatically on errors. Figure 1–10 shows a typical calculator—the Sharp EL-506W. (It is the calculator that we use for illustrative purposes throughout this book—see Notes. The EL-506W has regional variants—for example, it is sold in Canada as the EL-546W.) (Valuable tips on how to use calculators in circuit analysis are integrated throughout the text and summarized in Appendix B.)

NOTES...

A survey of current book adopters revealed a considerable variety of calculators in use, with no one calculator a clear winner—consequently, we make no recommendations about which one to buy. Be sure to check with your instructor (or your book list) before you make a choice.

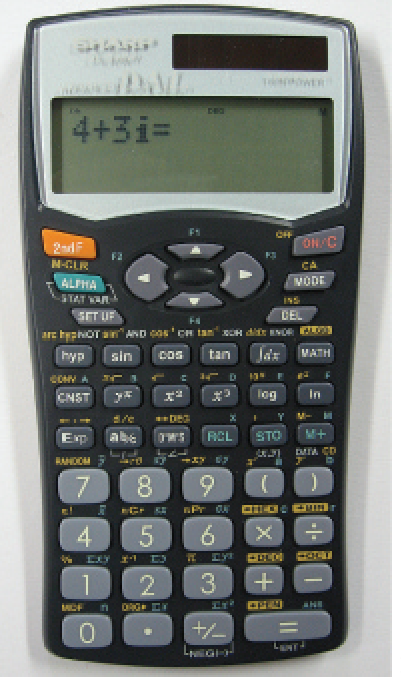


FIGURE 1–10 Calculators like this greatly simplify the work involved in circuit analysis. The photo shows a Sharp EL-506W, but check with your professor or consult your book list to see which calculator is recommended for your course.

Problems

1.3 Converting Units

1. Perform the following conversions:
   a. 27 minutes to seconds
   b. 0.8 hours to seconds
   c. 2 h 3 min 47 s to s
   d. 35 horsepower to watts
   e. 1827 W to hp
   f. 23 revolutions to degrees
2. Perform the following conversions:
   a. 27 feet to meters
   b. 2.3 yd to cm
   c. 36° F to degrees C
   d. 18 (US) gallons to liters
   e. 100 sq. ft to m^2
   f. 124 sq. in. to m^2
   g. 47-pound force to newtons
3. Set up conversion factors, compute the following, and express the answer in the units indicated.
   a. The area of a plate 1.2 m by 70 cm in m^2.
   b. The area of a triangle with base 25 cm, height 0.5 m in m^2.
   c. The volume of a box 10 cm by 25 cm by 80 cm in m^3.
   d. The volume of a sphere with 10 in. radius in m^3.

NOTES...

1. Conversion factors may be found on the inside of the front cover or in the tables of Chapter 1.
2. Difficult problems have their question number printed in red.
3. Answers to odd-numbered problems are in Appendix D.

4. An electric fan rotates at 300 revolutions per minute. How many degrees is this per second?
5. If the surface mount robot machine of Figure 1–3 places 15 parts every 12 s, what is its placement rate per hour?
6. If your laser printer can print 8 pages per minute, how many pages can it print in one-tenth of an hour?
7. A car gets 27 miles per US gallon. What is this in kilometers per liter?
8. The equatorial radius of the earth is 3963 miles. What is the earth's circumference in kilometers at the equator?
9. A wheel rotates 18° in 0.02 s. How many revolutions per minute is this?
10. The height of horses is sometimes measured in "hands," where 1 hand = 4 inches. How many meters tall is a 16-hand horse? How many centimeters?
11. Suppose $s = vt$ is given, where s is distance travelled, v is velocity, and t is time. If you travel at $v = 60$ mph for 500 seconds, you might make an unthinking substitution $s = vt = (60)(500) = 30{,}000$ miles. What is wrong with this calculation? What is the correct answer?
12. A round pizza has a circumference of 47 inches. How long does it take for a pizza cutter traveling at 0.12 m/s to cut diagonally across it?
13. Joe S. was asked to convert 2000 yd/h to meters per second. Here is Joe's work: velocity $= 2000 \times 0.9144 \times 60/60 = 1828.8$ m/s. Determine conversion factors, write units into the conversion, and find the correct answer.
14. The mean distance from the earth to the moon is 238 857 miles. Radio signals travel at 299 792 458 m/s. How long does it take a radio signal to reach the moon?
15. If you walk at a rate of 3 km/h for 8 minutes, 5 km/h for 1.25 h, then continue your walk at a rate of 4 km/h for 12 minutes, how far will you have walked in total?
16. Suppose you walk at a rate of 2 mph for 12 minutes, 4 mph for 0.75 h, then finish off at 5 mph for 15 minutes. How far have you walked in total?
17. You walk for 15 minutes at a rate of 2 km/h, then 18 minutes at 5 km/h, and for the remainder, your speed is 2.5 km/h. If the total distance covered is 2.85 km, how many minutes did you spend walking at 2.5 km/h?
18. You walk for 16 minutes at a rate of 1.5 mph, speed up to 3.5 mph for awhile, then slow down to 3 mph for the last 12 minutes. If the total distance covered is 1.7 miles, how long did you spend walking at 3.5 mph?
19. Your plant manager asks you to investigate two machines. The cost of electricity for operating machine #1 is 43 cents/minute, while that for machine #2 is $200.00 per 8-hour shift. The purchase price, production capacities, maintenance costs, and long-term reliability for both machines are identical. Based on this information, which machine should you purchase and why?
20. Given that 1 hp = 550 ft-lb/s, 1 ft = 0.3048 m, 1 lb = 4.448 N, 1 J = 1 N-m, and 1 W = 1 J/s, show that 1 hp = 746 W.

1.4 Power of Ten Notation

21. Express each of the following in power of ten notation with one nonzero digit to the left of the decimal point.

a. 8675
b. 0.008 72
c. 12.4×10^2
d. 37.2×10^{-2}
e. $0.003\ 48 \times 10^5$
f. $0.000\ 215 \times 10^{-3}$
g. 14.7×10^0

22. Express the answer for each of the following in power of ten notation with one nonzero digit to the left of the decimal point.
    a. $(17.6)(100)$
    b. $(1400)(27 \times 10^{-3})$
    c. $(0.15 \times 10^{6})(14 \times 10^{-4})$
    d. $1 \times 10^{-7} \times 10^{-4} \times 10.65$
    e. $(12.5)(1000)(0.01)$
    f. $(18.4 \times 10^{0})(100)(1.5 \times 10^{-5})(0.001)$
23. Repeat the directions in Question 22 for each of the following.
    a. $\dfrac{125}{1000}$
    b. $\dfrac{8 \times 10^{4}}{(0.001)}$
    c. $\dfrac{3 \times 10^{4}}{(1.5 \times 10^{6})}$
    d. $\dfrac{(16 \times 10^{-7})(21.8 \times 10^{6})}{(14.2)(12 \times 10^{-5})}$
24. Determine the answers for the following.
    a. $123.7 + 0.05 + 1259 \times 10^{-3}$
    b. $72.3 \times 10^{-2} + 1 \times 10^{-3}$
    c. $86.95 \times 10^{2} - 383$
    d. $452 \times 10^{-2} + (697)(0.01)$
25. Convert the following to power of ten notation and, without using your calculator, determine the answers.
    a. $(4 \times 10^{3})(0.05)^{2}$
    b. $(4 \times 10^{3})(-0.05)^{2}$
    c. $\dfrac{(3 \times 2 \times 10)^{2}}{(2 \times 5 \times 10^{-1})}$
    d. $\dfrac{(30 + 20)^{-2}(2.5 \times 10^{6})(6000)}{(1 \times 10^{3})(2 \times 10^{-1})^{2}}$
    e. $\dfrac{(-0.027)^{1/3}(-0.2)^{2}}{(23 + 1)^{0} \times 10^{-3}}$
26. For each of the following, convert the numbers to power of ten notation, then perform the indicated computations. Round your answer to four digits.
    a. $(452)(6.73 \times 10^{4})$
    b. $(0.009\ 85)(4700)$
    c. $(0.0892)/(0.000\ 067\ 3)$
    d. $12.40 - 236 \times 10^{-2}$
    e. $(1.27)^{3} + 47.9/(0.8)^{2}$
    f. $(-643 \times 10^{-3})^{3}$
    g. $[(0.0025)^{1/2}][1.6 \times 10^{4}]$
    h. $[(-0.027)^{1/3}]/[1.5 \times 10^{-4}]$
    i. $\dfrac{(3.5 \times 10^{4})^{-2} \times (0.0045)^{2} \times (729)^{1/3}}{[(0.00872) \times (47)^{3}] - 356}$
27. For the following,
    a. convert numbers to power of ten notation, then perform the indicated computation,
    b. perform the operation directly on your calculator without conversion. What is your conclusion?

    i. 842×0.0014 ii. $\dfrac{0.0352}{0.007\ 91}$
28. Express each of the following in conventional notation.
    a. 34.9×10^{4}
    b. 15.1×10^{0}
    c. 234.6×10^{-4}
    d. 6.97×10^{-2}
    e. $45\ 786.97 \times 10^{-1}$
    f. 6.97×10^{-5}
29. One coulomb (Chapter 2) is the amount of charge represented by 6 240 000 000 000 000 000 electrons. Express this quantity in power of ten notation.
30. The mass of an electron is 0.000 000 000 000 000 000 000 000 000 000 899 9 kg. Express as a power of ten with one nonzero digit to the left of the decimal point.
31. If 6.24×10^{18} electrons pass through a wire in 1 s, how many pass through it during a time interval of 2 h 47 min 10 s?
32. Compute the distance traveled in meters by light in a vacuum in 1.2×10^{-8} second.

33. How long does it take light to travel 3.47×10^5 km in a vacuum?
34. How far in km does light travel in one light-year?
35. While investigating a site for a hydroelectric project, you determine that the flow of water is 3.73×10^4 m^3/s. How much is this in liters/hour?
36. The gravitational force between two bodies is $F = 6.6726 \times 10^{-11} \dfrac{m_1 m_2}{r^2}$ N, where masses m_1 and m_2 are in kilograms and the distance r between gravitational centers is in meters. If body 1 is a sphere of radius 5000 miles and density of 25 kg/m^3, and body 2 is a sphere of diameter 20 000 km and density of 12 kg/m^3, and the distance between centers is 100 000 miles, what is the gravitational force between them?

1.5 Prefixes, Engineering Notation, and Numerical Results

37. What is the appropriate prefix and its abbreviation for each of the following multipliers?
    a. 1000
    b. 1 000 000
    c. 10^9
    d. 0.000 001
    e. 10^{-3}
    f. 10^{-12}
38. Express the following in terms of their abbreviations—for example, microwatts as μW. Pay particular attention to capitalization (e.g., V, not v, for volts).
    a. milliamperes
    b. kilovolts
    c. megawatts
    d. microseconds
    e. micrometers
    f. milliseconds
    g. nanoamps
39. Express the following in the most sensible engineering notation (e.g., 1270 μs = 1.27 ms).
    a. 0.0015 s
    b. 0.000027 s
    c. 0.00035 ms
40. Convert the following:
    a. 156 mV to volts
    b. 0.15 mV to microvolts
    c. 47 kW to watts
    d. 0.057 MW to kilowatts
    e. 3.5×10^4 volts to kilovolts
    f. 0.000 035 7 amps to microamps
41. Determine the values to be inserted in the blanks.
    a. 150 kV = ___ $\times 10^3$ V = ___ $\times 10^6$ V
    b. 330 μW = ___ $\times 10^{-3}$ W = ___ $\times 10^{-5}$ W
42. Perform the indicated operations and express the answers in the units indicated.
    a. 700 μA − 0.4 mA = ___ μA = ___ mA
    b. 600 MW + 300 $\times 10^4$ W = ___ MW
43. Perform the indicated operations and express the answers in the units indicated.
    a. 330 V + 0.15 kV + 0.2 $\times 10^3$ V = ___ V
    b. 60 W + 100 W + 2700 mW = ___ W
44. The voltage of a high-voltage transmission line is 1.15×10^5 V. What is its voltage in kV?

45. You purchase a 1500-W electric heater to heat your room. How many kW is this?

46. A portion of an electronic circuit is shown in Figure 1–11. As you will learn in Chapter 6, for this circuit, $I_4 = I_1 + I_2 + I_3$. If $I_1 = 1.25$ mA, $I_2 = 350\ \mu$A, and $I_3 = 250 \times 10^{-5}$ A, what is I_4?

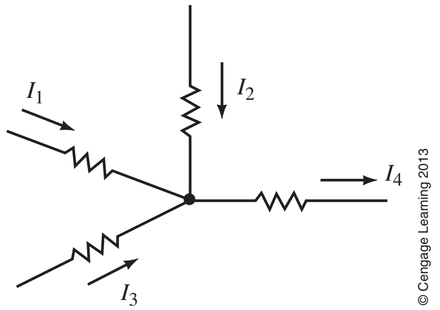


FIGURE 1–11 A nodal point in an electronic circuit. As you learn in Chapter 6, the current leaving the junction is equal to the sum of currents entering.

47. For Figure 1–12, $I_1 + I_2 - I_3 + I_4 = 0$. If $I_1 = 12$ A, $I_2 = 0.150$ kA and $I_4 = 250 \times 10^{-1}$ A, what is I_3?

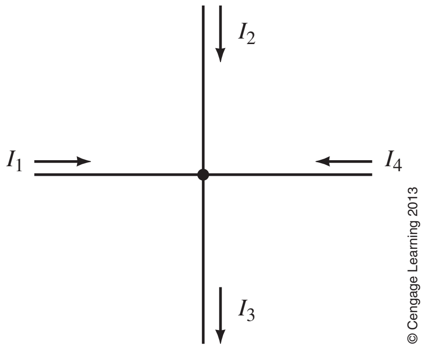


FIGURE 1–12

48. In a certain electronic circuit, $V_1 = V_2 - V_3 - V_4$. If $V_1 = 120$ mV, $V_2 = 5000\ \mu$V, and $V_3 = 20 \times 10^{-4}$ V, what is V_4?

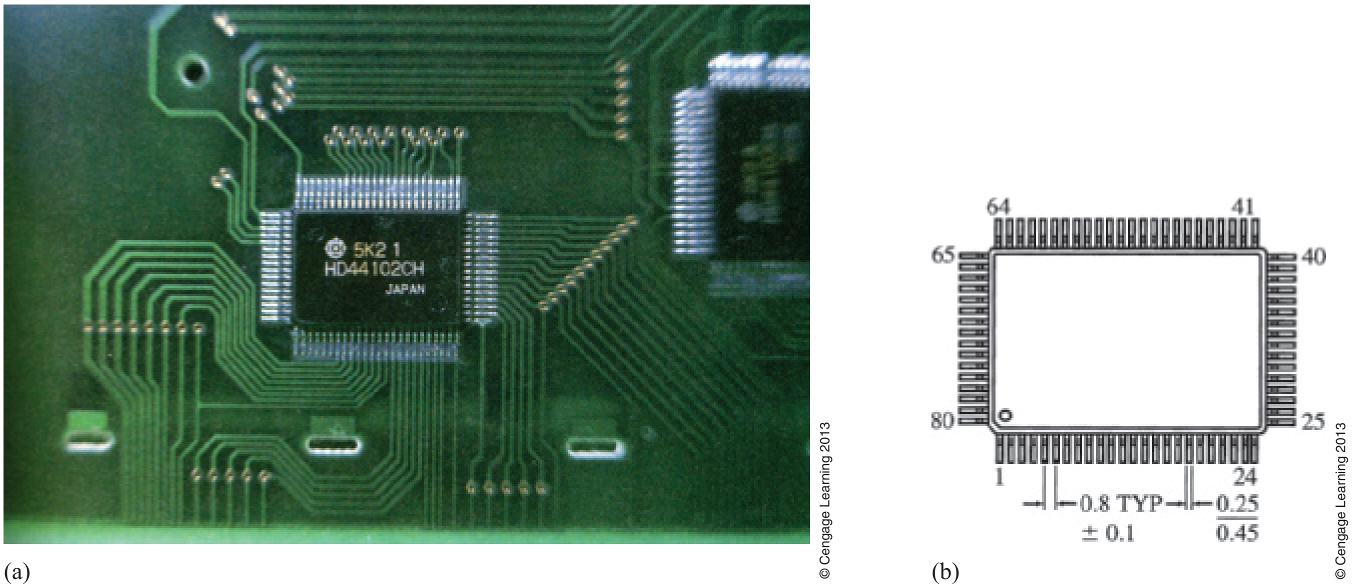
49. While repairing an antique radio, you come across a faulty capacitor designated 39 mmfd. After a bit of research, you find that "mmfd" is an obsolete unit meaning "micromicrofarads." You need a replacement capacitor of equal value. Consulting Table 1–6, what would 39 "micromicrofarads" be equivalent to?

50. a. If 0.045 coulomb of charge (Question 29) passes through a wire in 15 ms, how many electrons is this?

    b. At the rate of 9.36×10^{19} electrons per second, how many coulombs pass a point in a wire in 20 μs?

51. A radio signal travels at 299 792.458 km/s and a telephone signal at 150 m/μs. If they originate at the same point, which arrives first at a destination 5000 km away? By how much?

52. In Chapter 4, you will learn that dc power is given by the product of voltage times current, that is, $P = V \times I$ watts.
    a. If $V = 50$ V and $I = 24$ mA (both exact values), what is P in watts?
    b. If voltage is measured with a voltmeter as $V = 50.0 \pm 0.1$ volts, and current is measured with an ammeter as $I = 24.0 \pm 0.1$ mA, what can you conclude about P based on these measured values?
53. In Chapter 4, you will learn that resistance is given by the ratio of voltage to current, that is, $R = V \div I$ ohms.
    a. If $V = 50$ V and $I = 24$ mA (both exact values), what is R?
    b. If voltage is measured as $V = 50.0 \pm 0.1$ volts, and current as $I = 24.0 \pm 0.1$ mA, what can you conclude about R based on these measured values?
54. The component soldered onto the printed circuit of Figure 1–13(a) is an electronic device known as an integrated circuit. As indicated in (b), center-to-center spacing of its leads is 0.8 ± 0.1 mm. Lead diameters can vary from 0.25 mm to 0.45 mm. Considering these uncertainties, compute the minimum and maximum distance between leads due to these manufacturing tolerances.
55. Open the mini-tutorial *Significant Digits and Numerical Accuracy* found on the Web site and do the exercise problems.



(a) (b)

FIGURE 1–13

1.6 Circuit Diagrams

56. Consider the pictorial diagram of Figure 1–14. Using the appropriate symbols from Table 1–7, draw this in schematic form. Hint: In later chapters, there are many schematic circuits containing resistors, inductors, and capacitors. Use these as aids.

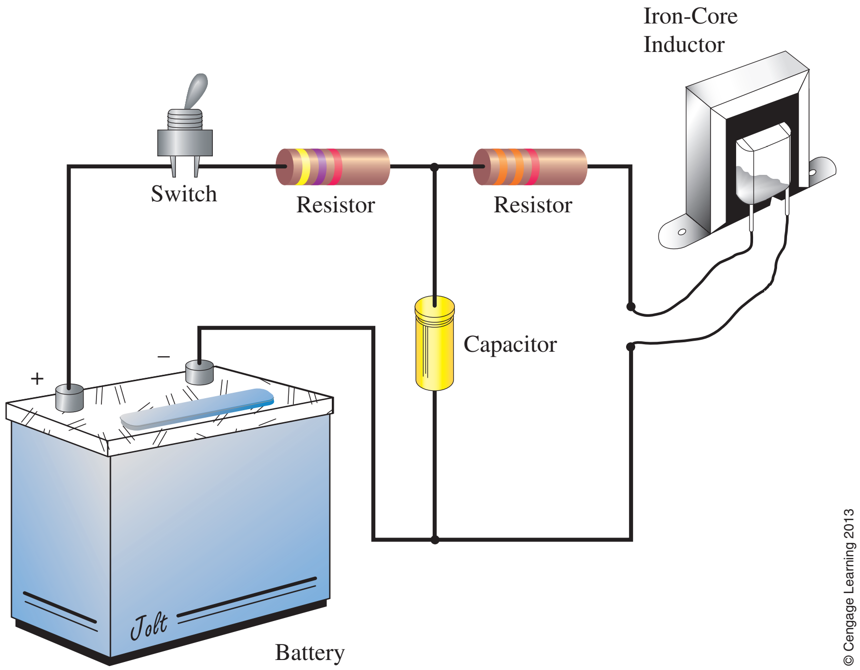


FIGURE 1–14

57. Draw the schematic diagram for a simple flashlight.

ANSWERS TO IN-PROCESS LEARNING CHECKS

IN-PROCESS LEARNING CHECK 1

1. One
2. 1280 cm
3. m/s
4. a. 4.27 s
   b. 1.53 mV
   c. 1.23 ms
5. a. $1.8 \times 10^4 = 18 \times 10^3$
   b. $36 \times 10^4 = 3.6 \times 10^5 = 0.36 \times 10^6$
   c. $4.45 \times 10^2 = 44.5 \times 10^1$
   d. $27 \times 10^{-6} = 2.7 \times 10^{-5}$
6. a. 0.752 mA
   b. 980 μV
   c. 400 μs = 0.4 ms

KEY TERMS

Ampere
Ampere-Hour
Atom
Autopolarity
Battery
Circuit Breaker
Conductor
Conventional Current
Coulomb
Coulomb's Law
Current
dc or Direct Current
dc Source
Electrical Charge
Free Electrons
Fuse
Insulator
Ion
Polarity
Potential Difference
Primary Batteries
Semiconductor
Secondary Batteries
Valence Electron
Voltage

OUTLINE

Atomic Theory Review
The Unit of Electrical Charge: The Coulomb
Voltage
Current
Practical dc Voltage Sources
Measuring Voltage and Current
Switches, Fuses, and Circuit Breakers

OBJECTIVES

After studying this chapter, you will be able to

- describe the basic makeup of an atom,
- explain the relationships between valence shells, free electrons, and conduction,
- describe the fundamental (coulomb) force within an atom and the energy required to create free electrons,
- describe what ions are and how they are created,
- describe the characteristics of conductors, insulators, and semiconductors,
- describe the coulomb as a measure of charge,
- define voltage,
- describe how a battery "creates" voltage,
- explain current as a movement of charge and how voltage causes current in a conductor,
- describe important battery types and their characteristics,
- describe how to measure voltage and current.

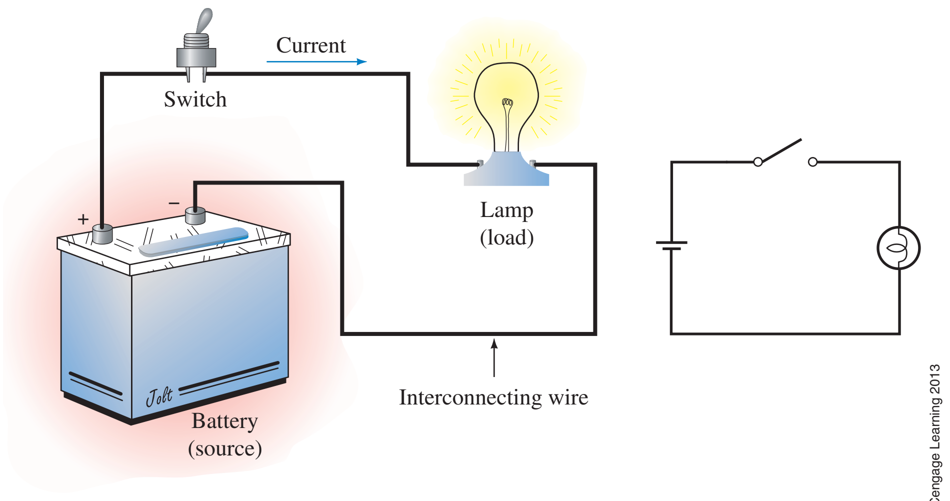
2

VOLTAGE AND CURRENT

CHAPTER PREVIEW

A basic electric circuit consisting of a source of electrical energy, a switch, a load, and interconnecting wire is shown in Figure 2–1. When the switch is closed, current in the circuit causes the light to come on. This circuit is representative of many common circuits found in practice, including those of flashlights and automobile headlight systems. We will use it to help develop an understanding of voltage and current—see Notes and icon *CircuitSim 02-1*.

CircuitSim 02-1



(a) Pictorial representation

(b) Schematic representation

FIGURE 2–1 A basic electric circuit.

NOTES...

CircuitSim 02-1 introduces a new innovation to circuit analysis textbooks—the ability to study the circuits of the textbooks "live" and fully functional on your computer—see *Learning Circuit Theory Interactively on Your Computer* in the Preface. Each time you see such an icon in this book, it means that there is a companion simulation available.

Elementary atomic theory shows that the current in Figure 2–1 is actually a flow of charges. The cause of their movement is the "voltage" of the source. While in Figure 2–1 this source is a battery, in practice it may be any one of a number of practical sources, including generators, power supplies, solar cells, and so on.

In this chapter we look at the basic ideas of voltage and current. We begin with a discussion of atomic theory. This leads us to free electrons and the idea of current as a movement of charge. The fundamental definitions of voltage and current are then developed. Following this, we look at a number of common voltage sources. The chapter concludes with a discussion of voltmeters and ammeters and the measurement of voltage and current in practice. ■

Putting It in Perspective

The Equations of Circuit Theory

In this chapter you meet the first of the equations and formulas that we use to describe the relationships of circuit theory. Remembering formulas is made easier if you clearly understand the principles and concepts on which they are based. As you may recall from high school physics, formulas can come about in only one of three ways: through experiment, by definition, or by mathematical manipulation.

Experimental Formulas

Circuit theory rests on a few basic experimental results. These are results that can be proven in no other way; they are valid solely because experiment has shown them to be true. The most fundamental of these are called "laws." Four examples are Ohm's law, Kirchhoff's current law, Kirchhoff's voltage law, and Faraday's law. (These laws will be met in various chapters throughout the book.) When you see a formula referred to as a law or an experimental result, remember that it is based on experiment and cannot be obtained in any other way.

Defined Formulas

Some formulas are created by definition, that is, we make them up. For example, there are 60 seconds in a minute because we define the second as 1/60 of a minute. From this we get the formula $t_{\text{sec}} = 60 \times t_{\text{min}}$.

Derived Formulas

This type of formula or equation is created mathematically by combining or manipulating other formulas. In contrast to the other two types of formulas, the only way that a derived relationship can be obtained is by mathematics.

An awareness of where circuit theory formulas come from is important to you. This awareness not only helps you understand and remember formulas, it helps you understand the very foundations of the theory—the basic experimental premises upon which it rests, the important definitions that have been made, and the methods by which these foundation ideas have been put together. This can help enormously in understanding and remembering concepts. ■

2.1 Atomic Theory Review

The basic structure of an **atom** is shown symbolically in Figure 2–2. It consists of a nucleus of protons and neutrons surrounded by a group of orbiting electrons. As you learned in physics, the electrons are negatively charged (−), while the protons are positively charged (+). Each atom (in its normal state) has an equal number of electrons and protons, and since their charges are equal and opposite, they cancel, leaving the atom electrically neutral, that is, with zero net charge. The nucleus, however, has a net positive charge, since it consists of positively charged protons and uncharged neutrons.

The basic structure of Figure 2–2 applies to all elements, but each element has its own unique combination of electrons, protons, and neutrons. For example, the hydrogen atom, the simplest of all atoms, has 1 proton and 1 electron, while the copper atom has 29 electrons, 29 protons, and 35 neutrons. Silicon, which is important because of its use in transistors and other electronic devices, has 14 electrons, 14 protons, and 14 neutrons.

In the model of Figure 2–2, electrons that have approximately the same orbital radiuses may be thought of as forming shells. This gives us the simplified picture of Figure 2–3, where we have grouped closely spaced orbits into shells designated *K*, *L*, *M*, *N*, and so on. Only certain numbers of electrons can exist within each shell, and no electrons can exist in the space between shells. The maximum that any shell can hold is $2n^2$ where n is the shell number. Thus, there can be up to 2 electrons in the *K* shell, up to 8 in the *L* shell, up to 18 in the *M* shell, and up to 32 in the *N* shell. The number in any shell depends on the element. For instance, the copper atom, which has 29 electrons, has all 3 of its inner shells completely filled, but its outer shell (shell *N*) has only 1 electron,

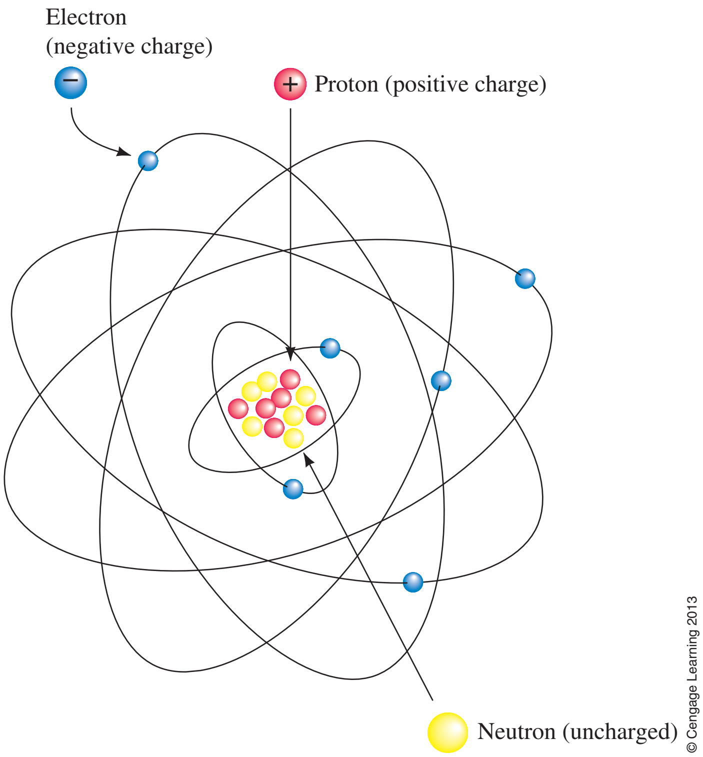


FIGURE 2–2 Bohr model of the atom. Electrons travel around the nucleus at incredible speeds, making billions of trips in a fraction of a second. The force of attraction between the electrons and the protons in the nucleus keeps them in orbit.

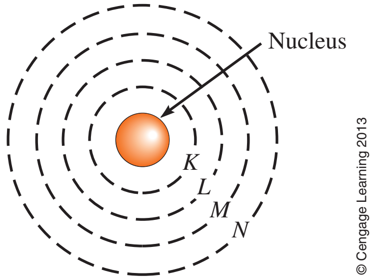


FIGURE 2–3 Simplified representation of the atom. Electrons travel in roughly spherical orbits called "shells."

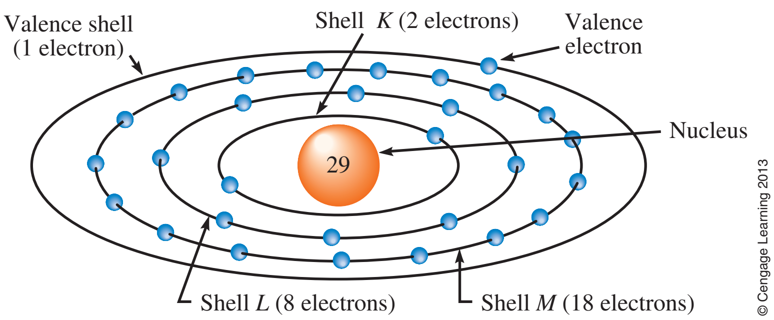


FIGURE 2–4 Copper atom. Since the valence electron is only weakly attracted to the nucleus, it is said to be "loosely bound."

as in Figure 2–4. This outermost shell is called its valence shell, and the electron in it is called its **valence electron.**

No element can have more than 8 valence electrons; when a valence shell has 8 electrons, it is filled. As we shall see, the number of valence electrons that an element has directly affects its electrical properties.

Electrical Charge

In the previous paragraphs, we mentioned the word "charge." However, we need to look at its meaning in more detail. First, we should note that **electrical charge** is an intrinsic property of electrons and protons that manifests itself in the form of forces—electrons repel other electrons but attract protons, while protons repel each other but attract electrons. It was through studying these forces that scientists determined that the charge on the electron is negative while that on the proton is positive.

However, the way in which we use the term "charge" extends beyond this. To illustrate, consider again the basic atom of Figure 2–2. It has equal numbers of electrons and protons, and since their charges are equal and opposite, they cancel, leaving the atom as a whole uncharged. However, if the atom acquires additional electrons (leaving it with more electrons than protons), we say that it (the atom) is negatively charged; conversely, if it loses electrons and is left with fewer electrons than protons, we say that it is positively charged. The term "charge" in this sense denotes an imbalance between the number of electrons and protons present in the atom.

Now move up to the macroscopic level. Here, substances in their normal state are also generally uncharged; that is, they have equal numbers of electrons and protons. However, this balance is easily disturbed—electrons can be stripped from their parent atoms by simple actions such as walking across a carpet, sliding off a chair, or spinning clothes in a dryer. (Recall "static cling.") Consider two additional examples from physics. Suppose you rub an ebonite (hard rubber) rod with fur. This action causes a transfer of electrons from the fur to the rod. The rod therefore acquires an excess of electrons and is thus negatively charged. Similarly, when a glass rod is rubbed with silk, electrons are transferred from the glass rod to the silk, leaving the rod with a deficiency and, consequently, a positive charge. Here again, charge refers to an imbalance of electrons and protons.

As the preceding examples illustrate, "charge" can refer to the charge on an individual electron or to the charge associated with a whole group of electrons. In either case, this charge is denoted by the letter Q, and its unit of measurement in the SI system is the coulomb. (The definition of the coulomb is considered in Section 2.2.) In general, the charge Q associated with a group of electrons is equal to the product of the number of electrons times the charge on each individual electron. Since charge manifests itself in the form of forces, charge is defined in terms of these forces. This is discussed next.

Coulomb's Law

The force between charges was studied by the French scientist Charles Coulomb (1736–1806). Coulomb determined experimentally that the force between two charges Q_1 and Q_2 (Figure 2–5) is directly proportional to the product of their charges and inversely proportional to the square of the distance between them. Mathematically, **Coulomb's law** states

$$F = k\frac{Q_1 Q_2}{r^2} \quad \text{[newtons, N]} \qquad \textbf{(2–1)}$$

where Q_1 and Q_2 are the charges in coulombs (to be defined in Section 2.2), r is the center-to-center spacing between them in meters, and $k = 9 \times 10^9$. Coulomb's law applies to aggregates of charges as in Figure 2–5(a) and (b), as well as to individual electrons within the atom as in (c).

As Coulomb's law indicates, force decreases inversely as the square of distance; thus, if the distance between two charges is doubled, the force decreases to $(1/2)^2 = 1/4$ (i.e., one quarter) of its original value. Because of this relationship, electrons in outer orbits are less strongly attracted to the nucleus than those in inner orbits; that is, they are less tightly bound to the nucleus than those close by. Valence electrons are the least tightly bound and will, if they acquire sufficient energy, escape from their parent atoms.

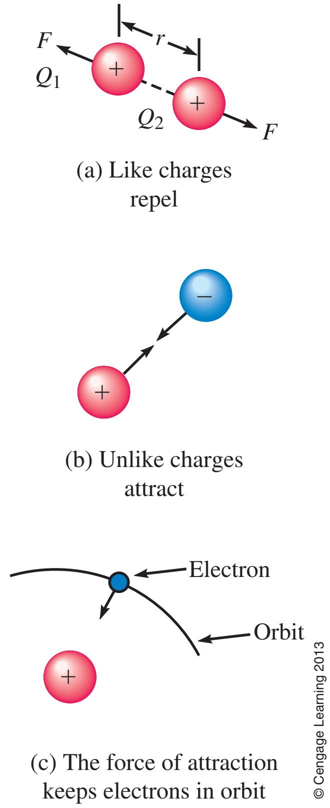


FIGURE 2–5 Coulomb law forces.

Free Electrons

The amount of energy required to escape depends on the number of electrons in the valence shell. If an atom has only a few valence electrons, there will be a relatively weak attraction between these electrons and the nucleus, and only a small amount of additional energy is needed. For example, for a metal like copper, valence electrons can gain sufficient energy from heat alone (thermal energy), even at room temperature, to escape from their parent atoms and wander from atom to atom throughout the material as depicted in Figure 2–6. (Note that these electrons do not leave the substance, they simply wander from the valence shell of one atom to the valence shell of another. The material therefore remains electrically neutral.) Such electrons are called **free electrons.** In copper, there are on the order of 10^{23} free electrons per cubic centimeter at room temperature. As we shall see, it is the presence of this large number of free electrons that makes copper such a good conductor of electric current. On the other hand, if the valence shell is full (or nearly full), valence electrons are much more tightly bound. Such materials have few (if any) free electrons.

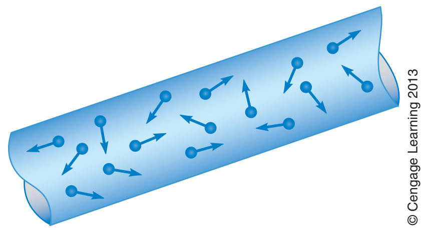


FIGURE 2–6 Random motion of free electrons in a conductor.

Ions

As noted earlier, when a previously neutral atom gains or loses an electron, it acquires a net electrical charge. The charged atom is referred to as an **ion.** If the atom loses an electron, it is called a positive ion; if it gains an electron, it is called a negative ion.

Conductors, Insulators, and Semiconductors

The atomic structure of matter affects how easily charges, that is, electrons, move through a substance and hence how it is used electrically. Electrically, materials are classified as conductors, insulators, or semiconductors.

Conductors

Materials through which charges move easily are termed **conductors.** The most familiar examples are metals. Good metal conductors have large numbers of free electrons that are able to move about easily. In particular, silver, copper, gold, and aluminum are excellent conductors. Of these, copper is the most widely used. Not only is it an excellent conductor, it is inexpensive and easily formed into wire, making it suitable for a broad spectrum of applications ranging from common house wiring to sophisticated electronic equipment. Aluminum, although it is only about 60% as good a conductor as copper, is also used, mainly in applications where light weight is important, such as in overhead power transmission lines. Silver and gold are too expensive for general use. However, gold, because it oxidizes less than other materials, is used in specialized applications; for example, critical electrical connectors in electronic equipment use it because it makes a more reliable connection than other materials.

Insulators

Materials that do not conduct (e.g., glass, porcelain, plastic, rubber, and so on) are termed **insulators.** The covering on electric lamp cords, for example, is an insulator. It is used to prevent the wires from touching and to protect us from electric shock.

Insulators do not conduct because they have full or nearly full valence shells and thus their electrons are tightly bound. However, when high enough voltage is applied, the force is so great that electrons are literally torn from their parent atoms, causing the insulation to break down and conduction to occur. In air, you see this as an arc or flashover. In solids, charred insulation usually results.

Semiconductors

Silicon and germanium (plus a few other materials) have half-filled valence shells and are thus neither good conductors nor good insulators. Known as **semiconductors,** they have unique electrical properties that make them important to the electronics industry. The most important material is silicon. It is used to make transistors, diodes, integrated circuits, and other electronic devices. Semiconductors have made possible personal computers, home theater systems, cell phones, calculators, iPods, and a host of other electronic products.

IN-PROCESS LEARNING CHECK 1

(Answers are at the end of the chapter.)

1. Describe the basic structure of the atom in terms of its constituent particles: electrons, protons, and neutrons. Why is the nucleus positively charged? Why is the atom as a whole electrically neutral?
2. What are valence shells? What does the valence shell contain?
3. Describe Coulomb's law and use it to help explain why electrons far from the nucleus are loosely bound.
4. What are free electrons? Describe how they are created, using copper as an example. Explain what role thermal energy plays in the process.
5. Briefly distinguish between a normal (i.e., uncharged) atom, a positive ion, and a negative ion.

2.2 The Unit of Electrical Charge: The Coulomb

As noted in the previous section, the unit of electrical charge in the SI system is the coulomb (C). The **coulomb** is defined as the charge carried by 6.24×10^{18} electrons. Thus, if an electrically neutral (i.e., uncharged) body has 6.24×10^{18} electrons removed, it will be left with a net positive charge of 1 coulomb, that is, $Q = 1$ C. Conversely, if an uncharged body has 6.24×10^{18} electrons added, it will have a net negative charge of 1 coulomb, that is, $Q = -1$ C. Usually, however, we are more interested in the charge moving through a wire. In this regard, if 6.24×10^{18} electrons pass through a wire, we say that the charge that passed through the wire is 1 C.

We can now determine the charge on one electron. It is $Q_e = 1/(6.24 \times 10^{18}) = 1.602 \times 10^{-19}$ C.

EXAMPLE 2–1

An initially neutral body has 1.7 μC of negative charge removed. Later, 18.7×10^{11} electrons are added. What is the body's final charge?

Solution Initially the body is neutral, that is, $Q_{initial} = 0$ C. When 1.7 μC of electrons is removed, the body is left with a positive charge of 1.7 μC. Now, 18.7×10^{11} electrons are added back. This is equivalent to

$$18.7 \times 10^{11} \text{ electrons} \times \frac{1 \text{ coulomb}}{6.24 \times 10^{18} \text{ electrons}} = 0.3\ \mu\text{C}$$

of negative charge. The final charge on the body is therefore $Q_f = 1.7\ \mu\text{C} - 0.3\ \mu\text{C} = +1.4\ \mu\text{C}$.

To get an idea of how large a coulomb is, we can use Coulomb's law. If it were possible to place 2 charges of 1 coulomb each 1 meter apart, the force between them would be

$$F = (9 \times 10^9)\frac{(1\text{ C})(1\text{ C})}{(1\text{ m})^2} = 9 \times 10^9 \text{ N, that is, about 1 million tons!}$$

PRACTICE PROBLEMS 1

1. Positive charges $Q_1 = 2$ μC and $Q_2 = 12$ μC are separated center to center by 10 mm. Compute the force between them. Is it attractive or repulsive?
2. Two equal charges are separated by 1 cm. If the force of repulsion between them is 9.7×10^{-2} N, what is their charge? What may the charges be, both positive, both negative, or one positive and one negative?
3. After 10.61×10^{13} electrons are added to a metal plate, it has a negative charge of 3 μC. What was its initial charge in coulombs?

Answers
1. 2160 N, repulsive; 2. 32.8 nC, both (+) or both (−); 3. 14 μC (+)

2.3 Voltage

When charges are detached from one body and transferred to another, a *potential difference* or *voltage* results between them. A familiar example is the voltage that develops when you walk across a carpet. Voltages in excess of ten thousand volts can be created in this way. (We will define the volt rigorously very shortly.) This voltage is due entirely to the separation of positive and negative charges, that is, charges that have been pulled apart.

Figure 2–7 illustrates another example. During electrical storms, electrons in thunderclouds are stripped from their parent atoms by the forces of turbulence and carried to the bottom of the cloud, leaving a deficiency of electrons (positive charge) at the top and an excess (negative charge) at the bottom. The force of repulsion then drives electrons away beneath the cloud, leaving the ground positively charged. Hundreds of millions of volts are created in this way. (This is what causes the air to break down and a lightning discharge to occur.)

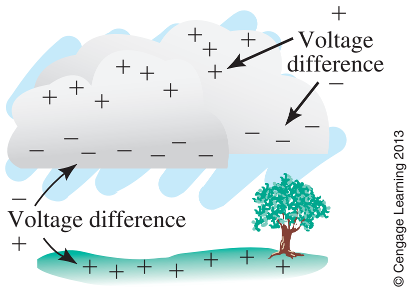


FIGURE 2–7 Voltages created by separation of charges in a thundercloud. The force of repulsion drives electrons away beneath the cloud, creating a voltage between the cloud and earth as well. If voltage becomes large enough, the air breaks down and a lightning discharge occurs.

Practical Voltage Sources

As the preceding examples show, voltage is created solely by the separation of positive and negative charges. However, static discharges and lightning strikes are not practical sources of electricity. We now look at practical sources. A common example is the **battery.** In a battery, charges are separated by chemical action. An ordinary alkaline flashlight battery, Figure 2–8, illustrates the concept. The alkaline material (a mixture of manganese dioxide, graphite, and electrolytic) and a gelled zinc powder mixture, separated by a paper barrier soaked in electrolyte, are placed in a steel can. The can is connected to the top cap to form the cathode or positive terminal, while the zinc mixture, by means of the brass pin, is connected to the bottom to form the anode or negative terminal. (The bottom is insulated from the rest of the can.) Chemical reactions result in an excess of electrons in the zinc mix and a deficiency in the manganese dioxide mix. This separation of charges creates a voltage of approximately 1.5 V, with the top end cap + and the bottom of the can −. The battery is useful as a source since its chemical action creates a continuous supply of energy that is able to do useful work, such as light a lamp or run a motor.

NOTES...

The source of Figure 2–8 is more properly called a cell than a battery, since "cell" refers to a single cell while "battery" refers to a group of cells. However, through common usage, such cells are referred to as batteries. In what follows, we will also call them batteries.

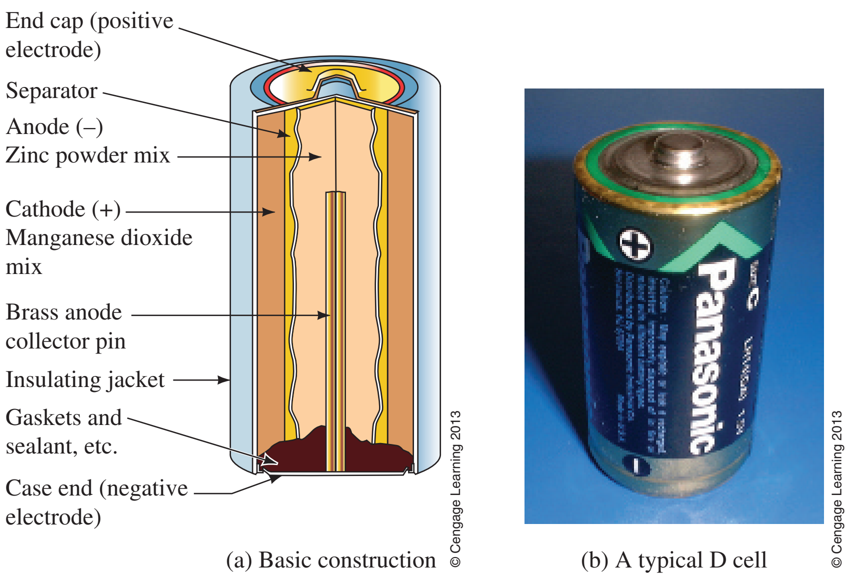


FIGURE 2–8 Alkaline cell. Voltage is created by the separation of charges due to chemical action. Nominal cell voltage is 1.5 V.

Potential Energy

The concept of voltage is tied into the concept of potential energy. We therefore look briefly at energy.

In mechanics, potential energy is the energy that a body possesses because of its position. For example, a bag of sand hoisted by a rope over a pulley has the potential to do work when it is released. The amount of work that went into giving it this potential energy is equal to the product of force times the distance through which the bag was lifted (i.e., work equals force times distance). In the SI system, force is measured in newtons and distance in meters. Thus, work has the unit newton-meters (which we call joules, Section 1.2, Chapter 1).

In a similar fashion, work is required to move positive and negative charges apart. This gives them potential energy. To understand why, consider again the cloud of Figure 2–7, redrawn in Figure 2–9. Assume the cloud is initially uncharged. Now assume a charge of Q electrons is moved from the top of the cloud to the bottom. The positive charge left at the top of the cloud exerts a force on the electrons that tries to pull them back as they are being moved away. Since the electrons are being moved against this force, work (force times distance) is required. Since the separated charges experience a force to return to the top of the cloud, they have the potential to do work if released, that is, they possess potential energy. Similarly for the battery of Figure 2–8, the charges, which have been separated by chemical action, also possess potential energy.

Definition of Voltage: The Volt

In electrical terms, a difference in potential energy is defined as **voltage.** In general, the amount of energy required to separate charges depends on the voltage developed and the amount of charge moved. By definition, *the voltage between two points is one volt if it requires one joule of energy to move one coulomb of charge from one point to the other.* In equation form,

$$V = \frac{W}{Q} \quad \text{[volts, V]} \tag{2–2}$$

where W is energy in joules, Q is charge in coulombs, and V is the resulting voltage in volts (see Notes).

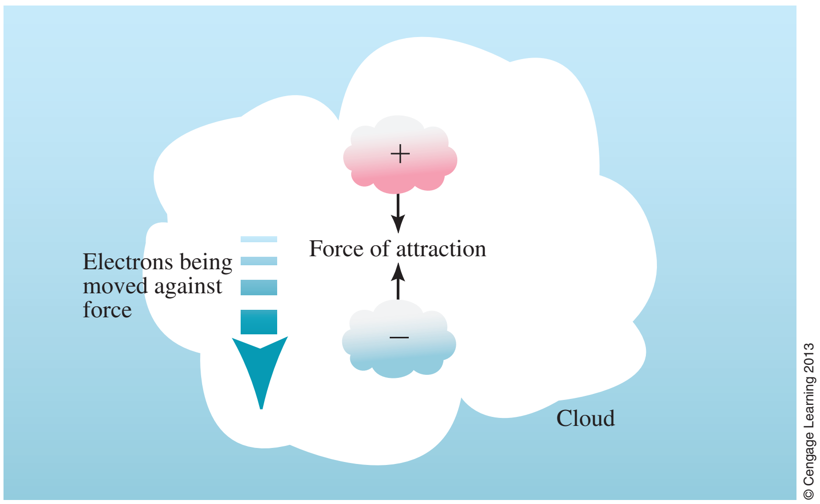


FIGURE 2–9 Work (force × distance) is required to move the charges apart.

NOTES...

The discussion found here may seem a bit abstract and somewhat detached from our ordinary experience, which suggests that voltage is the "force or push" that moves electric current through a circuit. While both viewpoints are correct (we look at the latter in great detail, starting in Chapter 4), in order to establish a coherent analytic theory, we need a rigorous definition. Equation 2–2 provides that definition. Although it is a bit abstract, it gives us the foundation upon which rest many of the important circuit relationships that you will encounter shortly.

Note carefully that voltage is defined between points. For the case of the battery, for example, voltage appears between its terminals. Thus, voltage does not exist at a point by itself; it is always determined with respect to some other point. (For this reason, voltage is also called **potential difference.** We often use the terms interchangeably.) Note also that this argument applies regardless of how you separate the charges, whether it be by chemical means as in a battery, by mechanical means as in a generator, by photoelectric means as in a solar cell, and so on.

Alternate arrangements of Equation 2–2 are useful:

$$W = QV \quad \text{[joules, J]} \tag{2–3}$$

$$Q = \frac{W}{V} \quad \text{[coulombs, C]} \tag{2–4}$$

EXAMPLE 2–2

If it takes 35 J of energy to move a charge of 5 C from one point to another, what is the voltage between the two points?

Solution

$$V = \frac{W}{Q} = \frac{35\text{ J}}{5\text{ C}} = 7\text{ J/C} = 7\text{ V}$$

PRACTICE PROBLEMS 2

1. The voltage between two points is 19 V. How much energy is required to move 67×10^{18} electrons from one point to the other?
2. The potential difference between two points is 140 mV. If 280 μJ of work are required to move a charge Q from one point to the other, what is Q?

Answers
1. 204 J; 2. 2 mC

Symbol for dc Voltage Sources

Consider again Figure 2–1. The battery is the source of electrical energy that moves charges around the circuit. This movement of charges, as we will soon see, is called an electric current. Because one of the battery's terminals is always positive and the other is always negative, current is always in the same direction. Such a unidirectional current is called **dc** or **direct current,** and the battery is called a **dc source.** Symbols for dc sources are shown in Figure 2–10. The long bar denotes the positive terminal. On actual batteries, the positive terminal is usually marked POS (+) and the negative terminal NEG (−). We refer to this designation as **polarity**—thus, the + terminal has positive polarity and the − terminal has negative polarity.

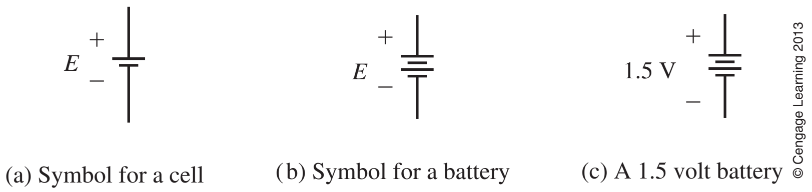


FIGURE 2–10 Battery symbol. The long bar denotes the positive terminal and the short bar the negative terminal—thus it is not necessary to put + and − signs on the diagram (although we often do). For simplicity, we use the symbol shown in (a) throughout this book for batteries as well as for cells.

2.4 Current

Earlier, you learned that there are large numbers of free electrons in metals like copper. These electrons move randomly throughout the material (Figure 2–6), but their net movement in any given direction is zero.

Assume now that a battery is connected as in Figure 2–11. Since electrons are attracted by the positive pole of the battery and repelled by the negative pole, they move around the circuit, passing through the wire, the lamp, and the battery. This movement of charge is called an electric **current.** The more electrons per second that pass through the circuit, the greater is the current. Thus, current is the *rate of flow* (or *rate of movement*) of charge.

The Ampere

Since charge is measured in coulombs, its rate of flow is coulombs per second. In the SI system, 1 coulomb per second is defined as 1 **ampere** (commonly abbreviated A). From this, we get that *1 ampere is the current in a circuit when 1 coulomb of charge passes a given point in 1 second* (Figure 2–11). The symbol for current is *I*. Expressed mathematically,

$$I = \frac{Q}{t} \quad \text{[amperes, A]} \qquad \textbf{(2–5)}$$

where Q is the charge (in coulombs) and t is the time interval (in seconds) over which it is measured. *In Equation 2–5, it is important to note that t does not*

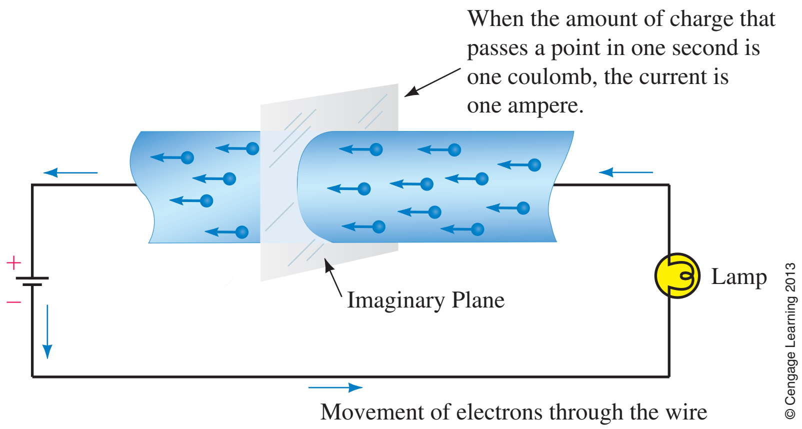


FIGURE 2–11 Electron flow in a conductor. Electrons (−) are attracted to the positive (+) pole of the battery. As electrons move around the circuit, they are replenished at the negative pole of the battery. This flow of charge is called an electric current.

represent a discrete point in time but is the interval of time during which the transfer of charge occurs. Alternate forms of Equation 2–5 are

$$Q = It \text{ [coulombs, C]} \tag{2–6}$$

and

$$t = \frac{Q}{I} \quad \text{[seconds, s]} \tag{2–7}$$

EXAMPLE 2–3

If 840 coulombs of charge pass through the imaginary plane of Figure 2–11 during a time interval of 2 minutes, what is the current?

Solution Convert t to seconds. Thus,

$$I = \frac{Q}{t} = \frac{840 \text{ C}}{(2 \times 60)\text{s}} = 7 \text{ C/s} = 7 \text{ A}$$

PRACTICE PROBLEMS 3

1. Between $t = 1$ ms and $t = 14$ ms, 8 μC of charge pass through a wire. What is the current?
2. After the switch of Figure 2–1 is closed, current $I = 4$ A. How much charge passes through the lamp between the time the switch is closed and the time that it is opened 3 minutes later?

Answers
1. 0.615 mA; 2. 720 C

Although Equation 2–5 is the theoretical definition of current, we never actually use it to measure current. In practice, we use an instrument called an ammeter (Section 2.6). However, it is an extremely important theoretical relationship that we will soon use to develop other more practical relationships.

NOTES...

A perfectly coherent theory can be built around either of the directions of Figure 2–12, and many circuit analysis and electronics textbooks have been written from each viewpoint. There are, however, compelling reasons for choosing the conventional direction. Among these are (1) Standard electronic symbols used in circuit diagrams and found in manufacturers' data books are based on it, (2) Computer software such as PSpice and Multisim utilizes it, and (3) All Engineering level and virtually all EET level college programs teach it.

Current Direction

In the early days of electricity, it was believed that current was a movement of positive charge and that these charges moved around the circuit from the positive terminal of the battery to the negative as depicted in Figure 2–12(a). Based on this, all the laws, formulas, and symbols of circuit theory were developed. (We now refer to this direction as the **conventional current** direction.) After the discovery of the atomic nature of matter, it was learned that what actually moves in metallic conductors are electrons and that they move through the circuit as in Figure 2–12(b). This direction is called the electron flow direction. We thus have two possible representations for current direction and a choice has to be made. *In this book, we use the conventional direction (see Notes).*

Alternating Current (ac)

So far, we have considered only dc. Before we move on, we will briefly mention ac or alternating current. Alternating current is current that changes direction cyclically—that is, charges alternately flow in one direction, then in

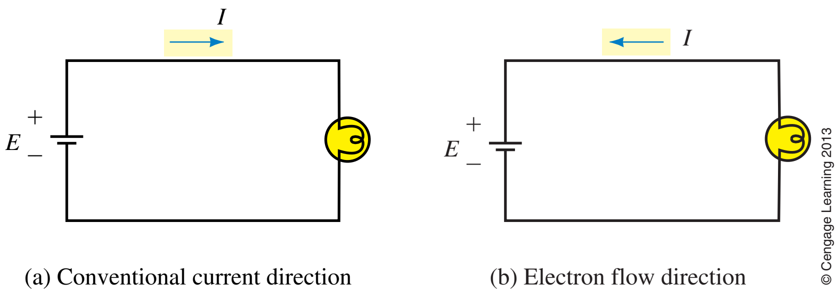


FIGURE 2–12 Conventional current versus electron flow. In this book, we use conventional current.

the other in a circuit. The most common ac source is the commercial ac power system that supplies energy to your home. We mention it here because you will encounter it briefly in Section 2.5. It is covered in detail in Chapter 15.

IN-PROCESS LEARNING CHECK 2

(Answers are at the end of the chapter.)

1. Body *A* has a negative charge of 0.2 μC and body *B* has a charge of 0.37 μC (positive). If 87×10^{12} electrons are transferred from *A* to *B*, what are the charges in coulombs on *A* and on *B* after the transfer?
2. Briefly describe the mechanism of voltage creation using the alkaline cell of Figure 2–8 to illustrate.
3. When the switch in Figure 2–1 is open, the current is zero, yet free electrons in the copper wire are moving about. Describe their motion. Why does their movement not constitute an electric current?
4. If 12.48×10^{20} electrons pass a certain point in a circuit in 2.5 s, what is the current in amperes?
5. For Figure 2–1, assume a 12-V battery. The switch is closed for a short interval, then opened. If $I = 6$ A and the battery expends 230 040 J moving charge through the circuit, how long was the switch closed?

2.5 Practical dc Voltage Sources

Batteries

Batteries are the most common dc source. They are made in a variety of shapes, sizes, and ratings, from miniaturized button batteries capable of delivering only a few microamps to large automotive batteries capable of delivering hundreds of amps. Common sizes are the AAA, AA, C, and D. All batteries use unlike conductive electrodes immersed in an electrolyte. Chemical interaction between the electrodes and the electrolyte creates the voltage of the battery. We now look at some of the more common types—see Notes.

Primary and Secondary Batteries

Batteries eventually become "discharged." Some types of batteries, however, can be "recharged." Such batteries are called **secondary batteries.** Other types, called **primary batteries,** cannot be recharged. A familiar example of a secondary battery is the automobile battery. It can be recharged by passing current

NOTES...

Only a brief overview of various battery types is presented here. More detailed information may be found by searching the Internet.

through it opposite to its discharge direction. A familiar example of a primary cell is the flashlight battery.

Types of Batteries and Their Applications

The voltage of a battery, its service life, and other characteristics depend on the material from which it is made.

Alkaline

These are popular, general-purpose batteries that are used in flashlights, portable radios, TV remote controllers, cameras, toys, and so on. With a nominal cell voltage of 1.5 V, they come in various sizes as depicted in Figure 2–13. While some alkaline batteries are designed to be recharged, most are not.

Lithium

Lithium batteries (Figure 2–14) feature small size and long life (e.g., some have shelf lives of 10 to 20 years). Applications include watches, pacemakers, cameras, and battery backup of computer memories. Several types of lithium cells are available, with voltages from of 2 V to 3.5 V and current ratings from the microampere to the ampere range.

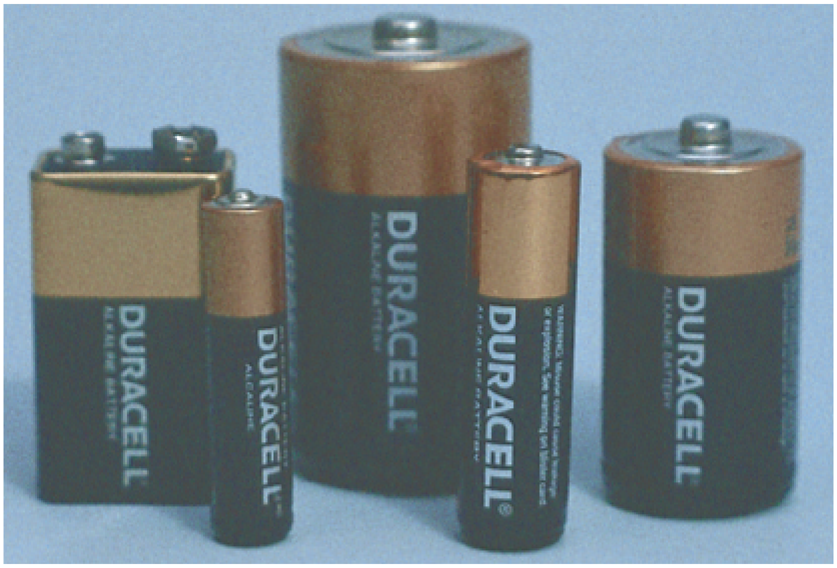


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FIGURE 2–13 Alkaline batteries. From left to right, a 9V rectangular battery, an AAA cell, a D cell, an AA cell, and a C cell.

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FIGURE 2–14 An assortment of lithium batteries. The battery on the computer motherboard is for memory backup.

Nickel-Cadmium (Ni-Cad)

Ni-Cads are general-purpose, rechargeable batteries that, although once popular, are gradually being superseded by NiMH and lithium ion batteries, which have better performance characteristics and higher energy densities. Uses include cordless power tools and home entertainment systems.

Nickel-Metal Hydride (NiMH)

NiMH batteries are rechargeable batteries that can have two to three times the capacity of an equivalent-sized Ni-Cad battery. They are used for powering electric vehicles, as well as in consumer electronics, such as cameras.

Lead-Acid

This is the familiar automotive battery. Its basic cell voltage is about 2 volts, but typically, six cells are connected internally to provide 12 volts at its terminals. Lead-acid batteries are capable of delivering large current (in excess of 100 A) for short periods as required, for example, to start an automobile.

Battery Capacity

Batteries run down under use. However, an estimate of their useful life can be determined from their capacity, that is, their **ampere-hour** rating. (The ampere-hour rating of a battery is equal to the product of its current drain times the length of time that you can expect to draw the specified current before the battery becomes unusable.) For example, a battery rated at 200 Ah can theoretically supply 20 A for 10 h, or 5 A for 40 h, and so on. The relationship between capacity, life, and current drain is

$$\text{life} = \frac{\text{capacity}}{\text{current drain}} \tag{2–8}$$

The capacity of batteries is not a fixed value as suggested above but is affected by discharge rates, operating schedules, temperature, and other factors. (For example, a battery discharged at a high rate will have a lower capacity than the same battery discharged at a lower rate.) At best, therefore, capacity is an estimate of expected life under certain conditions. To illustrate, consider Figure 2–15. It shows a typical variation of capacity of a Ni-Cad battery with changes in temperature.

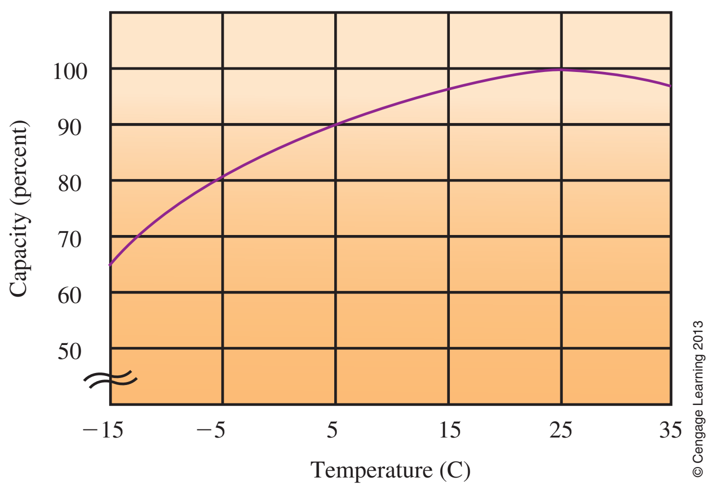


FIGURE 2–15 Typical variation of capacity versus temperature for a Ni-Cad battery.

Other Characteristics

Because batteries are not perfect, their terminal voltage drops as the amount of current drawn from them increases. (This issue is considered in Chapter 5.) In addition, battery voltage is affected by temperature and other factors that affect their chemical activity. However, these factors are not considered in this book.

EXAMPLE 2–4

Assume the battery of Figure 2–15 has a capacity of 240 Ah at 25° C. What is its capacity at −15° C?

Solution From the graph, capacity at –15° C is down to 65% of its value at 25° C. Thus, capacity = 0.65 × 240 = 156 Ah.

Cells in Series and Parallel

Cells may be connected as in Figure 2–16 and Figure 2–17 to increase their voltage and current capabilities. This is discussed in later chapters.

FIGURE 2–16 Cells connected in series to increase the available voltage.

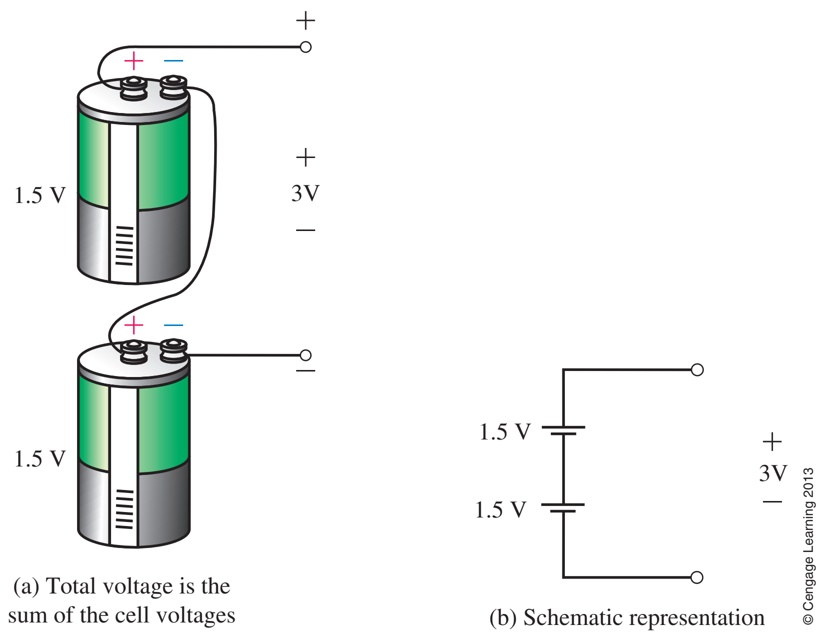
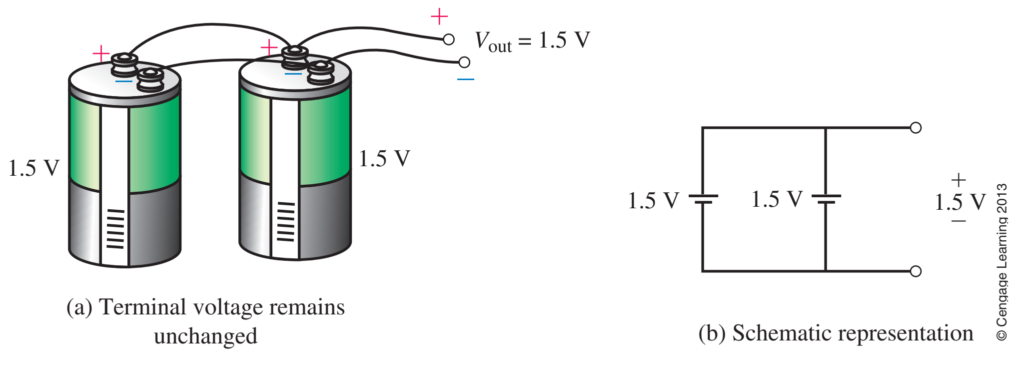


FIGURE 2–17 Cells connected in parallel to increase the available current. (Both must have the same voltage.) Do not do this for extended periods of time.



Electronic Power Supplies

Electronic systems such as TV sets, Blu-ray players, computers, and so on, require dc for their internal circuit operation. Except for portable units, which use batteries, they obtain their power from the commercial ac power lines by means of built-in power supplies. Figure 2–18 shows a fixed voltage supply built for such purposes. In other applications, variable voltage may be needed, as for example during prototype development and circuit testing. Figure 2–19 shows a remotely programmable, variable dc supply whose voltage and current can be set remotely by the user.

Solar Cells

Solar cells convert light energy to electrical energy using photovoltaic means. The basic cell consists of two layers of semiconductor material. When light strikes the cell, many electrons gain enough energy to cross from one layer to the other to create a dc voltage.

Solar energy has a number of practical applications. Large solar farms, for example (some covering nearly 1000 acres or 400 ha of land), use solar panels to create dc which is then converted to ac and fed into the adjacent commercial electrical power grid. Figure 2–20 shows a typical installation, built to serve the needs of an Air Force base. Other, much smaller installations are found on house rooftops in residential areas or on the roofs of commercial buildings. In

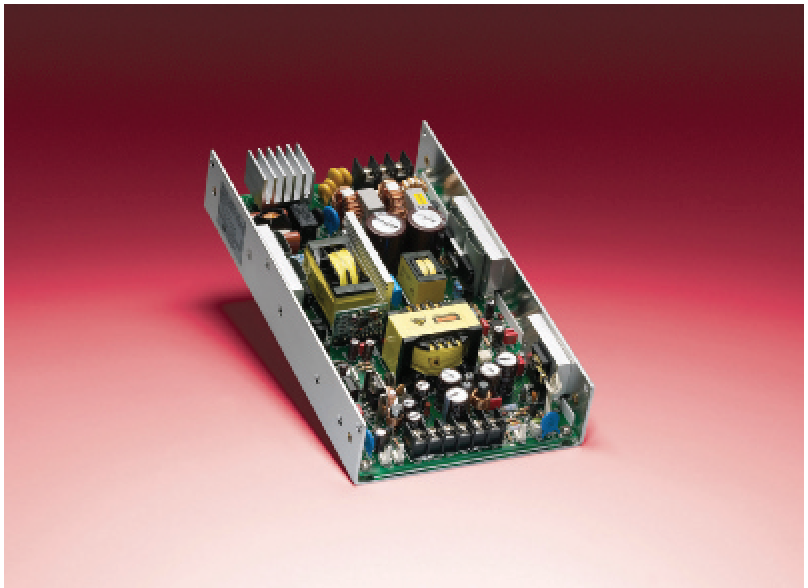


Photo courtesy of Kepco Inc.

FIGURE 2–18 General-purpose 300 W open frame power supply.

Photo courtesy of Kepco Inc.

FIGURE 2–19 Programmable power supply. Voltage and current values may be set locally or by remote control.

FIGURE 2–20 Solar panel installation at Nellis Air Force Base in Nevada. This array of panels (which employs an advanced sun tracking system) supplies a significant percentage of the base's electrical power needs.

FIGURE 2–21 AC adapters are used as a source of dc for many electronic devices.

remote areas, solar panels are used to power communications systems and irrigation pumps. In space, they are used to power satellites. In everyday life, they are used to power hand-held calculators.

AC Adapter

Many electronic devices—including laptop computers, answering machines, and modems—utilize an ac adapter in order to provide dc for powering their circuits. The adapter plugs into any standard 120 V ac outlet; converts ac to dc; and uses this dc to power the desired device (such as the keyboard of Figure 2–21).

2.6 Measuring Voltage and Current

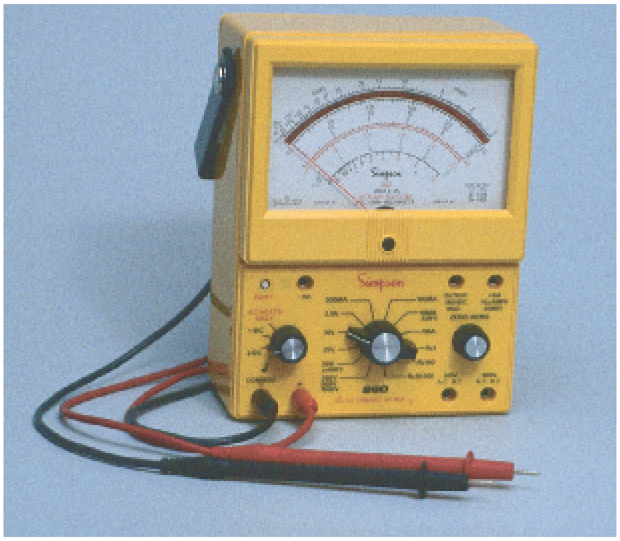
Voltage and current are usually measured in practice using a multimeter, an instrument that combines voltage, current, and resistance (and sometimes other) measuring functions in a single unit. While both digital and analog versions are available, the hand-held digital multimeter (DMM), is by far the most popular choice these days—see Notes. In terms of product choice, DMMs range from

NOTES...

In this book, we consider only digital multimeters. However, a mini-tutorial describing analog measurements may be found on our Web site at www.cengagebrain.com. Log in as per the instructions in the Preface and follow the links to *For Further Investigation* and select *Using Analog Multimeters*.

(a) Hand-held digital multimeter (DMM)

Courtesy of Fluke Corporation



(b) Analog multimeter (VOM). Analog multimeters have been largely superseded by DMMs.

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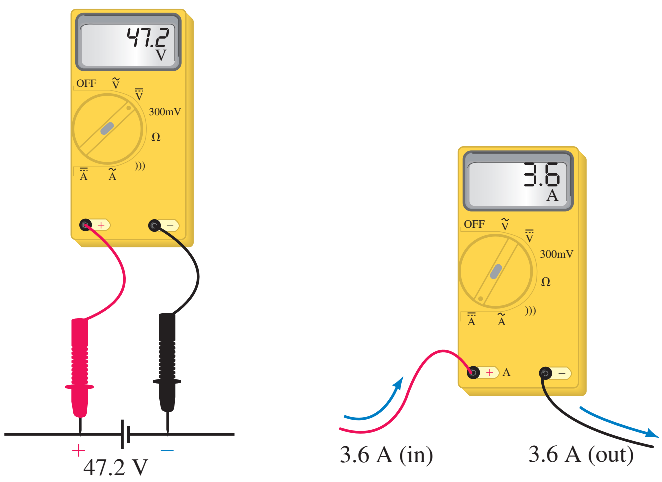
FIGURE 2–22 Multimeters are multipurpose test instruments that combine the functions of a voltmeter, ammeter, and ohmmeter (plus some secondary functions) into a single unit. Some instruments use terminal markings of VΩ and COM, while others use a + and − designation. Black and red color-coded test leads are industry standard.

inexpensive units such as those commonly used by home hobbyists to professional grade devices such as that shown in Figure 2–22.

Terminal Designations

Multimeters typically have a set of terminals marked VΩ, A, and COM that are color coded red and black as in Figure 2–22(a). Terminal VΩ is the terminal to use to measure voltage and resistance, while terminal A is used for current measurement. The terminal marked COM is the common terminal for all measurements. (Some multimeters combine the VΩ and A terminals into one terminal marked VΩA.) On some instruments the VΩ terminal is called the + terminal, and the COM terminal is called the − terminal. In the interests of generality, we use the +, − designation in this book (Figure 2–23).



(a) Set selector to $\overline{\overline{\text{V}}}$ to measure dc voltage

(b) Set selector to $\overline{\overline{\text{A}}}$ to measure dc current

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FIGURE 2–23 Measuring voltage and current with a multimeter. Be sure to set the selector switch to the correct function before you energize the circuit and connect the red lead to the VΩ (+) terminal and the black lead to the COM (−) terminal.

NOTES...

DMMs as Learning Tools

Voltage and current as presented earlier in this chapter are rather abstract concepts involving energy, charge, and charge movement. Voltmeters and ammeters are introduced at this point to help present the ideas in more physically meaningful terms. In particular, we concentrate on DMMs. Experience has shown them to be powerful learning tools. For example, when dealing with the sometimes difficult topics of voltage polarity conventions, current direction conventions, and so on (as in later chapters), the use of DMMs showing readings complete with signs for voltage polarity and current direction provides clarity and aids understanding in a way that simply drawing arrows and putting numbers on diagrams does not. You will find that in the first few chapters of this book DMMs are used for this purpose quite frequently.

NOTES...

Most DMMs have internal circuitry that automatically selects the correct range for voltage measurement. Such instruments are called "autoranging" or "autoscaling" devices.

Function Selection

DMMs generally include a function selector switch (or alternatively, a set of push buttons) that permit you to select the quantity to be measured—such as dc voltage, ac voltage, resistance, dc current, or ac current—and you must set the meter to the desired function before you make a measurement, (Figure 2–23). Note the symbols on the dial. The symbol $\overline{\overline{V}}$ denotes dc voltage, $\tilde{A}$ denotes ac voltage, Ω denotes resistance, and so on. When set to dc volts, the meter measures and displays the voltage between its VΩ (or +) and COM (or −) terminals as indicated in Figure 2–23(a); when set to dc current, it measures the current passing through it, that is, the current entering its A (or +) terminal and leaving its COM (or −) terminal. Be sure to note the sign of the measured quantity. (DMMs generally have an **autopolarity** feature that automatically determines the sign for you.) Thus, if the meter is connected with its + lead connected to the + terminal of the source, the display will show 47.2 V as indicated, while if the leads are reversed, the display will show −47.2 V. Similarly, if the leads are reversed for current measurement (so that current enters the COM terminal), the display will show −3.6 A. Be sure to observe the standard color convention for test lead connections—see Practical Notes.

How to Measure Voltage

Since voltage is the potential difference between two points, you measure voltage by placing the voltmeter leads *across* the component whose voltage you wish to determine as we saw in Figure 2–23(a). Figure 2–24 shows another example. To measure the voltage across the lamp, place one lead on each side of the lamp as shown. If the meter is not autoscale and you have no idea how large the voltage is, set the meter to its highest range, then work your way down to avoid damage to the instrument.

CircuitSim 02-2

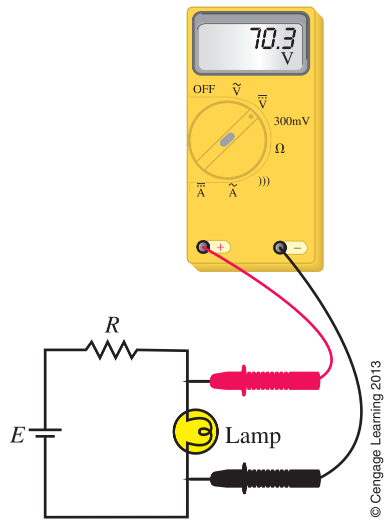


FIGURE 2–24 To measure voltage, place the voltmeter leads across the component whose voltage you wish to determine. If the voltmeter reading is positive, the point where the red lead is connected is positive with respect to the point where the black lead is connected.

PRACTICAL NOTES...

Color-coded test leads (red and black) are industry standard. Standard practice calls for you to insert the red lead into the VΩ (i.e., +) socket of your meter, and the black lead into the COM (−) socket. (This is a safety issue. If you follow this practice you will know simply by looking at the probe which test lead is connected to which socket on your meter.) Following this procedure, if the voltmeter indicates a positive value, the point where the red lead is touching is positive with respect to the point where the black lead is touching; inversely, if the meter indicates negative, the point where the red lead is touching is negative with respect to the point where the black lead is connected. For current measurements, if the meter indicates a positive value, this means that the direction of current is into the red, that is, (+) or VΩA terminal and out of the black, that is, (−) or COM terminal; conversely, if the reading is negative, this means that the direction of current is into the meter's COM terminal and out of its (+) or VΩA terminal.

How to Measure Current

As indicated by Figure 2–23(b), the current that you wish to measure must pass *through* the meter. Consider Figure 2–25(a). To measure this current, open the circuit as in (b) and insert the ammeter. The sign of the reading will be positive if current enters the A or (+) terminal or negative if it enters the COM (or −) terminal as described in the Practical Notes.

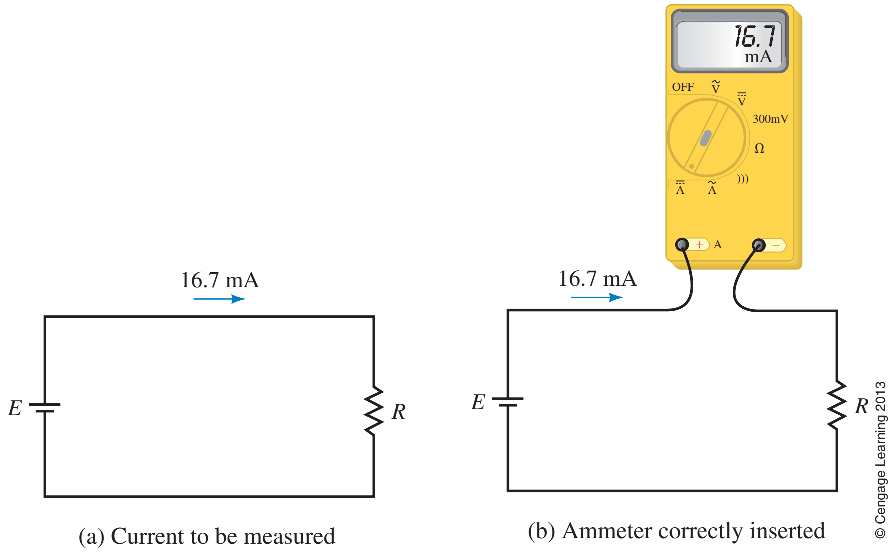


FIGURE 2–25 To measure current, insert the ammeter into the circuit so that the current you wish to measure passes through the instrument. The reading is positive here because current enters the + (A) terminal.

Meter Symbols

So far, we have shown meters pictorially. Usually, however, they are shown schematically. The schematic symbol for a voltmeter is a circle with the letter *V*, while the symbol for an ammeter is a circle with the letter *I*. The circuits of Figures 2–24 and 2–25 have been redrawn (Figure 2–26) to indicate this.

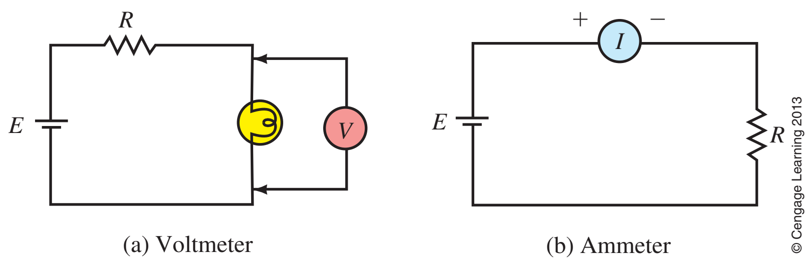


FIGURE 2–26 Schematic symbols for voltmeter and ammeter.

CircuitSim 02-3

PRACTICAL NOTES...

1. One sometimes hears statements such as "... the voltage through a resistor" or "... the current across a resistor." These statements are incorrect. Voltage does not pass through anything; voltage is a potential difference and appears across things. This is why we connect a voltmeter *across* components to measure their voltage. Similarly, current does not appear across anything; current is a flow of charge that passes *through* circuit elements. This is why we put the ammeter in the current path—to measure the current in it. Thus, the correct statements are "... voltage across the resistor ..." and "... current through the resistor. ..."
2. Do *not* connect ammeters directly across a voltage source. Ammeters have nearly zero resistance and damage will probably result.

2.7 Switches, Fuses, and Circuit Breakers

Switches

The most basic switch is a single-pole, single-throw (SPST) switch as shown in Figure 2–27. With the switch open, the current path is broken and the lamp is off; with it closed, the lamp is on. This type of switch is used, for example, for light switches in homes.

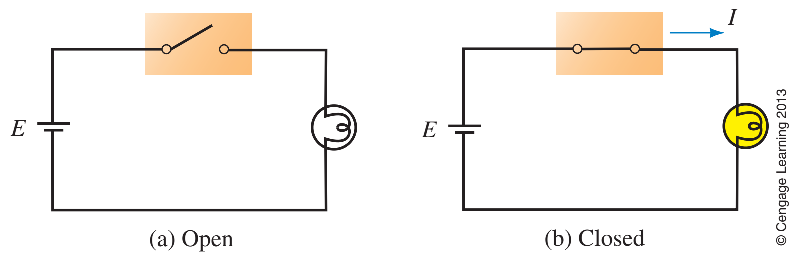


FIGURE 2–27 Single-pole, single-throw (SPST) switch.

Figure 2–28(a) shows a single-pole, double-throw (SPDT) switch. Two of these switches may be used as in (b) for two-way control of a light. This type of arrangement is sometimes used for stairway lights; you can turn the light on or off from either the bottom or the top of the stairs.

Many other configurations of switches exist in practice. However, we will leave the topic at this point.

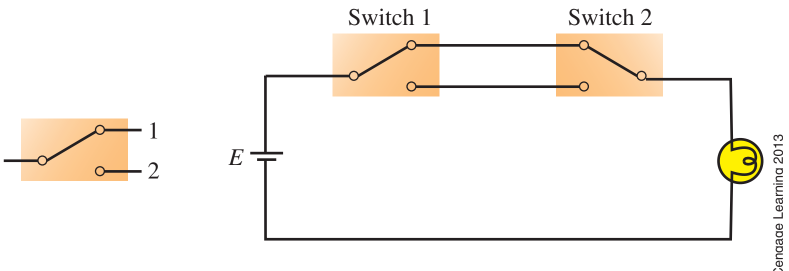
Fuses and Circuit Breakers

Fuses and **circuit breakers** are wired into a circuit between the source and the load as illustrated in Figure 2–29 to protect equipment or wiring against excessive current. For example, in your home, if you connect too many appliances to an outlet, the fuse or circuit breaker in your electrical panel “blows.” This opens the circuit to protect against overloading and possible fire. Fuses and circuit breakers may also be installed in equipment such as your automobile to protect against internal faults. Figure 2–30 shows a variety of fuses and breakers.

Fuses use a metallic element that melts when current exceeds a preset value. Thus, if a fuse is rated at 3 A, it will “blow” if more than 3 amps passes through it. Fuses are made as fast-blow and slow-blow types. Fast-blow fuses are very fast; typically, they blow in a fraction of a second. Slow-blow fuses, on the other hand, react more slowly so that they do not blow on small, momentary overloads.

CircuitSim 02-4

Circuit breakers work on a different principle. When the current exceeds the rated value of a breaker, the magnetic field produced by the excessive current operates a mechanism that trips open a switch. After the fault or overload condition has been cleared, the breaker can be reset and used again. Since they are mechanical devices, their operation is slower than that of a fuse; thus, they do not “pop” on momentary overloads as, for example, when you start a motor.



(a) SPDT switch (b) Two-way switch control of a light

FIGURE 2–28 Single-pole, single-throw (SPDT) switch.

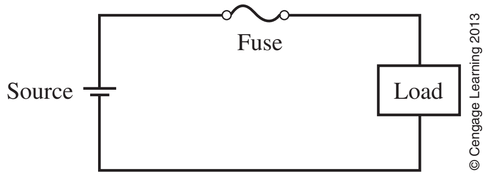
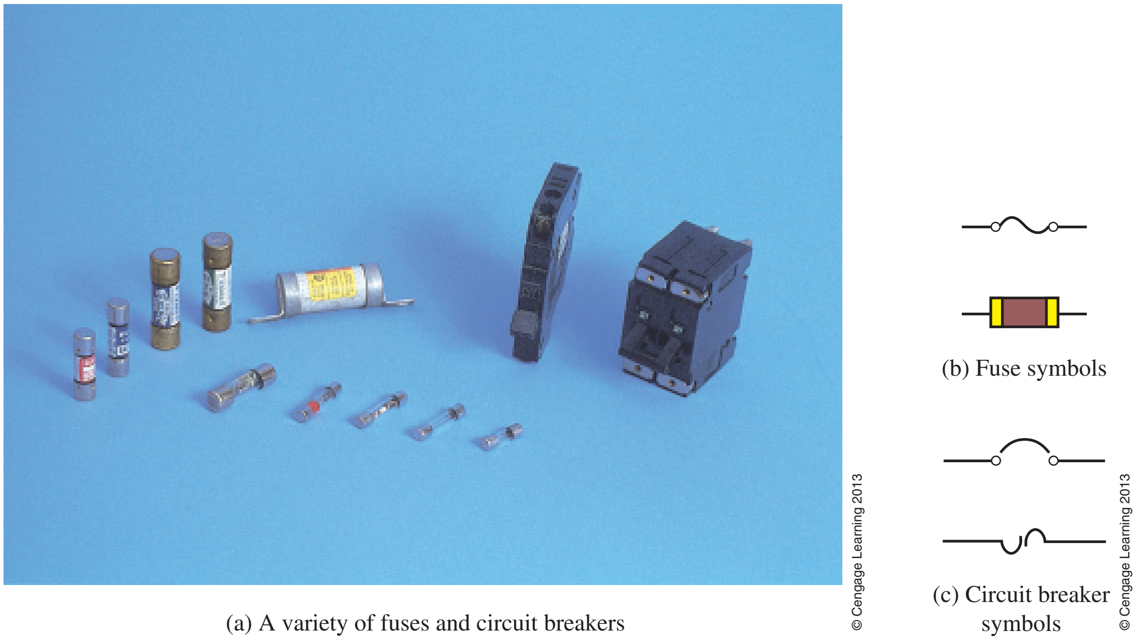


FIGURE 2–29 Using a fuse to protect a circuit.

Putting It into Practice

Your company is considering the purchase of an electrostatic air cleaner system for one of its facilities and your supervisor has asked you to prepare a short presentation for the Board of Directors. Members of the Board understand basic electrical theory but are unfamiliar with the specifics of electrostatic air cleaners. Go to your library (physics books are a good reference) or the Internet and research and prepare a short description of the electrostatic air cleaner. Include a diagram and a description of how it works.



(a) A variety of fuses and circuit breakers

(b) Fuse symbols

(c) Circuit breaker symbols

FIGURE 2–30 Fuses and circuit breakers.

Problems

2.1 Atomic Theory Review

1. How many free electrons are there in the following at room temperature?
   a. 1 cubic meter of copper
   b. a 5 m length of copper wire whose diameter is 0.163 cm
2. Two charges are separated by a certain distance, Figure 2–31. How is the force between them affected if
   a. the magnitudes of both charges are doubled?
   b. the distance between the charges is tripled?
3. Two charges are separated by a certain distance. If the magnitude of one charge is doubled and the other tripled and the distance between them halved, how is the force affected?
4. A certain material has 4 electrons in its valence shell and a second material has 1. Which is the better conductor?
5. a. What makes a material a good conductor? (In your answer, consider valence shells and free electrons.)
   b. Besides being a good conductor, list two other reasons why copper is so widely used.
   c. What makes a material a good insulator?
   d. Normally air is an insulator. However, during lightning discharges, conduction occurs. Briefly discuss the mechanism of charge flow in this discharge.
6. a. Although gold is very expensive, it is sometimes used in electronics as a plating on contacts. Why?
   b. Why is aluminum sometimes used when its conductivity is only about 60% as good as that of copper?

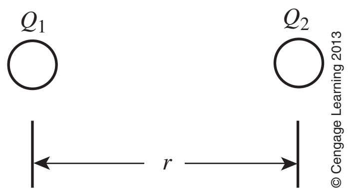


FIGURE 2–31

NOTES...

All spacings in these questions are center-to-center.

2.2 The Unit of Electrical Charge: The Coulomb

7. Compute the electrical force between the following charges and state whether it is attractive or repulsive.
   a. A + 1 μC charge and a +7 μC charge, separated 10 mm
   b. $Q_1 = 8$ μC and $Q_2 = -4$ μC, separated 12 cm
   c. Two electrons separated by 12×10^{-8} m
   d. An electron and a proton separated by 5.3×10^{-11} m
   e. An electron and a neutron separated by 5.7×10^{-11} m
8. What do we mean when we say that a body is "charged?"
9. The force between a positive charge and a negative charge that are 2 cm apart is 180 N. If $Q_1 = 4$ μC, what is Q_2? Is the force attraction or repulsion?
10. If you could place a charge of 1 C on each of two bodies separated 25 cm center to center, what would be the force between them in newtons? In tons?
11. The force of repulsion between two charges separated by 50 cm is 0.02 N. If $Q_2 = 5Q_1$, determine the charges and their possible signs.
12. How many electrons does a charge of 1.63 μC represent?
13. Determine the charge possessed by 19×10^{13} electrons.
14. An electrically neutral metal plate acquires a negative charge of 47 μC. How many electrons were added to it?
15. A metal plate has 14.6×10^{13} electrons added. Later, 1.3 μC of charge is added. If the final charge on the plate is 5.6 μC, what was its initial charge?

2.3 Voltage

16. Sliding off a chair and touching someone can result in a shock. Explain why.
17. If 360 joules of energy are required to transfer 15 C of charge through the lamp of Figure 2–1, what is the voltage of the battery?
18. If 600 J of energy are required to move 9.36×10^{19} electrons from one point to the other, what is the potential difference between the two points?
19. If 1.2 kJ of energy are required to move 500 mC from one point to another, what is the voltage between the two points?
20. How much energy is required to move 20 mC of charge through the lamp of Figure 2–24?
21. How much energy is gained by a charge of 0.5 μC as it moves through a potential difference of 8.5 kV?
22. If the voltage between two points is 100 V, how much energy is required to move an electron between the two points?
23. Given a voltage of 12 V for the battery in Figure 2–1, how much charge is moved through the lamp if it takes 57 J of energy to move it?

2.4 Current

24. For the circuit of Figure 2–1, if 27 C pass through the lamp in 9 seconds, what is the current in amperes?
25. If 250 μC pass through the ammeter of Figure 2–32 in 5 ms, what will the meter read?

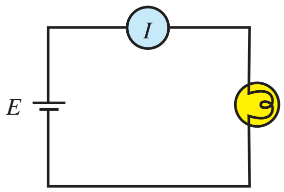


FIGURE 2–32

26. If the current $I = 4$ A in Figure 2–1, how many coulombs pass through the lamp in 7 ms?
27. How much charge passes through the circuit of Figure 2–25 in 20 ms?
28. How long does it take for 100 μC to pass a point if the current is 25 mA?
29. If 93.6×10^{12} electrons pass through a lamp in 5 ms, what is the current?
30. The charge passing through a wire is given by $q = 10t + 4$, where q is in coulombs and t in seconds,
    a. How much charge has passed at $t = 5$ s?
    b. How much charge has passed at $t = 8$ s?
    c. What is the current in amps?
31. The charge passing through a wire is $q = (80t + 20)$ C. What is the current? Hint: Choose two arbitrary values of time and proceed as in Question 30, or use calculus if you know how.
32. How long does it take 312×10^{19} electrons to pass through the circuit of Figure 2–32 if the ammeter reads 8 A?
33. If 1353.6 J are required to move 47×10^{19} electrons through the lamp of Figure 2–32 in 1.3 min, what are E and I?

2.5 Practical dc Voltage Sources

34. What do we mean by dc? By ac?
35. Consider three batteries connected as in Figure 2–33.
    a. If $E_1 = 1.47$ V, $E_2 = 1.61$ V, and $E_3 = 1.58$ V, what is E_T?
    b. If the connection to source 3 is reversed, what is E_T?
36. How do you charge a secondary battery? Make a sketch. Can you charge a primary battery?
37. A battery rated 1400 mAh supplies 28 mA to a load. How long can it be expected to last?
38. The battery of Figure 2–15 is expected to last 17 h at a current drain of 1.5 A at 25° C. How long do you expect it to last at 5° C at a current drain of 0.8 A?
39. The battery of Figure 2–15 is rated at 81 Ah at 5° C. What is the expected life (in hours) at a current draw of 5 A at −15° C?

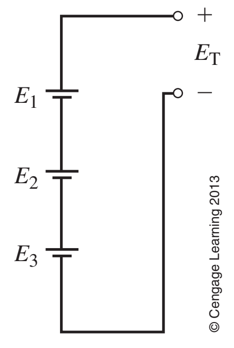


FIGURE 2–33

2.6 Measuring Voltage and Current

CircuitSim 02-5

40. The digital voltmeters of Figure 2–34 have autopolarity. For each case, determine the readings.
41. The current in the circuit of Figure 2–35 is 9.17 mA. Which ammeter correctly indicates the current? (a) Meter 1, (b) Meter 2, (c) both.
42. Redraw the circuit of Figure 2–35 using schematic symbols for ammeters instead of multimeter pictorials.
43. Current in the circuit of Figure 2–36 is 7 A. What are the expected readings for Meter 1 and Meter 2?
44. What is wrong with the statement that the voltage through the lamp of Figure 2–24 is 70.3 V?
45. What is wrong with the metering scheme shown in Figure 2–37? Fix it.

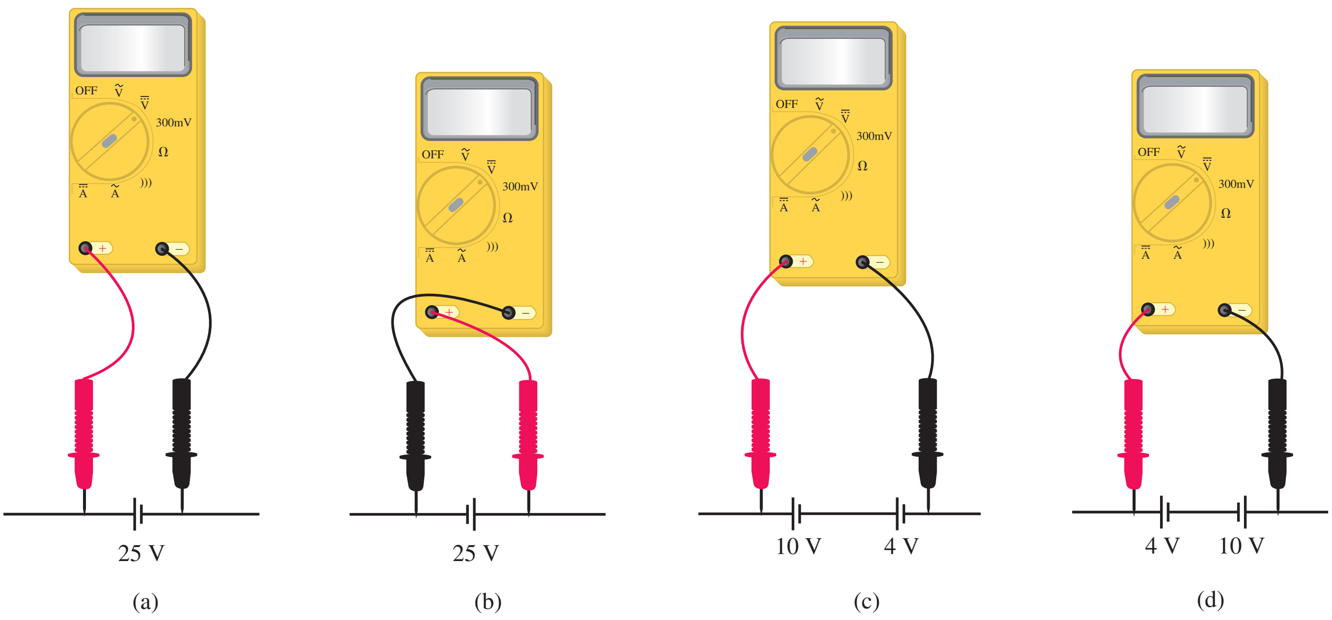


FIGURE 2–34

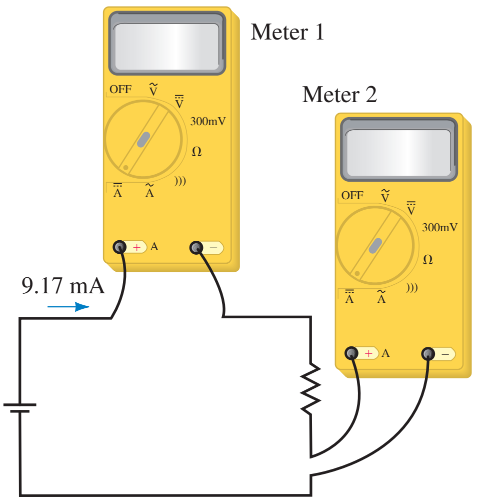


FIGURE 2–35

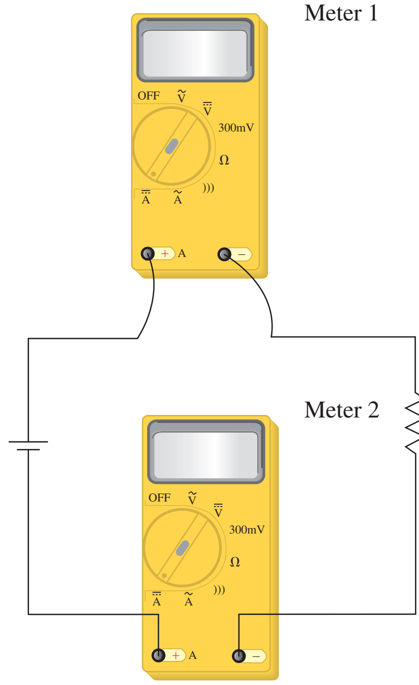


FIGURE 2–36

CircuitSim 02-6

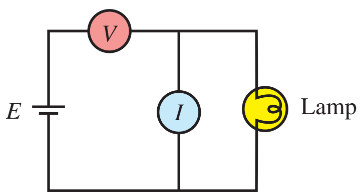


FIGURE 2–37 What is wrong here?

2.7 Switches, Fuses, and Circuit Breakers

46. We wish to control a light using two switches as indicated in Table 2–1. Draw the required circuit.
47. Fuses have a current rating so that you can select the proper size to protect a circuit against overcurrent. They also have a voltage rating. Why? Hint: Read the section on insulators, Section 2.1.

TABLE 2–1

Switch 1	Switch 2	Lamp
Open	Open	Off
Open	Closed	On
Closed	Open	On
Closed	Closed	On

ANSWERS TO IN-PROCESS LEARNING CHECKS

IN-PROCESS LEARNING CHECK 1

1. An atom consists of a nucleus of protons and neutrons orbited by electrons. The nucleus is positive because protons are positive, but the atom is neutral because it contains the same number of electrons as protons, and their charges cancel.
2. The valence shell is the outermost shell. It contains the atom's valence electrons. The number of electrons in this shell determines the properties of the material with regard to whether it is a conductor, insulator, or semiconductor.
3. The force between charged particles is proportional to the product of their charges and inversely proportional to the square of their spacing. Since force decreases as the square of the spacing, electrons far from the nucleus experience little force of attraction.
4. If a loosely bound electron gains sufficient energy, it may break free from its parent atom and wander throughout the material. Such an electron is called a free electron. For materials like copper, heat (thermal energy) can give an electron enough energy to dislodge it from its parent atom.
5. A normal atom is neutral because it has the same number of electrons as protons and their charges cancel. An atom that has lost an electron is called a positive ion, while an atom that has gained an electron is called a negative ion.

IN-PROCESS LEARNING CHECK 2

1. $Q_A = 13.7\ \mu\text{C}$ (pos.), $Q_B = 13.6\ \mu\text{C}$ (neg.)
2. Chemical action creates an excess of electrons in the zinc mixture and a deficiency in the manganese dioxide mix. This separation of charges results in a voltage of 1.5 V. The zinc mixture is connected to the top end cap by the steel can (making it the positive electrode) and the manganese dioxide mixture is connected to the bottom of the can by the brass pin (making it the negative electrode).
3. Motion is random. Since the net movement in all directions is zero, current is zero.
4. 80 A
5. 3195 s