1 Introduction

Outline

Learning Outcomes

After completing this chapter, you will be able to

- briefly describe the history and significance of the electrical industries
- use SI units of measurement correctly, including SI prefixes
- perform operations with powers of ten
- understand and correctly apply concepts of significant digits, accuracy and rounding off

Key Terms

1.1 Electrical Industries

Modern industrialized civilization runs on electricity. From the moment your clock radio wakens you in the morning until you switch off the lights at night, you are surrounded by electrical equipment. Electricity boils the water for your coffee, transports you to work, keeps you in touch with your friends, and provides your entertainment.

There are many industries that can be classified as electrical. They range from power companies that generate and distribute electrical energy to the multitude of manufacturers and users of electrical and electronic equipment. In the electrical power field, they include devices for converting electrical energy to mechanical energy, to heat, and to light. In communications there are telephones, radio, and television, together with their great variety of recording devices. Now, with a computer on every desk, there is another whole cluster of industries involving data manipulation, storage, and transmission.

Beyond the great growth of new industries, electronic control circuits have penetrated into many other fields. Wherever precision and reliability are required, you are likely to find electronic control—from the ignition system of car engines to the almost total operation of plants for refining oil or manufacturing steel. Many specialized electronic components are needed to measure and control a wide range of physical processes.

Every one of these systems and devices contains numerous electrical circuits. The workers who design, manufacture, and service them require a clear understanding of the principles of electrical and electronic circuits. This text is designed to provide you with the foundations for understanding and working with electric circuits. You will find that however much electrical industries grow and diversify, these foundations will continue to supply a solid base for whatever advanced industry you choose to work in.

1.2 A Brief History

Less than two hundred years ago, transportation and communication were limited to the speeds of running horses and sailing ships. Today you can travel in hours, or communicate in seconds, all around the world. Steam engineers and mechanical artisans made the first steps in this transformation. However, that early stage of the industrial revolution could not have advanced to our present stage without electricity. The technologies of steam and iron grew out of the craft traditions of earlier centuries, but electricity was born in the laboratories of scientists—scientists who were curious about the operations of the forces of nature.

Early Electrical Science

After 1700, the scientific works of Isaac Newton provided scientists with techniques for analyzing a variety of motions in terms of the mechanical and gravitational forces that caused them. By the middle of that century, some scientists were applying that analysis to the forces involved in electricity produced by friction and the close contact of dissimilar materials. Benjamin Franklin was able to show that lightning was a form of this **static electricity**. In France, Charles Coulomb invented equipment for measuring tiny forces. He found that electric forces obeyed the same inverse-square law that Newton had demonstrated for gravity. Although a significant amount of mathematical work was done on electric forces, it had very few immediate practical results.

In 1800, Alessandro Volta in Italy found that he could produce a continuous flow of electricity from cells containing alternating plates of copper and zinc, separated by cloth soaked in acid. Initially, Volta thought the electricity came from the copper-zinc contact, using his previous experience with static electricity. In the 1830s, Michael Faraday in England showed that the electricity came from chemical activity of the acid on the two metals. In the meantime, Volta's device, the **voltaic cell**, provided scientists with a powerful new tool. A collection of many pairs of copper and zinc plates in jars of dilute acid could produce significant *electric currents*. Applying such currents to molten salts, Humphrey Davy in England isolated the metallic elements sodium and potassium. His work in the early 1800s laid the foundation for the electrochemical industry—used for metal extraction and electroplating.

In 1820, Hans Christian Oersted in Denmark discovered that wires carrying an electric current were surrounded by a magnetic field. Soon, many laboratories in Europe and America were displaying large electromagnets. Also, André-Marie Ampère in France developed a complex theory of electric currents, and George Simon Ohm in Germany established the relation between current and voltage in electric circuits.

By 1830, electricity had become a field of intense scientific investigation, but was not yet a major force in industry. That began to change when Michael Faraday discovered that the motion of a conductor in a magnetic field generated a current in the conductor. He quickly used this finding to develop electrical generators and basic motors. Many inventors worked to improve generators that were powered by steam engines, and produced respectable amounts of electrical energy. Their earliest practical applications beyond the chemical industry involved powering arc lamps in lighthouses in Britain.

Electrical Communications

The first important electrical industry was the telegraph. Using various electromagnetic devices, Charles Wheatstone in England and Samuel Morse in the United States created systems and codes for communicating along electrical wires. Because these systems did not need much power, they operated on voltaic cells. When the industrial demand increased, a number of workers made various improvements in the electrodes and chemical solutions used in Volta's simple cells.

Telegraph lines were strung along railroad rights of way. Steam transportation on railroads expanded rapidly starting in the 1830s. During the 1840s, as the railroads spread across Europe and North America, the telegraph lines spread along with them. England was linked with Europe in 1851, and with North America in 1866. In 1862, Britain had 24 000 km of telegraph lines, Europe 130 000 km, and America 80 000 km. Undersea cables connected most of the major cities of the world by 1872.

The telephone grew out of the telegraphic industry. Alexander Graham Bell was a Scottish immigrant to Canada working in Boston, MA, teaching deaf children to speak. In his spare time he worked on telegraph inventions. He discovered that wires could carry varying currents that reproduced the sound patterns of speech and music. Following his startling demonstrations in 1876, Bell began installing telephone lines between the major cities of the U.S. eastern seaboard. Because his parents still lived in Brantford, Bell also soon established telephone systems in southern Ontario. After that, telephone lines rapidly grew up within and between cities across the United States and Canada, and soon after in Britain and Europe. Transcontinental telephoning began in 1915.

The quality of telephone equipment improved quickly as industrial research was directed to the many problems of switching and amplification. Much of this work was done at the Bell Telephone Laboratories, which continue today as leaders in research in electronics and communications technology.

Electrical Power Industries

The first major demand for large amounts of electrical energy came from inventions in electrical lighting. Thomas Edison began as an inventor of telegraph equipment in the United States. About 1880 he began to manufacture the first successful incandescent lamp. His research laboratory also designed the generators driven by steam engines to provide the electricity to light New York City.

At about the same time, European electrical engineers, working to improve generators, realized that electric motors could have the same basic design as generators. An early major application of motors was in electric street railways. The power of a remote steam engine could be supplied by means of electricity on city streets, avoiding smoke and grime in built-up areas. The first commercial street railway was built in Richmond, VA in 1887.

Manufacturers and electrical engineers soon proposed the same approach for factories. Instead of having a steam engine drive all the machinery of a textile mill by rods, pulleys, and belts, each machine could operate from its own electric motor. The great demand for this technology created intense pressure on research and investment in the 1890s. But the fact that all systems up to that time had operated on *direct current* blocked progress. For safety reasons, the machinery had to operate at only one or two hundred volts. But large energy losses in low voltage transmission meant that the distances between generation and use had to be kept short—only a few kilometres.

ac Wins the Battle

The great demand for electrical energy prompted the idea of harnessing water power. Niagara Falls was an early prime target. If the generating installations at Niagara had been confined to direct current, industries would have had to line the banks of the Niagara River. However, electrical engineers decided to install *alternating current* machinery. The recently developed *transformer* permitted generation at relatively low voltages, stepping up to high voltage for transmission over great distances, and stepping down to low voltages for use. This decision was vigorously opposed by Thomas Edison, who had a large investment in direct current systems.

The success of ac was greatly assisted by the invention of a practical ac motor by Nikolai Tesla. Born in Serbia, Tesla moved to the United States to work for Thomas Edison. Soon, he struck out on his own and became an outstanding, if somewhat unstable, inventor of many electrical devices.

The early decades of the twentieth century saw the electrification of most of North America and Europe. Household electrical appliances began to be produced, which transformed the way we cook and clean, and brush our teeth.

Electronics

Although electronics is strongly associated with radio, radio began before electronics. After starting work on the radio in Italy in the 1890s, Guglielmo Marconi soon moved to Britain, where he demonstrated successful transmissions over a few kilometres. Then, in 1901, from a transmitter in Cornwall, Marconi received the first transatlantic radio signal in St. John's, Newfoundland.

Although Marconi's early equipment used ac machinery to generate gigantic sparks, soon electron tubes were being developed to perform all the radio functions of transmission and reception.

Electron tubes work by having a heated filament give off electrons into an evacuated space in a glass tube. Other plates and grids within the tube receive and control the electron currents.

After 1910, a great many electron tubes were developed to generate, modulate, detect, and amplify high frequency currents and waves. Until about 1920, radio was used mainly for communication by Morse code with ships at sea. Then, the marriage of radio and telephony produced commercial broadcasting that spread like wildfire across the world.

The most complex electron tubes, developed in the 1930s, are the television camera and picture tubes. Although most other control circuits now use solid state devices, these tubes are still traversed by streams of electrons in evacuated spaces. However, there are now also many solid state imaging and display devices.

Solid-State Electronics

You have seen that electrical technology grew out of scientific research in the early 1800s. As electrical industries grew in the following decades, experimental and theoretical investigations also continued. For example, in the 1860s, the Scot James Clerk Maxwell developed the foundations of electromagnetic theory. It was this work that inspired Marconi and others to develop radio. And it was in scientific laboratories that streams of electrons were investigated, leading to the discovery of electrons and atomic structure, and to x-ray tubes.

In the 1920s, physicists had developed effective theories of atomic structure. In the 1930s, some of them began to investigate more closely the behaviour of electrons in solids. Improved knowledge of the energy levels of electrons in solids inspired workers at the Bell Telephone Laboratories to seek ways to gain fine control of currents in solid-state devices. In 1947 William Shockley, John Bardeen, and Walter H. Brattain invented the **transistor** (Fig. 1.1), a device that uses layers of specially prepared crystal to control current in a circuit. Despite massive investments in electron-tube technology, the transition to solid-state devices proceeded rapidly. Before 1970, investment in solid-state devices had surpassed that in electron tubes. Intensive research was needed to produce transistors capable of handling the relatively modest power outputs of stereo amplifiers. That work still continues as solid-state devices gradually replace the electron tubes used for the large power outputs of radio and television transmitters.

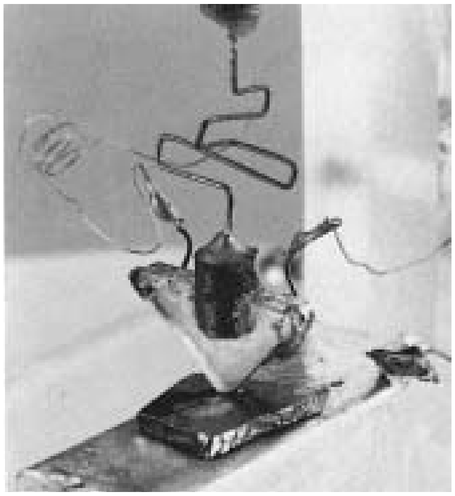

FIG. 1.1
The first transistor. (Courtesy of AT&T, Bell Laboratories.)

The greatest contribution of solid-state devices came from miniaturization. Although even the earliest transistors were much smaller than the tubes they replaced, the drive was on to produce smaller and smaller devices. Soon, solid-state devices were developed that combined the

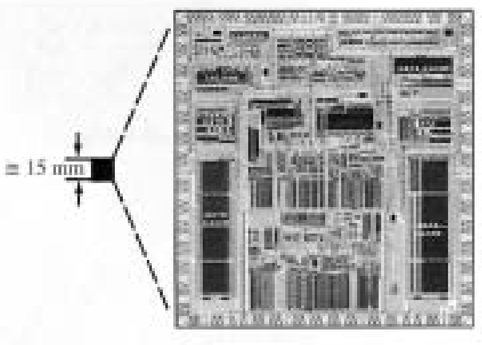

FIG. 1.2
Integrated circuit. (Courtesy of Motorola Semiconductor Products.)

actions of many transistors within a single chip. The first **integrated circuit** (**IC**) was developed in 1958 at Texas Instruments. In 1961 the first commercial integrated circuit was manufactured by the Fairchild Corporation. Since then, integrated circuits have been getting smaller and more powerful (Fig. 1.2).

Integrated circuits and their accompanying printed circuit boards transformed the electronics industry. Besides being involved in all aspects of communication and control devices, ICs formed the basis for the creation of handheld calculators, and soon inspired the take-off of the computer industry.

Computers

Mechanical calculators began to be invented in the 1600s. For a long time they suffered from the limitations of craft skills. In the 1820s, Charles Babbage had designs for complex computing machines that were beyond the abilities of artisans to build. By 1900, electric cash registers and card-sorting machines helped with data manipulation. Under the pressures of World War II, great efforts were applied to increasing calculation speeds. In 1946, the first successful electronic system contained 18 000 tubes and weighed thirty tonnes. Today, you can hold in your hand many times the computing power that filled a whole room half a century ago.

Conclusion

Electrical industries are founded on the results of scientific research. As scientists from many countries deepened our knowledge of electrical phenomena, engineers and technologists applied that knowledge to create devices for practical applications. With massive investments by entrepreneurs, whole new industries have been established. Nowadays, many research and development laboratories continue to produce new products that are smaller, faster, and more powerful. Electrical and electronic industries play a central role in modern life.

1.3 Systems of Units

The design and operation of electric circuits require the measurement and calculation of many different electrical quantities. These quantities are expressed by numbers and *units*. In any measurement, the units tell you the basic nature of the quantity, and the number tells you how many of those units you have. If you pace across your classroom, you might find its width to be 7 paces. You could convert the unit *pace* by measuring it with a metre stick. If the length of your pace (the unit) is 0.7 m, then the width of the classroom is $7 \times 0.7 \text{ m} = 4.9 \text{ m}$.

Every measurement consists of a number of units.

As in the above example, we express measurements by using *standard units*. The units of electrical measurements belong to the *International System of Units*, abbreviated **SI**. This collection of units is systematic in having a minimum number of independently defined base units, from which all other units are derived. The derivations depend on physical laws, some of which will be introduced in later chapters of this text. The SI based units have developed out of the metric system that was introduced in France in 1792.

Although there are seven SI base units, we only show in Table 1.1 the five that are commonly required for electrical work. Note that each of the units is designated by a symbol, such as "m" for "metre." It is essential that you use the style in which these symbols are expressed—whether lower case or capitalized. The principle is that unit symbols are capitalized only when they are derived from a person's name; for example "A" for "amperes," named after the French physicist André M. Ampère.

TABLE 1.1

SI base units

Quantity	Unit	Symbol
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin	K

Each of the SI base units has a very precise physical definition. Length (1 m) and time (1 s) are defined in terms of atomic processes. The mass of 1 kg is that of a specific lump of matter preserved at the International Bureau of Weights and Measures in France. The fundamental definition of 1 A depends on the force between two current-carrying conductors. The different definition we give in Chapter 2 is equivalent to this one. The temperature unit is defined in thermodynamic terms.

All other measurement units are defined by some combination of the base units. The *derived units* needed for electrical analysis are listed in Table 1.2. You will note that they are all named for scientists whose work contributed to their development.

TABLE 1.2

SI derived units

Quantity	Unit	Symbol	Definition
Celsius temperature	degree Celsius	°C	K
Frequency	hertz	Hz	s^{-1}
Force	newton	N	$kg \cdot m/s^2$
Energy	joule	J	$N \cdot m$
Power	watt	W	J/s
Electric charge	coulomb	C	$A \cdot s$
Electric potential difference	volt	V	J/C
Electrical resistance	ohm	Ω	V/A
Electrical conductance	siemens	S	Ω^{-1}
Electrical capacitance	farad	F	C/V
Magnetic flux	weber	Wb	$V \cdot s$
Magnetic flux density	tesla	T	Wb/m^2

You know that there are other systems of units in use. However, with very few exceptions, electrical work is limited to SI units. Two exceptions that you will encounter are the centimetre (0.01 m) and the horsepower (described in Section 4.3).

SI Prefixes

Because there is large variation in the magnitudes of measured quantities, the SI system uses a number of multiplier *prefixes*. The full list ranges in steps of 1000 from 10^{18} to 10^{-18}. Table 1.3 lists the SI prefixes, with their symbols. As with the symbols for units, you should always use the precise symbol shown for the prefixes. Note for example that "m" is the symbol for "milli" (10^{-3}), while "M" is the symbol for "mega" (10^{6}).

TABLE 1.3
SI Prefixes

Name	Symbol	Definition
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}

It is important for you to become proficient in using units and prefixes. The next section will review operations with powers of ten and illustrate how to use the SI prefixes.

1.4 Powers of Ten

In ordinary decimal notation, large and small numbers are inconvenient to handle because of the need to count place-holding zeros. Power of ten notation helps to avoid errors by counting the zeros for you. For example, the speeds of electrons in a vacuum and in a solid might be found to be

94 300 000 m/s and 0.000 057 m/s respectively.

Simply replacing the zeros with powers of ten would result in

$$943 \times 10^{5} \text{ m/s and } 0.57 \times 10^{-4} \text{ m/s.}$$

However, it is more common to express these values in scientific notation (see page 11) as

$$9.43 \times 10^{7} \text{ m/s and } 5.7 \times 10^{-5} \text{ m/s.}$$

To make sure that you can handle powers of ten easily, you should review the basic operations given below. The values of m and n can be any real number.

$$\frac{1}{10^{n}} = 10^{-n} \qquad \frac{1}{10^{-n}} = 10^{n} \tag{1.1}$$

Equation (1.1) shows that shifting a power of ten from the denominator to the numerator, or the reverse, requires simply changing the sign of the power. Note that $10^{0} = 1$.

EXAMPLE 1.1

a. $$\frac{1}{1000} = \frac{1}{10^{+3}} = 10^{-3}$$

b. $$\frac{1}{0.000\,01} = \frac{1}{10^{-5}} = 10^{+5}$$

The product of powers of ten:

$$(10^n)(10^m) = 10^{(n+m)} \tag{1.2}$$

EXAMPLE 1.2

a. $$(1000)(10\,000) = (10^3)(10^4) = 10^{(3+4)} = 10^7$$

b. $$(0.000\,01)(100) = (10^{-5})(10^2) = 10^{(-5+2)} = 10^{-3}$$

The division of powers of ten:

$$\frac{10^n}{10^m} = 10^{(n-m)} \tag{1.3}$$

EXAMPLE 1.3

a. $$\frac{100\,000}{100} = \frac{10^5}{10^2} = 10^{(5-2)} = 10^3$$

b. $$\frac{1000}{0.0001} = \frac{10^3}{10^{-4}} = 10^{(3-(-4))} = 10^{(3+4)} = 10^7$$

Note the use of parentheses in the second example to ensure that the proper sign is used.

The power of powers of ten:

$$(10^n)^m = 10^{(nm)} \tag{1.4}$$

EXAMPLE 1.4

a. $$(100)^4 = (10^2)^4 = 10^{(2)(4)} = 10^8$$

b. $$(1000)^{-2} = (10^3)^{-2} = 10^{(3)(-2)} = 10^{-6}$$

c. $$(0.01)^{-3} = (10^{-2})^{-3} = 10^{(-2)(-3)} = 10^6$$

Basic Arithmetic Operations

Let us now examine the use of powers of ten to perform some basic arithmetic operations using numbers that are not just powers of ten.

The number 5000 can be written as $5 \times 1000 = 5 \times 10^3$, and the number 0.0004 can be written as $4 \times 0.0001 = 4 \times 10^{-4}$. Of course, 10^5 can also be written as 1×10^5 if it clarifies the operation to be performed.

ADDITION AND SUBTRACTION To perform addition or subtraction using powers of ten, the power of ten *must be the same for each term;* that is,

$$A \times 10^n \pm B \times 10^n = (A \pm B) \times 10^n \tag{1.5}$$

EXAMPLE 1.5

a. $6300 + 75\,000 = (6.3)(1000) + (75)(1000)$
$= 6.3 \times 10^3 + 75 \times 10^3$
$= (6.3 + 75) \times 10^3$
$= \mathbf{81.3 \times 10^3}$

b. $0.000\,96 - 0.000\,086 = (96)(0.000\,01) - (8.6)(0.000\,01)$
$= 96 \times 10^{-5} - 8.6 \times 10^{-5}$
$= (96 - 8.6) \times 10^{-5}$
$= \mathbf{87.4 \times 10^{-5}}$

Multiplication

In general,

$$(A \times 10^n)(B \times 10^m) = (A)(B) \times 10^{n+m} \tag{1.6}$$

revealing that the *operations with the powers of ten can be separated from the operation with the multipliers.*

EXAMPLE 1.6

a. $(0.0002)(0.000\,007) = [(2)(0.0001)][(7)(0.000\,001)]$
$= (2 \times 10^{-4})(7 \times 10^{-6})$
$= (2)(7) \times (10^{-4})(10^{-6})$
$= \mathbf{14 \times 10^{-10}}$

b. $(340\,000)(0.000\,61) = (3.4 \times 10^5)(61 \times 10^{-5})$
$= (3.4)(61) \times (10^5)(10^{-5})$
$= 207.4 \times 10^0$
$= \mathbf{207.4}$

Division

In general,

$$\frac{A \times 10^n}{B \times 10^m} = \frac{A}{B} \times 10^{n-m} \tag{1.7}$$

revealing again that the *operations with the powers of ten can be separated from the same operation with the multipliers.*

EXAMPLE 1.7

a. $$\frac{0.000\,47}{0.002} = \frac{47 \times 10^{-5}}{2 \times 10^{-3}} = \left(\frac{47}{2}\right) \times \left(\frac{10^{-5}}{10^{-3}}\right)$$
$$= \mathbf{23.5 \times 10^{-2}}$$

b. $$\frac{690\,000}{0.000\,000\,13} = \frac{69 \times 10^{4}}{13 \times 10^{-8}} = \left(\frac{69}{13}\right) \times \left(\frac{10^{4}}{10^{-8}}\right)$$
$$= \mathbf{5.31 \times 10^{12}}$$

Powers

In general,

$$(A \times 10^{n})^{m} = A^{m} \times 10^{nm} \qquad \textbf{(1.8)}$$

which again permits the separation of the *operation with the powers of ten from the multipliers.*

EXAMPLE 1.8

a. $$(0.000\,03)^{3} = (3 \times 10^{-5})^{3} = (3)^{3} \times (10^{-5})^{3}$$
$$= \mathbf{27 \times 10^{-15}}$$

b. $$(90\,800\,000)^{2} = (9.08 \times 10^{7})^{2} = (9.08)^{2} \times (10^{7})^{2}$$
$$= \mathbf{82.4464 \times 10^{14}}$$

Scientific Notation

Frequently, the most regular way to express measurements in power of ten notation is to choose the power of ten that gives the multiplying number a single digit before the decimal. This is called **scientific notation**. Here are a couple of examples:

The speed of light is $2.997\,924\,58 \times 10^{8}$ m/s.

The rest mass of an electron is $9.109\,534 \times 10^{-31}$ kg.

The rules for power of ten operations can be used to perform calculations with these numbers. Example 1.9 will show you how it is done.

EXAMPLE 1.9

At speeds up to about one-fifth of the speed of light, the kinetic energy of moving objects is given by the standard formula, $E = \frac{1}{2}mv^{2}$. Use the values given above to calculate the kinetic energy of an electron travelling at 1/5 the speed of light.

Solution

The speed of the electron is

$$v = \frac{2.997\,924\,58 \times 10^{8}}{5} \text{ m/s}$$

continued

The mass of the electron is $m = 9.109\,534 \times 10^{-31}$ kg.

Substitute the values into the formula

$$E = \frac{mv^2}{2}$$

$$= \frac{9.109\,534 \times 10^{-31}}{2}\left(\frac{2.997\,924\,58 \times 10^{8}}{5}\right)^2 \text{ kg}\cdot\text{m}^2/\text{s}^2$$

$$= 4.554\,767 \times 10^{-31}\left(0.599\,584\,9^2 \times 10^{16}\right) \text{ kg}\cdot\text{m}^2/\text{s}^2$$

$$= 1.637\,448 \times 10^{-15}\text{ J}$$

Here, we have given an intermediate step to show some of the power of ten operations. However, you could perform the whole operation with your scientific calculator in a single sequence of operations. Note that the units for kinetic energy do work out to the definition of *joule* given in Table 1.2. Depending on the number of digits your calculator carries, you may get a slightly different result from the one given here.

SI Prefixes and Engineering Notation

Most often in electrical work, it is convenient to use the SI prefixes to describe very large or very small quantities. You are probably familiar with the units of gigabytes and nanoseconds used for computers. To convert a quantity to this form, you will want to express it with a power of ten that is evenly divisible by 3. In Example 1.9, the final answer had the power of –15, which is divisible by 3. From Table 1.3, the corresponding prefix is *femto*, so the answer could be written as 1.637 448 f J.

The power of 8 in the speed of light is not evenly divisible by 3. You could express the value either by the power of 6 or of 9 (mega or giga). Rounding the numerical part to 3.00 for convenience, we could write

$$v = 3.00 \times 10^8\text{ m/s} = 300 \times 10^6\text{ m/s} = 300\text{ Mm/s}$$

or

$$= 0.300 \times 10^9\text{ m/s} = 0.300\text{ Gm/s}$$

In the first case, you *reduce* the power by 2, so you have to multiply the numerical part by 100. In the second case, you *increase* the power by 1, so you have to multiply the numerical part by 1/10. Once you have a power of ten divisible by 3, you simply convert it to the appropriate SI prefix. Usual practice is to choose the SI prefix that makes the numerical part fall between 1 and 999. However, the example of 0.300 Gm/s is not unusual.

Engineering notation uses only the powers of ten that are divisible by 3. This makes it easy to convert a quantity in engineering notation to an appropriate SI prefix. For example, the annual energy consumption of a province of 235 billion joules could be expressed variously as:

$$235\,000\,000\,000\text{ J}$$

$$235\,000\,000 \times 10^3\text{ J} = 235\,000\,000\text{ kJ}$$

$$235\,000 \times 10^6\text{ J} = 235\,000\text{ MJ}$$

$$235 \times 10^9\text{ J} = 235\text{ GJ}$$

$$0.235 \times 10^{12}\text{ J} = 0.235\text{ TJ}$$

Converting Between Powers of Ten

It is often necessary to convert from one power of ten to another. For instance, if a meter measures kilohertz (kHz), it may be necessary to find the corresponding level in megahertz (MHz). If time is measured in milliseconds (ms), it may be necessary to find the corresponding time in microseconds (μs) for a graphical plot. The process is not difficult if you simply keep in mind that an increase or decrease in the power of ten must be associated with the opposite effect on the multiplying factor. The procedure is best described by a few examples.

EXAMPLE 1.10

a. Convert 20 kHz to megahertz.

Solution: In the power-of-ten format:

$$20\text{ kHz} = 20 \times 10^{3}\text{ Hz}$$

The conversion requires that we find the multiplying factor to appear in the space below:

Increase by 3

$$20 \times 10^{3}\text{ Hz} \Rightarrow \_\_\_ \times 10^{6}\text{ Hz}$$

Decrease by 3

Since the power of ten will be *increased* by a factor of *three*, the multiplying factor must be *decreased* by moving the decimal point *three* places to the left, as shown below:

$$020. = 0.02$$

3

and $$20 \times 10^{3}\text{ Hz} = 0.02 \times 10^{6}\text{ Hz} = \mathbf{0.02\ MHz}$$

b. Convert 0.01 ms to microseconds.

Solution: In the power-of-ten format:

$$0.01\text{ ms} = 0.01 \times 10^{-3}\text{ s}$$

Reduce by 3

and $$0.01 \times 10^{-3}\text{ s} = \_\_\_ \times 10^{-6}\text{ s}$$

Increase by 3

Since the power of ten will be *reduced* by a factor of three, the multiplying factor must be *increased* by moving the decimal point three places to the right, as follows:

$$0.010 = 10$$

3

and $$0.01 \times 10^{-3}\text{ s} = 10 \times 10^{-6}\text{ s} = \mathbf{10\ \mu s}$$

You might think, when comparing -3 to -6, that the power of ten has increased, but keep in mind when making your judgment about increasing or decreasing the magnitude of the multiplier that 10^{-6} is a great deal smaller than 10^{-3}.

continued

c. Convert 0.002 km to millimetres.

Solution:

Reduce by 6

$$0.002 \times 10^{3}\ \text{m} \Rightarrow \_\_\_ \times 10^{-3}\ \text{m}$$

Increase by 6

In this example we have to be very careful because the difference between +3 and −3 is a factor of 6, requiring that the multiplying factor be modified as follows:

$$0.002000 = 2000$$

6

and $$0.002 \times 10^{3}\ \text{m} = 2000 \times 10^{-3}\ \text{m} = \mathbf{2000\ mm}$$

1.5 Significant Digits

In general, there are two types of numbers, *exact* and *approximate*. Exact numbers are precise to the number of digits given, for example, one dozen apples is exactly 12 apples, not 12.001. On the other hand, all readings obtained in the laboratory should be considered *approximate*. In making a measurement or taking a reading, you read the digits on a scale or dial. How many digits you read can give you an indication of the accuracy of the measurement.

For example, you could measure the length of a room to the nearest metre, 7 m; or the nearest centimetre, 7.35 m; or the nearest millimetre, 7.346 m. Every time you read an additional digit, your measurement gets closer to the "true" value of the length, but it is still an *approximate* measurement. The digits you read are called *significant digits*. The 7.346-m measurement has four significant digits and is said to have 4-digit accuracy, while the 7-m measurement has only 1-digit accuracy. Many of meters used in the laboratory have readouts with 3- or 4-digit accuracy.

You can see how digits indicate accuracy by considering an airline flight of 7346 km. This distance is known to within 1 km, so it has 4-digit accuracy. However, if you were told the flight was 7000 km long, you cannot be certain of the degree of accuracy because the three trailing zeros could be either significant digits or only place-holders. If the measurement had a 3-digit accuracy (that is, to the nearest 10 km), then the distance could be shown using scientific notation: 7.00×10^{3} km. The appearance of the zeros after the decimal point indicates that they are significant digits.

For all calculations you should realize that

Calculations cannot increase the accuracy of measurements.

For multiplication and division:

The number of significant digits in a result of multiplication or division must be limited to the number of significant digits in the least accurate measurement used in the calculation.

Consider a trip of 275 km in 3.7 h. You can calculate your average speed by dividing the distance by time. The result on you calculator is 74.324 324. Clearly you cannot know the speed to this accuracy given your original measurements, so the final result should be reported using only two significant digits, that is, 74 km/h.

TABLE 1.4

Symbol	Meaning
$\neq$	Not equal to $6.12 \neq 6.13$
$>$	Greater than $4.78 > 4.20$
$\gg$	Much greater than $840 \gg 16$
$<$	Less than $430 < 540$
$\ll$	Much less than $0.002 \ll 46$
$\geq$	Greater than or equal to $x \geq y$ is satisfied for $y = 3$ and $x > 3$ or $x = 3$
$\leq$	Less than or equal to $x \leq y$ is satisfied for $y = 3$ and $x < 3$ or $x = 3$
$\cong$	Approximately equal to $3.14159 \cong 3.14$
Σ	Sum of $\Sigma\,(4 + 6 + 8) = 18$
$\lvert\ \rvert$	Absolute magnitude of $\lvert a \rvert = 4$, where $a = -4$ or $+4$
$\therefore$	Therefore $x = \sqrt{4} \quad \therefore x = \pm 2$
$\equiv$	By definition Establishes a relationship between two or more quantities

For addition and subtraction:

The number of significant digits in a result of an addition or subtraction must be limited to the precision of the least accurate measurement used in the calculation.

Consider your airline trip of 7346 km. If you need to walk an additional 375 m to get to the terminal, you might want to say you traveled 7346.375 km. However, since the distance you walked is less than the 1 km uncertainty of the larger measurement, you would report the final result as the 7346 km for your travel distance.

A common practice for minimizing round-off errors is to carry up to two additional significant digits for intermediate calculations. The final result is then rounded off to the correct number of significant digits. For rounding off, drop the unnecessary digits unless the leftmost digit to be dropped is 5 or more. For example, the speed of light to different degrees of accuracy is given in the following list:

$2.997\,924\,58 \times 10^8$ m/s	9 significant digits
$2.997\,924\,6 \times 10^8$ m/s	8 significant digits
$2.997\,925 \times 10^8$ m/s	7 significant digits
$2.997\,9 \times 10^8$ m/s	5 significant digits
2.998×10^8 m/s	4 significant digits
3.00×10^8 m/s	3 significant digits

EXAMPLE 1.11

Perform the indicated operations with the following approximate numbers and round off to the appropriate level of accuracy. The symbol $\cong$ means *approximately equal to.*

a. $532.6 + 4.02 + 0.036 = 536.656 \cong$ **536.7** (as determined by 532.6)
b. $0.04 + 0.003 + 0.0064 = 0.0494 \cong$ **0.05** (as determined by 0.04)
c. $4.632 \times 2.4 = 11.1168 \cong$ **11** (as determined by the two significant digits of 2.4)
d. $3.051 \times 802 = 2446.902 \cong$ **2450** (as determined by the three significant digits of 802)
e. $1402/6.4 = 219.0625 \cong$ **220** (as determined by the two significant digits of 6.4)
f. $0.0046/0.05 = 0.0920 \cong$ **0.09** (as determined by the one significant digit of 0.05)

To better illustrate some of the principles of circuit theory, many calculations in this textbook treat nominal values for circuit variables as exact numbers. Note that this approach sometimes gives answers with more significant digits than would be justified if the given variables were actual measured values.

1.6 Symbols

Throughout the text, various symbols will be used that you may not have seen before. Some are defined in Table 1.4, and others will be defined in the text as they are used.

PROBLEMS

Note: More difficult problems are indicated by an asterisk (*) throughout the text.

SECTION 1.2 A Brief History

1. Write a short essay naming every electrical device you use during the course of a single day. For each, say how it affects your life, or how you would manage without it.
2. Visit your local library or search the web to investigate how much help (in print and electronic media) it can give people interested in learning about electrical technologies. Write a report on your findings.
3. Choose an area of particular interest in this field and write a very brief report on the history of the subject.
4. Choose an individual of particular importance in this field and write a very brief review of his or her life and important contributions.

SECTION 1.3 Systems of Units

5. Use the definitions of derived units in Table 1.2 to verify the following relations:
   a. 1 A = 1 C/s
   b. $1\ \text{kg}\cdot\text{m}^2/\text{s}^2 = 1\ \text{J}$
   c. 1 W = 1 V·A
   d. $1\ \text{A}^2\cdot\Omega = 1\ \text{W}$
   e. $1\ \text{J} = 1\ \text{F}\cdot\text{V}^2$
   f. $1\ \text{C}^2/\text{F} = 1\ \text{J}$

SECTION 1.4 Powers of Ten

6. Express the folowing numbers as powers of ten:
   a. 10 000
   b. 1 000
   c. 0.000 000 01
   d. 0.000 001
   e. 1 000 000 000
   f. 0.000 000 000 000 1
7. Perform the following operations and express your answer as a power of ten:
   a. 4200 + 6 800 000
   b. $9 \times 10^4 + 3.6 \times 10^3$
   c. $0.5 \times 10^{-3} - 6 \times 10^{-5}$
   d. $1.2 \times 10^3 + 50\,000 \times 10^{-3} - 0.006 \times 10^5$
8. Perform the following operations and express your answer as a power of ten:
   a. (100)(100)(100) **b.** $(10^3)(10^5)$
   c. $(10^{-4})(10\,000)$ **d.** $(0.01)(1000)^2$
   e. (1000)(0.000 001) **f.** $(10\,000)(10^{-6})(10^{27})$
9. Perform the following operations and express your answer as a power of ten:
   a. (50 000)(0.0003)
   b. 2200×0.08
   c. (0.000 082)(0.000 07)
   d. $(30 \times 10^{-4})(0.0002)(7 \times 10^8)$
10. Perform the following operations and express your answer as a power of ten:
   a. $\dfrac{100}{1000}$ **b.** $\dfrac{0.01}{100}$
   c. $\dfrac{10\,000}{0.000\,01}$ **d.** $\dfrac{0.000\,000\,1}{100}$
   e. $\dfrac{10^{38}}{0.000\,100}$ **f.** $\dfrac{(100)^{1/2}}{0.01}$
11. Perform the following operations and express your answer as a power of ten:
   a. $\dfrac{2000}{0.000\,08}$ **b.** $\dfrac{0.004\,08}{60\,000}$
   c. $\dfrac{0.000\,215}{0.000\,05}$ **d.** $\dfrac{78 \times 10^9}{4 \times 10^{-6}}$
12. Perform the following operations and express your answer as a power of ten:
   a. $(100)^3$ **b.** $(0.0001)^{1/2}$
   c. $(10\,000)^8$ **d.** $(0.000\,000\,10)^9$
13. Perform the following operations and express your answer as a power of ten:
   a. $(2.2 \times 10^3)^3$
   b. $(0.0006 \times 10^2)^4$
   c. $(0.004)(6 \times 10^2)^2$
   d. $[(2 \times 10^{-3})(0.8 \times 10^4)(0.003 \times 10^5)]^3$
14. Perform the following operations and express your answer in scientific notation:
   a. $(-0.001)^2$ **b.** $\dfrac{(100)(10^{-4})}{10}$
   c. $\dfrac{(0.001)^2(100)}{10\,000}$ **d.** $\dfrac{(10^2)(10\,000)}{0.001}$
   e. $\dfrac{(0.0001)^3(100)}{1\,000\,000}$ ***f.** $\dfrac{[(100)(0.01)]^{-3}}{[(100)^2][0.001]}$
15. Repeat problem 9 expressing the result in engineering notation.
16. Repeat problem 11 expressing the result in engineering notation.

*17. Perform the following operations and express your answer in engineering notation:
   a. $\dfrac{(300)^2(100)}{10^4}$ **b.** $[(40\,000)^2][(20)^{-3}]$
   c. $\dfrac{(60\,000)^2}{(0.02)^2}$ **d.** $\dfrac{(0.000\,027)^{1/3}}{210\,000}$
   e. $\dfrac{[(4000)^2][300]}{0.02}$
   f. $[(0.000\,016)^{1/2}][(100\,000)^5][0.02]$
   g. $\dfrac{[(0.003)^3][(0.000\,07)^2][(800)^2]}{[(100)(0.000\,9)]^{1/2}}$ (a challenge)

18. Fill in the blanks of the following conversions:
   a. $6 \times 10^3 = \_\_\_\_ \times 10^6$
   b. $4 \times 10^{-4} = \_\_\_\_ \times 10^{-6}$
   c. $50 \times 10^5 = \_\_\_\_ \times 10^3 = \_\_\_\_ \times 10^6 = \_\_\_\_ \times 10^9$
   d. $30 \times 10^{-8} = \_\_\_\_ \times 10^{-3} = \_\_\_\_ \times 10^{-6} = \_\_\_\_ \times 10^{-9}$

19. Perform the following conversions.
- **a.** 2000 μs to milliseconds
- **b.** 0.04 ms to microseconds
- **c.** 0.06 μF to nanofarads
- **d.** 8400 ps to microseconds
- **e.** 0.006 km to millimetres
- **f.** 260×10^3 mm to kilometres

For Problems 20 and 21, convert the following:

20.
- **a.** 1.5 min to seconds
- **b.** 0.04 h to seconds
- **c.** 0.05 s to microseconds
- **d.** 0.16 m to millimetres
- **e.** 0.000 000 12 s to nanoseconds
- **f.** 3 620 000 s to days
- **g.** 1020 mm to metres

21.
- **a.** 0.1 μF (microfarad) to picofarads
- **b.** 0.467 km to meters
- **c.** 63.9 mm to centimetres
- **d.** 69 cm to kilometres
- **e.** 3.2 h to milliseconds
- **f.** 0.016 mm to micrometres
- **g.** 60 cm^2 to square metres (m^2)

SECTION 1.5 Significant Digits

22. Express the results of the following calculations to the correct number of significant digits:
- **a.** Calculate the distance travelled in 5.27 hours at an average speed of 67 km/h.
- **b.** Calculate the speed of an electron that travels 3.3 mm in 17.58 ns.
- **c.** Calculate the time for an electron to travel 98.7 μm at a speed of $2.998 \text{ x } 10^7$ m/s.

23. Calculate the length of time it takes a light signal travelling at 3.0×10^8 on a fibre optic network to travel the 5000 km from Montreal to Vancouver. Express your answer in
- **a.** scientific notation
- **b.** engineering notation
- **c.** a form using the most appropriate prefix from Table 1.3