Electric Circuit

Basic Concepts:

In electrical engineering, we are often interested in communicating or transferring energy from one point to another. To do this requires an interconnection of electrical devices. Such interconnection is referred to as an *electric circuit*, and each component of the circuit is known as an *element*.

An *electric circuit* is an interconnection of electrical elements.

A simple electric circuit is shown in Fig.1. It consists of three basic elements: a battery, a lamp, and connecting wires. Such a simple circuit can exist by itself; it has several applications, such as a flashlight, a searchlight, and so forth.

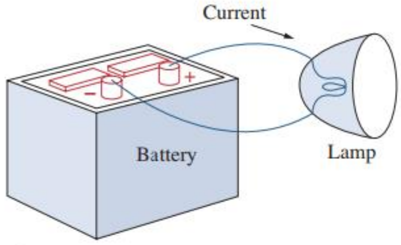


Figure 1
A simple electric circuit.

A complicated real circuit is displayed in Fig. 2, representing the schematic diagram for a radio receiver.

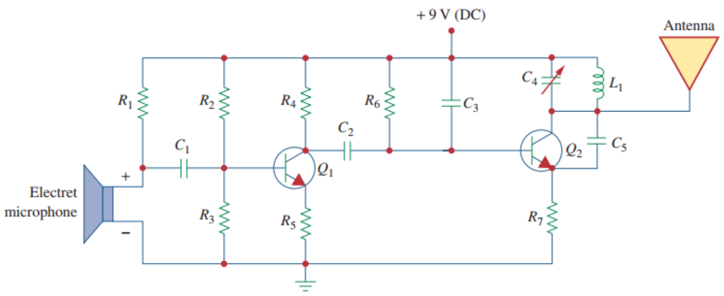


Figure 2
Electric circuit of a radio transmitter.

Systems of Units:

As electrical engineers, we deal with measurable quantities. Our measurement, however, must be communicated in a standard language that virtually all professionals can understand, irrespective of the country where the measurement is conducted. Such an international measurement language is the International System of Units (SI), adopted by the General Conference on Weights and Measures in 1960.

In the past, the systems of units most commonly used were the English and metric, as outlined by Table (1). Note that while the English system is based on a single standard, the metric is subdivided into two interrelated standards: the MKS and CGS. The two systems draw their names from the units of measurement used with each system; the MKS system uses Meter, Kilograms, and Seconds. While the CGS system uses Centimeters, Grams, and Seconds.

Table (1): Comparison of the English and metric systems of units.

	Metric		
English	**MKS**	**CGS**	**SI**
Length: Yard (yd) (0.914 m)	Meter (m) (39.37 in.) (100 cm)	Centimeter (cm) (2.54 cm = 1 in.)	Meter (m)
Mass: Slug (14.6 kg)	Kilogram (kg) (1000 g)	Gram (g)	Kilogram (kg)
Force: Pound (1b) (4.45 N)	Newton (N) (100000 dynes)	Dyne	Newton (N)
Temperature: Fahrenheit (°F) $(=\frac{9}{5}\,°C + 32)$	Celsius or C Centigrade (°C) $[=\frac{5}{9}\,(°F-32)]$	Centigrade (°C)	Kelvin (K) K=273.15+°C
Energy: Foot-Pound (ft-1b) (1.356 Joules)	Newton-meter (N-m) or Joule (J) (0.7378 ft-1b)	Dyne-Centimeter or Erg (1 Joule=10^7 ergs)	Joule (J)
Time: Second (s)	Second (s)	Second (s)	Second (s)

<u>Charge:</u>

The concept of electric charge is the underlying principle for explaining all electrical phenomena. Also, the most basic quantity in an electric circuit is the electric charge. We all experience the effect of electric charge when we try to remove our wool sweater and have it stick to our body or walk across a carpet and receive a shock.

Charge is an electrical property of the atomic particles of which matter consists, measured in coulombs (C). We know from elementary physics that all matter is made of fundamental building blocks known as atoms and that each atom consists of electrons, protons, and neutrons. We also know that the charge *e* on an electron is negative and equal in magnitude to C, while a proton carries a positive charge of the same magnitude as the electron. The presence of equal numbers of protons and electrons leaves an atom neutrally charged.

<u>Current</u>:

Consider a short length of copper wire cut with an imaginary perpendicular plane, producing the circular cross section shown in Fig. 3.

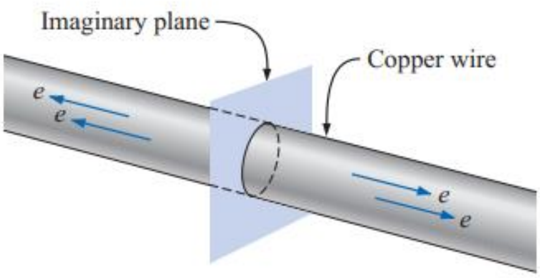


Figure. 3. Random motion of electrons in a copper wire
with no external “pressure” (voltage) applied.

At room temperature with no external forces applied, there exists within the copper wire the random motion of free electrons created by the thermal energy that the electrons gain from the surrounding medium.

When atoms lose their free electrons, they acquire a net positive charge and are referred to as *positive ions*. The free electrons are able to move within these positive ions and leave the general area of the parent atom, while the positive ions only oscillate in a mean fixed position. For this reason, *the free electron is the charge carrier in a copper wire or any other solid conductor of electricity*.

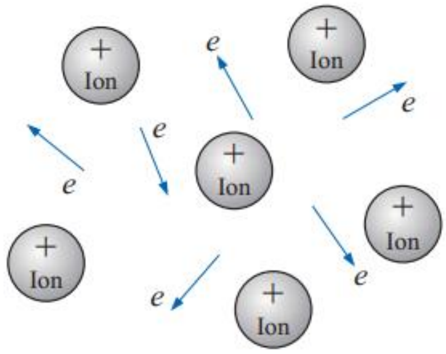


Figure (4) Random motion of free electrons in an atomic structure.

An array of positive ions and free electrons is depicted in Fig. 4. Within this array, the free electrons find themselves continually gaining or losing energy by virtue of their changing direction and velocity. Some of the factors responsible for this random motion include (1) the collisions with positive ions and other electrons, (2) the attractive forces for the positive ions, and (3) the force of repulsion that exists between electrons. This random motion of free electrons is such that over a period of time, the number of electrons moving to the right across the circular cross section of Fig. 3 is exactly equal to the number passing over to the left. *With no external forces applied, the net flow of charge in a conductor in any one direction is zero.*

Consider the configuration in Fig. 5, where a copper wire has been used to connect a light bulb to a battery to create the simplest of electric circuits. The instant the final connection is made, the free electrons of negative charge drift toward the positive terminal, while the positive ions left behind in the copper wire simply oscillate in a mean fixed position. The flow of charge (the electrons) through the bulb heats up the filament of the bulb through friction to the point that it glows red-hot and emits the desired light.

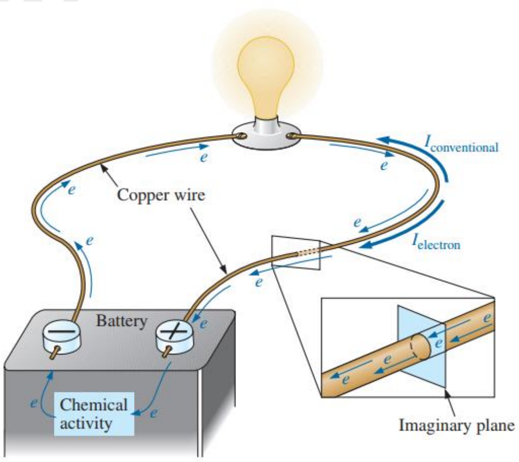


Figure (5) Basic electric circuit.

In total, therefore, the applied voltage has established a flow of electrons in a particular direction. In fact, by definition, *if 6.242 x 10^{18} electrons (1 coulomb) pass through the imaginary plane in 1 second, the flow of charge, or current, is said to be 1 ampere (A).*

The unit of current measurement, *ampere*, was chosen to honor the efforts of André Ampère in the study of electricity in motion. Using the coulomb as the unit of charge, the current in amperes can be determined using the following equation:

$$\boxed{I = \frac{Q}{t}} \qquad \begin{aligned} I &= \text{amperes (A)} \\ Q &= \text{coulombs (C)} \\ t &= \text{time (s)} \end{aligned}$$

The current associated with only a few electrons per second would be inconsequential and of little practical value. To establish numerical values that permit immediate comparisons between levels, a **coulomb** (C) of charge was defined as the total charge associated with 6.242×10^{18} electrons. The charge associated with one electron can then be determined from

$$\text{Charge/electron} = Q_e = \frac{1\ C}{6.242 \times 10^{18}} = 1.6 \times 10^{-19}\ C$$

Example:

The charge flowing through the imaginary surface of Fig. (5) is 0.16 C every 64 ms. Determine the current in amperes.

Solution:

$$I = \frac{Q}{t} = \frac{0.16\ C}{64 \times 10^{-3}\ s} = \frac{160 \times 10^{-3} C}{64 \times 10^{-3}\ s} = 2.50\ A$$

Homework (1): Determine the time required for $4 \times 10^{16}\ electrons$ to pass through the imaginary surface of Fig. (5). If the current is 5 mA.

Homework (2): If 465 C of charge pass through a wire in 2.5 min, find the current in Amperes.

Homework (3): If 0.784×10^{18} electrons pass through a wire in 643 ms, find the current.

Ammeters *are used to measure current levels*. If the current levels are usually of the order of milliamperes, the instrument will typically be referred to as a *milliammeter*, and if the current levels are in the microampere range, as a *microammeter*. Ammeters are connected as shown in Fig. 6. Since ammeters measure the rate of flow of charge, the meter must be placed in the network such that the charge flows through the meter. The only way this can be accomplished is to open the path in which the current is to be measured and place the meter between the two resulting terminals.

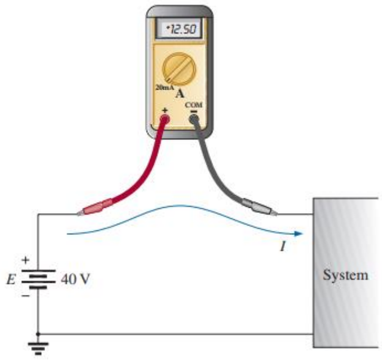


Figure 6. Ammeter connection for an up-scale reading.

Voltage:

In the battery of Fig. 5, the internal chemical action will establish an accumulation of negative charges (electrons) on one terminal (the negative terminal) and positive charges (positive ions) on the other (the positive terminal). A "positioning" of the charges has been established that will result in a *potential difference* between the terminals. If a conductor is connected between the terminals of the battery, the electrons at the negative terminal have sufficient potential energy to overcome collisions with other particles in the conductor and the repulsion from similar charges to reach the positive terminal to which they are attracted.

A potential difference of 1 volt (V) exists between two points if 1 joule (J) of energy is exchanged in moving 1 coulomb (C) of charge between the two points.

The unit of measurement *volt* was chosen to honor Alessandro Volta. The potential difference between two points is determined by

$$V = \frac{W}{Q} \qquad (volts)$$

W = joules (J),

Q = coulombs (C).

Example: Find the potential difference between two points in an electrical system if 60 J of energy are expended by a charge of 20 C between these two points.

Solution: $V = \frac{W}{Q} = \frac{60\text{ J}}{20\text{ C}} = 3\text{ V}$

Voltmeters are used to measure the potential difference between two points. The potential difference between two points can be measured by simply connecting the leads of the meter *across the two points*, as indicated in Fig.7.

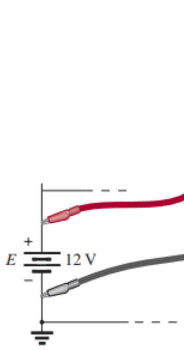


Figure 7 Voltmeter connection for an up-scale reading.

Homework (1): How much charge passes through a battery of 22.5 V if the energy expended is 90 J?

Homework (2): Charge is flowing through a conductor at the rate of 420 C/min. If 742 J of electrical energy are converted to heat in 30 s, what is the potential drop across the conductor?

Resistance:

The flow of charge through any material encounters an opposing force similar in many respects to mechanical friction. This opposition, due to the collisions between electrons and between electrons and other atoms in the material, *which converts electrical energy into another form of energy such as heat*, is called the **resistance** of the material. The unit of measurement of resistance is the **ohm,** for which the symbol is, the capital Greek letter omega (Ω). The circuit symbol for resistance appears in Fig. 8 with the graphic abbreviation for resistance (*R*).

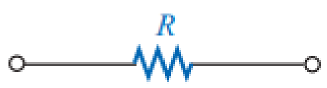


Fig. (8) Resistance symbol and notation.

The resistance of any material with a uniform cross-sectional area is determined by the following four factors:

1. Material

2. Length

3. Cross-sectional area

4. Temperature

The chosen material, with its unique molecular structure, will react differentially to pressures to establish current through its core. Conductors that permit a generous flow of charge with little external pressure will have low resistance levels, while insulators will have high resistance characteristics. As one might expect, the longer the path the charge must pass through, the higher the resistance level, whereas the larger the area, the lower the resistance. Resistance is thus directly proportional to length and inversely proportional to area.

As the temperature of most conductors increases, the increased motion of the particles within the molecular structure makes it increasingly difficult for the "free" carriers to pass through, and the resistance level increases.

At a fixed temperature of 20°C (room temperature), the resistance is related to the other three factors by

$$R = \frac{\rho\, l}{A} \qquad (ohms, \Omega)$$

ρ = resistivity,

l = length,

A = cross-sectional area.

The *ohmmeter* is an instrument used to measure the resistance of elements. The resistance of a resistor can be measured by simply connecting the two leads of the meter across the resistor, as shown in Fig. 9.

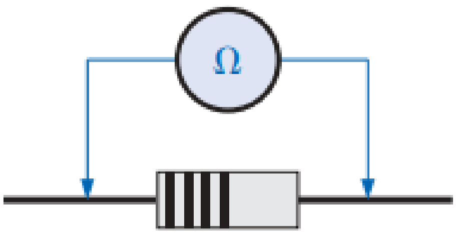
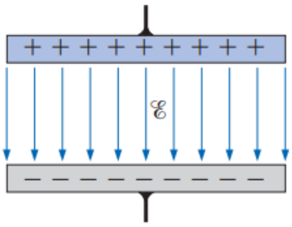


Figure (9) Measuring the resistance of a single element.

Capacitance:

Capacitor consists of two parallel conducting plates (surfaces) separated by an insulating material such as air. *The conducting surfaces may be in the form of either circular (or rectangular) plates or be of spherical or cylindrical shape. The purpose of a Capacitor is to store electrical energy*. *Capacitance* is a measure of a capacitor's ability to store charge on its plates—in other words, its storage capacity. Capacitance is also defined as the amount of charge required to create a unit potential difference between its plates as shown in Fig. below.



A capacitor has a capacitance of 1 farad if 1 coulomb of charge is deposited on the plates by a potential difference of 1 volt across the plates.

$$C = \frac{Q}{V}$$

C = Farads (F),

Q = Coulombs (C),

V = Volts (V).

Inductance:

Inductors are coils of various dimensions designed to introduce specified amounts of inductance into a circuit. Inductance is measured in henries (H).

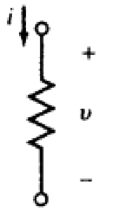
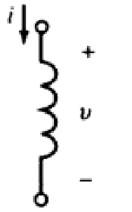
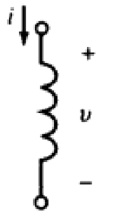
Inductance (L) is a property of a conductor (often in the shape of a coil) that is measured by the size of the electromotive force, or voltage, induced in it, compared with the rate of change of the electric current that produces the voltage.

Voltage-Current Relations:

The passive circuit elements resistance (R), inductance (L), and Capacitance (C) are defined by the manner in which the voltage and current are related for the individual element. For example, if the voltage v and current I for a single element are related by a constant, then the element is a resistance, R is the constant of proportionality, and $v = RI$. Similarly, if the voltage is the time derivative of the current, then the element is an inductance, L is the constant of proportionality, and $v = L\ dI/dt$. Finally, if the current in the element is the time derivative of the voltage, then the element is a capacitance, C is the constant of proportionality, and $I = C\ dv/dt$. Table (2) summarizes these relationships for the three passive circuit elements. Note the current directions and the corresponding polarity of the voltages.

The function $\frac{dv}{dt}$ is called the derivative of the voltage with respect to time t. and $\frac{di}{dt}$ is called the derivative of the current with respect to time t.

Table (2): relationships for the three passive circuit elements.

Circuit element	Units	Voltage	Current	Power
 **Resistance**	ohms (Ω)	$v = Ri$ **(Ohms's law)**	$i = \frac{v}{R}$	$p = vi = i^2 R$
 **Inductance**	henries (H)	$v = L\frac{di}{dt}$	$i = \frac{1}{L}\int v\,dt + k_1$	$p = vi = Li\frac{di}{dt}$
 **Capacitance**	farads (F)	$v = \frac{1}{C}\int i\,dt + k_2$	$i = C\frac{dv}{dt}$	$p = vi = Cv\frac{dv}{dt}$