

# Electronic Instrumentation and Measurements

**THIRD EDITION**

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# CHAPTER 1

## Measurement Systems, Units, and Standards

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### Objectives

*After studying this chapter, you will be able to*

1. Discuss CGS, MKS, and SI unit systems and explain the need for a practical units system.
2. Use scientific notation, engineering notation, and metric prefixes in stating quantities.
3. Identify the three fundamental mechanical units in the SI system, and define SI mechanical derived units.
4. Identify the fundamental electrical unit in the SI system, and define the SI derived units for various electrical and magnetic quantities.
5. Explain SI temperature scales.
6. Convert between SI and non-SI units when solving problems.
7. Determine the dimensions of all fundamental and derived units.
8. Explain the various measurement standards and their applications.

### INTRODUCTION

Before standard systems of measurement were invented, many approximate units were used. A long distance was often measured by the number of *days* it would take to ride a horse over the distance; a horse's height was measured in *hands*; liquid was measured by the *bucket* or *barrel*. English-speaking peoples adopted the *foot* and the *mile* for measuring distances, the *pound* for mass, and the *gallon* for liquid. Other nations followed the lead of the French in adopting a *metric system*, in which large and small units are very conveniently related by a factor of 10. With the development of science and engineering, accurate units had to be devised, and several different unit systems were used before an international system was adopted.

### 1-1 UNIT SYSTEMS

#### CGS and MKS Systems

For many years, systems using the *centimeter*, *gram*, and *second* (CGS) as the fundamental mechanical units were employed for scientific and engineering purposes. These were termed *absolute systems* because all quantities could be defined in terms of the three fundamental units. There are two CGS systems: an *electrostatic system* of units (*esu*) and an *electromagnetic units system* (*emu*). In the electrostatic system, the *permittivity of free space* ( $\epsilon_0$ ) is defined as 1, and the unit of electrical charge is defined as the charge that exerts unit force on a

similar charge located at 1 cm distance. In the electromagnetic system, the permeability of free space ( $\mu_0$ ) is defined as 1, and the unit magnetic pole is defined as the pole that exerts unit force on a similar pole located at 1 cm distance.

Except in the case of electrostatic research, the electromagnetic system tended to be more convenient to use than the electrostatic system. However, some of the esu and emu units were different in magnitude, and care had to be taken in making conversions. Many CGS units were too small or too large for practical engineering applications, so a system of *practical units* was also used. Thus, there were two CGS (esu and emu) systems for use in research work, and a third (practical) system for engineering applications. Furthermore, both CGS systems were regarded as *irrational* (or *unrationalized*) because of the presence of the factor  $4\pi$  in equations where it seemed inappropriate, and its absence in other equations where it was appropriate.

These factors led to the proposed use of the practical units in an MKS system, using the meter (m), kilogram (kg), and second (s) as the fundamental units. The name *Giorgi system* is also applied to the MKS system, in reference to Italian Professor Giorgi who first suggested its use. The MKS system was also *rationalized*, to relocate the factor  $4\pi$  to appropriate equations, and (instead of 1) the permittivity and permeability of free space were redefined as:  $\epsilon_0 = 1/(36 \pi \times 10^{-9})$  and  $\mu_0 = 4 \pi \times 10^{-7}$ .

### The SI System

To facilitate the exchange of scientific information, it was necessary to establish a single system of units of measurement that would be acceptable internationally. A metric system which uses the *meter*, *kilogram*, and *second* as fundamental mechanical units is now generally employed around the world. This was first devised in France, and it is known (from “système international”) as the *SI system*.

The meter, kilogram, and second are the *fundamental mechanical units* of the SI system. Other units which are defined in terms of the fundamental units are termed *derived units*; for example, the unit of area is meters squared ( $m \times m = m^2$ ). Thus,  $m^2$  is a derived unit. Some other derived units are those for force, work, energy, and power.

A fundamental electrical unit is required in the SI system, and this is the *ampere* (A), the unit of electric current. With this addition, the MKS system became an *MKSA system*. Fundamental units are also required for temperature and illumination calculations, and these are the *kelvin* (K) and the *candela* (cd), respectively. The fundamental mechanical units are sometimes referred to as the *primary fundamental units*, and the units for current, temperature, and illumination are then termed *auxiliary fundamental units*.

When solving problems, it is sometimes necessary to convert between SI and other unit systems. Appendix 1 provides a list of conversion factors for this purpose.

**Section Review**

1-1.1 Explain the following in relationship to unit systems: CGS, MKSA, esu, emu, absolute system, practical units.

**1-2 SCIENTIFIC NOTATION AND METRIC PREFIXES****Scientific Notation**

Very large or very small numbers are conveniently written as a number multiplied by 10 raised to a power:

$$100 = 1 \times 10 \times 10 = 1 \times 10^2$$

$$10\,000 = 1 \times 10 \times 10 \times 10 \times 10 = 1 \times 10^4$$

$$0.001 = 1/(10 \times 10 \times 10) = 1/10^3 = 1 \times 10^{-3}$$

$$1500 = 1.5 \times 10^3$$

$$0.015 = 1.5 \times 10^{-2}$$

Numbers presented in this form are said to use *scientific notation*. Note that in the SI system of units, spaces are used instead of commas when writing large numbers. Four-numeral numbers are an exception. One thousand is written as 1000, while ten thousand is 10 000.

**Metric Prefixes**

Metric prefixes and the letter symbols for the various multiples and submultiples of 10 are listed in Table 1-1, with those most commonly used with electrical units shown in bold type. The prefixes are employed to simplify the representation of very large and very small quantities. Thus, 1000  $\Omega$  can be expressed as 1 *kilohm*, or 1 k $\Omega$ . Here *kilo* is the prefix that represents 1000, and k is the symbol for *kilo*. Similarly,  $1 \times 10^{-3}$  A can be written as 1 *milliampere*, or 1 mA.

**TABLE 1-1** Scientific Notation and Metric Prefixes

Value	Scientific notation	Prefix	Symbol
1 000 000 000 000	$10^{12}$	tera	T
1 000 000 000	$10^9$	<b>giga</b>	<b>G</b>
1 000 000	$10^6$	<b>mega</b>	<b>M</b>
1000	$10^3$	<b>kilo</b>	<b>K</b>
100	$10^2$	hecto	h
10	10	deka	da
0.1	$10^{-1}$	deci	d
0.01	$10^{-2}$	centi	c
0.001	$10^{-3}$	<b>milli</b>	<b>m</b>
0.000 001	$10^{-6}$	<b>micro</b>	<b><math>\mu</math></b>
0.000 000 001	$10^{-9}$	<b>nano</b>	<b>n</b>
0.000 000 000 001	$10^{-12}$	<b>pico</b>	<b>p</b>

## Engineering Notation

As already discussed, 1 k $\Omega$  is  $1 \times 10^3 \Omega$ , and 1 mA is  $1 \times 10^{-3}$  A. Note also from Table 1-1 that  $1 \times 10^6 \Omega$  is expressed as 1 M $\Omega$ , and  $1 \times 10^{-6}$  A can be written as 1  $\mu$ A. These quantities, and most of the metric prefixes in Table 1-1, involve multiples of  $10^3$  or  $10^{-3}$ . Quantities that use  $10^3$  or  $10^{-3}$  are said to be written in *engineering notation*. A quantity such as  $1 \times 10^4 \Omega$  is more conveniently expressed as  $10 \times 10^3 \Omega$ , or 10 k $\Omega$ . Also,  $47 \times 10^{-4}$  A is best written as  $4.7 \times 10^{-3}$  A, or 4.7 mA. For electrical calculations, engineering notation is more convenient than ordinary scientific notation.

### Example 1-1

Write the following quantities using (a) scientific notation, (b) engineering notation, (c) metric prefixes: 12 000  $\Omega$ , 0.000 3 V, 0.000 01 A.

*Solution*

	(a) Scientific notation	(b) Engineering notation	(c) Metric prefixes
12 000 $\Omega$	$1.2 \times 10^4 \Omega$	$12 \times 10^3 \Omega$	12 k $\Omega$
0.000 3 V	$3 \times 10^{-4}$ V	$300 \times 10^{-6}$ V	300 $\mu$ V
0.000 01 A	$1 \times 10^{-5}$ A	$10 \times 10^{-6}$ A	10 $\mu$ A

### Practice Problem

1-2.1 Express the following quantities using engineering notation: 0.005, 77700,  $6 \times 10^{-8}$ ,  $6.8 \times 10^4$ ,  $5.9 \times 10^7$ , 0.00033

## 1-3 THE SI MECHANICAL UNITS

### Fundamental Mechanical Units

As discussed above, the three fundamental mechanical units in the SI system are:

Unit of *length*: the *meter* (m)

Unit of *mass*: the *kilogram* (kg)

Unit of *time*: the *second* (s)

The *meter* was originally defined as one ten-millionth of a meridian passing through Paris from the North Pole to the equator. The kilogram was defined as 1000 times the mass of one cubic centimeter of distilled water. The *liter* is 1000 times the volume of one cubic centimeter of liquid. Consequently, one liter of water has a mass of 1 kilogram. Because of the possibility of error in the original measurement, the meter was redefined in terms of atomic radiation. Also, the kilogram is now defined as the mass of a certain platinum-iridium standard bar kept at the International Bureau of Weights and Measures in France. The *second* is, of course,  $1/(86\,400)$  of a mean solar day, but it is more accurately defined by atomic radiation.

## Unit of Force

The SI unit of force is the newton<sup>1</sup> (N), defined as that force which will give a mass of 1 kilogram an acceleration of one meter per second per second.

When a body is to be accelerated or decelerated, a force must be applied proportional to the desired rate of change of velocity, that is, proportional to the acceleration (or deceleration).

$$\text{Force} = \text{mass} \times \text{acceleration}$$

$$F = m a \quad (1-1)$$

Equation 1-1 gives the force in newtons when the mass is in kilograms and the acceleration is in  $\text{m/s}^2$ .

If the body is to be accelerated vertically from the earth's surface, the acceleration due to gravity ( $g$ ) must be overcome before any vertical motion is possible. In SI units:

$$g = 9.81 \text{ m/s}^2 \quad (1-2)$$

Thus, a mass of 1 kg has a gravitational force of 9.81 N.

## Work

When a body is moved, a force is exerted to overcome the body's resistance to motion.

The work done in moving a body is the product of the force and the distance through which the body is moved in the direction of the force.

$$\text{Work} = \text{force} \times \text{distance} \quad (1-3)$$

$$W = F d$$

The SI unit of work is the joule<sup>2</sup> (J), defined as the amount of work done when a force of one newton acts through a distance of one meter.

Thus, the joule may also be termed a newton-meter. For the equation  $W = F d$ , work is expressed in joules when  $F$  is in newtons and  $d$  is in meters.

## Power

Power is the time rate of doing work.

If a certain amount of work  $W$  is to be done in a time  $t$ , the power required is

$$\text{Power} = \frac{\text{work}}{\text{time}}$$

$$P = \frac{W}{t} \quad (1-4)$$

The SI unit of power is the watt<sup>3</sup> (W), defined as the power developed when one joule of work is done in one second.

For  $P = W/t$ ,  $P$  is in watts when  $W$  is in joules and  $t$  is in seconds.

<sup>1</sup>Named for the great English philosopher and mathematician Sir Isaac Newton (1642–1727).

<sup>2</sup>Named after the English physicist James P. Joule (1818–1899).

<sup>3</sup>Named after the Scottish engineer and inventor James Watt (1736–1819).

## Energy

Energy is defined as the capacity for doing work. Consequently, energy is measured in the same units as work.

When 1 W of power is used for one hour, the energy consumed (or work done) is one *watt-hour* (1 Wh). When 1 kW is used for one hour, 1 *kilowatt-hour* (1 kWh) of energy is consumed. Recall that power is the time rate of doing work, and that a power of 1 W represents a work rate of *one joule per second* (1 J/s). Therefore, when 1 W of power is dissipated for 1 s, 1 J of energy is consumed, or 1 J of work is done. Similarly, when 1 kW of power is expended for 1 minute

$$\begin{aligned}\text{Energy consumed} &= 1 \text{ kW} \times 60 \text{ s} \\ &= 60 \text{ kJ}\end{aligned}$$

and when 1 kW is expended for 1 hour,

$$\begin{aligned}\text{Energy consumed} &= 1 \text{ kW} \times 60 \text{ s} \times 60 \text{ min} \\ &= 3600 \text{ kJ} \\ &= 3.6 \text{ MJ}\end{aligned}$$

The megajoule (MJ) is the SI unit of energy consumption.

### Example 1-2

Calculate the power required to raise a 100 kg load 100 m vertically in 30 s.

#### Solution

$$\begin{aligned}\text{Eqs. 1-1 \& 1-2,} \quad F &= m \times a = 100 \text{ kg} \times 9.81 \text{ m/s}^2 \\ &= 981 \text{ N}\end{aligned}$$

$$\begin{aligned}\text{Eq. 1-3,} \quad W &= F \times d = 981 \text{ N} \times 100 \text{ m} \\ &= 98\,100 \text{ J}\end{aligned}$$

$$\begin{aligned}\text{Eq. 1-4,} \quad P &= \frac{W}{t} = \frac{98\,100 \text{ J}}{30 \text{ s}} \\ &= 3.27 \text{ kW}\end{aligned}$$

## Section Review

1-3.1 State the SI units for power and work, and define each unit.

## Practice Problem

1-3.1 Determine how long it takes for an engine with a 750 W output to raise a 50 kg load vertically through 65 m.

## 1-4 THE SI ELECTRICAL UNITS

### Units of Current and Charge

Electric current ( $I$ ) is a flow of charge carriers. Therefore, current could be defined in terms of the quantity of electricity ( $Q$ ) that passes a given point in a conductor during a time of 1 s.

*The coulomb<sup>4</sup> (C) is the unit of electrical charge or quantity of electricity.*

The coulomb was originally selected as the fundamental electrical unit from which other units were derived. However, because it is much easier to measure current accurately than it is to measure charge, the unit of *current* is now the *fundamental electrical unit* in the SI system. Consequently, the coulomb is a *derived unit*, defined in terms of the unit of electric current.

*The ampere<sup>5</sup> (A) is the unit of electric current.*

*The ampere (also termed an absolute ampere) is defined as that constant current which, when flowing in each of two infinitely long parallel conductors 1 meter apart, exerts a force of  $2 \times 10^{-7}$  newton per meter of length on each conductor.*

*The coulomb is defined as that charge which passes a given point in a conductor each second, when a current of 1 ampere flows.*

These definitions show that the coulomb could be termed an *ampere-second*. Conversely, the ampere can be described as a *coulomb per second*:

$$\text{Amperes} = \frac{\text{coulomb}}{\text{second}} \quad (1-5)$$

It has been established experimentally that 1 coulomb is equal to the total charge carried by  $6.24 \times 10^{18}$  electrons. Therefore, the charge carried by one electron is

$$\begin{aligned} Q &= 1 / (6.24 \times 10^{18}) \\ &= 1.602 \times 10^{-19} \text{ C} \end{aligned}$$

### Emf, Potential Difference, and Voltage

*The volt<sup>6</sup> (V) is the unit of electromotive force (emf) and potential difference.*

*The volt (V) is defined as the potential difference between two points on a conductor carrying a constant current of one ampere when the power dissipated between these points is one watt.*

As already noted, the coulomb is the charge carried by  $6.24 \times 10^{18}$  electrons. One joule of work is done when  $6.24 \times 10^{18}$  electrons are moved through a potential difference of 1 V. One electron carries a charge of  $1 / (6.24 \times 10^{18})$  coulomb. If only one electron is moved through 1 V, the energy involved is an *electron volt (eV)*.

$$1 \text{ eV} = 1 / (6.24 \times 10^{18}) \text{ J} \quad (1-6)$$

<sup>4</sup>Named after the French physicist Charles Augustin de Coulomb (1736–1806).

<sup>5</sup>Named after the French physicist and mathematician Andre Marie Ampere (1775–1836).

<sup>6</sup>Named in honour of the Italian physicist Count Alessandro Volta (1745–1827), inventor of the voltaic pile.



The electron-volt is frequently used in the case of the very small energy levels associated with electrons in orbit around the nucleus of an atom.

### Resistance and Conductance

The ohm<sup>7</sup> is the unit of resistance, and the symbol used for ohms is  $\Omega$ ; the Greek capital letter omega.

The ohm is defined as that resistance which permits a current flow of one ampere when a potential difference of one volt is applied to the resistance.

The term conductance (G) is applied to the reciprocal of resistance. The siemens<sup>8</sup> (S) is the unit of conductance. The unit of conductance was previously the mho (*ohm* spelled backwards).

### Magnetic Flux and Flux Density

The weber<sup>9</sup> (Wb) is the SI unit of magnetic flux.

The weber is defined as the magnetic flux which, linking a single-turn coil, produces a 1 V emf when the flux is reduced to zero at a constant rate in 1 s.

The tesla<sup>10</sup> (T) is the SI unit of magnetic flux density.

The tesla is the flux density in a magnetic field when 1 weber of flux occurs in a plane of 1 square meter; that is, the tesla can be described as 1 Wb/m<sup>2</sup>.

### Inductance

The SI unit of inductance is the henry<sup>11</sup> (H).

The inductance of a circuit is 1 henry, when a 1 V emf is induced by the current changing at the rate of 1 A/s.

### Capacitance

The farad<sup>12</sup> (F) is the SI unit of capacitance.

The farad is the capacitance of a capacitor that contains a charge of 1 coulomb when the potential difference between its terminals is 1 volt.

#### Example 1-3

A bar magnet with a 1 inch square cross-section has 500 maxwells (see Appendix 1) total magnetic flux. Determine the flux density in teslas.

##### Solution

From Appendix 1,

$$\begin{aligned} \text{Total flux, } \Phi &= (500 \text{ maxwell}) \times 10^{-8} \text{ Wb} \\ &= 5 \mu\text{Wb} \end{aligned}$$

<sup>7</sup>Named after the German physicist Georg Simon Ohm (1787–1854), whose investigations led to his statement of *Ohm's law of resistance*.

<sup>8</sup>Named after Sir William Siemens (1823–1883), a British engineer who was born Karl William von Siemens in Germany.

<sup>9</sup>Named after the German physicist Wilhelm Weber (1804–1890).

<sup>10</sup>Named for the Croatian-American researcher and inventor Nikola Tesla (1856–1943).

<sup>11</sup>Named for the American physicist Joseph Henry (1797–1878).

<sup>12</sup>Named for the English chemist and physicist Michael Faraday (1791–1867).

$$\begin{aligned}
 \text{Area,} \quad A &= (1 \text{ in} \times 1 \text{ in}) \times (2.54 \times 10^{-2})^2 \text{ m}^2 \\
 &= 2.54^2 \times 10^{-4} \text{ m}^2 \\
 \text{Flux density,} \quad B &= \frac{\Phi}{A} = \frac{5 \mu\text{Wb}}{2.54^2 \times 10^{-4}} \\
 &= 7.75 \text{ mT}
 \end{aligned}$$

### Section Review

- 1-4.1 State the SI units for current and charge, and define each unit.  
 1-4.2 State the SI units for magnetic flux and flux density, and define each unit.

### Practice Problem

- 1-4.1 A bar magnet has a cross-section of 0.75 in  $\times$  0.75 in and a flux density of 1290 lines per square inch. Calculate the total flux in webers.

## 1-5 TEMPERATURE UNITS

### Temperature Scales

There are two SI temperature scales, the *Celsius scale*<sup>13</sup> and the *Kelvin scale*.<sup>14</sup> The Celsius scale has 100 equal divisions (or *degrees*) between the freezing temperature and the boiling temperature of water. At normal atmospheric pressure, water freezes at 0°C (*zero degrees Celsius*) and boils at 100°C.

The Kelvin temperature scale, also known as the *absolute scale*, commences at absolute zero of temperature, which corresponds to  $-273.15^\circ\text{C}$ . Therefore, 0°C is equal to 273.15 K, and 100°C is the same temperature as 373.15 K. A temperature difference of 1 K is the same as a temperature difference of 1°C. With the (non-SI) *Fahrenheit scale*, 32°F is the freezing temperature of water and 212°F is the boiling temperature.

#### Example 1-4

The normal human body temperature is given as 98.6°F. Determine the equivalent Celsius and Kelvin scale temperatures.

#### Solution

From Appendix 1,

$$\text{Celsius temperature} = \frac{^\circ\text{F} - 32^\circ}{1.8} = \frac{98.7^\circ - 32^\circ}{1.8} = 37^\circ\text{C}$$

$$\begin{aligned}
 \text{Kelvin temperature} &= \frac{^\circ\text{F} - 32^\circ}{1.8} + 273.14 \\
 &= 310.15 \text{ K}
 \end{aligned}$$

<sup>13</sup>Invented by the Swedish astronomer and scientist Anders Celsius (1701–1744).

<sup>14</sup>Named for the Irish-born scientist and mathematician William Thomson, who became Lord Kelvin (1824–1907).

### Joules Equivalent

To raise a liter of water through  $1^\circ\text{C}$  requires an energy input of 4187 J. This is known as *Joules equivalent*, or the *mechanical equivalent of heat*. Using Joules equivalent, the energy required to raise a quantity of water through a given temperature change can be easily calculated. When water is heated, the container must also be raised to the same temperature as the water, so each container is usually defined as having a certain *water equivalent*. The water equivalent is the quantity of water that would absorb the same amount of energy as the container when heated through a specified temperature change.

#### Practice Problem

1-5.1 Calculate the time required for a kettle with a 1500 W heating element and a 0.5 liter water equivalent to raise 2 liters of water from  $24^\circ\text{C}$  to boiling point.

### 1-6 DIMENSIONS

Table 1-2 gives a list of quantities, quantity symbols, units, unit symbols, and quantity dimensions. The symbols and units are those approved for use with the SI system. To understand the dimensions column, consider the fact that the area of a rectangle is determined by multiplying the lengths of the two sides:

$$\text{Area} = \text{length} \times \text{length}$$

The *dimensions* of area are  $(\text{length})^2$

$$\text{or,} \quad [\text{area}] = [L][L] = [L]^2$$

$$\text{Similarly,} \quad [\text{velocity}] = \frac{[\text{length}]}{[\text{time}]} = \frac{[L]}{[T]} = [LT^{-1}]$$

$$[\text{acceleration}] = \frac{[\text{velocity}]}{[\text{time}]} = \frac{[LT^{-1}]}{[T]} = [LT^{-2}]$$

$$\begin{aligned} [\text{force}] &= [\text{mass}] \times [\text{acceleration}] \\ &= [M][LT^{-2}] = [MLT^{-2}] \end{aligned}$$

$$\begin{aligned} [\text{work}] &= [\text{force}] \times [\text{distance}] \\ &= [MLT^{-2}][L] = [ML^2T^{-2}] \end{aligned}$$

$$[\text{power}] = \frac{[\text{work}]}{[\text{time}]} = \frac{[ML^2T^{-2}]}{[T]} = [ML^2T^{-3}]$$

For the electrical quantities, current is another fundamental unit. So, electrical quantities can be analyzed to determine dimensions in the fundamental units of  $L$ ,  $M$ ,  $T$ , and  $I$ .

$$\text{Charge} = \text{current} \times \text{time}$$

$$[\text{charge}] = [I][T] = [IT]$$

**Example 1-5**

Determine the dimensions of voltage and resistance.

**Solution**

From,

$$P = EI$$

$$\begin{aligned} \text{voltage} \quad [E] &= \frac{[P]}{[I]} = \frac{[ML^2T^{-3}]}{[I]} \\ &= [ML^2T^{-3}I^{-1}] \end{aligned}$$

$$\begin{aligned} \text{resistance,} \quad [R] &= \frac{[E]}{[I]} = \frac{[ML^2T^{-3}I^{-1}]}{[I]} \\ &= [ML^2T^{-3}I^{-2}] \end{aligned}$$

**TABLE 1-2** SI Units, Symbols, and Dimensions

Quantity	Symbol	Unit	Unit symbol	Dimensions
Length	$l$	meter	m	$[L]$
Mass	$m$	kilogram	kg	$[M]$
Time	$t$	second	s	$[T]$
Area	$A$	square meter	m <sup>2</sup>	$[L^2]$
Volume	$V$	cubic meter	m <sup>3</sup>	$[L^3]$
Velocity	$v$	meter per second	m/s	$[LT^{-1}]$
Acceleration	$a$	meter per second per second	m/s <sup>2</sup>	$[LT^{-2}]$
Force	$F$	newton	N	$[MLT^{-2}]$
Pressure	$p$	newton per square meter	N/m <sup>2</sup>	$[ML^{-1}T^{-2}]$
Work	$W$	joule	J	$[ML^2T^{-2}]$
Power	$P$	watt	W	$[ML^2T^{-3}]$
Electric current	$I$	ampere	A	$[I]$
Electric charge	$Q$	coulomb	C	$[IT]$
Emf	$V$	volt	V	$[ML^2T^{-3}I^{-1}]$
Electric field strength	$\xi$	volt per meter	V/m	$[MLT^{-3}I^{-1}]$
Resistance	$R$	ohm	$\Omega$	$[ML^2T^{-3}I^{-2}]$
Capacitance	$C$	farad	F	$[M^{-1}L^{-2}T^4I^2]$
Inductance	$L$	henry	H	$[ML^2T^{-2}I^{-2}]$
Magnetic field strength	$H$	ampere per meter	A/m	$[LI^{-1}]$
Magnetic flux	$\Phi$	weber	Wb	$[ML^2T^{-2}I^{-1}]$
Magnetic flux density	$B$	tesla	T	$[MT^{-2}I^{-1}]$

**Practice Problems**

- 1-6.1 Determine the dimensions of power from  $P = I^2 R$  and from  $P = V^2/R$ .
- 1-6.2 The permeability of a magnetic material is  $\mu = B/H$ . Determine the dimensions of  $\mu$ .

**1-7 MEASUREMENT STANDARDS****Standard Classifications**

Electrical measurement standards are precise resistors, capacitors, inductors, voltage sources, and current sources, which can be used for comparison purposes when measuring electrical quantities. For example, resistance can be accurately measured by means of a Wheatstone bridge (see Section 8-2) which uses a standard resistor. Similarly, standard capacitors and inductors may be employed in bridge (or other) methods to accurately measure capacitance and inductance.

Measurement standards are classified in four levels: *international standards*, *primary standards*, *secondary standards*, and *working standards*.

*International standards* are defined by international agreements, and are maintained at the International Bureau of Weights and Measures in France. These are as accurate as it is scientifically possible to achieve. They may be used for comparison with primary standards, but are otherwise unavailable for any application.

*Primary standards* are maintained at institutions in various countries around the world, such as the National Bureau of Standards in Washington. They are also constructed for the greatest possible accuracy, and their main function is checking the accuracy of secondary standards.

*Secondary standards* are employed in industry as references for calibrating high-accuracy equipment and components, and for verifying the accuracy of working standards. Secondary standards are periodically checked at the institutions that maintain primary standards.

*Working standards* are the standard resistors, capacitors, and inductors usually found in a measurements laboratory. Working standard resistors are usually constructed of manganin or a similar material, which has a very low temperature coefficient. They are normally available in resistance values ranging from  $0.01 \Omega$  to  $1 \text{ M}\Omega$ , with typical accuracies of  $\pm 0.01\%$  to  $\pm 0.1\%$ . A working standard capacitor could be air dielectric type, or it might be constructed of silvered mica. Available capacitance values are  $0.001 \mu\text{F}$  to  $1 \mu\text{F}$  with a typical accuracy of  $\pm 0.02\%$ . Working standard inductors are available in values ranging from  $100 \mu\text{H}$  to  $10 \text{ H}$  with typical accuracies of  $\pm 0.1\%$ . *Calibrators* provide standard voltages and currents for calibrating voltmeters and ammeters (see Section 14-2).

**IEEE Standards**

Standards published by the Institute of Electrical and Electronic Engineers (IEEE) are not the kind of measurement standards discussed above. Instead,

for example, they are standards for electrical hardware, for the controls on instrument front panels, for test and measuring procedures, and for electrical installations in particular situations. Standard device and logic graphic symbols for use on schematics are also listed. For instrumentation systems, a very important IEEE standard is standard hardware for interfacing instruments to computers for monitoring and control purposes. Detailed information about IEEE standards is available on the internet.

### Section Review

- 1-7.1 List the various categories of measurement standards, and discuss their applications.

## REVIEW QUESTIONS

### Section 1-1

- 1-1 Identify the two CGS units systems, and discuss difficulties that occur with their use.
- 1-2 Briefly discuss the origins of the SI system as an MKS system, and why the MKS system became the preferred practical units system.
- 1-3 Define the following in respect to a units system: Fundamental units, derived units, primary fundamental units, auxiliary fundamental units, rationalized system.
- 1-4 State the expressions for the permittivity of free space and the permeability of free space in the CGS unit systems and in the SI system.

### Section 1-2

- 1-5 List the names of the various metric prefixes and the corresponding symbols. Also, list the value of each prefix in scientific notation.

### Section 1-3

- 1-6 List the three fundamental SI mechanical units and unit symbols, and discuss their origin.
- 1-7 Define the SI units for force and work.
- 1-8 Define  $g$ , and state its numerical value in SI units.
- 1-9 Identify the SI units and unit symbols for energy and power. Define each unit.

### Section 1-4

- 1-10 State the SI units and unit symbols for electric current and charge. Define each unit.
- 1-11 Define the SI units for electrical resistance and conductance.
- 1-12 Identify the SI units and unit symbols for magnetic flux and flux density. Define each unit.
- 1-13 Define the SI units for inductance and capacitance.

### Section 1-5

- 1-14 Name the two SI temperature scales, and identify the freezing and boiling temperatures of water for each scale.

### Section 1-6

- 1-15 State the dimensions of the four fundamental units in the SI system, and write the dimensions for volume, velocity, and charge.

**Section 1-7**

- 1-16 List the various levels of measurement standards, and discuss the application of each classification.

**PROBLEMS****Section 1-2**

- 1-1 Express the following quantities using (a) scientific notation, (b) metric prefixes: 0.029 A, 13 000  $\Omega$ , 5240 V, 0.0003 H, 738 000  $\Omega$ .
- 1-2 Perform the following calculations to produce the answers using scientific notation: (a)  $0.29 \times 1300/0.006$ , (b)  $83\,400/5.13$ , (c)  $0.4^2 \times 300$ , (d)  $3^{10}/(\sqrt{169})$ , (e)  $0.005^3/1200$ .
- 1-3 Express the following quantities using (a) engineering notation, (b) metric prefixes: 6800  $\Omega$ , 0.000 05 A, 0.027 H, 82 000  $\Omega$ , 0.0005 F.

**Section 1-3**

- 1-4 Referring to the unit conversion factors in Appendix 1, perform the following conversions: (a) 6215 miles to kilometers, (b) 50 miles per hour to kilometers per hour, and (c) 12 square feet to square centimeters.
- 1-5 Determine how long it takes light to travel to earth from a star 1 million miles away. The speed of light is  $3 \times 10^8$  m/s.
- 1-6 The speed of sound in air is 345 m/s. Calculate the distance in miles from a thunderstorm when the thunder is heard 5 s after the lightning flash.
- 1-7 A 140 lb person has a height of 5 ft 7 in. Convert these measurements into kilograms and centimeters.
- 1-8 Determine the force that must be exerted by a crane to lift a 20 000 kg load.
- 1-9 A 2000 kg automobile is accelerated to 70 km/h in a 20 s time period. Neglecting all friction effects, calculate the force exerted by the engine.
- 1-10 A 1000 kg elevator with a 1500 kg load is raised through a height of 60 m in 1 minute. Calculate the work done and the power involved.
- 1-11 One thousand liters of water is pumped through a 20 m height in a 30 minute time period. Determine the work done and the power required.

**Section 1-4**

- 1-12 A 1/4 horsepower electric motor is operated 8 hours per day for 5 days every week. Assuming 100% efficiency, calculate the amount of energy consumed in 1 year in kWh and in MJ.
- 1-13 Calculate the number of electrons that pass through a resistor in a 1.5 h period when a 500 mA current flows.
- 1-14 Determine the work done in joules when a 2 A current flows through a 12  $\Omega$  resistor for 45 minutes.
- 1-15 An electrical appliance consumes 1500 W of power when connected to a 115 V supply. Determine the supply current and the energy consumed in 5 h of operation.
- 1-16 Calculate the conductance of a lamp that dissipates 60 W when connected to a 120 V supply.
- 1-17 An electronic amplifier produces 12 W output to a speaker. The amplifier draws a current of 650 mA from a 25 V supply. Calculate the amplifier efficiency.

- 1-18 A 115 V electrical appliance with 80% efficiency absorbs 3 kW from the supply. Determine the energy consumed by the appliance and the energy output from the supply over a 12 h period.
- 1-19 A total flux of  $0.5 \mu\text{Wb}$  is emitted from one pole of a bar magnet. The pole dimensions are 0.48 inches  $\times$  0.48 inches. Calculate the flux density in tesla within the metal. Also, determine the flux density at a short distance from the pole if all of the flux is contained in an area of 2 inches  $\times$  2 inches.

**Section 1-5**

- 1-20 Calculate the Celsius and Kelvin scale equivalents of  $80^\circ\text{F}$ .
- 1-21 An electric water heater takes 6 minutes to boil 1 liter of water in a pot which has a 0.2 liter water equivalent. If the element draws 11 A from the 115 V supply, calculate the efficiency of the heater.

**Section 1-6**

- 1-22 Determine the dimensions of area, volume, velocity, and acceleration.
- 1-23 Derive the dimensions for force, work, energy, and power.
- 1-24 Derive the dimensions for charge, voltage, and resistance.
- 1-25 Determine the dimensions of capacitance and inductance.
- 1-26 The balance equations for a Maxwell-Wein bridge (Section 10-4) gives  $L_s = C_3 R_1 R_4$ . Use dimensional analysis to show that the right side of the equation has the dimensions of inductance.

**Practice Problem Answers**

- 1-2.1  $5 \times 10^{-3}, 77.7 \times 10^3, 60 \times 10^{-9}, 59 \times 10^6, 330 \times 10^{-6}$
- 1-3.1 42.5 s
- 1-4.1  $7 \mu\text{Wb}$
- 1-5.1 8.8 min
- 1-6.1  $[ML^2T^{-3}]$
- 1-6.2  $[MLT^{-2}I^{-2}]$