CHAPTER 9

CAPACITOR AND CAPACITANCE

A capacitor is used as an electric circuit component to store electrical energy. The capacitor is similar to a rechargeable battery. The capacitor was originally known as a condenser. In this chapter, we shall study the capacitors, capacitance and applications of capacitors.

Learning Outcomes

It is expected that students will

- examine various types of capacitors and their applications.
- investigate the capacitance and dielectric constant.
- understand the energy stored in a capacitor.
- explain the charging and discharging of the capacitors.
- deduce the combination of capacitors.

9.1 CAPACITORS

A capacitor is an electrical device that stores electrical energy in the form of an electric field. A capacitor consists of two conductors separated by a small distance. An insulator is inserted between its conductors.

Types and Applications of Capacitors

The various types of capacitors and their applications are described below.

Film Capacitors: Film capacitors are the ones that use plastic film as the dielectric medium. They are available in nearly any value and working voltages up to 1500 V. They range from 10 % to 0.01 % in tolerance.

Ceramic Capacitors: Ceramic capacitors are the ones that use ceramic as the dielectric material. It is used in high-frequency circuits such as audio frequency (*af*) to radio frequency (*rf*). In ceramic capacitors, one can develop both high capacitance and low capacitance by altering the thickness of the ceramic disc. Ceramic capacitors are mainly used for high stability performances with low losses. The capacitance values of these capacitors are stable with respect to the applied voltage, frequency and temperature.

Electrolytic Capacitors: Electrolytic capacitors are the ones that use the oxide layer as the dielectric material. It has a wide tolerance capacity. There are mainly two types of electrolytic capacitors; tantalum and aluminum. They are available with working voltages of up to approximately 500 V. The failure of electrolytic capacitors can be hazardous, resulting in an explosion or fire. Electrolytic capacitors are used for filtering and smoothing rectified alternating voltage, buffering and interim storage for direct voltage supplies, uninterruptible power supplies and energy storage in flash devices.

Variable Capacitors: Variable capacitors mostly use air as the dielectric medium. The capacitance can be mechanically adjusted. For example, this form of the capacitor is used to set the resonance frequency in tuner devices. Variable capacitors are mostly used in AC circuits especially for high frequency, high power and low loss. They are used in radio tuning applications, antenna tuning and so on.

Supercapacitors: A supercapacitor (SC), also called an ultracapacitor, is a high-capacity capacitor with a capacitance value much higher than other capacitors, but with lower voltage limits, that bridges the gap between electrolytic capacitors and rechargeable batteries. It typically stores 10 to 100 times more energy than electrolytic capacitors. It can accept and deliver charge much faster than batteries, and tolerates many more charge and discharge cycles than rechargeable batteries.

Supercapacitors are used in applications requiring many rapid charge/discharge cycles, rather than long-term compact energy storage in automobiles, buses, trains, cranes and elevators, where they are used for regenerative braking and short-term energy storage or burst-mode power delivery. Smaller units are used as power backup for static random-access memory (SRAM).

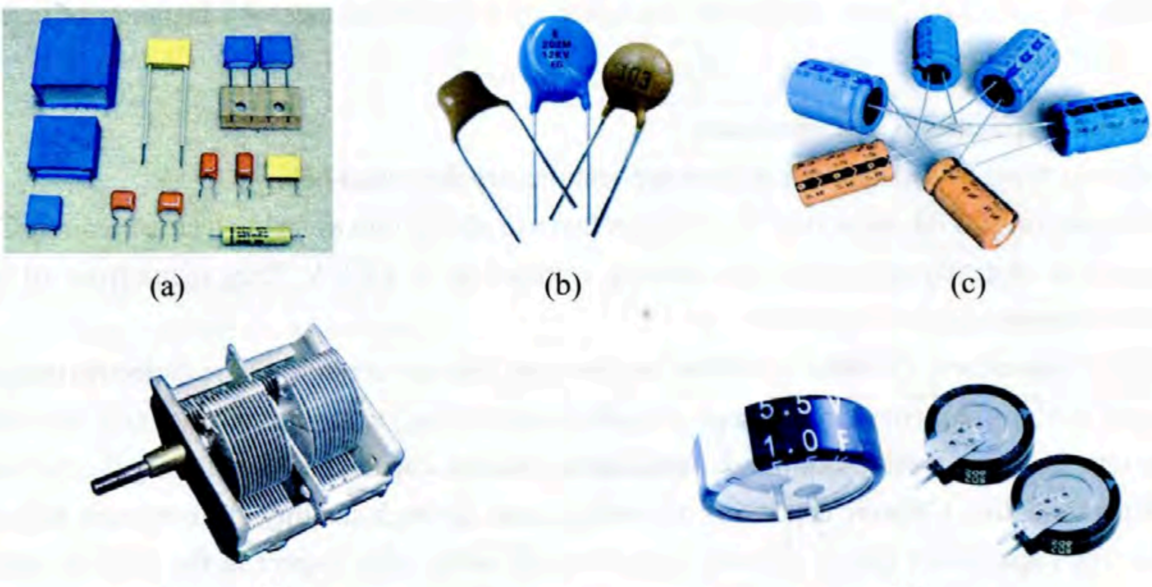


Figure 9.1 The various types of capacitors (a) film capacitors (b) ceramic capacitors (c) electrolytic capacitors (d) variable capacitor (e) supercapacitors

Film capacitors and ceramic capacitors are non-polarized capacitors which means that they do not have polarities (positive and negative terminals).

The symbols of a polarized capacitor, a fixed capacitor and a variable capacitor are shown in Figure 9.2.

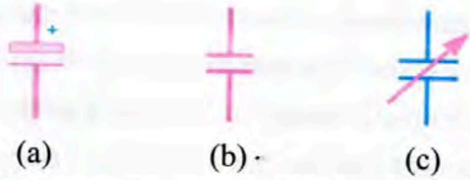


Figure 9.2 Symbols of (a) polarized capacitor (b) fixed capacitor (c) variable capacitor

The capacitors are used in both electrical and electronic applications such as filters, energy storage systems, engine starters, signal processing devices, etc.

Capacitors are used;

- for storing energy, which can be used by the device for temporary power outages whenever they need additional power.
- for blocking DC current after getting fully charged but allow the AC current to pass through it.
- as filters in power supplies and energy-storing devices in electronic flash units. They are also used to tune the frequency of radio receivers and to eliminate sparking in automobile ignition systems.
- as the sensor for measuring humidity, fuel levels, mechanical strain, etc.

Capacitors can also be used in a time-dependent circuit (timer circuit). This could be connected to any LED or loudspeaker system, and it is likely that any flashing light or regular beeping uses a timing capacitor.

Reviewed Exercise

- Which capacitor is used as tuning capacitor?

Key Words: film capacitor, ceramic capacitor, electrolytic capacitor, varible capacitor

9.2 CAPACITANCE OF A CAPACITOR

When a capacitor is connected to a battery (an electrical power source) the two conductors of the capacitor have charges of equal magnitude and opposite signs. If one conductor has a charge $+Q$ the other has a charge $-Q$. The magnitude of the charge on each conductor, Q, is called the charge of the capacitor. The potential difference between two conductors of the capacitor, V, is called the potential difference of the capacitor. The quantity of charge Q on the capacitor is linearly proportional to the potential difference V between the conductors; that is, $Q \propto V$. This relationship can be written as $Q = C\,V$, where C is called capacitance of the capacitor.

The capacitance of a capacitor is defined as the ratio of the charge to the potential difference of the capacitor.

The capacitance is represented as,

$$C = \frac{Q}{V} \qquad (9.1)$$

where C is capacitance of the capacitor, Q is charge of the capacitor and V is potential difference between two conductors of the capacitor.

In the SI system, the unit of capacitance is farad (F). If the potential difference of the capacitor is 1 V when it is given a charge 1 C, its capacitance is 1 C V^{-1} (or) 1 F. Therefore 1 F is equivalent to 1 C V^{-1}. The unit farad is named in honor of Michael Faraday. The farad is a very large unit of capacitance. In practice, typical devices have capacitances ranging from microfarad (μF) to picofarad (pF). The sub-multiple units of farad are

1 microfarad (μF) = 10^{-6} F
1 nanofarad (nF) = 10^{-9} F
1 picofarad (pF) = 10^{-12} F

When the charge on the capacitor is increased, the potential difference also increases proportionally, as mentioned previously. Therefore, the capacitance of a capacitor remains constant.

Although the capacitance of a capacitor does not depend on Q and V, it depends on the size and the shape of the capacitor, and on the nature of the insulator between the two conductors.

Like a capacitor, if a conductor is given some charge its potential will also change. The amount of charge given to a conductor to change its potential by one unit is called the electric capacity of the conductor. The electric capacity is also expressed by Eq. (9.1) and its SI unit is also farad.

Example 9.1 A capacitor has a capacitance of 5 μF. How much of the charge should be removed in order that the potential difference between its plates decreases by 40 V?

Capacitance of capacitor $C = 5$ μF,

Change in potential difference $\Delta V = 40$ V,

Let the charge removed be ΔQ,

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

$$\Delta Q = C\,\Delta V$$

$$= 5 \times 40 = 200\ \mu\text{C}$$

Hence, 200 μC charge should be removed.

Reviewed Exercise

1. When the charge on a capacitor is increased, does its capacitance increase? Explain.
2. A capacitor stores charge Q at a potential difference V. What happens if the voltage applied to the capacitor is doubled?

Key Words: capacitor, capacitance, electric capacity, charge of capacitor, potential difference, farad

9.3 PARALLEL-PLATE CAPACITOR

A parallel-plate capacitor is the simplest capacitor. It consists of two parallel metal plates separated by air or other insulating material as shown in Figure 9.3 (a). Charging a capacitor means connecting the capacitor to a battery as shown in Figure 9.3 (b). It can be presented by an electric circuit diagram as shown in Figure 9.3 (c).

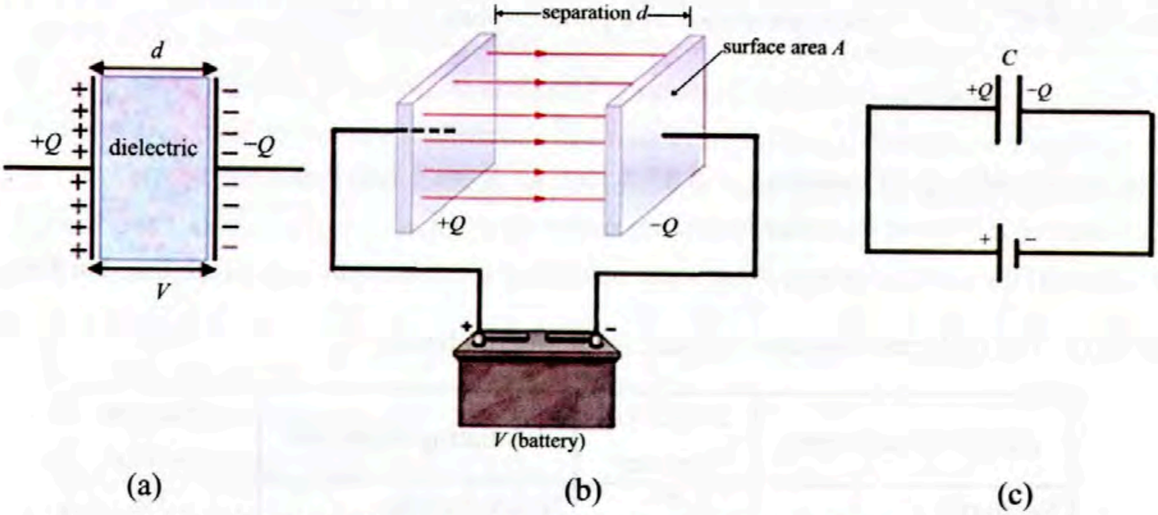


Figure 9.3 (a) Parallel-plate capacitor (b) charging a capacitor (c) circuit diagram

Two parallel, metallic plates of equal surface area A are separated by a distance d as shown in Figure 9.3 (a) and (b). One plate carries a charge $+Q$, and the other carries a charge $-Q$. The surface charge density (charge per unit surface area) on each plate is $\sigma = Q/A$. If the plates are very close together, the electric field between the plates is uniform.

Suppose that an insulating material of permittivity ε is placed between the plates. The value of the electric field between the plates can be expressed in terms of surface charge density σ as

$$E = \frac{\sigma}{\varepsilon}$$

$$E = \frac{Q}{\varepsilon A} \qquad (9.2)$$

Because the electric field between the plates is uniform, the magnitude of the potential difference V between the plates equals $E\,d$, therefore,

$$V = E\,d = \frac{Q\,d}{\varepsilon A} \qquad (9.3)$$

The capacitance of the parallel plate capacitor is

$$C = \frac{Q}{V} = \frac{Q}{Q\,d/\varepsilon A}$$

$$C = \frac{\varepsilon A}{d} \qquad (9.4)$$

That is, for a given insulating material the capacitance of a parallel-plate capacitor is directly proportional to the area of its plates and inversely proportional to the separation of the plates.
The permittivity ε of an insulating material is related to that of a vacuum ε_0 as

$$\varepsilon = \kappa \varepsilon_0 \quad (9.5)$$

Here κ is the dielectric constant or the relative permittivity of the insulating material.
From Eq. (9.4) and (9.5) the capacitance of a parallel-plate capacitor is

$$C = \frac{\kappa \varepsilon_0 A}{d} \quad (9.6)$$

where the permittivity of vaccum $\varepsilon_0 = 8.85 \times 10^{-12}\ C^2\ N^{-1}m^{-2}$ (or) $F\ m^{-1}$
For a vacuum $\kappa = 1$ and for other insulating materials $\kappa > 1$.
The values of dielectric constant κ for some insulating materials (dielectric) are listed in Table 9.1.

Table 9.1 The dielectric constant of some insulating materials

Insulating materials	Dielectric constant	Insulating materials	Dielectric constant
Vacuum	1	Nylon (solid)	3.8
Air (1 atm)	1.0006	Mica	3 – 6
Waxed paper	2	Glass	5 – 8
Plywood	2.1	Marble	6
Rubber (hard)	3	Ammonia (liquid)	25
Amber	3	Ethyl alcohol (0 °C)	28.4
Paper	3.6	Water (18 °C)	81

Dielectric Constant

As previously mentioned, the permittivity ε of an insulating material is

$$\varepsilon = \kappa \varepsilon_0$$

$$\kappa = \frac{\varepsilon}{\varepsilon_0} \quad (9.7)$$

Thus, the dielectric constant of an insulating material is the ratio of its permittivity to that of vacuum.
If a parallel-plate capacitor has an insulating material between its plates, according to Eq. (9.6), its capacitance C is

$$C = \frac{\kappa \varepsilon_0 A}{d}$$

If there is a vacuum between its plates, its capacitance C_0 is

$$C_0 = \frac{\varepsilon_0 A}{d}$$

Hence, the dielectric constant κ of the insulating material is

$$\kappa = \frac{C}{C_0} \tag{9.8}$$

Therefore, the dielectric constant can be defined as the ratio of two capacitances as follows.

The ratio of the capacitance of a capacitor with an insulating material between its two conductors to the capacitance of that capacitor with a vacuum between its two conductors is called the dielectric constant of that insulating material.

When a charged capacitor is disconnected from a battery and the air medium between its plates is replaced by an insulating material (dielectrics) as shown in Figure 9.4, the potential difference of the capacitor is found to decrease. Since the charge Q of the capacitor does not change, it indicates that the capacitance of the capacitor increases.

With vacuum $C_0 = \frac{Q}{V_0}$ and with insulating material $C = \frac{Q}{V}$.

Since $V < V_0$, $C > C_0$

$$\frac{C}{C_0} = \frac{V_0}{V} = \kappa \tag{9.9}$$

According to Eq. (9.9), dielectric constant can be expressed as the ratio of capacitances as well as the ratio of potential differences.

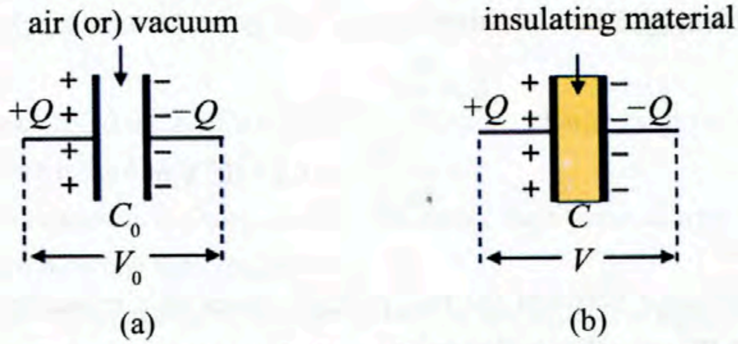


Figure 9.4 A charged capacitor (a) before and (b) after insertion of an insulating material (dielectrics) between the plates

Insulating materials have values of dielectric constant κ greater than unity; that is, their dielectric strength is greater than that of air. Therefore, a dielectric provides the following advantages:

- increase in capacitance,
- increase in maximum operating voltage,
- possible mechanical support between the plates, which allows the plates to be close together without electrical contact, thereby decreasing d and increasing C.

A dielectric increases the maximum operating voltage of a capacitor even though the physical size of the capacitor doesn't change. The dielectric may be able to withstand a larger electric field (higher potential difference) between the plates than air.

Example 9.2 The area of each plate of a parallel-plate capacitor is 1 m^2 and the distance between two plates is 1 mm. If the potential difference between the plates is 120 V and the dielectric constant of the material inserted between them is 3, find (i) the capacitance of the parallel-plate capacitor, (ii) the magnitude of the charge on each plate, (iii) the electric field intensity between the plates.

(i) Area of each plate $A = 1\ m^2$, distance between two plates $d = 1\ mm = 1 \times 10^{-3}\ m$, dielectric constant of the material $\kappa = 3$, $\varepsilon_0 = 8.85 \times 10^{-12}\ C^2\ N^{-1}m^{-2}$

The capacitance is

$$C = \frac{\kappa\varepsilon_0 A}{d}$$

$$= \frac{3 \times 8.85 \times 10^{-12} \times 1}{1 \times 10^{-3}} = 26.55 \times 10^{-9}\ F$$

(ii) If the potential difference between the plates is $V = 120$ V, the magnitude of the charge Q on each plate is,

$$Q = C\,V$$

$$= 26.55 \times 10^{-9} \times 120$$

$$= 3.19 \times 10^{-6}\ C = 3.19\ \mu C$$

(iii) Electric field intensity E between the plates is

$$E = \frac{V}{d}$$

$$= \frac{120}{1 \times 10^{-3}} = 1.2 \times 10^{5}\ V\,m^{-1}$$

Reviewed Exercise

1. When the distance between the two parallel plates of a capacitor is doubled, by what percent does its capacitance change?
2. When the distance between two parallel plates having the charges of equal magnitude and opposite signs is reduced, what will happen to the capacitance and potential difference of the plates?
3. When an insulating material is inserted between the conductors of a capacitor in a vacuum, does its capacitance increase or decrease? Explain.

Key Words: parallel-plate capacitor, dielectric constant, surface charge density, permittivity, relative permittivity

9.4 ENERGY STORED IN A CAPACITOR

A capacitor stores electrical energy in the form of an electric field. We shall now calculate the energy stored by a capacitor.

When the capacitor is charged, the charging process can be viewed as the apparent transfer of charge between two conductors. The charge has been transferred from a conductor at lower potential to a conductor at higher potential. Work has been done for such a transfer of charge. The magnitude of the charge on the two conductors increases gradually and the potential difference between them also increases gradually. The energy stored by the capacitor can be analyzed from the *Q*-*V* graph. Figure 9.5 shows the proportionality between the voltage and the charge of a capacitor.

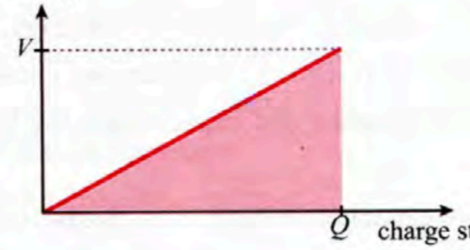


Figure 9.5 The graphical analysis of energy stored in a capacitor

The work done in charging the capacitor is given by the shaded area under the curve (area of the shaded triangle). This work done is equal to $\frac{1}{2}QV$ which is the energy stored by the capacitor. This energy can also be calculated using the average potential difference of the capacitor during charging process.

Before a capacitor is charged each of its conductors has no charge, and the potential difference between two conductors is zero.

Suppose that after the capacitor is charged each conductor receives a charge of magnitude Q and the potential difference between the conductors is V.

If the average potential difference of the capacitor before and after it is charged is $\overline{V}$, then

$$\overline{V} = \frac{0+V}{2} = \frac{V}{2} \qquad (9.10)$$

The work done W for transferring charge of Q between the two conductors is,

$$W = \overline{V}\,Q$$
$$= \frac{1}{2}V\,Q$$

This amount of work is, in fact, the electrical energy stored by the capacitor in the form of an electric field.

Therefore the energy of the capacitor is $\frac{1}{2}VQ$.

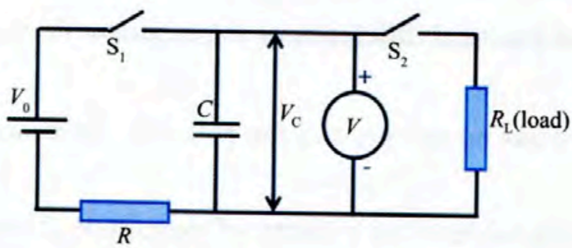
Since $C = Q/V$, the energy, W, of the capacitor can be expressed as

$$\left.\begin{aligned} W &= \frac{1}{2}VQ \\ W &= \frac{1}{2}CV^2 \\ W &= \frac{1}{2}\frac{Q^2}{C} \end{aligned}\right\} \quad (9.11)$$

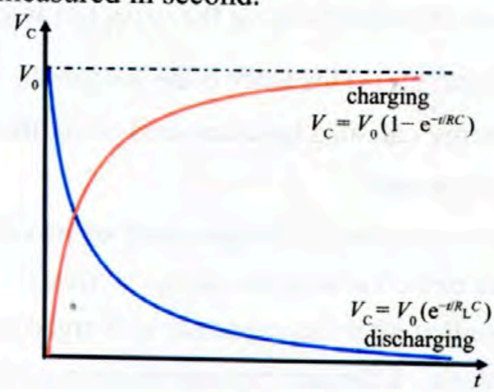
Charging and Discharging of a Capacitor

When the switch S_2 is open and S_1 is closed in Figure 9.6 (a), the capacitor is charged by the power supply through the resistor R. Placing a resistor in the charging circuit slows down the charging process. The greater the values of resistance and capacitance, the longer it takes to charge the capacitor.

Figure 9.6 (b) shows the variation of capacitor voltage V_C with time t during charging process. The voltage rises with time according to the equation $V_C = V_0(1-e^{-t/RC})$. V_0 is the voltage provided by the power supply. The product of the resistance R and the capacitance C is called the time constant τ of a capacitor charging or discharging process. It is measured in second.



(a)



(b)

Figure 9.6 (a) The circuit diagram for charging and discharging a capacitor
(b) Voltage characteristics of charging and discharging a capacitor

After being charged, as described above, the capacitor can then be discharged through the load resistor R_L by opening the switch S_1 and closing S_2 of Figure 9.6 (a). The variation of capacitor voltage with time during this discharging process is shown in Figure 9.6(b). The voltage of the capacitor falls off with time according to the equation $V_C = V_0(e^{-t/R_LC})$.

Example 9.3 What potential difference must be applied across a 10 μF capacitor if it is to have an energy content of 1 J?

Capacitance $C = 10\ \mu F = 10 \times 10^{-6}$ F, energy of capacitor $W = 1$ J,

$$W = \frac{1}{2} C V^2$$

$$V^2 = \frac{2W}{C}$$

$$= \frac{2 \times 1}{10 \times 10^{-6}} = 20 \times 10^4$$

$$V = 447.2 \text{ V}$$

Example 9.4 A charged capacitor of capacitance $C = 35\ \mu F$ is discharged through a resistor of resistance $R = 120\ \Omega$. (i) What is the time constant τ of the discharging process? (ii) What is the elapsed time when the voltage falls to 10 % of its original value?

$C = 35\ \mu F = 35 \times 10^{-6}$ F, $R = 120\ \Omega$

(i) The time constant $\tau = R\,C = 120 \times 35 \times 10^{-6} = 4.2 \times 10^{-3}$ s $= 4.2$ ms

(ii) After a time t the voltage across the capacitor will be $V_C = V_0(e^{-t/R_L C})$. Since the voltage falls to 10 % of its original value, $V_C = 0.1\ V_0$

$$0.1\ V_0 = V_0\,(e^{-t/\tau})$$

$$e^{-t/\tau} = 0.1$$

$$\ln e^{-t/\tau} = \ln 0.1$$

$$= 2.303 \log_{10} 0.1$$

$$-\frac{t}{\tau} = -2.303$$

$$t = 2.303 \times 4.2 \times 10^{-3}$$

$$= 9.673 \times 10^{-3} \text{ s}$$

$$= 9.67 \text{ ms}$$

Reviewed Exercise

1. A parallel-plate capacitor of capacitance C is given the charge Q and then disconnected from the circuit. How much work is required to pull apart the plates of this capacitor to twice their original separation?
2. In capacitor charging and discharging, why is a resistor required to connect with the capacitor?

Key Words: electrical energy, work, charging and discharging, time constant

9.5 COMBINATION OF CAPACITORS

Several capacitors can be connected together to be used in a variety of applications. There are two types of combination namely; (i) parallel and (ii) series.

(i) Capacitors in Parallel

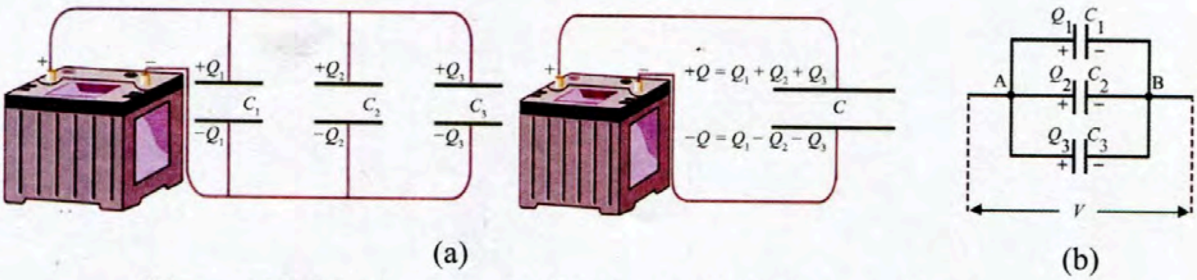


Figure 9.7 Capacitors in parallel (a) schematic diagrams (b) in symbols

In Figure 9.7 three capacitors are connected in parallel. The plates of the capacitors connected together at the point A have positive charges and the plates connected together at the point B have negative charges. All the capacitors have the same potential difference, but they carry different amounts of charges.

The respective capacitors have capacitances C_1, C_2 and C_3 and charges Q_1, Q_2 and Q_3 respectively. If the potential difference of each capacitor is V,

$$C_1 = \frac{Q_1}{V}\ ,\ C_2 = \frac{Q_2}{V}\ ,\ C_3 = \frac{Q_3}{V}$$

If Q is the total charge on the three capacitors, then

$$Q = Q_1 + Q_2 + Q_3$$

$$Q = V(C_1 + C_2 + C_3)$$

$$\frac{Q}{V} = C_1 + C_2 + C_3 \qquad \text{(i)}$$

We can replace the three capacitors in parallel with a single capacitor provided that it has the same total charge Q when the same potential difference V is applied. Such a capacitor is called an equivalent capacitor and its capacitance is the equivalent capacitance of the three capacitors in parallel.

If the capacitance of the equivalent capacitor is C, then

$$C = \frac{Q}{V} \qquad \text{(ii)}$$

From (i) and (ii),

$$C = C_1 + C_2 + C_3 \qquad (9.12)$$

If n capacitors, having capacitances C_1, C_2, C_3, ..., C_n and charges Q_1, Q_2, Q_3,..., Q_n respectively, are connected in parallel the equivalent capacitance C is

$$C = C_1 + C_2 + C_3 + \ldots + C_n \qquad (9.13)$$

The equivalent capacitance of the capacitors connected in parallel is the sum of the capacitances of the individual capacitors.

The equivalent capacitance C_p of the parallel combination of n identical capacitors, each of capacitance C, is $C_p = n\,C$.

(ii) Capacitors in Series

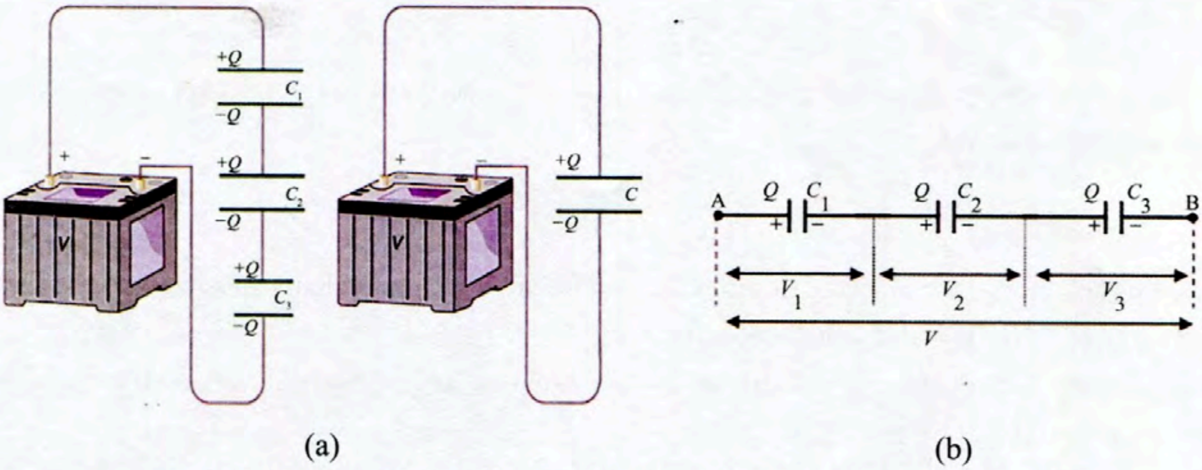


Figure 9.8 Capacitors in series (a) schematic diagrams (b) in symbols

In Figure 9.8 three capacitors having the capacitances C_1, C_2 and C_3 respectively, are connected in series. The negatively charged plate of one capacitor is connected to the positively charged plate of the other.

Since the capacitors are connected in series each capacitor has the same charge. But they have different potential differences.

If the charge on the individual capacitors is Q and their potential differences are V_1, V_2 and V_3, then their capacitances are:

$$C_1 = \frac{Q}{V_1}\ ,\ C_2 = \frac{Q}{V_2}\ ,\ C_3 = \frac{Q}{V_3}\ .$$

Suppose that V is the total potential difference of the capacitor combination.

$$V = V_1 + V_2 + V_3$$

$$= \frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3}$$

$$= Q\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right) \qquad \text{(i)}$$

As in the case of capacitors in parallel, we can replace the three capacitors in series with an equivalent capacitor. The charge of the equivalent capacitor is Q when the total potential difference V is applied.

If the capacitance of the equivalent capacitor is C, then

$$C = \frac{Q}{V} \qquad \text{(ii)}$$

From (i) and (ii)

$$\frac{Q}{C} = Q\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right)$$

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \qquad (9.14)$$

If n capacitors having capacitances C_1, C_2, C_3, ... C_n respectively, are connected in series, the equivalent capacitance C is

$$\frac{1}{C} = \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots + \frac{1}{C_n}\right) \qquad (9.15)$$

When the capacitors are connected in series the reciprocal of the equivalent capacitance is the sum of the reciprocals of their individual capacitances.

The equivalent capacitance C_s of the series combination of n identical capacitors, each of capacitance C, is $C_s = \frac{C}{n}$.

Example 9.5 If two capacitors having the capacitances of 4 μF and 12 μF are connected in series, find the equivalent capacitance of the combination of the two capacitors. If the potential difference of the combination is 200 V, find the potential difference of 12 μF capacitor.

$C_1 = 4\ \mu F$, $C_2 = 12\ \mu F$, $V = 200\ V$

The equivalent capacitance C of the combination of the two capacitors

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

$$= \frac{1}{4} + \frac{1}{12}$$

$$C = 3\ \mu F$$

Suppose that magnitude of the charge on the combination is Q.

$$Q = CV$$

$$= 3 \times 10^{-6} \times 200$$

$$= 600 \times 10^{-6} = 600\ \mu C$$

This magnitude of charge is received by the individual capacitors. Therefore, if the potential difference of 12 μF capacitor is V_2.

$$V_2 = \frac{Q}{C_2}$$

$$= \frac{600}{12} = 50\ V$$

Reviewed Exercise

1. In which connection of the capacitors has each capacitor the same charge?
2. In which connection of the capacitors is the potential difference of each capacitor the same?

Key Words: equivalent capacitance, potential difference, total charge

SUMMARY

A **capacitor** is an electrical device that stores electrical energy in the form of an electric field.

A **parallel-plate capacitor** is the simplest capacitor. It consists of two parallel metal plates separated by air or other insulating material.

The ratio of the capacitance of a capacitor with an insulating material between its two conductors to the capacitance of that capacitor with a vacuum between its two conductors is called the **dielectric constant** of that insulating material.

EXERCISES

1. State whether the following are True (T) or False (F),
   (i) If one conductor of a capacitor has a charge $+Q$ the other has a charge $-Q$.
   (ii) The charge of the capacitor is the magnitude of the charge on each conductor.
   (iii) The potential difference of the capacitor is twice the potential difference between two conductors of the capacitor.
2. When a parallel-plate capacitor is connected to a 50 V battery each plate receives a charge of magnitude 0.002 C. Find its capacitance. If the capacitor is connected to a 100 V battery, does the capacitance change? Does the charge still remain the same?
3. Choose the correct answer from the following.
   The plates of a parallel-plate capacitor of capacitance C are brought together to a third of their original separation. The capacitance is now
   A. $\frac{1}{9}C$ B. $\frac{1}{3}C$ C. $3C$ D. $9C$
4. What must be done to increase the capacitance of a capacitor?
5. How does a dielectric affect the maximum operating voltage of a capacitor even though the physical size of the capacitor does not change?
6. The plates of a parallel-plate capacitor arc 50 cm^2 in area and 1 mm apart, (i) What is its capacitance? (ii) When the capacitor is connected to a 24 V battery, what is the charge on each plate? (iii) What is the energy of the capacitor?
7. The capacitance of a parallel-plate capacitor is increased from 8 μF to 50 μF when a sheet of glass is inserted between its plates. What is the dielectric constant of the glass?
8. In a capacitor charging RC circuit, C = 50 μF. What is the value of resistance R that would produce a voltage rise to 20 % of supply voltage after 1 s?

9. Three capacitors have capacitances of 5 μF, 10 μF and 15 μF.
   (i) Find the equivalent capacitance when they are connected in parallel.
   (ii) Find the equivalent capacitance when they are connected in series.
10. Find the capacitance that can be obtained by combining three 10 μF capacitors in all possible ways.
11. The equivalent capacitance is 10 μF when n identical capacitors are connected in parallel and 0.4 μF when they are connected in series. Determine n and the capacitance of each capacitor.
12. A 35 μF capacitor is needed, but only 10 μF capacitors are available. How should a minimum number of 10 μF capacitors be connected so that the combination has a capacitance of 35 μF?
13. Three capacitors have capacitances of 3 μF, 10 μF, and 15 μF. How should they be connected to obtain the equivalent capacitances of (i) 2 μF (ii) 9 μF (iii) 12.5 μF?
14. Three capacitors of capacitances 3 μF, 10 μF and 15 μF are connected in series with 100 V battery. What is the charge and the potential difference on each capacitor?
15. A capacitor having a capacitance of 2 μF and a charge of 2000 μC is connected in series with another capacitor having a capacitance of 8 μF and a charge of 1600 μC. (i) Find the potential difference of the individual capacitors prior to the connection. (ii) Find the potential difference of the individual capacitors after the connection.

CONCEPT MAP

CAPACITOR AND CAPACITANCE

Capacitor
- types and applications
- capacitance

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

Energy of a Capacitor

$$W = \frac{1}{2}VQ$$

$$W = \frac{1}{2}CV^2$$

$$W = \frac{1}{2}\frac{Q^2}{C}$$

Combination of Capacitors
- capacitors in parallel

$$C = C_1 + C_2 + C_3$$

- capacitors in series

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

Parallel plates capacitor

$$C = \frac{\kappa \varepsilon_0 A}{d}$$

- dielectric constant

$$\kappa = \frac{\varepsilon}{\varepsilon_0} = \frac{C}{C_0}$$

Charging and discharging of a capacitor
- charging

$$V_C = V_0(1 - e^{-t/RC})$$

- discharging

$$V_C = V_0(e^{-t/R_L C})$$

CHAPTER 10

ELECTRICAL ENERGY, POWER AND HEATING EFFECT OF ELECTRIC CURRENT

Electrical energy can be transformed into a wide variety of other useful forms of energy. The transformation of electrical energy into heat energy is very useful and important. Many home appliances use the heat generated from such transformation. Electrical energy is provided by source of electromotive force such as batteries and generators. In this chapter we shall discuss the electromotive force, electrical energy, electrical power and some applications of heating effect of electric current.

Learning Outcomes

It is expected that students will

- study the electromotive force and electric circuits.
- understand series and parallel connection of batteries.
- distinguish between electrical energy and power.
- state and apply Joule's law of electricity and heat.
- identify some applications of the heating effect of electric current.

10.1 ELECTROMOTIVE FORCE AND ELECTRIC CIRCUITS

When a potential difference is set up between the two ends of a conductor, a current flows through it. A steady current will flow through the conductor if a steady potential difference is maintained between its ends by using batteries and generators. Batteries and generators are called sources of electromotive force.

The sources of electromotive force convert energy from some other forms into electrical form. For example, a battery converts chemical energy into electrical energy to provide electrical power. In an electric generator, mechanical energy is converted into electrical energy.

Electromotive Force

A source of electromotive force has a positive terminal and a negative terminal as shown in Figure 10.1. The positive charges are sent from the negative terminal to the positive terminal within the source. Alternately, it can be said that the main function of the source is to send negative charges from the positive terminal to the negative terminal within the source. In doing so work has to be done by the source.

Electromotive force, abbreviated as emf, is the amount of energy provided by the battery per unit charge to move round the complete circuit.

It is measured in unit of volt (V), equivalent to joule per coulomb of electric charge ($J\ C^{-1}$)..Despite its name, electromotive force is not actually a force.

Internal Resistance of a Source and Circuit Equation

Generally, a source of electromotive force has an internal resistance. The internal resistance of a battery depends on its size, chemical properties, life time, and temperature. A battery which has an internal resistance r must be viewed as shown in Figure 10.1(a). This means that a resistor of resistance r must be regarded as being connected in series to the battery. The symbol shown in Figure 10.1(b) also represents a battery which has an internal resistance r.

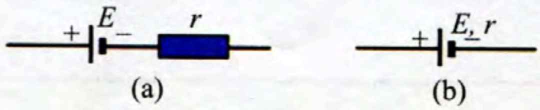


Figure 10.1 Symbols for a battery

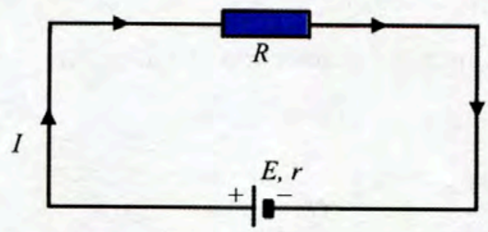


Figure 10.2 A battery connected to an external circuit

In Figure 10.2 a battery of emf E and internal resistance r is connected to a resistor R. A current I flows through the circuit. By Ohm's law, the potential difference across the resistor is $V = I R$. This is the work done in moving a unit positive charge from one end to another of the resistor R. Similarly, the work done in moving a unit positive charge from one end to another of the internal resistance r of the battery is $I r$.

The total work done in moving a unit positive charge round the complete circuit is $I R + I r$, which is the emf E of the battery.

Hence, $$E = I R + I r$$

$$I = \frac{E}{R + r} \qquad (10.1)$$

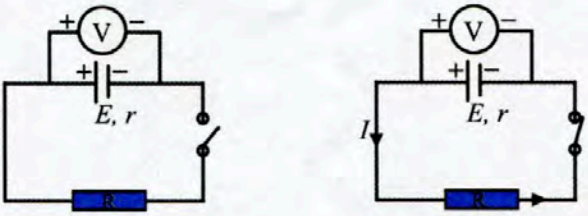
This equation is called the circuit equation.

Eq.(10.1) can be rewritten as, $$I R = E - I r$$

The two ends of the resistor are connected to the positive and negative terminals of the battery as shown in Figure 10.2. Hence, the potential difference between the terminals of a battery when it is connected to an external circuit is given by $V = E - I r$.

When a battery having an internal resistance is used in an electric circuit, the potential difference between the terminals of the battery is always less than its emf. The potential difference across the terminals of a battery connected to an external circuit is called the terminal voltage (or available voltage) of the battery.

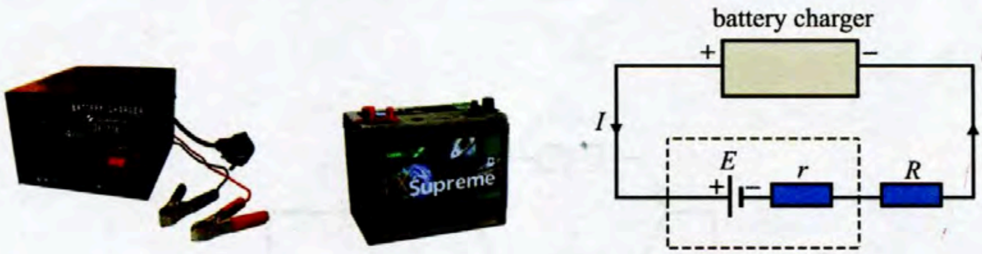
Hence, electromotive force (emf) is the potential difference between the two terminals of a battery or cell in an open circuit (when no current flows) as shown in Figure 10.3 (a). Terminal voltage (available voltage) is the potential difference between the two terminals of a battery or cell in a closed circuit as shown in Figure 10.3 (b). Thus, emf is an open-circuit voltage and terminal voltage is a closed-circuit voltage.



(a) (b)

Figure 10.3 Illustration of (a) emf (b) terminal voltage of a battery

Charging a battery means the chemical energy of the battery which has been used up is now supplied back by electrical energy from some external source (battery charger) shown in Figure 10.4. The external electrical energy required for unit positive charge is equal to the emf E of the battery plus the energy per unit positive charge dissipated in the battery as heat, which is $I\,r$. Therefore, in charging a battery, the potential difference between the terminals is equal to $E + I\,r$.



(a) (b) (c)

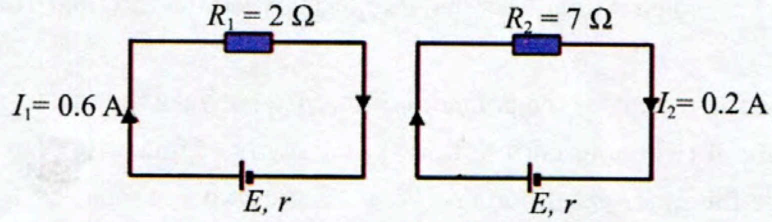
Figure 10.4 (a) Battery charger (b) battery (c) charging circuit

The terminal voltage of a battery when (i) discharging (in use) $V = E - I\,r$, $V < E$ (ii) open circuit (not in use) $V = E$ (iii) charging $V = E + I\,r$, $V > E$.

Example 10.1 When a battery is connected to a 2 Ω resistor it drives a current of 0.6 A through the resistor. When it is connected to a 7 Ω resistor it drives a current of 0.2 A through the resistor. Find the emf and the internal resistance of the battery.

$R_1 = 2\ \Omega, I_1 = 0.6$ A, $R_2 = 7\ \Omega, I_2 = 0.2$ A

Let the emf of the battery be E and internal resistance of the battery be r,



(a) (b)

The current in the circuit (a),

$$I_1 = \frac{E}{R_1 + r}$$

$$E = I_1 (R_1 + r)$$

$$= 0.6 (2 + r) \quad (1)$$

The current in the circuit (b),

$$I_2 = \frac{E}{R_2 + r}$$

$$E = I_2 (R_2 + r)$$

$$= 0.2 (7 + r) \quad (2)$$

From Eq. (1) and (2),

$$0.6 (2 + r) = 0.2 (7 + r)$$

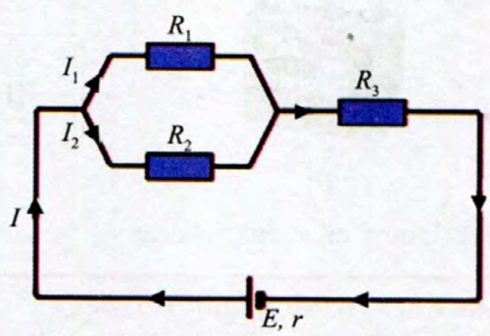
$$0.4\, r = 0.2$$

$$r = 0.5\ \Omega$$

Substituting the value of r into Eq. (1), $E = 0.6 (2 + 0.5) = 1.5$ V

Example 10.2 Find the current flowing through each resistor and the potential difference across the 1 Ω resistor in the circuit diagram given below.

$R_1 = 4\ \Omega,\ R_2 = 6\ \Omega,\ R_3 = 1\Omega,\ E = 12$ V, $r = 0.6\ \Omega$



If the equivalent resistance of R_1 and R_2 is R_p,

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{4} + \frac{1}{6} = \frac{5}{12}$$

$$R_p = 2.4\ \Omega$$

If the equivalent resistance of R_p and R_3 is R,

$$R = R_p + R_3 = 2.4 + 1 = 3.4\ \Omega$$

If the current in the circuit is I,

$$I = \frac{E}{R + r}$$

$$= \frac{12}{3.4 + 0.6}$$

$$= \frac{12}{4} = 3\ \text{A}$$

The potential difference across R_3 is V_3,

$$V_3 = I R_3 = 3 \times 1 = 3\ \text{V}$$

The potential difference between the ends of the combination of R_1 and R_2 resistors is V_p,

$$V_p = I R_p = 3 \times 2.4 = 7.2\ \text{V}$$

Since R_1 and R_2 resistors are connected in parallel, the same potential difference of 7.2 V appears across each resistor.

The current flowing through R_1,

$$I_1 = \frac{V_P}{R_1} = \frac{7.2}{4} = 1.8\ \text{A}$$

The current flowing through R_2,

$$I_2 = \frac{V_P}{R_2} = \frac{7.2}{6} = 1.2\ \text{A}$$

Example 10.3 What is the difference between electromotive force (emf) and potential difference (voltage)?

Electromotive force (emf) is the amount of energy, provided by the battery, per unit charge to move round the complete circuit.

The potential difference or voltage is the amount of energy required to move a unit charge from one end to another end of a circuit element.

Reviewed Exercise

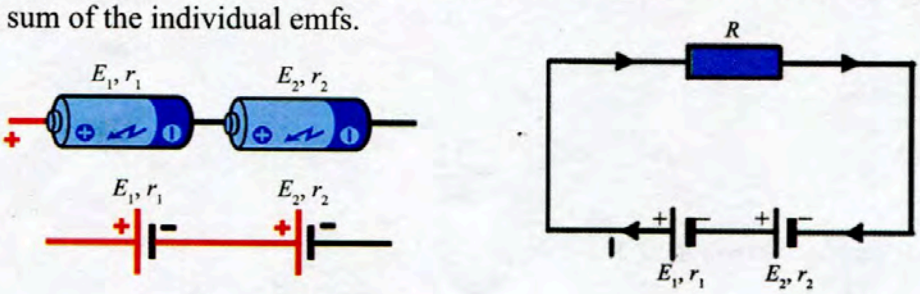
1. What is meant by terminal voltage (available voltage) of a battery and how is it related to emf?
2. What are (i) open circuit and (ii) closed circuit? Illustrate with diagrams.

Key Words: electromotive force (emf), available voltage, internal resistance, open circuit, closed circuit, current

10.2 BATTERIES IN SERIES AND IN PARALLEL

1. **Batteries in Series**

When two or more electromotive sources (batteries) are connected in series, the resultant emf is the algebraic sum of the individual emfs.



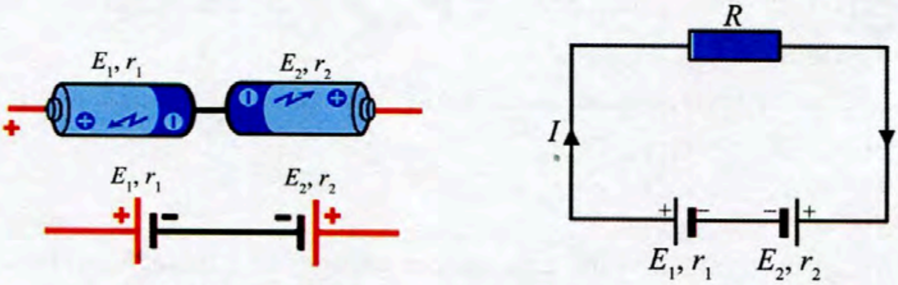
(a) (b)

Figure 10.5 (a) Batteries in series aiding

(b) batteries in series aiding connected with an external resistor

In Figure 10.5 (a) two batteries are connected in series aiding. In this arrangement the currents leaving the batteries are in the same direction so that the resultant emf is $E_1 + E_2$. Such a connection of batteries is called series aiding. The total internal resistance of those two batteries is $(r_1 + r_2)$. They can be regarded as a single battery having an emf $(E_1 + E_2)$ and internal resistance $(r_1 + r_2)$. In Figure 10.5 (b) two batteries in series aiding arrangement are connected to an external resistor (resistance R). The current in the circuit is

$$I = \frac{E_1 + E_2}{R + r_1 + r_2} \qquad (10.2)$$



(a) (b)

Figure 10.6 (a) Batteries in series opposing

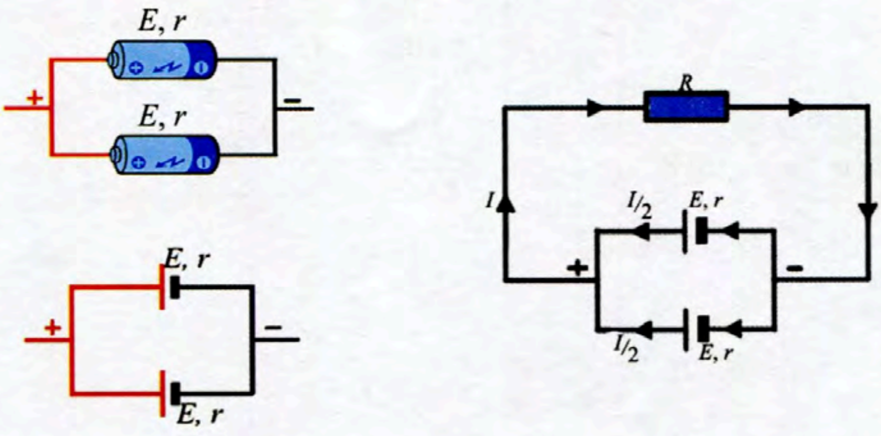
(b) batteries in series opposing connected with an external resistor

In Figure 10.6 (a) two batteries are connected in series opposing. The emfs of the batteries are in opposition. Thus, the resultant emf is the difference between the individual emfs. Such a connection of batteries is called series opposing. If E_1 is greater than E_2 the resultant emf of those two batteries is $(E_1 - E_2)$. But their total internal resistance is still $(r_1 + r_2)$. Thus, they can be regarded as a single battery having an emf $(E_1 - E_2)$ and an internal resistance $(r_1 + r_2)$.

In Figure 10.6 (b) two batteries in series opposing arrangement are connected to an external resistor (resistance R). The current in the circuit is

$$I = \frac{E_1 - E_2}{R + r_1 + r_2} \qquad (10.3)$$

2. **Batteries in Parallel**



(a) (b)

Figure 10.7 (a) Batteries in parallel
(b) batteries in parallel connected with an external resistor

In Figure 10.7 (a) two batteries having equal emfs and equal internal resistances are connected in parallel. It should be noticed that the same polarity terminals of the batteries are connected together. The resultant emf of the parallel-combination is just the emf E of a single battery. Since the internal resistances of the batteries are in parallel, the resultant internal resistance is $\frac{r}{2}$. This combination can be regarded as a single battery having an emf E and an internal resistance $\frac{r}{2}$.
In Figure 10.7 (b), the two batteries in parallel combination are connected to an external resistor (resistance R). In the circuit the resultant emf is E and the total resistance is $(R + \frac{r}{2})$.

$$I = \frac{E}{R + \frac{r}{2}} \qquad (10.4)$$

Since the two batteries have equal emfs and equal internal resistances the current flowing through each battery is $\frac{I}{2}$.

In parallel connection of batteries, care must be taken that the terminal of the same polarity should be connected together. Otherwise, batteries may be damaged.

Example 10.4 Two batteries each having an emf of 6 V and an internal resistance of 0.5 Ω are connected (i) in series and (ii) in parallel. Find the current in each case when the batteries are connected to a 1 Ω resistor.

(i) in series aiding $E_1 = E_2 = 6$ V, $r_1 = r_2 = 0.5\ \Omega$, $R = 1\ \Omega$

The current in the circuit is,
$$I = \frac{E_1 + E_2}{R + r_1 + r_2}$$
$$= \frac{6+6}{1+0.5+0.5} = \frac{12}{2} = 6 \text{ A}$$

(ii) in series opposing

The current in the circuit is,
$$I = \frac{E_1 - E_2}{R + r_1 + r_2}$$
$$= \frac{6-6}{1+0.5+0.5} = 0$$

(iii) The batteries in parallel is, $E = E_1 = E_2 = 6$ V

The current in the circuit is,
$$I = \frac{E}{R + \frac{r}{2}}$$
$$= \frac{6}{1 + \frac{0.5}{2}} = 4.8 \text{ A}$$

Reviewed Exercise

1. What are the advantages and disadvantages of (i) the series aiding connection of batteries (ii) the parallel connection of batteries?
2. A battery has an emf of 6 V and an internal resistance of 0.5 Ω. How many batteries are necessary to pass a current of 1 A through a 22 Ω resistor in an electric circuit?

Key Words: internal resistance, series aiding, series opposing, parallel combination, resultant emf

10.3 ELECTRICAL ENERGY AND ELECTRICAL POWER

Electrical Energy

Electrical energy is energy associated with the flow of charge through any part of circuit. Electrical energy can be generated from source of emf such as batteries, generators, dynamos and photovoltaic cells. It can also be stored in other forms for future application using fuel cells, batteries, capacitors and inductors.

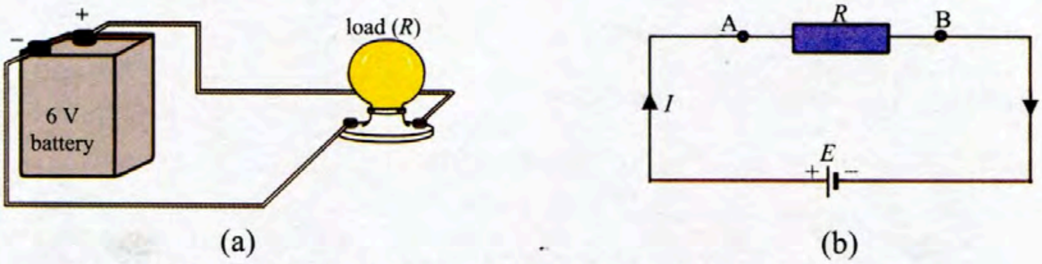


Figure 10.8 Conversion of electrical to heat energy in the resistor

In Figure 10.8, a load of resistance R is connected to a battery, which is a source of emf. As the current I flows through R, the potential at the point A is higher than that at the point B. Suppose that the potential difference between A and B is V. By the definition of potential difference, the work done in bringing a unit positive charge from A to B is V.

Therefore, the work done W in bringing the amount of charge Q from A to B is

$$W = Q\,V$$

Suppose the amount of charge Q passes through a cross-sectional area of the resistor R in the time t.

$$I = \frac{Q}{t} \quad (\text{or}) \quad Q = I\,t$$

The work done W is obtained as, $W = V\,I\,t$

The work done W by the battery in taking the charge Q from A to B is, in fact, the electrical energy supplied by the battery. This electrical energy is transformed into heat energy in the resistor R. It is because the electrons collide with the atoms in the resistor R when they pass through it. Hence the atoms acquire additional energy and therefore heat energy is produced.

Since the potential difference between A and B is $V = I\,R$, the work done (or) the electrical energy W produced by the battery is

$$\left.\begin{aligned} W &= V\,I\,t \\ W &= I^2\,R\,t \\ W &= \frac{V^2}{R}t \end{aligned}\right\} \qquad (10.5)$$

If an electric motor, instead of electric lamp, is connected between A and B in Figure 10.8 (a) the electrical energy will be transformed into mechanical energy.

Unit of Electrical Energy

The practical unit of electrical energy is kilowatt hour (kWh). The relation between the unit of electrical energy kWh and the unit of work J is

$$1 \text{ kWh} = 1000 \text{ W} \times 1 \text{ h}$$
$$= 1000 \times 60 \times 60 = 3.60 \times 10^6 \text{ J}$$

Example 10.5 If a current of 2 A flows through a 50 Ω resistor for 30 min find the amount of electrical energy dissipated in the resistor.

$R = 50\ \Omega,\ I = 2\ \text{A},\ t = 30\ \text{min} = \frac{1}{2}\ \text{h}$

Let W be the electrical energy dissipated in the resistor,

$$W = I^2 R t$$
$$= 2^2 \times 50 \times \frac{1}{2}$$
$$= 100\ \text{Wh} = 0.1\ \text{kWh}$$

Example 10.6 An electric lamp of 60 Ω connected to a 240 V mains line is used for 45 min. (i) Find the amount of electrical energy dissipated in the lamp. (ii) Find the cost of using it if electricity costs 35 kyats per unit.

$R = 60\ \Omega,\ V = 240\ \text{V},\ t = 45\ \text{min} = \frac{3}{4}\ \text{h}$

(i) Let W be the amount of electrical energy dissipated in the lamp.

$$W = \frac{V^2}{R} t$$
$$= \frac{(240)^2}{60} \times \frac{3}{4}$$
$$= 720\ \text{Wh} = 0.72\ \text{kWh}$$

(ii) One unit of electricity = 1 kWh

The cost of using 0.72 kWh = 35 × 0.72 = 25.2 kyats

Electrical Power

Electrical power is the rate of transfer of electrical energy. If the electrical energy W is transferred in the time t, then the electrical power P is,

$$P = \frac{W}{t}$$

Since

$$W = V I t = I^2 R t = \frac{V^2}{R} t$$

$$P = V I = I^2 R = \frac{V^2}{R} \qquad (10.6)$$

Unit of electrical power

The unit of electrical power P is the watt (W). If 1 joule (J) of electrical energy is transferred in 1 second (s) the electrical power is 1 joule per second (J s^{-1}) or 1 watt (W).

Example 10.7 If a 1200 W electric iron is used for 50 min, by how many units does the electricity meter reading increase? Calculate the payment if one unit of electricity costs 35 kyats.

$P = 1200$ W, $t = 50$ min $= \frac{5}{6}$ h

Let W be the electrical energy used by the electric iron.

$$P = \frac{W}{t}$$

$$W = P\,t = 1200 \times \frac{5}{6}$$

$$= 1000 \text{ Wh} = 1 \text{ kWh}$$

The electricity meter reading increases by 1 uint of electricity.

One unit of electricity = 1 kWh

Therefore, the payment = 1 × 35 = 35 kyats

Reviewed Exercise

1. Which quantity determines the rate at which electrical energy is delivered by a current?
2. When an air conditioner is connected to a 220 V mains line it draws a current of 10 A and is used for 6 h. (i) Find the amount of electrical energy consumed by it. (ii) Calculate the cost of using it if the electrical energy costs 50 kyats per unit.

Key Words: potential difference, electrical energy, electrical power, electricity meter

10.4 JOULE'S LAW OF ELECTRICITY AND HEAT

When electric current passes through a conductor, the electrons in the conductor are accelerated due to electric field. Therefore, they collide with the other atoms and lose their kinetic energy which appears heat energy.

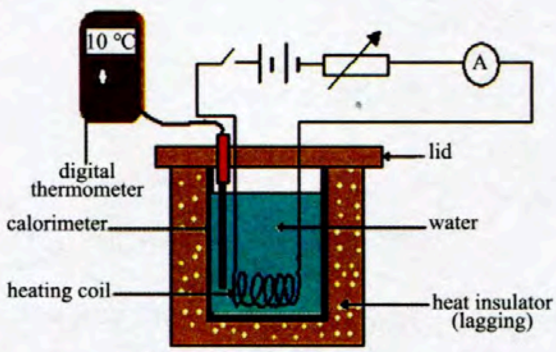


Figure 10.9 Joule's calorimeter

English physicist James Prescott Joule in 1841 experimentally studied the heating effect of electric current. Heat energy is produced in the resistor R (heating coil) as shown in Figure 10.9. The electrical energy W supplied by the battery is transformed into heat energy H in the resistor R. The electrical energy W (measured in joule) is related to the amount of heat H (measured in calorie) as follows.

$$W = J H \qquad (10.7)$$

where J is a constant called Joule's mechanical equivalent of heat ($J = 4.2$ J cal^{-1}).

When $W = I^2 R t$ is substituted in equation (10.7) the following equation is obtained.

$$H = \frac{I^2 R t}{J} \qquad (10.8)$$

This equation represents Joule's law of electricity and heat which can be stated as follows.

The amount of heat produced in a resistor due to a current flowing through it is directly proportional to the square of the current, the value of resistance and the time taken by the current to pass through the resistor.

H can also be written as follows:

$$H = \frac{V I t}{J} = \frac{V^2 t}{R J} \qquad (10.9)$$

Example 10.8 If a 60 W electric lamp is connected to a 220 V mains line find (i) the current in the lamp (ii) the resistance of tungsten wire of the lamp (iii) the amount of charge passing through the filament in 1 min and (iv) the amount of heat produced by the filament in 1 min.

(i) $P = 60$ W, $V = 220$ V

Let I be the current in the filament.

$$P = V I$$

$$I = \frac{P}{V}$$

$$= \frac{60}{220} = 0.27 \text{ A}$$

(ii) Let R be the resistance of the filament.

$$P = \frac{V^2}{R}$$

$$R = \frac{V^2}{P}$$

$$= \frac{220 \times 220}{60} = 806.67\ \Omega$$

(iii) Let Q be the amount of charge passing through the filament in 1 min.

$$I = \frac{Q}{t}$$

$$Q = I t$$

$$= 0.27 \times 60 = 16.2 \text{ C}$$

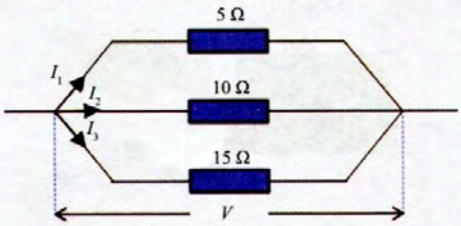
(iv) Let H be the amount of heat generated in 1 min.

$$H = \frac{V I t}{J}$$

$$= \frac{P\,t}{J}$$

$$= \frac{60 \times 60}{4.2} = 857.14 \text{ cal}$$

Example 10.9 One 5 Ω, one 10 Ω and one 15 Ω resistors are connected in parallel. If each resistor has an electrical power rating of 0.5 W, find the maximum potential difference which may be supplied to the parallel combination and the current in each resistor.



Since, the resistors are connected in parallel the potential difference across each resistor is the same. The electrical power dissipated in the 5 Ω resistor (minimum resistance) would be maximum according to $P = \frac{V^2}{R}$. Therefore, the 5 Ω resistor must be used to find the maximum potential difference.

$$0.5 = \frac{V^2}{5}$$

$$V = 1.58\ V$$

The current in the 5 Ω resistor, $I_1 = \frac{V}{R_1}$

$$= \frac{1.58}{5} = 0.32 \text{ A}$$

The current in the 10 Ω resistor, $I_2 = \frac{V}{R_2}$

$$= \frac{1.58}{10} = 0.16 \text{ A}$$

The current in the 15 Ω resistor, $I_3 = \frac{V}{R_3}$

$$= \frac{1.58}{15} = 0.11 \text{ A}$$

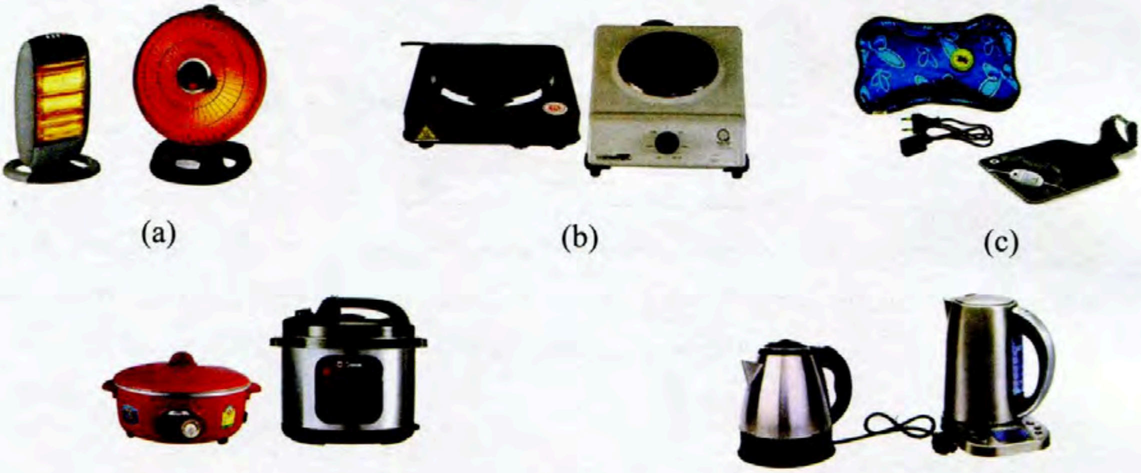
Reviewed Exercise

1. On which factors does the heat produced in a current carrying conductor depend?
2. An electric stove of 1200 W is connected to a 220 V mains line. (i) Find its resistance. (ii) Find the current flowing through it. (iii) Find the amount of calories produced in one second by it. (iv) Find the electrical power produced by it when the voltage of the mains line drops to 180 V.

Key Words: electrical energy, heat energy, Joule's mechanical equivalent of heat, power rating

10.5 SOME APPLICATIONS OF THE HEATING EFFECT OF CURRENT

Electrical energy can be transformed into a wide variety of other useful forms of energy. In general, most of the electrical energy supplied to a resistor in an electric circuit is converted into heat. The heating effect of electric current has special applications in domestic appliances. For example, electric stoves, electric cookers, electric irons, electric kettle, electric heaters and electric heating bag as shown in Figure 10.10. They change electrical energy into heat energy.



(a) (b) (c) (d) (e)

Figure 10.10 Domestic electrical appliances (a) electric heater (b) electric stove (c) electric heating bag (d) electric cooker (e) electric kettle

Some electrical appliances which use the heating effect of current are described below.

Light bulb

An electric light bulb is made of a glass bulb consisting a tungsten filament which has high melting point (~3000 °C) as shown in Figure 10.11. A small amount of argon, an inert gas, is added after the air is removed. The tungsten filament becomes hot when a current flows through it. At a temperature of 1800 °C it emits white light. Since the inert gas is added the light bulb can be used safely up to the temperature 2500 °C. The inert gas also reduces evaporation of the filament. The electric light bulb converts most of the electrical energy into heat and light energy.

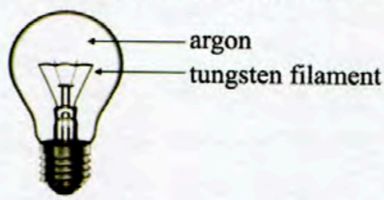


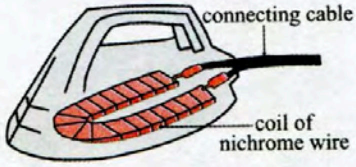
Figure 10.11 Tungsten filament lamp

Electric light bulbs are various sizes and electrical power. A small light bulb used in a torch has a few watts and the bulbs used for illuminating airfields have electrical power of the order of 5000 W. The voltage and the power of a simple light bulb are usually specified as 220 V, 60 W etc.

Electric Iron

Figure 10.12 shows an electric iron. A mica sheet is wound around the nichrome wire and is inserted between two other mica sheets. Mica is a good electrical insulator and can withstand very high temperature. The combination is then placed on a heavy metal plate and is sandwiched with another metal plate. When a current flows through the nichrome wire it produces heat energy. The heating element is controlled by a thermostat that switches the current on and off to maintain the selected temperature. The position of the nichrome wire in the electric iron is shown in Figure 10.12 (b). An electric iron has an electric power of 750-1000 W.

(a)



(b)

Figure 10.12 Electric iron

Electric stove

In an electric stove, a coil of nichrome wire is placed in the groove of the heat-resistant material as shown in Figure 10.13. When a current flows through the nichrome coil, it produces heat energy. An electric stove has an electrical power ranging from 600 W to 2000 W.

Figure 10.13 Electric stove

The electrical power of some electrical appliance used in homes are given in Table 10.1.

Table 10.1 The electrical power of some electrical appliance used in homes

Electrical Appliance	Electrical Power (W)
Laptop computer	15 -45
Reading lamp	40 -100
Refrigerator	100 -250
Radio and television receiver	~ 150
Electric iron	750 -1000
Electric stove	~ 1200

Fuse

A fuse is a thin short wire of tin-lead alloy which is used in electric circuits to prevent electrical appliances from being damage if excessive current flows through them. The fuse wire is fitted in a glass tube (cartridge) or on a porcelain block as shown in Figure 10.14. For example, a 3 A fuse is used in the electric circuit. When a current greater than 3 A flows in the circuit, the fuse becomes so hot that it will melt and break the circuit. Thus, the current stops flowing and electrical appliance in the circuit is not damaged. For an appliance rated as 700 W or less, a 3 A fuse should be fitted. For appliances above 700 W, a 13 A fuse should be fitted.

Figure 10.14 Fuses

Example 10.10 A 3 A fuse is used in a circuit which contains a source of 220 V. Find the maximum power which can safely be consumed.

$V = 220$ V, $I = 3$ A

Let P be the maximum power which can safely be consumed.

$$P = VI$$
$$= 220 \times 3 = 660 \text{ W}$$

Reviewed Exercise

1. An electric circuit installed in a house contains a 5 A fuse and the voltage is 220 V. Can twenty 60 W electric lamps be used at the same time in that current?
2. What should the rating of the fuse be used for an electric stove of 1200 W, 220 V?

Key Words: heating effect, electrical appliances, tungsten filament, nichrome wire, mica, fuse

SUMMARY

Electromotive force, abbreviated as emf is the amount of energy, provided by the battery, per unit charge to move round the complete circuit.

The potential difference across the terminals of a battery connected to an external circuit is called the **terminal voltage** (or **available voltage**) of the battery.

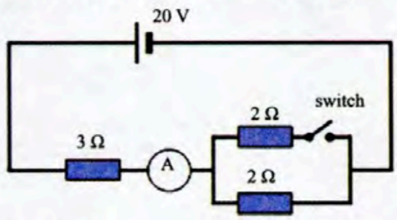
Electrical energy is energy associated with the flow of charge through any part of circuit. **Electrical power** is the rate of transfer of electrical energy.

Joule's law stated as the amount of heat produced in a resistor due to a current flowing through it is directly proportional to the square of the current, the value of resistance and the time taken by the current to pass through the resistor.

A fuse is a thin short wire of tin-lead alloy which is used in electric circuits to prevent electrical appliances from being damage if excessive current flows through them.

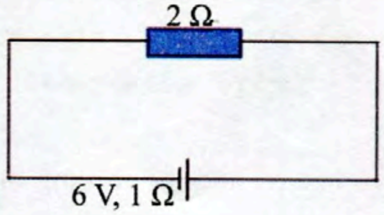
EXERCISES

1. How is electricity produced by an electric cell?
2. In an electric circuit, which component is used for (i) supply electricity, (ii) close (or) open the electric circuit, (iii) providing a path for the flow of electric current?
3. Can the terminal voltage of a battery ever exceed its emf? If so, explain the necessary condition.
4. In the electric circuit shown below, find the reading of the ammeter A when the switch is (i) open (ii) closed. (Neglect the internal resistance of the battery.)

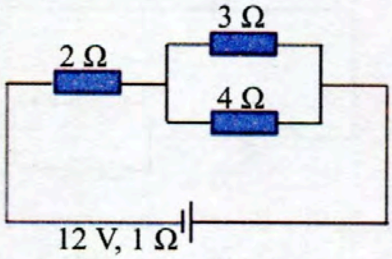


5. When a 12 V battery of negligible internal resistance is connected to a resistor, a current of 3 A flows through it. When another battery of emf 6 V is in the circuit in series with the first one, the current flowing through the resistor remains at 3 A. Find the internal resistance of the second battery.
6. When two 6 V batteries, having the same internal resistance and connected in series, are connected to a 5 Ω resistor, the current in the circuit is 2 A. When these batteries are in parallel, a current of 1.5 A flows through when connected to another resistor. Find the resistance of the resistor.
7. With two identical batteries, how would you arrange the bulbs and batteries in a circuit to get the maximum possible total power out? (Assume the batteries have negligible internal resistance.)
8. What is electrical energy? Express its unit.
9. (i) Define electrical power. (ii) Write down the unit of electrical power. (iii) How many joules are there in 1 kWh?
10. Why do we use fuses in an electric circuit?
11. Two heaters of the same power and the same resistance are used to heat the water. In which of the following cases will the water heat up faster? (i) if heaters are connected in series (ii) if heaters are connected in parallel.
12. Which draws more current, a 100 W light bulb or a 75 W light bulb when connected to a main line? Which has higher resistance?

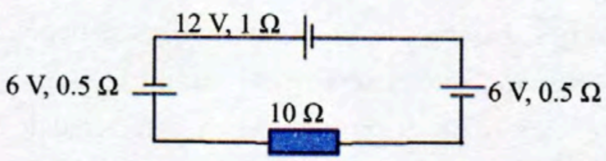
13. State the Joule's law of electricity and heat.
14. Why is electrical energy transformed into heat energy when a current flows through a resistor?
15. An electric iron draws a current of 3 A when it is connected to a 220 V mains line. How many kcal of heat are produced per min?
16. Find the amount of calories produced per second by a 2 Ω resistor in the circuit diagram shown below.



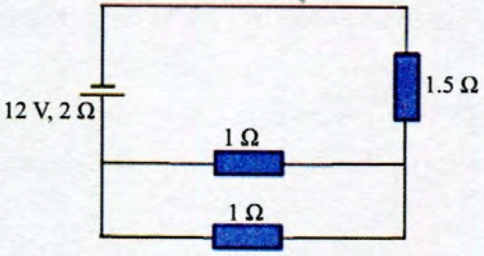
17. Find the rate of production of heat by the equivalent resistance of resistors in the circuit diagram shown below.



18. Find the amount of heat produced in 10 min by a 10 Ω resistor in the circuit diagram shown below.



19. Find the rate of production of heat in the battery in the circuit diagram shown below.



20. Which of the following metals cannot be used as fuse wire?
A. iron B. silver C. tin-lead alloy
21. Why should the material used for fuse have low melting point?
22. An electric circuit installed in a house contains a 5 A fuse and the voltage is 220 V. Find the maximum electrical power which can safely be used.

23. An electric circuit installed in an office contains a 10 A fuse and the voltage is 220 V. Ten 100 W electric lamps and two 150 W refrigerators are being used there. (i) Find the cost of using all the lamps and two refrigerators for 10 h. (ii) Find the maximum number of 60 W electric lamps which can be safely used in addition. (Assume that electricity costs 50 kyats per unit.)

CONCEPT MAP

ELECTRICAL ENERGY, POWER AND HEATING EFFECT OF ELECTRIC CURRENT

Electromotive Force (emf)

$$I = \frac{E}{R + r}$$

Batteries in series and in parallel

- batteries in series aiding

$$I = \frac{E_1 + E_2}{R + r_1 + r_2}$$

- batteries in series opposing ($E_1 > E_2$)

$$I = \frac{E_1 - E_2}{R + r_1 + r_2}$$

- batteries in parallel

$$I = \frac{E}{R + \frac{r}{2}}$$

Electrical Energy and Electrical Power

- electrical energy

$$W = VIt = I^2Rt = \frac{V^2}{R}t$$

- electrical power

$$P = VI = I^2R = \frac{V^2}{R}$$

Joule's law of electricity and heat

$$W = JH$$

$$H = \frac{I^2Rt}{J}$$

Some applications of the heating effect of current

- light bulb
- electric iron
- electric stove
- fuse

CHAPTER 11

ELECTROMAGNETIC INDUCTION, GENERATION AND DISTRIBUTION OF ELECTRICITY

A changing magnetic field could produce a current. The discovery was made in 1831 by Michael Faraday and Joseph Henry working independently at the same time. The effect is called electromagnetic induction and it is the physics behind the generators that provide the electricity used in our modern society.

Learning Outcomes

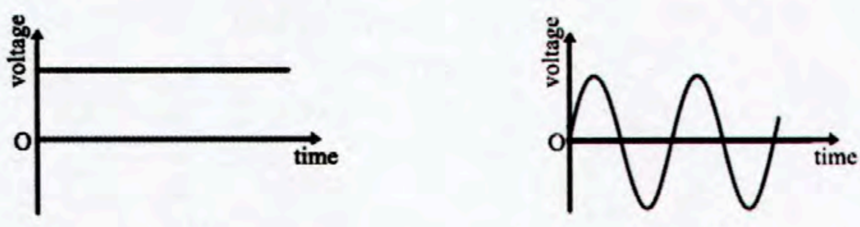
It is expected that students will

- identify two types of electric current.
- investigate electromagnetic induction and its applications.
- understand the generation and distribution of electricity.
- describe the principles of house wiring and explain the dangers associated with electricity.

11.1 ALTERNATING CURRENT

Electric current can be classified as two types: direct current (DC) and alternating current (AC). The direct current is a steady unidirectional current. In a direct current the electrons flow steadily in the same direction all the time. The current that flows in a flashlight, cell phones, laptops, and any appliance running on the batteries is direct current.

Another type of current is of great industrial important. This is the alternating current. An alternating current is a current that reverses its direction at regular time intervals. In the alternating current the direction of the flow of electrons changes periodically. Current flowing in power lines and normal household electricity from a wall outlet (plug) is alternating current. In Japan and in the most of America, the voltage is between 100 V and 120 V, whereas Europe and most other countries in the world (including Myanmar) use a voltage between 220 V and 240 V. The frequency of AC current is 50 Hz/60 Hz in Japan, 60 Hz in US and 50 Hz in Europe and most other parts of the world.



(a) (b)

Figure 11.1 Graphical representations of the magnitude of (a) DC (b) AC voltages as a function of time

Figure 11.1 shows the graphical representations of the magnitude of DC and AC voltages as a function of time.

The method of production of an alternating current is described below. When a coil of wire having quite a few turns is rotated a few cycles per second continuously in a magnetic field, an emf is induced in the coil as shown in Figure 11.2. When a galvanometer is connected across the ends of the rotating coil, the galvanometer will show a peculiar result. In each revolution the current produced in the coil due to the induced emf, rises to a maximum value, then falls to zero, reverses, rises to a maximum and falls to zero again.

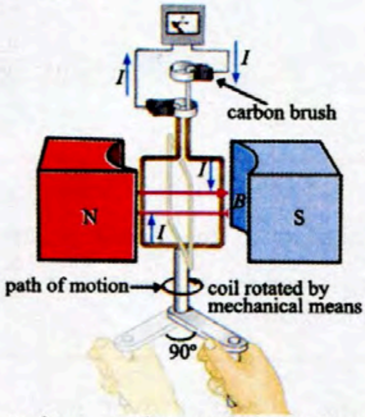


Figure 11.2 Generating an alternating current in a rotating coil

As the coil continues to rotate, this sequence of changes occurs in a periodic manner. The current having this characteristics is, in fact, the alternating current, called induced current. The induced emf also shows such periodic variation. Variation of induced emf is shown in Figure 11.3 for one complete rotation of the coil.

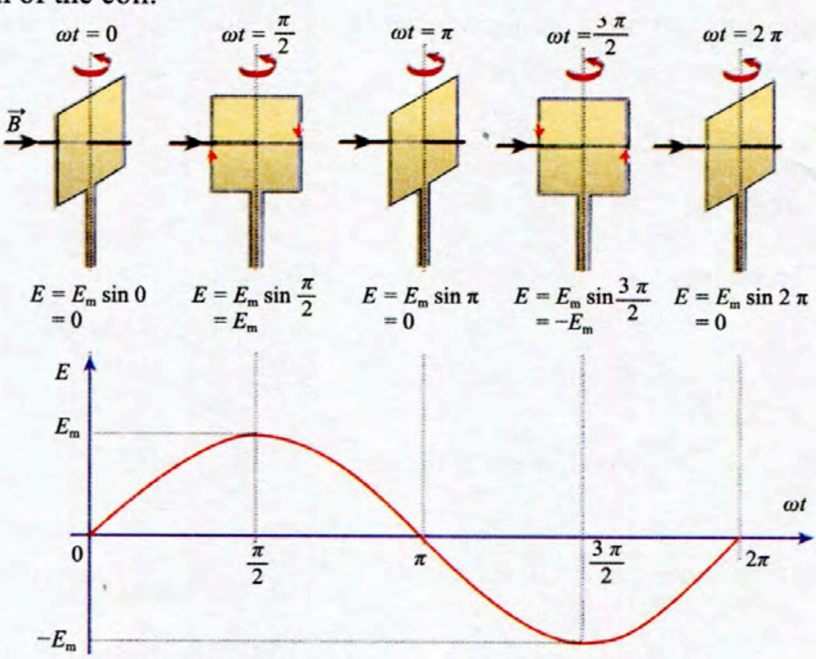


Figure 11.3 Variation of induced emf as a function of ωt

The waveform of the emf shown in Figure 11.3 is called a sine wave. It is represented by

$$E = E_m \sin \omega t \qquad (11.1)$$

where E is the induced emf at a particular instant, E_m is the maximum value of emf and ω is the angular velocity of the rotating coil.

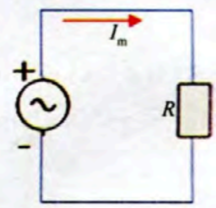
The angular velocity ω is equal to $2\pi f$, where f is the frequency of the emf, (i.e. the number of complete cycles generated in 1 s). Therefore, a rotating coil in a magnetic field is the basic of an AC generator (a device for generating alternating current). The magnitude of an alternating current at any instant varies precisely the same way as shown by Eq. (11.1) and is given by

$$I = I_m \sin \omega t \qquad (11.2)$$

The alternating current is universally used for household lighting, heating, cooking and other domestic functions.

The advantage of alternating current is that it is relatively easy to change the voltage of the current. Furthermore, the inevitable loss of energy that occurs when current is distributed over long distances is far smaller with alternating current (at high voltage and low current) than with direct current.

Example 11.1 An AC generator has an output given by $E = 150 \sin 377\, t$. (i) Find the maximum emf output, the frequency of the source, and the emf at $t = 1/120$ s. (ii) Find the maximum current in the circuit when generator is connected to a 50 Ω resistor in the figure.



$E = 150 \sin 377\, t$

By comparing the expression of the emf produced by a generator $E = E_m \sin \omega t$.

$E_m = 150$ V, $\omega = 377 \text{ rad s}^{-1} = 120\pi \text{ rad s}^{-1}$

(i) The maximum emf output $E_m = 150$ V

Angular frequency $\omega = 2\pi f$

Frequency $f = \dfrac{\omega}{2\pi} = \dfrac{120\pi}{2\pi} = 60$ Hz

The emf at $t = \dfrac{1}{120}$ s, $E = 150 \sin 377\, t$

$$= 150 \sin 120\pi \times \frac{1}{120} = 150 \sin \pi = 0$$

(ii) $R = 50\ \Omega$, The maximum current in the circuit $I_m = \dfrac{E_m}{R}$

$$= \frac{\mathbf{150}}{\mathbf{50}} = 3 \text{ A}$$

Example 11.2 The current in an AC circuit at any time t seconds is given by $I = 20 \sin(100\pi t)$ A. Find (i) the peak value (maximum value) of current, the period and the frequency (ii) the value of the current when t = 0 (iii) the value of the current when t = 8 ms and (iv) the time when the current reaches 10 A.

By comparing the expression of $I = I_m \sin \omega t$.

$$I = 20 \sin(100\pi t)$$

(i) Peak value $I_m = 20$ A, $\omega = 100\pi$

$$\text{Period} \quad T = \frac{2\pi}{\omega} = \frac{2\pi}{100\pi} = 0.02 \text{ s} = 20 \text{ ms}$$

$$\text{Frequency} \quad f = \frac{1}{T} = \frac{1}{0.02} = 50 \text{ Hz}$$

(ii) When $t = 0$, $\quad I = 20 \sin(0) = 0$

(iii) When $t = 8$ ms, $\quad I = 20 \sin[100\pi(0.008)]$

$$= 11.76 \text{ A}$$

(iv) When $I = 10$ A, $\quad 10 = 20 \sin(100\pi t)$

$$0.5 = \sin(100\pi t)$$

$$t = 0.0017 \text{ s} = 1.7 \text{ ms}$$

Reviewed Exercise

1. What is the major difference between AC and DC current?
2. Why AC current is better than DC in long distance distribution of electrical power?
3. Is the current from the outlet of telephone charger, AC or DC?

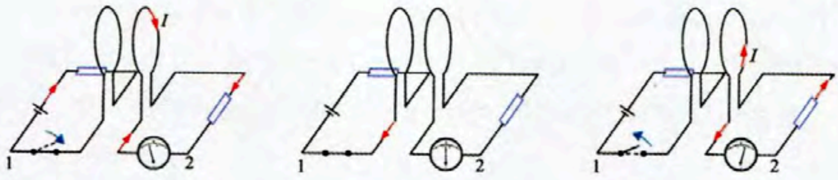
Key Words: direct current, alternating current, flow of electrons, induced emf, waveform, angular velocity, frequency, angular frequency

11.2 ELECTROMAGNETIC INDUCTION

Faraday's Experiments of Induced Current

In 1831, Joseph Henry and Michael Faraday independently discovered the methods of producing electric current from magnetic field. Faraday's experiments are described below.

The first wire loop is connected to a battery through a switch and the second wire loop is connected to a galvanometer as shown in Figure 11.4. As soon as the switch is closed, a current flows through the first loop and the galvanometer gives a brief deflection as shown in Figure 11.4 (a). That is, a momentary current flows through the second loop. When the switch is kept closed as shown in Figure 11.4 (b), the galvanometer shows no deflection (there is no induced current in the second loop). However, when the switch is opened again, the galvanometer shows the brief deflection in the other direction as shown in Figure 11.4 (c), which indicates that the induced current flows in the opposite direction.



(a) (b) (c)

Figure 11.4 Induced current produced by a wire loop carrying current

Again, a momentary current flows through the second loop (Q) when the first loop (P) carrying a current is moved abruptly towards or away from the second loop as shown in Figure 11.5.

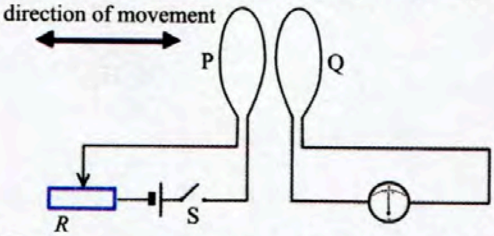


Figure 11.5 Induced current produced by a moving coil carrying current

Moreover, the same thing happens when a magnet, instead of the current-carrying first loop, is moved abruptly towards or away from the second loop as shown in Figure 11.6.

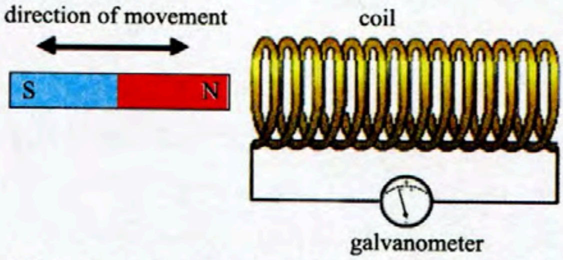


Figure 11.6 Induced current produced by a moving magnet

In the above experiments, switching the current in the first loop ON and OFF (or) the motion of the current-carrying loop (or) the motion of the magnet; all causes a change in the magnetic lines of force through the second loop and causes a momentary current to flow through it.

That is, a current flows through a loop of wire whenever there is a change in the magnetic lines of force through the loop. This phenomenon is called electromagnetic induction. As mentioned above, this current is called an induced current and the electromotive force (emf) which causes the induced current to flow is called an induced emf.

Magnetic Flux Density and Magnetic Flux

The magnetic flux density or magnetic induction B is the number of magnetic lines of force passing perpendicularly through a unit area of material. Magnetic flux density B is related to magnetic field strength (magnetic field intensity) H by

$$B = \mu H \qquad (11.3)$$

where μ is the permeability of the medium in which the magnetic field exists. The permeability of free space (vacuum) $\mu_0 = 4\pi \times 10^{-7}$ H m^{-1} = 1.257×10^{-6} H m^{-1}.

The SI unit of magnetic flux density is tesla (T) which is equivalent to weber per metre squared (Wb m^{-2}).

Magnetic flux ϕ_B is a measurement of the total magnetic lines of force which passes through a surface area. In electromagnetism, the magnetic flux through a surface is the surface integral of the normal component of the magnetic field B over that surface.

$$\phi_B = \int \vec{B} \cdot d\vec{A} \qquad (11.4)$$

where $d\vec{A}$ is the elemental surface area.

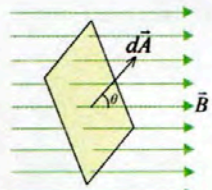
If the magnetic field is uniform over a plane area A, the magnetic flux ϕ_B passing through that area A is simply

$$\phi_B = \int \vec{B} \cdot d\vec{A} = \int B \cos\theta \, dA = B \cos\theta \int dA$$

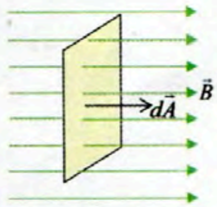
$$\phi_B = B A \cos\theta \qquad (11.5)$$

where θ is the angle between the magnetic field $\vec{B}$ and $d\vec{A}$.

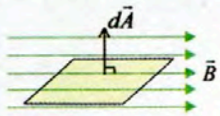
When the field is subtended an angle θ to the surface area, $\phi_B = B A \cos\theta$.



When the field is perpendicular to the surface area, $\theta = 0°$.
Hence, $\phi_B = B A \cos 0° = B A$



When the field is parallel to the surface area, $\theta = 90°$.
Hence, $\phi_B = B A \cos 90° = 0$ as shown in figure.



The SI unit of magnetic flux is the weber (Wb). The weber is named after the German physicist Wilhelm Eduard Weber (1804-1891). 1 Wb = 1 V s = 1 kg m^2 s^{-2} A^{-1}. Table 11.1 shows the SI units of magnetic parameters.

Table 11.1 The SI unit of B, H, ϕ

Quantity	SI unit
Magnetic flux density B	tesla (T)
Magnetic field strength H	ampere per metre (A m^{-1})
Magnetic flux ϕ	weber (Wb)

Magnetic field strength and magnetic flux density are vector quantities whereas magnetic flux is a scalar quantity.

Example 11.3 A square loop of wire 10 cm on a side is in a magnetic field of 1.25 T. What are the maximum and minimum values of flux that can pass through the loop?

Area of square loop $A = 10 \times 10 = 100\ \text{cm}^2 = 0.01\ \text{m}^2$

The magnetic flux passing through the area A is $\phi_B = B A \cos\theta$

When the plane of loop is perpendicular to $\vec{B}$, it is a maximum for $\theta = 0°$.

$$\phi_B = B A \cos 0° = 1.25 \times 0.01 \times 1 = 0.0125\ \text{Wb}$$

When the plane of loop is aligned with $\vec{B}$, the minimum value occurs for $\theta = 90°$.

$$\phi_B = B A \cos 90° = 0$$

Reviewed Exercise

- Differentiate between the magnetic flux and magnetic flux density.

Key Words: electromagnetic induction, induced current, induced emf, magnetic flux, magnetic flux density

11.3 FARADAY'S LAW AND LENZ'S LAW

Faraday's Law

In Faraday's experiments mentioned above, the change in magnetic flux through a wire loop produces an induced emf. Based on these experiments, Michael Faraday (1831) discovered the law of electromagnetic induction stated as below.

The magnitude of induced emf in a wire loop is directly proportional to the rate of change of magnetic flux through that loop.

For one turn of a wire loop, induced emf is

$$E = -\frac{d\,\phi_B}{d\,t}$$

For a wire loop with N identical turns,

$$E = -N\frac{d\,\phi_B}{d\,t} \qquad (11.6)$$

In the above equation, the minus sign gives the direction of the induced emf.

If the wire loop is not moving (or) is moving parallel to the magnetic field lines, there is no induced emf (or) induced current.

Lenz's Law

Faraday's law gives the magnitude of the induced emf and Lenz's law gives its direction. In 1834, the Russian physicist Heinrich Friedrich Emil Lenz stated a law as follows.

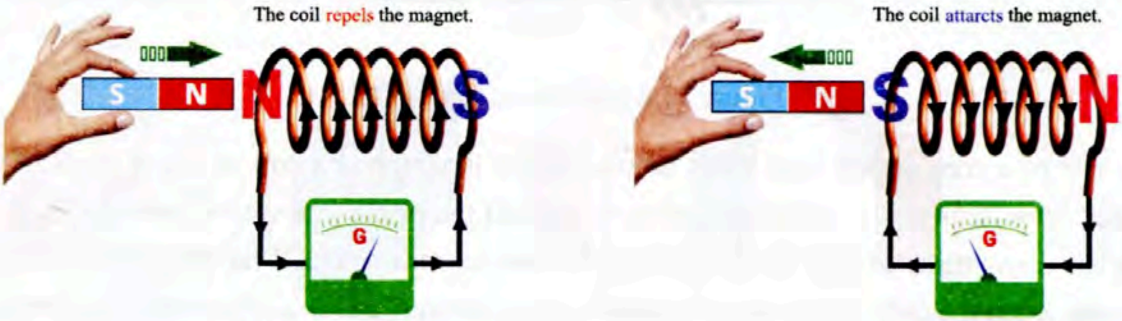
An induced emf is always in a direction that opposes the change in the original magnetic flux that causes it.

The direction of induced current can be found by applying Lenz's law. The change in magnetic flux is, in fact, a decrease or an increase in the magnetic lines of force.

Lenz's law is a good example of the principle of conservation of energy. It shows how the energy from the mechanical work done against the opposing force experienced by the moving magnet or rotating coil is transformed into electrical energy.

In Figure 11.7 (a), when a magnet is moved towards the coil, the magnetic flux through the coil increases. The induced current in the coil must produce a magnetic field which opposes an increase in the original magnetic flux. This means that the direction of the magnetic field produced by the induced current must be towards the magnet. In order to be so the end of the coil nearer the magnet must act as a north pole. Therefore, the current in the coil must be flowing in a counter clockwise direction if viewed from the magnet according to right-hand rule.

If the magnet is moved away from the coil the induced current will flow in the opposite direction as shown in Figure 11.7(b). The direction of the induced current can be found as explained above.



(a) (b)

Figure 11.7 (a) When N pole of the magnet is moved towards the coil, the induced current flows in the counter clockwise direction.

(b) When N pole of the magnet is moved away from the coil, the induced current flows in the clockwise direction if viewed from the magnet.

Reviewed Exercise

1. Why is Faraday's law important?
   (Hint: how changing magnetic fields can cause the flow of current in wires.)
2. What does negative sign indicate in Faraday's law of electromagnetic induction formula?

Key Words: magnetic flux, magnetic lines of force, induced current, induced emf

11.4 APPLICATIONS OF ELECTROMAGNETIC INDUCTION

1. Induction Coil

One of the useful applications of electromagnetic induction is an induction coil. In 1851, a German instrument maker named Heinrich Ruhmkorff showed how an electric spark 30 cm long could be produced by using a battery of only a few volts. The apparatus he used is called an induction coil or Ruhmkorff spark coil. The construction of an induction coil is shown in Figure 11.8.

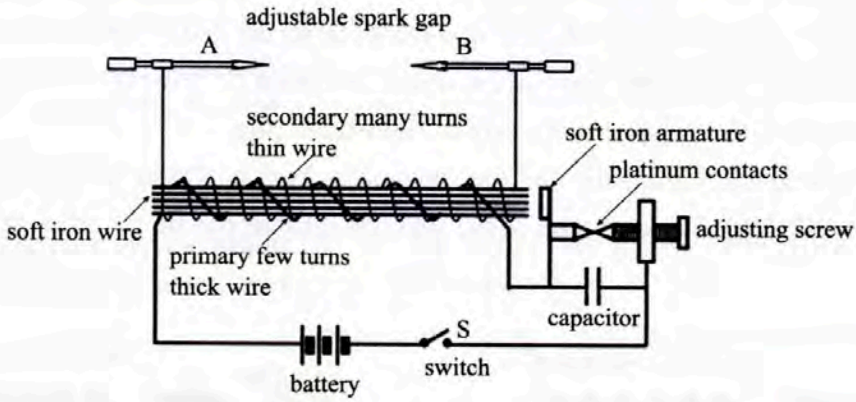


Figure 11.8 Induction (spark) coil

It consists of a core of soft iron wires around which is wrapped a coil of a few turns of thick insulated wire. This coil is called the primary. Around the primary is wound the secondary coil, which has many turns of thin insulated wire. Two metal rods A and B having insulated handles are connected to the ends of the secondary. The gap between A and B is adjustable. The primary is connected to a battery.

When the switch S is pressed a current flows through the primary. As soon as the current flows in the primary an induced emf develops in every turn of the secondary. Since the secondary consists of many turns, the induced emf is very high indeed.

As the current flows through the primary, the soft iron core becomes an electromagnet which attracts a soft iron armature mounted on the spring. When this happens, the platinum contacts are separated and hence the current stops flowing. As soon as the current stops flowing, very high induced emf develops in the secondary again.

Since there is no current in the primary, the soft iron core becomes demagnetized. At that moment the armature is returned by the spring to its original position. The contact is remade again and the whole process is repeated. When the primary is connected to a 6 V battery a voltage of about 30 000 V can develop across the terminals A and B. When the terminal of A and B are kept a small distance apart, sparks are formed between them. A capacitor is connected across the platinum contacts to prevent sparking and wearing away of contacts.

The induction coil is used in the ignition system of motor cars. The primary of an induction coil is connected to a 6 V or 12 V battery and the secondary is connected to a sparking plug. As a very high voltage is set up between the two terminals of the plug, sparking occurs and the mixture of gases is ignited.

2. AC Generator

A generator is an electromagnetic device which converts mechanical energy into electrical energy. Most generators give out alternating current. AC generators are also called alternators.

AC generators work on the principle of Faraday's law of electromagnetic induction. A simple AC generator is shown in Figure 11.9 (a). It consists of a rectangular coil mounted on an axle which is fixed between the poles of a permanent magnet. When the coil is rotated, the magnetic field through it changes. This induces a current in the coil. Using Fleming's right-hand rule, the induced current flows from A to B, and C to D in the coil.

This induced current flows through the two slip rings (S_1 and S_2) and then through the external load from P to Q as shown in Figure 11.9 (b). The two slip rings (S_1 and S_2) each make sliding contact with two fixed carbon brushes (B_1 and B_2), respectively.

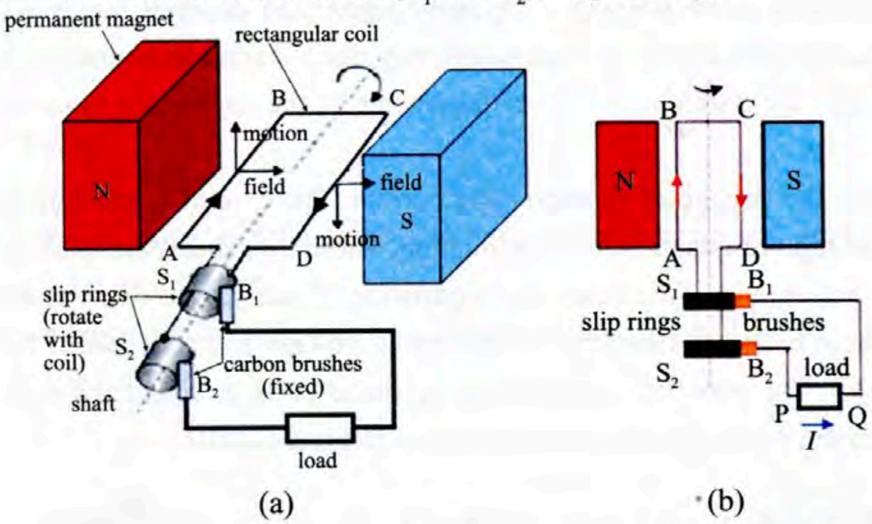


Figure 11.9 The working principle of an AC generator

When the coil has rotated through 180° the sides of the coil will have changed places. Now the current flows from B to A and D to C in the coil, and from Q to P in the external load as shown in Figure 11.9 (c). Every time the coil turns through 180° the current reverses its direction. This is an alternating current which changes its direction when the coil is vertical.

If the speed of rotating coil is doubled, both the frequency of the alternating current and the rate of cutting of the magnetic lines of force will be doubled. This means that the maximum output voltage is also doubled. When the number of turns in the coil is doubled, the frequency of the output voltage is the same although its magnitude is doubled.

The induced electromotive force of a generator can be increased by (i) increasing the speed of rotation of the coil, (ii) increasing the area, (iii) the number of turns in the coil, and (iv) using stronger magnets.

The shaft (axle) of the coil is rotated by an external force such as falling water or an engine. If the wire loop is rotating with a constant angular velocity ω, $\theta = \omega t$ and $\phi_B = B A \cos \omega t$.

The induced emf is $E = -\frac{d\phi_B}{dt} = -BA\frac{d}{dt}(\cos \omega t) = B A \omega \sin \omega t$

For a coil of N loops, $$E = N B A \omega \sin \omega t = E_m \sin \omega t \quad (11.7)$$

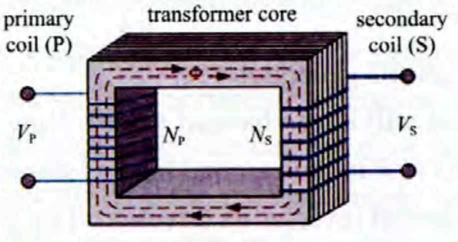
where $E_m = N B A \omega$.

There is no structural difference between a generator and an electric motor. The difference lies in the way energy is converted. In an electric motor, electrical energy is used to rotate the coil to provide mechanical energy. In the case of generators, mechanical energy is used to rotate the coil to produce electrical energy.

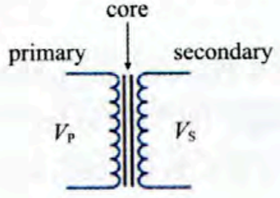
3. Transformer

One of the another useful application is the construction of transformers that are commonly used today. Different electrical appliances need different working voltages. The doorbell may work on a 6 V supply whereas a picture tube in old television sets may need several thousand volts. Transformers are used to provide the different voltage requirements of the appliances from the mains supply.

A transformer is used to change the voltage of an alternating current. The core of a transformer is built up of thin iron sheets of high resistance, called lamination. These iron sheets are made to be electrically insulated from one another. Two coils, each consisting of many turns of wire, are wound on the core. One of these coils connected to an alternating voltage source is called the primary coil and is denoted by P. The other coil S, called the secondary coil, is connected to an electrical device to which electrical power to be supplied as shown in Figure 11.10.



(a)



(b)

(c)

Figure 11.10 (a) Simple transformer (b) its symbol (c) actual photograph of a transformer

When an alternating voltage is applied to the primary P, an alternating current flows through it. The alternating current in the primary produces an alternating magnetic flux in the core and nearly all the flux passes through the secondary S. This changing magnetic flux produces an induced emf and an induced current in the secondary. Hence, an alternating voltage is obtained from the secondary. The voltage in the secondary and the voltage in the primary have the same frequency.

The use of laminated iron (mumetal) core is to minimize the power loss due to the induced current flowing in the core. There is also a power loss due to heating of wire used in the coils when the current flows through them. In a systematically constructed transformer, the power losses are so small that the power input can be assumed to be equal to the power output.

Suppose that V_p is the voltage applied to the primary, and V_s is the voltage obtained from the secondary. If I_p is the current flowing in the primary, and I_s is that flowing in the secondary, then

power input = power output

$$V_p I_p = V_s I_s \qquad \text{(i)}$$

As the product of voltage and current is the same on both coils of a transformer, it follows that a transformer which increases the voltage will reduce the current in the same proportion, and vice versa.

Suppose that E_p and E_s are the induced emfs in the primary and secondary, respectively. Since the same magnetic flux passes through both the primary and secondary windings in an ideal transformer, the emf in each coil is proportional to the number of turns in the coil.

Hence,

$$\frac{E_S}{E_P} = \frac{N_S}{N_P} \qquad \text{(ii)}$$

where N_p and N_s are the number of turns in the primary and secondary, respectively, and $\frac{N_S}{N_P}$ is called the turns ratio.

In an ideal transformer, with no power losses, $E_p = V_p$ and $E_s = V_s$. Therefore, combining equations (i) and (ii)

$$\frac{E_S}{E_P} = \frac{V_S}{V_P} = \frac{N_S}{N_P} = \frac{I_P}{I_S} \qquad (11.8)$$

From the above equation, $V_s > V_p$ when $N_s > N_p$. If the secondary has more turns than the primary, the voltage obtained from the secondary is greater than the voltage applied to the primary. Such a transformer is called a step-up transformer.

On the other hand, $V_s < V_p$ when $N_s < N_p$. If the secondary has fewer turns than the primary, the voltage obtained from the secondary is smaller than the voltage applied to the primary. Such a transformer is called a step-down transformer.

In a transformer, the changing magnetic field not only induces currents in the secondary coil, but also currents in the iron core itself. These currents flow in little circles in the iron core and are called eddy currents.

The efficiency of a transformer is the ratio of the output power to the input power as usual. Most of the transformers have full load efficiency from 95% to 98.5%. Because of power losses, there is no ideal transformer with 100% efficiency.

To improve the efficiency of a transformer, the following features should be taken into consideration.

- Soft magnetic material should be used to make the core.
- A laminated core should be used to reduce the flow of eddy current.
- A special core design should be used to ensure that the magnetic field from the primary coil completely links with the secondary coil.
- Low-resistance copper wires should be used as coils to reduce energy loss in the form of heat.

> Transformers work on AC, but not on DC. Unless there is a changing current in the input coil, no voltage is induced in the output coil.
> Note that, a transformer connected to a DC supply can be damaged as the high current flowed through the input coil can make it overheat.

Example 11.4 The generator coil with 200 turns is rotated through one-fourth of a revolution in 15 ms. The turn of circular coil has a 5 cm radius and is in a uniform magnetic field of 1.25 T. Find the induced emf in 15 ms.

$N = 200$, $t = 15\text{ ms} = 15 \times 10^{-3}\text{ s}$, $r = 5\text{ cm} = 0.05\text{ m}$, $B = 1.25\text{ T}$

Area of loop $A = \pi r^2 = 3.142 \times (0.05)^2 = 7.86 \times 10^{-3}\text{ m}^2$

Since the area of the loop and the magnetic field are constant, change in magnetic flux due to rotational angle from 0° to 90° (one-fourth of a revolution).

$$\phi = B A \cos\theta$$

The change in magnetic flux is

$$\Delta\phi = B A \Delta(\cos\theta)$$
$$= 1.25 \times 7.86 \times 10^{-3} \times (\cos 90° - \cos 0°) = -\ 0.0098\text{ Wb}$$

The induced emf $\quad E = -N\dfrac{\Delta\phi_B}{\Delta t}$

$$= -\ 200 \times \frac{(-0.0098)}{15 \times 10^{-3}} = 130.7\text{ V}$$

Example 11.5 A step-down transformer is used to light a 12 V, 24 W lamp from the 240 V mains. The current through the primary is 125 mA. What is the efficiency of the transformer?

$V_p = 240\text{ V}$, $V_s = 12\text{ V}$, output power $P_{out} = 24\text{ W}$, $I_p = 125\text{ mA} = 0.125\text{ A}$

Input power $P_{in} = V_p I_p$

$$= 240 \times 0.125 = 30\text{ W}$$

$$\text{Efficiency} = \frac{\text{output power}}{\text{input power}} \times 100\ \%$$

$$= \frac{24}{30} \times 100\ \% = 80\ \%$$

Example 11.6 A 2 kW transformer is used to step down an AC supply of 240 V to 60 V. (i) What is the turns ratio of this transformer? (ii) What will the output current be if there is a 10 % power loss in the transformer? (iii) How large is the output current if there is no power loss (i.e. 100 % efficiency)?

$V_p = 240$ V, $V_s = 60$ V, input power $P_{in} = 2$ kW = 2000 W

(i) Turns ratio $$\frac{N_S}{N_P} = \frac{V_S}{V_P} = \frac{60}{240} = \frac{1}{4}$$

(ii) If there is a 10 % power loss,

$$\text{output power} = 90\ \%\ \text{of input power}$$

$$60 \times I_S = \frac{90}{100} \times 2000$$

$$I_S = \frac{90}{100} \times \frac{2000}{60} = 30\ \text{A}$$

The output current is 30 A if there is a 10 % power loss.

(iii) If there is no power loss,

$$\text{output power} = \text{input power}$$

$$V_s I_s = V_p I_p$$

$$60 \times I_s = 2000$$

$$I_s = 33.33\ \text{A}$$

The output current is 33.33 A if there is no power loss.

Reviewed Exercise

1. What devices must be used to deliver (i) thousands of voltage at the terminals of a sparking plug of motorcar engine using a 12 V battery (ii) 12 V AC from 220 V AC mains?
2. Explain each of the following: (i) A transformer will not work on DC. (ii) The core of a transformer needs to be laminated. (iii) If a transformer increases voltage, it reduces current.
3. (i) Which type of transformer must be used to change a high current and a low alternating voltage into a lower current and a higher alternating voltage? (ii) Which type of transformer must be used to change a low current and a high alternating voltage into a higher current and a lower alternating voltage? (iii) Which type of transformer is used in a welding machine? Why?

Key Words: induction coil, primary coil, secondary coil, lamination, mumetal, eddy current, step-down transformer, step-up transformer, turn ratio

11.5 POWER TRANSMISSION

The electricity generated at the power station is transmitted to the consumers through the power cables. For instance, a generator produces 10 MW of electrical power at 10 kV. The current supplied can be calculated as follows.

$$P = VI$$

Thus the current, $$I = \frac{P}{V} = \frac{10 \times 10^6}{10 \times 10^3} = 1000\ \text{A}$$

This is a large amount of current. If it is transmitted through the power cables, which may have a resistance of 1 ohm per kilometre, then the amount of electrical power lost as heat in 1 km of transmission line will be given by

$$\text{Power loss} = I^2 R = (1000)^2 \times 1 = 1\ \text{MW}$$

This is equivalent to almost 10 % of power generated at the power station. Power loss is one of the main problems in the long distance transmission of electricity.

One way to reduce power loss is to use very thick cables of low resistance. These cables would, however, be very heavy and uneconomical. A more practical way would be to reduce the magnitude of the transmission current by stepping up the voltage. In the above example, if the electrical power is transmitted at 20 kV, then

Transmission current, $$I = \frac{P}{V} = \frac{10 \times 10^6}{20 \times 10^3} = 500\ \text{A}$$

Hence, power loss per km $= I^2 R = (500)^2 \times 1 = 250\,000\ \text{W} = 250\ \text{kW}$

The power loss would only about 2.5 % of the power generated at the power station. When increased the voltage 10 kV to 20 kV at the power station, the power loss will be reduced to 4 times.

The national grid system is used to distribute electricity around the country. An advantage of the grid system is power stations in areas where the demand is low can be used to supply areas where the demand is high. First, an alternating current is generated at high voltage (e.g. 10 kV) from the power station. The voltage is then stepped up (e.g. 230 kV) for transmission and finally stepped down at the substations in stages (e.g. 66 kV, 22 kV, 11 kV, 6.6 kV, 440 V, 230 V) before it is used in factories and homes. This process can be carried out with the help of transformers. Power distribution through a grid system is illustrated in Figure 11.11.

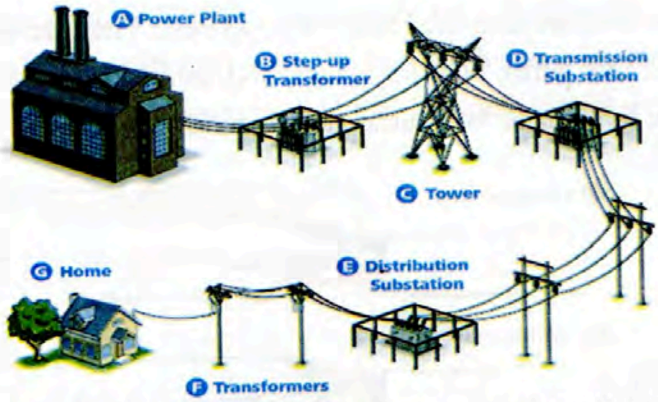


Figure 11.11 Illustration of electrical power distribution

Reviewed Exercise

- Explain why AC rather than DC is used for transmitting electrical power.

Key Words: electrical power, transmission, power loss, power cables, national grid system

11.6 PRINCIPLES OF HOUSE WIRING

Now we will study the proper way of using electricity in a home, that is house wiring system. Electricity supplied to the house is a single-phase form of alternating current (AC), carried by a thick cable which contains two wires which are well insulated from each other. One of these wires is the live wire (L) and the other is the neutral wire (N). The current enters the house through one wire and returns to the local substation through the other. The live wire (L) is a dangerous wire as it carries a high voltage while the neutral wire (N) is usually at zero volt.

The electricity is fed into the house through the main fuse, meter, main switch and then to the distribution box as shown in Figure 11.12. From the distribution box there are normally three circuits; namely the lighting circuit, the power circuit (ring main circuit) and heating circuit (e.g. cooker circuit) for high power cookers.

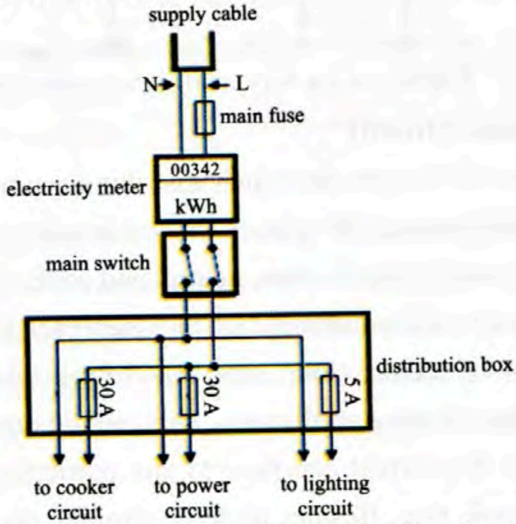


Figure 11.12 Electricity distribution in a house

Three cables (or conductors) are also used in a wiring system. They are colour coded with brown for live (L) (also called live wire), blue for neutral (N), striped green-yellow for earth (E). The old colour code: red for live, black for neutral and green for earth, is also still in use as shown in Figure 11.13.

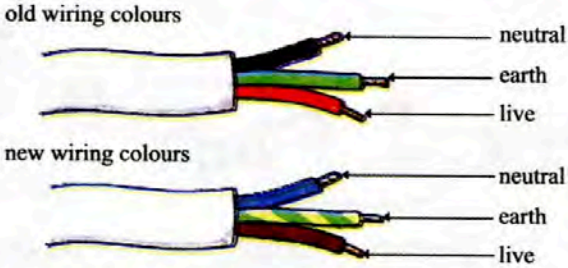


Figure 11.13 The colour coding of electrical wires.

1. Lighting Circuit

In the lighting circuit, the light bulbs are arranged in parallel across the mains line as shown in Figure 11.14. Each bulb has a potential difference of 240 V when connected to the mains line of 240 V. Since the bulbs are connected in parallel, the other bulbs are not affected when one bulb is switched ON or OFF. This means that the lighted bulbs continue to be ON no matter what is done the other bulbs. If the bulbs are connected in series switching OFF one bulb would switch OFF all the others. The lighting circuit differs from the other two in that there are only two wires, live and neutral. A lighting circuit must be connected sequentially as live wire, fuse, switch, load and then to neutral wire.

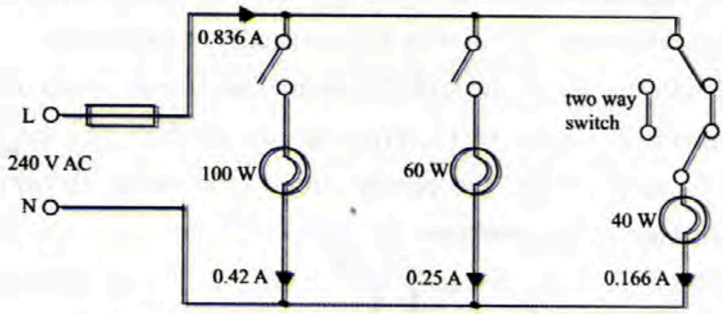
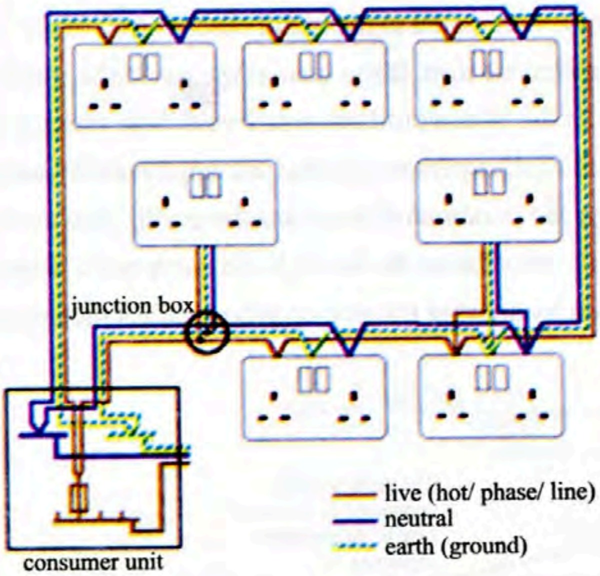


Figure 11.14 A typical lighting circuit

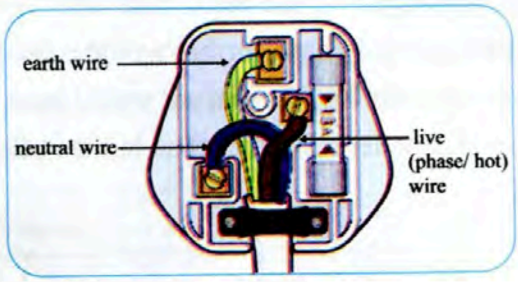
2. Power Circuit (Ring Main Circuit)

A power circuit is an electrical system in which distribution points are connected to the main supply in a continuous closed circuit. The power sockets in a house are connected by means of a ring main circuit. In a ring main circuit the live, neutral and earth wires form a loop of cable going from the consumer unit to all of the sockets in turn and then back to the consumer unit.

Power circuit is for the use of radios, computers, televisions, table lamps and other appliances that consume less power than heating appliances. This circuit supplies electricity to all the wall sockets in the house. Since the current can flow to any particular socket by two ways, thinner wires can be used in the whole ring. Besides both the live and neutral wires running a complete ring round the house, an earth wire (E) is also added for safety reasons. The power needed to domestic appliances can be taken off any part of the ring. Each main ring circuit also use a 30 A fuse. Three-pin sockets and three-pin plugs are used in the ring main circuit as shown in Figure 11.15.



(a)



(b)

Figure 11.15 (a) A ring main circuit with three-pin sockets (b) three-pin plug

3. Heating Circuit

Heating circuit is for the utilization of appliances such as electric cookers, ovens, hot plates, washing machines and dryers. Appliances connected in heating circuits use relatively large amounts of power so that they have their own circuits. Each fuse used in such a circuit is rated at 30 A.

Whatever the type of circuit uses, care must be taken not to be overloaded. And the fuse of each circuit must be connected in the live (L) lead and must never be in the neutral (N) lead. A fuse connected in the neutral lead is pointless; it will in no way protect the appliances used in the circuit.

4. Circuit Breaker

From the consumer unit or distribution box, the wires branch into several parallel circuits for the lights, cookers, immersion heater, and mains sockets. Each circuit passes through a fuse or a circuit breaker. A circuit breaker is an automatic switch which trips (turns OFF) when the current rises above the specified value. It can be reset by turning the switch ON (or) pressing a button.

5. Earthing

Earthing of an electrical appliance is the most important safety precaution. An earthing system (or) grounding system connects specific parts of an electric power system with the ground, typically the earth's conductive surface, for safety and functional purposes.

In any electrical appliance the earth wire is always connected to the metal case. Figure 11.16 shows the earth wire connected to the metal case of an electric iron. If the insulation inside the iron breaks down or the live wire becomes loose, the case of the iron would become live at high voltage of the mains supply. If the metal case were not earthed and a person touches the appliance by accident, a dangerously high current would pass through the person and then into the earth. However, with proper earthing, the current would pass directly into the earth through the earth wire, which has much smaller resistance than human being, thereby sparing the person who touches the appliance.

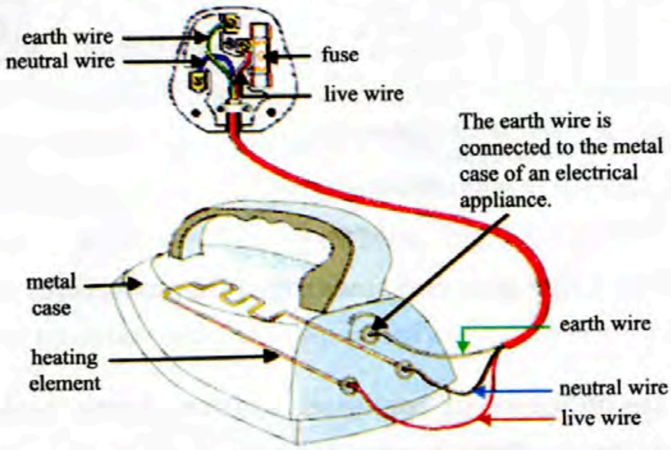


Figure 11.16 Earthing connection of an electric iron

Reviewed Exercise

1. Why are the lamps connected in parallel in the lighting circuit?
2. Why are the fuses and switches placed on the live wire of the circuit?
3. Mention the appropriate wiring circuit for the following electrical appliances (i) bulb and fluorescent lamp (ii) electric iron (iii) water pump motor (iv) electric stove.

Key Words: lighting circuit, ring main circuit, heating circuit, circuit breaker, distribution box, earthing

11.7 DANGERS OF ELECTRICITY

Although electricity plays a very important part in our daily life, it can also be very dangerous if improperly used. Electrical faults in appliances or circuits can cause fires, electric shocks, as well as electrocution to users. Either high current or high voltage can be dangerous to human. The dangers of electricity can be traced to three possible causes: damaged insulation, overheating of cables and damp conditions.

1. Damaged Insulation

All electrical appliances require two wires, the live and neutral wires to form a complete circuit. The live wire is the dangerous wire because it carries a high voltage while the neutral wire is close to zero voltage. These two wires are insulated in vulcanised rubber and they are housed together in either a circular PVC sheathed cable or a circular braided rubber-insulated cable.

Insulating materials deteriorate with time and use. For example, the electrical cables connecting the hair dryer and the electric iron are always bent and twisted because of the way the appliances are used. This will cause the electrical insulation to crack and break as shown in Figure 11.17, thus exposing the conducting wires inside. If the vulcanised rubber covering the live wire is also damaged, the exposed live wire can cause a severe electric shock to the user if the user touches it accidentally. This can lead to serious injury and even death.

Figure 11.17 Damaged insulation

2. Overheating of Cables

The overheating of cables is due to the extremely large current flowing in the conducting wires under certain conditions such as a short circuit or overloading. A short circuit can result when the live wire makes electrical contact with the neutral wire due to damaged insulation between them. This will produce a large current and the large amount of heat generated can melt the insulation, and start a fire.

Overuse of extension cords and multiple plug adapters on the same circuit are typical causes of an electrical overload by placing too much current on the circuit. Overload also occurs when an equipment draws an excess current from the supply which leads to overheating of the cables. Figure 11.18 shows a typical example of overloading by using too many plugs connected to the same power point.

Figure 11.18 Many plugs connected to the same power point

3. Damp Conditions

Many electrical accidents occur in damp conditions in a wet bathroom. In the event of damaged insulation or for any other reason that the live wire should be exposed, the person taking bath is exposed to the danger of electrocution. If water from the wet floor touches the live wire, it provides a conducting path for a large amount of current to flow through it and through the body of the person in the bath tub. The human body can only withstand up to about 50 mA but the current in this case is very much higher due to the sharp decrease in the resistance of the wet body. Other possible hazards include using hair dryers, electric irons or changing a light bulb with wet hands. Table 11.2 gives the possible physiological effects of an electric current passing through the body.

Table 11.2 Physiological effects of an electric current passing through the body

Current (approximately) (mA)	Effect
1	Threshold (no pain below this point)
5	A frightening but harmless shock
10 – 20	Uncontrolled muscular contractions
50	Pain and exhaustion (breathing affected)
100 – 300	Uncoordinated contraction of the heart leading to death

Since water can conduct electric current, one should never operate an electrical appliance with wet hands. Switches, plugs, sockets, connecting wires, etc. should always be in a dry condition.

Example 11.7 If an electrician accidentally touches a live wire of 220 V, what possible effect would he experience if his skin (i) were dry and had a resistance of 100 kΩ? (ii) were wet and had a resistance of 1000 Ω ?

$V = 220$ V

(i) If his skin were dry, resistance $R = 100\ \text{k}\Omega = 100 \times 10^3\ \Omega$

Current flow through the body $I = \dfrac{V}{R}$

$$= \frac{220}{100 \times 10^3} = 2.2\ \text{mA}$$

The electrician would experience a mild shock.

(ii) If his skin were wet , resistance $R = 1000\ \Omega$

Current flow through the body $I = \dfrac{V}{R}$

$$= \frac{220}{1000} = 220\ \text{mA}$$

The electrician would be electrocuted.

Reviewed Exercise

1. Which quantity determines whether you receive an electrical shock?
2. What causes by the overheating of cable?

Key Words: damaged insulation, overheating, damp conditions, electrocution

SUMMARY

A current flows through a loop of wire whenever there is a change in the magnetic lines of force through the loop. This phenomenon is called **electromagnetic induction**.

The voltage of **live wire** goes alternately negative and positive, making the current flow backwards and forwards through the circuit.

Neutral wire completes the circuit. It is kept at zero voltage by the electricity supply company.

Earth wire is a safety wire. It connects the metal body of the kettle to earth and stops it becoming live. If the live wire comes loose and touches the metal body, a current immediately flows to earth and blows the fuse. This means that the kettle is then safe to touch.

In a transformer, the changing magnetic field not only induces currents in the secondary coil, but also currents in the iron core itself. These currents flow in little circles in the iron core, and are called **eddy currents**.

EXERCISES

1. What is a transformer? How does a step-up transformer differ from a step-down transformer?
2. (i) What is electromagnetic induction? (ii) State the methods by which an induced emf can be produced in a coil.
3. Suggest any two ways to increase the output voltage of an AC generator.
4. In an AC generator, the speed at which the coil rotates is tripled. How would this affect (i) the frequency (ii) the maximum output voltage?
5. Explain how magnetic flux passing through a surface can be zero when the magnetic field is not zero.
6. Discuss the factors determining the induced emf in a closed loop of wire.
7. (i) Does the induced emf in a circuit depend on the resistance of the circuit? (ii) Does the induced current depend on the resistance of the circuit?
8. Why are ordinary circuit breakers and fuses not effective in preventing shocks?
9. A square loop of wire of side 5.0 cm is in a uniform magnetic field 0.16 T. What is the magnetic flux in the loop (i) when magnetic field is perpendicular to the surface of the loop and (ii) when magnetic field is at an angle of 30° to the surface of the loop?

10. A circular coil of radius 8 cm and 20 turns is rotated about its vertical diameter with an angular speed of 150 rad s^{-1} in a uniform horizontal magnetic field of 3×10^{-2} T. Obtain the maximum emf induced in the coil. If the coil forms a closed loop of resistance 10 Ω, calculate the maximum value of current in the coil.
11. The armature of a 60 Hz AC generator rotates in a magnetic field of 0.15 T. If the area of the coil is 2.0×10^{-2} m^2, how many loops must the coil contain if the maximum output is to be 170 V?
12. One coil of a transformer has 50 turns and the other coil has 1000 turns. The alternating voltage of 220 V is applied to the primary. Find the alternating voltage from the secondary when it is used as (i) a step-up transformer and (ii) a step-down transformer.
13. The primary coil of a step-up transformer having 220 turns is connected to a 110 V alternating voltage source. The secondary delivers a voltage of 12 000 V and a current of 40 mA. (i) How many turns are there in the secondary? (ii) What is the current in the primary? (iii) What is the power output?
14. An electric welding machine uses a current of 400 A. The machine has a transformer whose primary coil has 400 turns and draws 4 A from a 220 V power line. (i) How many turns does the secondary coil have? (ii) What is the voltage across the secondary coil?
15. A transformer has 2000 turns in primary, 100 turns in secondary and its efficiency 100 %. It is used for 10 V, 40 W bulb. Calculate (i) the supply voltage and (ii) the current through the input coil.
16. 120 kW of electric power is sent to a small town from a power plant 10 km away. The transmission lines have a resistance of 0.40 Ω per km. Calculate the power loss if the power is transmitted at (i) 240 V and (ii) 24 000 V.

CONCEPT MAP

ELECTROMAGNETIC INDUCTION, GENERATION AND DISTRIBUTION OF ELECTRICITY

Electromagnetic Induction

- magnetic flux density
  $B = \mu H$
- magnetic flux
  $\phi_B = \int \vec{B} \cdot d\vec{A}$

Faraday's law and Lenz's law

$E = -N \dfrac{d\phi_B}{dt}$

Applications of electromagnetic induction

- induction coil
- AC generator
  $E = N B A \omega \sin \omega t$
- transformer
  $\dfrac{V_s}{V_p} = \dfrac{E_s}{E_p} = \dfrac{N_s}{N_p} = \dfrac{I_p}{I_s}$

Generation and Distribution of Electricity

- alternating emf
  $E = E_m \sin \omega t$
- alternating current
  $I = I_m \sin \omega t$

Power transmission

- grid system

Principles of house wiring

- lighting circuit
- power circuit
- heating circuit
- circuit breaker
- earthing

Dangers of electricity

- damaged insulation
- overheating of cables
- damp conditions

CHAPTER 12

DIGITAL ELECTRONICS AND COMMUNICATION SYSTEM

The world's reliance on electronics is so great that commentators claim people live in an electronic age. Nowadays, people are surrounded by electronic appliances such as televisions, radios, computers, mobile phones, laptops, and DVD players; and also the products of electric components such as hearing aids, pacemakers, blood pressure monitor, oximeter and various medical instruments, microwave ovens, refrigerators, washing machines and other kitchen appliances, automatic vehicles, robotics, as well as numerous applications in diverse areas.

Learning Outcomes

It is expected that students will

- develop conceptual understanding of the analogue and digital electrical/electronic circuits, and aware of new and emerging technologies.
- describe how light emitting diodes (LEDs) and light dependent resistor (LDR) work and how they are made.
- understand the structure of liquid crystal displays (LCDs).
- identify common logic gates, their functions and truth tables.
- determine the corresponding Boolean expression for the circuit output.
- understand the term modulation and be able to distinguish between amplitude modulation (AM) and frequency modulation (FM).
- explore the technology and operation of radio receiver.

12.1 ELECTRONIC SYSTEM

The branch of physics and technology concerned with the design of circuits using transistors, integrated circuits and microchips, and also with the behaviour and movement of electrons in a semiconductor, conductor or vacuum is known as electronics.

Electronic devices contain circuitry that involve active electrical components and associated passive interconnection technologies. Active electrical components are vacuum tubes, transistors, diodes, ICs (Integrated Circuits), TRIACs (Three terminal AC switches), SCRs (Silicon Controlled Rectifiers), LEDs (Light Emitting Diodes), etc. and requires a power source to operate. Passive electrical components are capable of operating without an external power source. Passive electrical components are resistors, capacitors, inductors, transformers, LDR, transducer, etc.

In Grade 11, we have already mentioned electronic devices which are fabricated using semiconductors: pn junction diode and transistor. Now, we are going to introduce some special applications of junction diode such as zener diode and optoelectronic devices such as LEDs, and photodiode.

1. Zener Diode

Zener diode is a heavily doped semiconductor (silicon or germanium) pn junction diode. It makes the current flow in the backward direction when reverse biased. It operates like the normal diode when in the forward-bias mode, and has a turn-on voltage of between 0.3 and 0.7 V.

When the voltage across the terminals of a zener diode is reversed and the potential reaches the zener voltage (V_Z) (breakdown voltage or knee voltage), the junction breaks down and the current flows in the reverse direction. This effect is known as the zener effect. That is, as the reverse voltage increases to the breakdown voltage, large current starts flowing through the diode. The symbol and characteristics of a zener diode is shown in Figure 12.1.

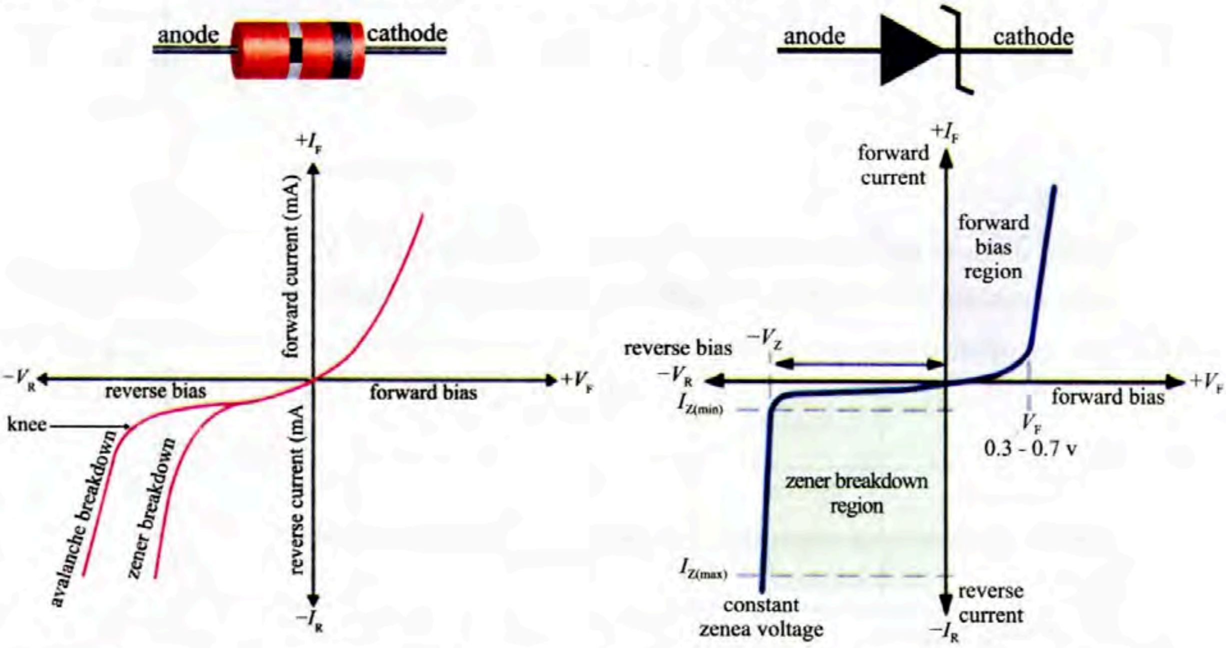


Figure 12.1 The physical, circuit symbol and characteristics of zener diode

The main difference between a zener diode and a normal diode lies in the passage of current. A normal diode allows current to flow only in one direction while zener diode allows current to flow in both directions.

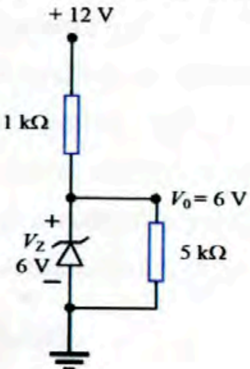
There are two types of reverse breakdown regions in a zener diode: (i) avalanche breakdown and (ii) zener breakdown.

Avalanche breakdown occurs at junctions which being lightly doped have wide depletion layers.

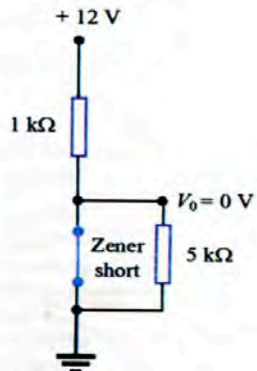
Zener breakdown occurs at junctions which being heavily doped have narrow depletion layers.

For normal operation of a zener diode, in breakdown region, the current through the diode should be limited by an external circuit. It has a reverse-breakdown voltage at which the diode starts to conduct electric current, and remains continuous in the reverse-bias mode. The voltage drop across the zener diode always remains constant irrespective of the applied voltage, and this feature of the zener diode makes it suitable for voltage regulation as reference elements, surge suppressors, and in switching applications and clipper circuits.

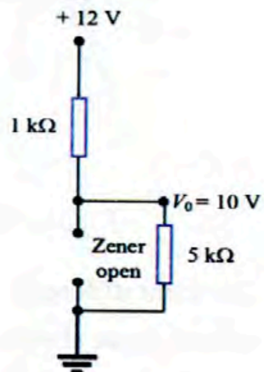
Example 12.1 Figure shows the basic zener diode circuits. What will be the circuit behaviour if the zener is (i) working properly (ii) shorted and (iii)·open-circuited?



(i) If the zener diode is working properly, the voltage V_0 across the load (5 kΩ) will be nearly 6 V.



(ii) If the zener diode is short, the voltage V_0 across the load will be 0 V. The same problem could also be caused by a shorted load resistor (5 kΩ) or an opened source resistor (1 kΩ).



(iii) If the zener diode is open-circuited, the voltage V_0 across the load (5 kΩ) is

$$R_{total} = 1 + 5 = 6\ \text{k}\Omega$$

$$I = \frac{V}{R_{total}} = \frac{12}{6} = 2\ \text{mA}$$

$$V_{5\,k\Omega} = I R_L = 2 \times 5 = 10\ \text{V}$$

2. Light Emitting Diode (LED)

A LED is a semiconductor light source that emits light when current flows through it. A light emitting diode (LED) is known to be one of the best optoelectronic devices. It is a semiconductor light source capable of emitting a fairly narrow bandwidth of visible (or) invisible light when its internal diode junction attains a forward-biased current (or) voltage. The visible lights that an LED emits are usually orange, red, yellow, or green. The commonly used invisible light for LED is infrared light. A modern light source that requires low voltages is the light emitting diode (LED).

The LEDs are made from exotic semiconductor compounds such as Gallium Arsenide (GaAs), Gallium Phosphide (GaP), Gallium Arsenide Phosphide (GaAsP), Silicon Carbide (SiC) or Gallium Indium Nitride (GaInN) all mixed together at different ratios to produce a distinct wavelength of colour. In LED the energy is radiated in the form of light. LEDs do not directly produce white light. Using a blue LED with a phosphor coating to convert blue light to white light by a process called fluorescence. Different types of LEDs are shown in Figure 12.2.

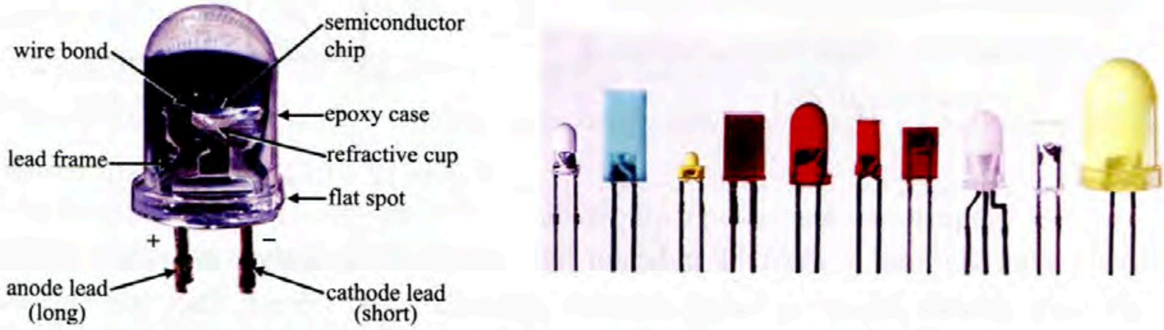


Figure 12.2 The different types of LEDs [CREDIT: Source from the Internet]

Typical semiconductor materials used for LEDs are shown in Table 12.1 together with their emission wavelength, colour and forward voltage V_F at 20 mA current.

Table 12.1 Typical LED characteristics

Semiconductor material	Wavelength (nm)	Colour	V_F at 20 mA (V)
GaAs	850-940	Infra-red	1.2
GaAsP	630-660	Red	1.8
GaAsP	605-620	Amber	2.0
GaAsP:N	585-595	Yellow	2.2
AlGaP	550-570	Green	3.5
SiC	430-505	Blue	3.6
GaInN:P		White	4.0

The circuit symbol of LED and the forward biased LED characteristic curves are shown in Figure 12.3 and 12.4.

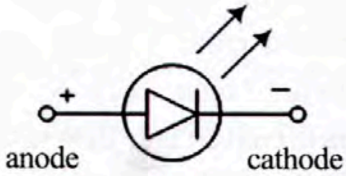


Figure 12.3 The circuit symbol for LED (Two arrows indicate the emission of radiation from the diode.)

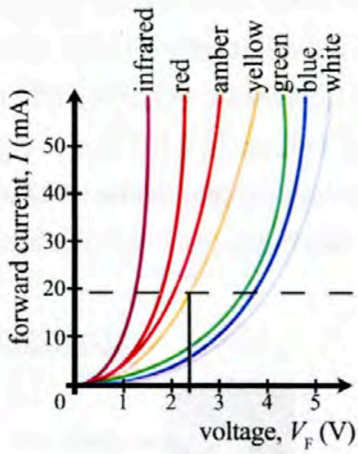
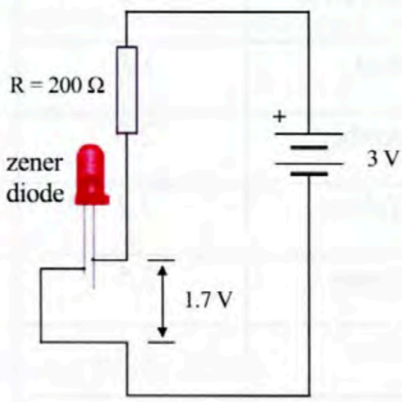


Figure 12.4 LED characteristic curves

LEDs are typically used as ON/OFF indicator lights in electrical appliances such as televisions, VCR (video cassette recorder), video cameras, computers, and stereos. They are also used to display numbers in some alarm clocks, radios, and microwave ovens. Another use is very large video displays at sporting events and concerts.

LED as an Indicator

Figure 12.5 is an LED indicator circuit, one of the main applications of LED. A current limiting resistor should be connected in series with LED in the circuit to protect the LED. The value of the series resistance should be chosen that the voltage drop at LED must be nearly equal to that at the limiting resistor.



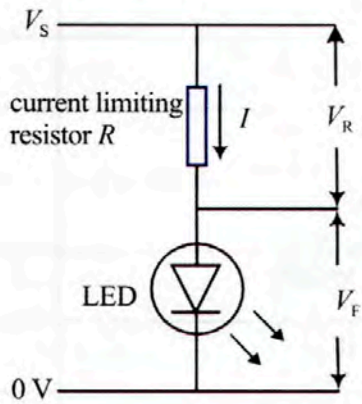


Figure 12.5 Simple LED indicator circuit

In Figure 12.5, let V_S be the supply voltage, V_F be the required forward bias voltage for the LED, I be the desired current flowing through LED. Then, the current limiting resistance R is

$$V_R = V_S - V_F$$

$$R = \frac{V_R}{I} = \frac{V_S - V_F}{I}$$

Advantages of LED

- Very low voltage (1 to 2 V) and current (5 to 20 mA) are enough to drive the LED.
- Less power consumption (less than 150 mW).
- Fast action and no warmup time. (The response time is about 10 ns)
- Miniature in size and hence light weight.
- Long life span and ruggedness.
- More reliable, more efficient to use under cold temperature.

Disadvantages of LED

- A slight excess in voltage or current can damage the device.
- The device is known to have a much wider bandwidth (wavelength spread) compared to the laser.
- The device temperature depends on the radiant output power and wavelength.
- Little effective in wide-area.

Example 12.2 An LED is lit from a 9 V supply and takes a current of 15 mA. Calculate the value of the current limiting resistor required for the LED. (Assume that the forward voltage drop will be 2 V)

$V_s = 9$ V, $V_F = 2$ V, $I = 15$ mA $= 15 \times 10^{-3}$ A

The current limiting resistor required for the LED,

$$R = \frac{V_R}{I} = \frac{V_S - V_F}{I}$$

$$= \frac{9-2}{15 \times 10^{-3}} = 466.67\ \Omega \text{ (in practice, } 470\ \Omega \text{ is used)}$$

Reviewed Exercise

1. Where are LEDs used?
2. Describe some applications of LEDs.
3. An amber-coloured LED with a forward voltage drop of 2 V is to be connected to a 5 V stabilized DC power supply. Calculate the value of the series resistor required to limit the forward current to less than 10 mA. Also calculate the current flowing through the diode if a 100 Ω of current limitting resistor is used.

Key Words: zener diode, avalanche breakdown, zener breakdown, light emitting diode, zener effect, forward biased current

3. Photodiode

A photodiode is a semiconductor device that converts light into electrical current. The current is generated when photons are absorbed in the photodiode. Photodiodes work in reverse biased mode. Figure 12.6 shows photodiode and its circuit symbol.

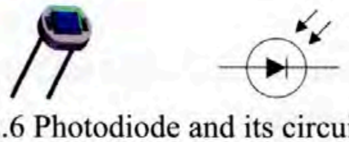


Figure 12.6 Photodiode and its circuit symbol

When the photodiode is illuminated with light (photons) of energy $h\nu$ greater than the energy gap E_g of the semiconductor, then electron-hole pairs are generated due to absorption of photons. When an external load is connected, the current flows. This current is called photocurrent. The magnitude of the photocurrent depends on the intensity of incident light. Thus, the photodiode can be used as a photodetector to detect the optical signals.

A small amount of current (dark current), due to the flow of minority carriers, is also produced when no light is falling. Silicon is most often used to fabricate photodiodes, though germanium and gallium arsenide can also be used.

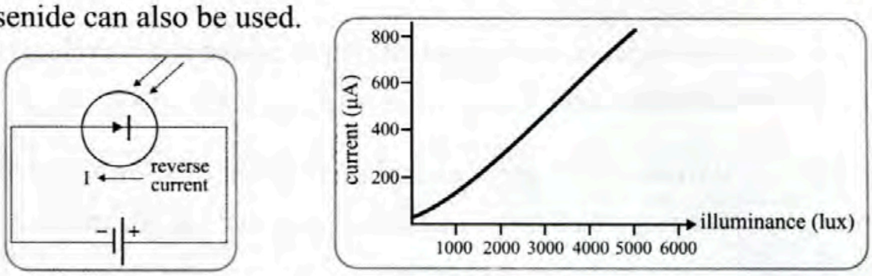


Figure 12.7 Simple circuit diagram of photodiode and its characteristics curve

Photodiodes are used as photosensors in compact disc (CD) players, televisions, air conditioners and many other electronics devices. Photodiodes can also be used for light measurement in light meters and to respond light levels, and in switching on street lighting after dark.

Photocurrent is an electric current produced by electromagnetic radiation in the photoelctric effect, photovoltaic effect or photoconductivity.

Reviewed Exercise

- Explain symbol, circuit diagram and function of a photodiode.

Key Words: photodiode, energy gap, photosensors, electron-hole pairs, photocurrent, photon, dark current

4. Light Dependent Resistor (Photoresistor/ Photocell)

A light dependent resistor (LDR) is a light controlled variable resistor. LDR consists of a disc of semiconductor material on its surface with two electrodes. LDR is also called light sensitive variable resistors. Its resistance depends on the intensity of light falling on its surface. In the dark or in dim light, the material of the disc has a relatively small number of free electrons in it. That is few electrons to carry electric charge. It becomes a poor conductor of electric current. Its resistance is quite high (~ MΩ) called dark resistance. In the bright light, more electrons escape from the atoms of the semiconductor. Since there are more electrons to carry electric charge, it becomes a good conductor. Its resistance is low (few hundred Ω). As light level increases, the LDR resistance decreases. Figure 12.8 shows LDR and its circuit symbol.

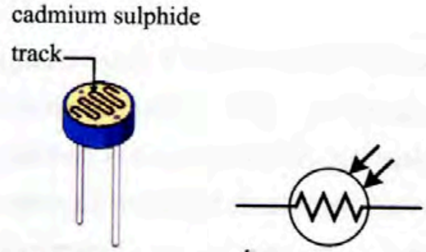


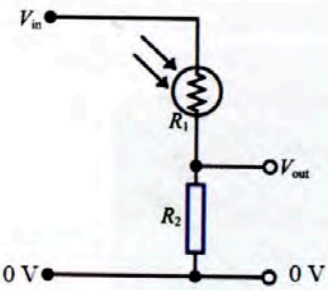
Figure 12.8 Light dependent resistor and its circuit symbol

When LDR is exposed to light, it takes a few milliseconds to lowers its resistance and it may take a few seconds to return to its dark resistance after removal of light.

Special semiconductor crystal, such as cadmium sulfide (or) lead sulfide is used to make photo resistors. LDRs are used as light activated relay switches (to trip a relay whenever the light intensity changes) in burglar alarm, alarm clock, light intensity meters, etc.

Example 12.3 In the figure the resistance of R_2 is 2000 Ω and V_{in} is 6 V. (i) In daylight the resistance of R_1 is 500 Ω. Calculate the voltage across R_2. (ii) In the dark the resistance of R_1 is 198 000 Ω. Calculate the voltage across R_2.

$R_2 = 2000\ \Omega$, $V_{in} = 6$ V



(i) In daylight, $R_1 = 500\ \Omega$

Since $I = \dfrac{V_{in}}{(R_1 + R_2)}$ and $V_{out} = I R_2$

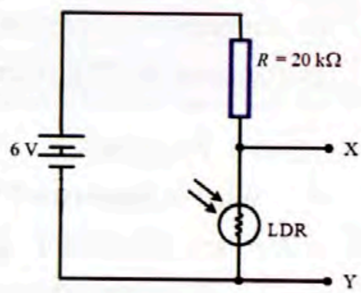
$$V_{out} = V_{in} \times \frac{R_2}{(R_1 + R_2)} = 6 \times \frac{2000}{(500 + 2000)} = 4.8\ \text{V}$$

(ii) In dark, $R_1 = 198000\ \Omega$

$$V_{out} = V_{in} \times \frac{R_2}{(R_1 + R_2)} = 6 \times \frac{2000}{(198000 + 2000)} = 0.06\ \text{V}$$

Reviewed Exercise

1. What effect does an increase of light intensity on LDR have on its resistance?
2. The circuit shows a potential divider, which consists of a fixed resistor and a light dependent resistor (LDR). The potential divider is used to switch on a lamp when it gets dark. The resistance of fixed resistor is 20 kΩ. The potential difference across XY is 4 V when the lamp is switched on. What is the resistance of the light-dependent resistor (LDR)?
(Hint: $V_S = V_R + V_{LDR}$, $I = \dfrac{V_R}{R}$ and $R_{LDR} = \dfrac{V_{LDR}}{I}$)



Key Words: light dependent resistor, photoresistors, activated relay switch, dark resistance

5. Thermistor

A thermistor is a temperature sensor that exhibits a large change in resistance proportional to a change in temperature. It can therefore convert changes in temperature into changes in electric current. It contains semiconducting metallic oxides whose resistance decreases when the temperature raises either due to heating the thermistor directly or to passing a current through it. Thermistor, its circuit symbol and characteristics are shown in Figure 12.9. There are two types of thermistors. The most commonly used is the Negative Temperature Coefficient (NTC) thermistor. The NTC's resistance decreases as the temperature increases, and vice versa. In the Positive Temperature Coefficient (PTC) thermistor, the resistance increases as the temperature increases, and is used to break the circuit at preset temperatures. The various shapes of thermistors are as shown in Figure 12.10.

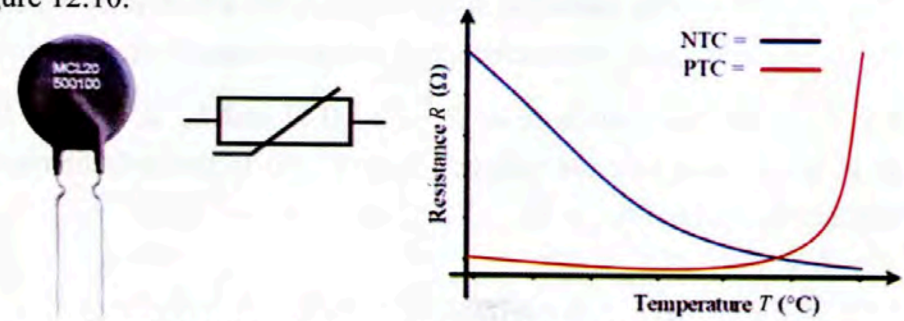


Figure 12.9 Thermistor, circuit symbol and its characteristics

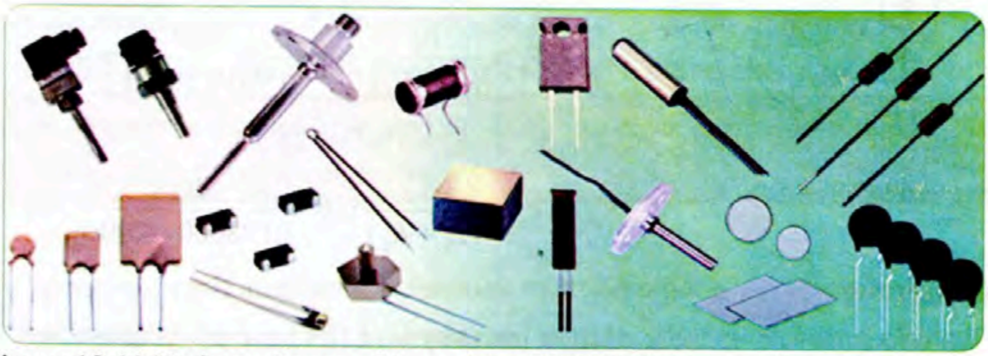


Figure 12.10 Various shapes of thermistor [CREDIT: Source from the Internet]

> As temperature increases, the resistance of the NTC thermistor decreases whereas the resistance of the PTC thermistor increases.

Reviewed Exercise

- What is thermistor? What is the main difference between NTC and PTC thermistor?

Key Words: thermistor, negative temperature coefficient, positive temperature coefficient, temperature sensor

6. Liquid Crystal Display (LCD)

Liquid crystals are a state of matter which has properties between those of conventional liquids and those of solid crystals. A liquid crystal display (LCD) is a flat-panel display or other electronically modulated optical device that uses the light-modulating properties of liquid crystals combined with polarizers. Liquid crystals do not emit light directly, instead using a backlight or reflector to produce images in color or monochrome.

LCDs are lit by a backlight, and pixels are switched ON and OFF electronically while using liquid crystals to rotate polarized light. A polarizing glass filter is placed in front and behind all the pixels, the front filter is placed at 90 degrees. In between both filters are the liquid crystals, which can be electronically switched ON and OFF.

LCDs can be commonly found in smartphones, televisions, computer monitors and instrument panels (Figure 12.11). It is a big leap in technology in which LCDs replace light-emitting diodes (LEDs) and gas-plasma displays. LCDs allowed displays to be much thinner than cathode ray tube (CRT) technology. LCDs consume much less power than LEDs and gas-plasma displays because they work on the principle of blocking light rather than emitting it. Where an LED emits light, the liquid crystals in an LCD produce an image using a backlight. Although LCDs have replaced older display technologies (i.e. CRT), LCDs have begun being replaced by new display technologies such as organic light-emitting diodes (OLEDs).

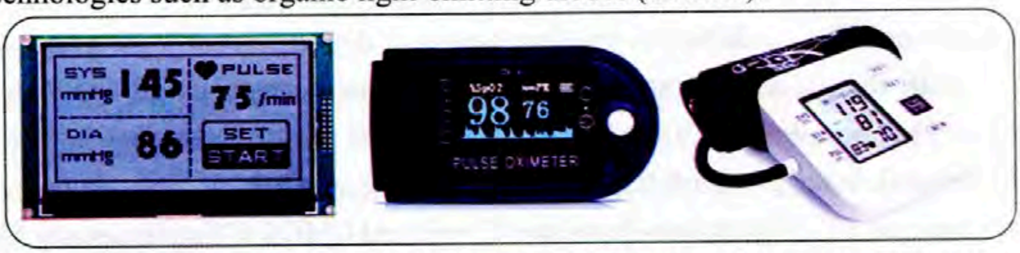


Figure 12.11 Liquid Crystal Displays [CREDIT: Source from the Internet]

> A polarizer is an optical device that can convert an unpolarized light wave into a polarize light wave by blocking all other vibrations.

Reviewed Exercise

- What is the disadvantage of LCD displays?

Key Words: liquid crystal display, organice light emitding diode, reflector, gas-plasma display, polarizer

12.2 DIGITAL ELECTRONICS

Digital electronics is a field of electronics involving the study of digital signals and the engineering of devices that use or produce them. This is in contrast to analog electronics and analog signals.

Digital electronic circuits are usually made from large assemblies of logic gates, often packaged in integrated circuits. Complex devices may have simple electronic representations of Boolean logic functions. An advantage of digital circuits when compared to analog circuits is that signals represented digitally can be transmitted without degradation caused by noise.

Many of our household items make use of digital electronics such as computers, laptops, televisions, remote controls and other entertainment systems (or) kitchen appliances like dishwashers and washing machines.

An IC (integrated circuit), sometimes called a chip (or) microchip, is a semiconductor wafer on which thousands (or) millions of tiny resistors, capacitors and transistors are fabricated. An IC can function as an amplifier, oscillator, timer, counter, computer memory, or microprocessor. A particular IC is categorized as either linear analog (or) digital, depending on its intended application. ICs are of linear, digital and mixed types.

Linear ICs have continuously variable output (theoretically capable of attaining an infinite number of states) that depends on the input signal level. As the term implies, the output signal level is a linear function of the input signal level. Linear ICs are used as af (audio-frequency) and rf (radio-frequency) amplifiers.

Digital ICs operate at only a few defined levels or states, rather than over a continuous range of signal amplitudes. These devices are used in computers, computer networks, modems and frequency counters. The fundamental building blocks of digital ICs are logic gates, which work with binary data, that is, signals that have only two different states, called LOW (logic 0) and HIGH (logic 1). These logic ICs are usually supplied in plastic DIL (dual in line) packages containing several logic gates of the same type. There are two common types of package available, known as TTL (Transistor-Transistor Logic) and CMOS (Complementary Metal Oxide Semiconductor).

Boolean Algebra and Logic Gates

In Grade 11, we have described the five common logic gates. Now we will give a brief review of these gates. The symbols and truth tables for the different gates are given in Figure 12.12 and Table 12.2. The AND gate with inverted output is called a NAND gate. The OR gate with inverted output is called a NOR gate. The inverted connection (inverted gate) is indicated by a bubble.

There are two remaining gates of the primary electronics logic gates: XOR, which stands for Exclusive OR, and XNOR, which stands for Exclusive NOR. In an XOR gate, the output is HIGH if one, and only one, of the inputs is HIGH. That is, XOR gate produces a 0 when both inputs match. The XOR gate operator is written as $A \oplus B$. An XNOR gate is an XOR gate whose output is inverted. Thus, XNOR gate operator is written as $\overline{A \oplus B}$.

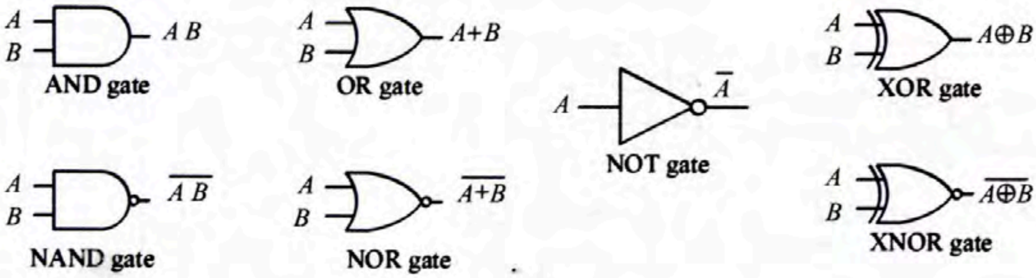


Figure 12.12 Gate symbols

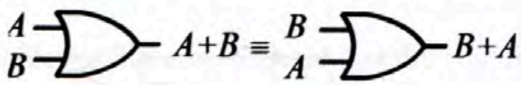
Table 12.2 The truth table for different gates

A	B	NOT $\bar{A}$	AND AB	NAND $\overline{AB}$	OR $A+B$	NOR $\overline{A+B}$	XOR $A \oplus B$	XNOR $\overline{A \oplus B}$
0	0	1	0	1	0	1	0	1
0	1	1	0	1	1	0	1	0
1	0	0	0	1	1	0	1	0
1	1	0	1	0	1	0	0	1

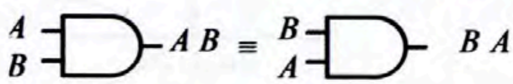
The Basic Laws of Boolean Algebra and De Morgan's Theorems

Boolean algebra is a branch of mathematics where variables can have only two possible values: false and true, (or) logic values 0 and 1. It is also called Binary algebra or Logical algebra. Boolean algebra is used to analyze and simplify the digital (logic) circuits. The basic operations in Boolean algebra are AND, OR, and NOT. Boolean algebra gives a more compact way to describe a combinational logic circuit than truth tables alone. The commutative, associative and distributive laws for addition and multiplication are the same as in ordinary algebra.

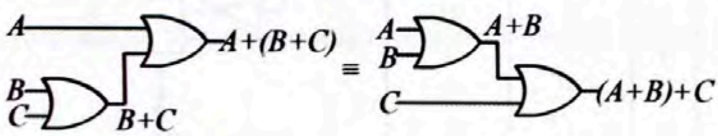
1. $A + B = B + A$ (commutative law of addition)



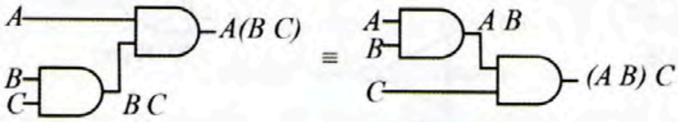
2. $A\ B = B\ A$ (commutative law of multiplication)



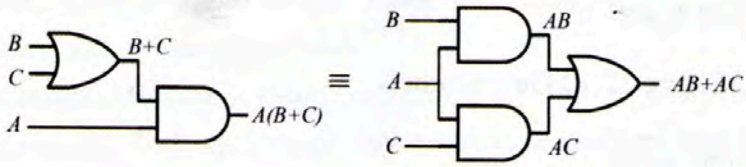
3. $A + (B + C) = (A + B) + C$ (associative law of addition)



4. $A(BC) = (AB)C$ (associative law of multiplication)



5. $A(B + C) = AB + AC$ (distributive law)

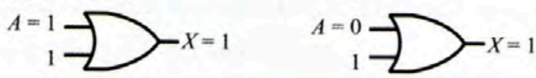


Basic Rules of Boolean Algebra

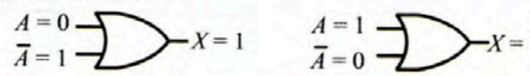
1. $A + 0 = A$

5. $A + A = A$

2. $A + 1 = 1$

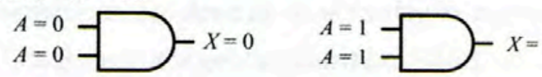


6. $A + \bar{A} = 1$

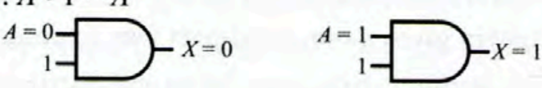


3. $A \cdot 0 = 0$

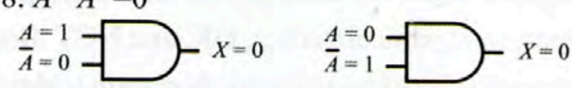
7. $A \cdot A = A$



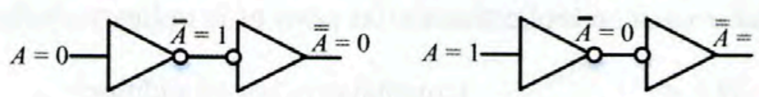
4. $A \cdot 1 = A$



8. $A \cdot \bar{A} = 0$



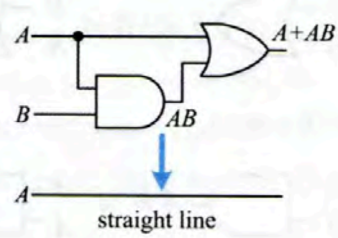
9. $\bar{\bar{A}} = A$



10. $A + AB = A$

A	B	AB	$A + AB$
0	0	0	0
0	1	0	0
1	0	0	1
1	1	1	1

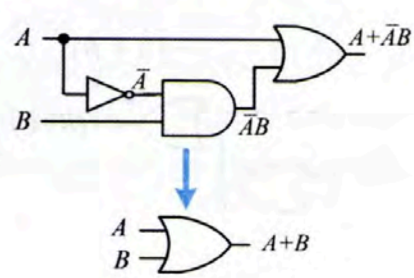
equal



11. $A + \bar{A}\ B = A + B$

A	B	$\bar{A}B$	$A + \bar{A}B$	$A + B$
0	0	0	0	0
0	1	1	1	1
1	0	0	1	1
1	1	0	1	1

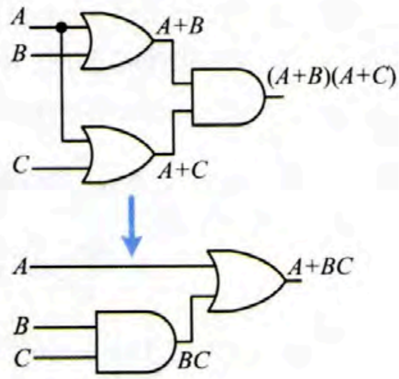
equal



12. $(A + B)(A + C) = A + BC$

A	B	C	$A+B$	$A+C$	$(A+B)(A+C)$	BC	$A + BC$
0	0	0	0	0	0	0	0
0	0	1	0	1	0	0	0
0	1	0	1	0	0	0	0
0	1	1	1	1	1	1	1
1	0	0	1	1	1	0	1
1	0	1	1	1	1	0	1
1	1	0	1	1	1	0	1
1	1	1	1	1	1	1	1

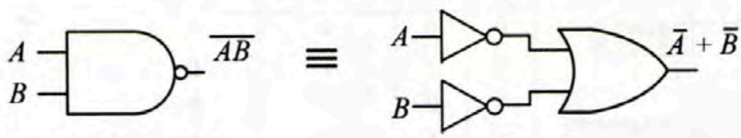
equal



De Morgan's Theorem

Augustus De Morgan formulated an extension to English mathematician George Boole's algebraic logic that has become very important in digital logic. The theorem comprises two laws that describe how inverting the inputs to a gate, changes the gate's function.

The first theorem is stated that the complement of two or more ANDed variables is equivalent to the OR of the complements of the individual variables.



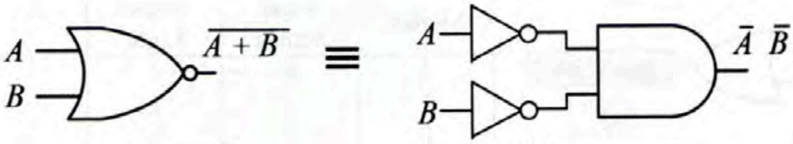
$X = \overline{AB}$ $\quad$ $X = \bar{A} + \bar{B}$

input		output	
A	B	$\overline{AB}$	$\bar{A} + \bar{B}$
0	0	1	1
0	1	1	1
1	0	1	1
1	1	0	0

The formula for expressing this theorem for two variables is

$$\overline{AB} = \bar{A} + \bar{B}$$

The second theorem is stated that the complement of two or more ORed variables is equivalent to the AND of the complements of the individual variables.



$X = \overline{A + B}$ $\quad$ $X = \bar{A}\,\bar{B}$

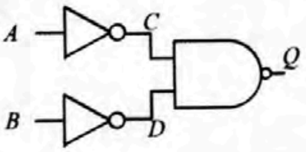
input		output	
A	B	$\overline{A + B}$	$\bar{A}\bar{B}$
0	0	1	1
0	1	0	0
1	0	0	0
1	1	0	0

The formula for expressing this theorem for two variables is

$$\overline{A + B} = \bar{A}\,\bar{B}$$

Combination and Uses of Logic Gates

Consider a system that consists of two NOT gates and one NAND gate as shown in Figure 12.13. To deduce the logical output Q of the system, we have to work out first the intermediate outputs C and D from the NOT gates, which act as the two inputs to the NAND gate. Check the truth table given to confirm whether this system is equivalent to an OR gate.



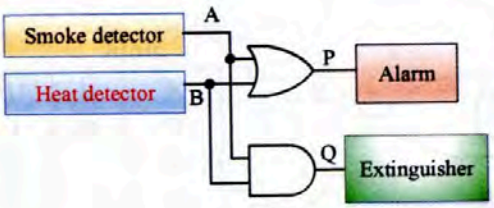
A	B	C	D	Q
0	0	1	1	0
0	1	1	0	1
1	0	0	1	1
1	1	0	0	1

Figure 12.13 The sample circuit diagram of deduce the logical output and the truth table

Logic gates can be used as processors in electronic control systems. Many of these can be demonstrated by connecting together commercial modules.

(a) Fire Alarm System

The fire alarm system consists of smoke detector, heat detector and two logic gates as shown in Figure 12.14. The fire alarm will turn on when either smoke or heat is detected. If both smoke and heat are detected, the fire extinguisher will also be set to operate.

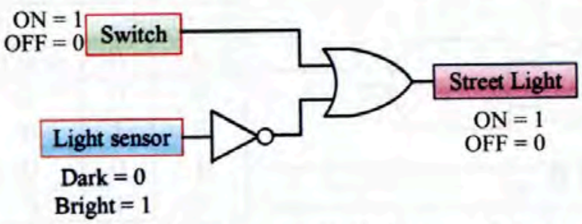


A	B	$P = A+B$	$Q = AB$
0	0	0	0
0	1	1	0
1	0	1	0
1	1	1	1

Figure 12.14 The circuit diagram of fire alarm system and its truth table

(b) Street Lighting System

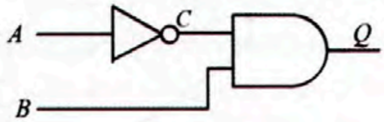
A system is required which allows the street lights either to be turned on manually by a switch at any time or automatically by a light sensor when it is dark. The arrangement in Figure 12.15 achieves this since the OR gate gives a 1 output when either or both of its inputs are 1.



Switch	Light Sensor	Street Light
1	0	1
1	1	1
0	0	1
0	1	0

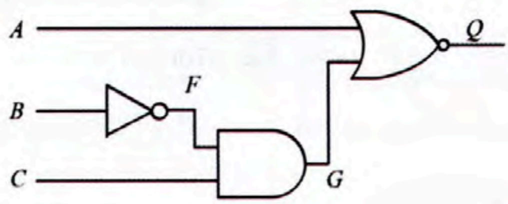
Figure 12.15 The circuit diagram of street lighting system and its truth table

Example 12.3 Check the following logic system carefully and then construct the truth table that follows:



A	B	C	Q
0	0	1	0
0	1	1	1
1	0	0	0
1	1	0	0

Example 12.4 Check the following logic system carefully and then construct the truth table that follows:



Truth Table

A	B	C	F	G	Q
0	0	0	1	0	1
1	0	0	1	0	0
0	1	0	0	0	1
1	1	0	0	0	0
0	0	1	1	1	0
1	0	1	1	1	0
0	1	1	0	0	1
1	1	1	0	0	0

Example 12.5 Simplify the expression $AB + A(B + C) + B(B + C)$ and draw the equivalent gate diagram.

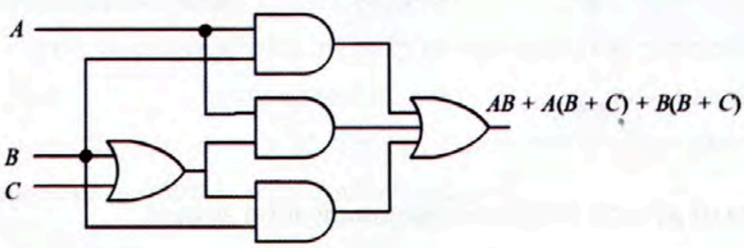
$$AB + A(B + C) + B(B + C) = AB + AB + AC + BB + BC$$

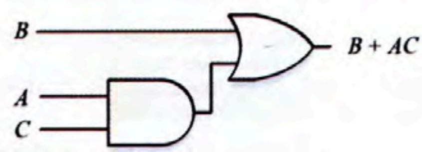
$$= AB + AB + AC + B + BC \qquad (BB = B)$$

$$= AB + AC + B + BC \qquad (AB + AB = AB)$$

$$= AB + AC + B \qquad (B + BC = B)$$

$$= B + AC \qquad (AB + B = B)$$





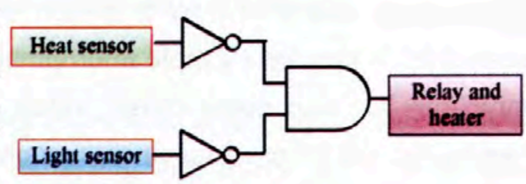
Example 12.6 Apply De Morgan's theorems to the expression $\overline{XYZ}$ and $\overline{X + Y + Z}$.

$$\overline{XYZ} = \overline{X} + \overline{Y} + \overline{Z}$$

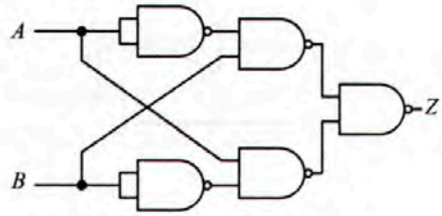
$$\overline{X + Y + Z} = \overline{X}\,\overline{Y}\,\overline{Z}$$

Reviewed Exercise

1. State the names of the two types of logic gate used in following figure. Explain what happens to the outputs of the three logic gates when (i) it is cold (0) and dark (0), (ii) it is cold (0) and bright (1).



2. Write the truth table of the following circuit. To what gate is it equivalent?



3. For the circuit below, write the value of Z as a Boolean expression, using A and B.

Key Words: integrated circuits, Boolean algebra, logic gates, De Morgan's theorem, TTL, CMOS

12.3 BASIC ELECTRONIC COMMUNICATION

In general, an electronic communication system is composed of the transmission, reception, and processing of information between two or more locations with the use of electronic circuits. The basic components of an electronic communication system are the transmitter, communication channel or medium receiver and noise (as a source of disturbance). The block diagram shown in Figure 12.16 depicts the general form of a communication system.

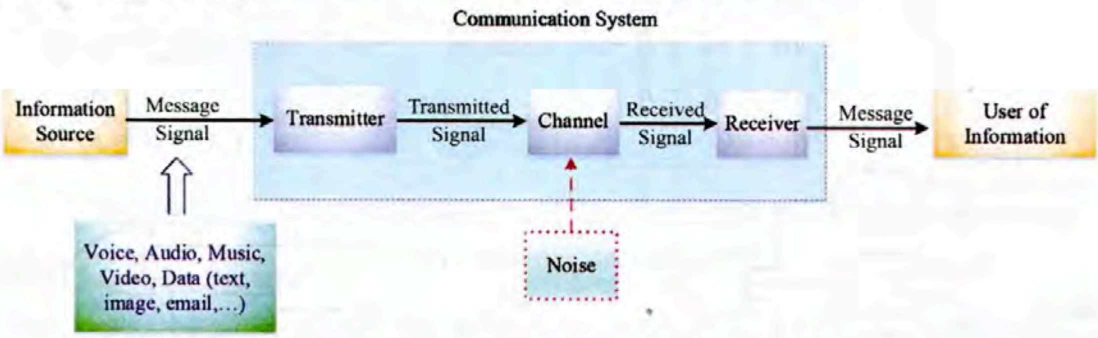


Figure 12.16 Block diagram of general electronic communication system

Analog signals (human voice) or digital signals (binary data) are inputted to the system, processed within the electronic circuits for transmission, then decoded by the receiver. The system is claimed to be reliable and effective only errors are minimized within the process. Examples: internet, public switched telephone network, intranet and extranet, smart home systems and television.

Information source - It is a device that generates information (messages or data) to be transmitted. It may be a simple microphone and computer keyboard. The messages generated by source may be voice, audio, music, video, data (text, image, email, temperature, pressure, etc.)

Transmitter - It is the arrangement that processes the message signal into an appropriate form for transmission and subsequent reception.

Channel - It is the medium that connects transmitter and receiver to convey the information. Depending upon the type of communication system, a channel may be copper wires, coaxial cable, optical fibre, radio links, satellite channel or combination of any of these.

Noise - Noise is an unwanted signal that disturbs, interferes and affects the transmitted signal. Noise cannot be prevented but can be minimized. The measure of noise is usually expressed in terms of SNR (signal to noise ratio). The external noise is often minimized and eliminated by the appropriate design of the channel, shielding of cables. Digital signals are more immune to noise than analog signals.

Receiver - The receiver is to reconstruct the transmitted signal and delivers it to the destination called user of information. It accepts the transmitted message from the channel and converts to a form understandable by humans. Receivers contain amplifiers, oscillators, mixers, tuned circuits, filters and a demodulator (detector).

Modes of Communication System

There are two basic modes of communication: point-to-point and broadcast. In point-to-point mode, communication takes place over a link between a single transmitter and a receiver. Telephony is an example of point-to-point communication. In the broadcast mode, there are a large number of receivers corresponding to a single transmitter. Radio and television are examples of broadcast mode of communication.

Analog Communication

Analog communication is the process of conveying (sending, receiving, and processing) of information including image, voice and video by using analog signals. In analog comunication, the data is transferred with the help of analog signal in between transmitter and receiver as shown in Figure 12.17. Analog communication uses an analog signal which varies in amplitude, phase, or some other property with time. For example, a sinusoidal signal is continuous in nature. It has continuous amplitude with continuous time.

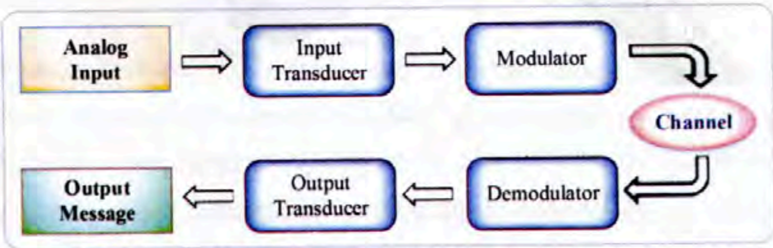


Figure 12.17 Block diagram for analog communication system

Digital Communication

There are many types of digital communication, commonly referred to as digital communication channels. These include email, phone calls, video conferencing and many types of instant messaging like short message service (SMS) and web chats. Transfer of data occurs in the form of digital bit stream, i.e. 0 or 1 over a point-to-point (or) point-to-multipoint transmission medium. The block diagram of digital communication system is shown in Figure 11.18. Data can be broken into packets as discrete messages which is not allowed in analog communication. With digital communication, transmission errors can be detected and corrected.

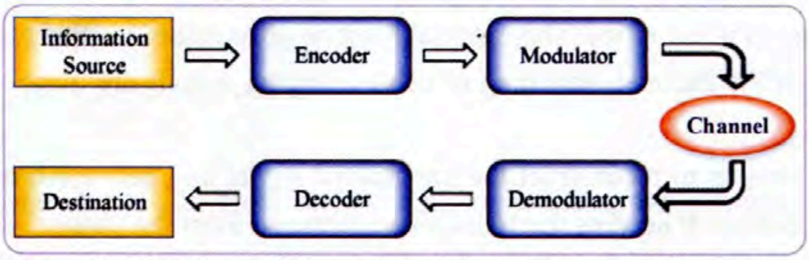
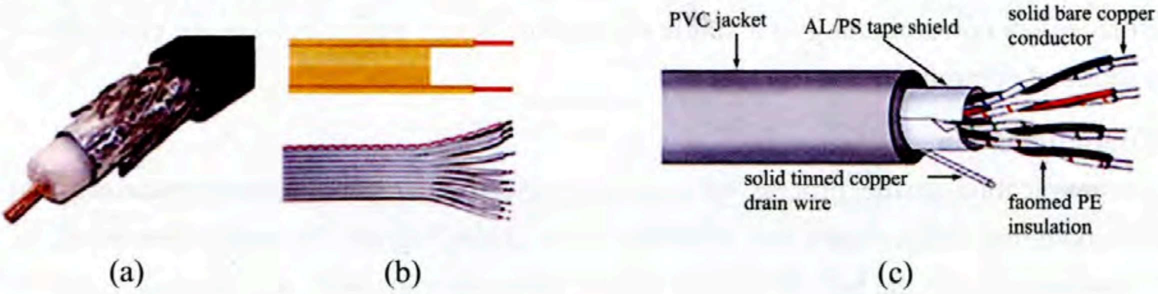


Figure 12.18 Block diagram for digital communication system

Wired (Line) Communication

In line communication, there is a physical connection between source and destination. The wired connections between two points are known as transmission lines. The wires that are most popular for wired communication are: co-axial, parallel wire lines, twisted pair cables and optical fibre as shown in Figure 12.19.



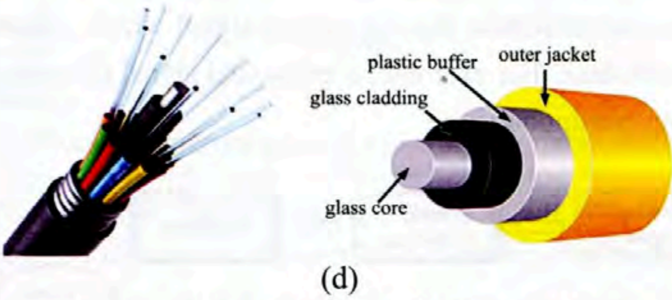


Figure 12.19 (a) Co-axial (b) parallel wire lines and (c) twisted pair cables (d) optical fibre [CREDIT: Source from the Internet]

Wireless (Space) Communication

The simplest space communications rely on two things: a transmitter and a receiver. A transmitter encodes a message onto electromagnetic waves through modulation, which changes properties of the wave to represent the data. These waves flow through space toward the receiver. Figure 12.20 shows the space communication system.

Figure 12.20 The space communication system [CREDIT: Source from the Internet]

Transducer

A transducer is a device for converting a non-electrical input into an electrical signal (or) vice versa. The process of converting energy from one form to another is known as transduction. Transducer contains two parts that are closely related to each other, i.e. the sensing element and transduction element. The sensing element is called the sensor. Sensor is a device which produces a measurable response due to a change in physical conditions. The transduction element converts the sensor output to suitable electrical form as shown in Figure 12.21.

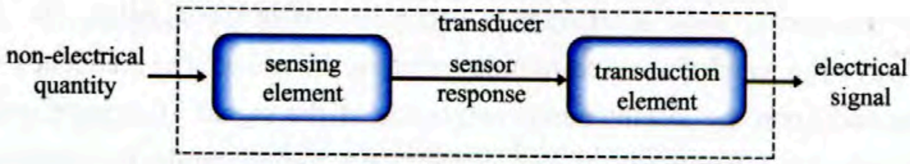


Figure 12.21 Block diagram of a transducer

In general, a transducer is a device that transforms a signal from one energy form to another energy form. Some common examples of transducers include loudspeakers, microphones, oximeter, thermometers, LEDs and antenna.

Modulation

The process of changing some characteristics (e.g. amplitude, frequency or phase) of a carrier wave (e.g. radio wave) in accordance with the intensity of the signal is known as modulation. The resultant wave is called modulated wave, and contains the audio signal. In modulation, the sound wave is electrically impressed on an electromagnetic wave.

Modulation permits the transmission to occur at high frequency while it simultaneously allows the carrying of the audio signal. It is also the process of manipulating the amplitude, the frequency or phase of a carrier wave in response to an incoming voice, video or data signal.

Types of Modulation

There are three basic types of modulation: (i) Amplitude modulation (AM), (ii) Frequency modulation (FM) and (iii) Phase modulation (PM).

(i) **Amplitude Modulation**

When the amplitude of high frequency carrier wave is changed in accordance with the intensity of the signal, it is called amplitude modulation (Figure 12.22). In amplitude modulation, only the amplitude of the carrier wave is changed in accordance with the intensity of the signal but the frequency of the modulated wave (i.e. carrier frequency) remains the same. It is commonly used to transmit information in portable two-way radios, VHF (Very High Frequency), aircraft radios and in computer modems.

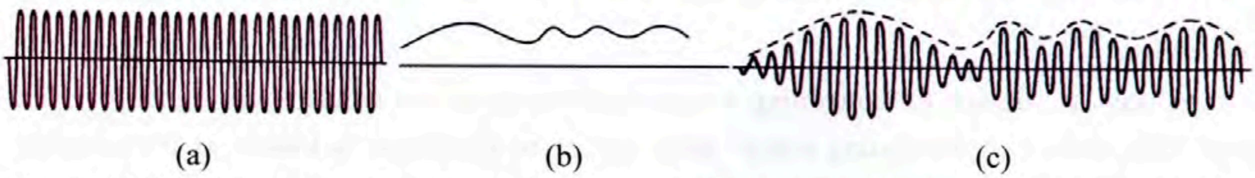


Figure 12.22 (a) unmodulated carrier wave (b) sound wave (c) amplitude modulated wave (AM)

(ii) **Frequency Modulation**

When the frequency of carrier wave is changed in accordance with the intensity of the signal, it is called frequency modulation (FM) as shown in Figure 12.23. In frequency modulation, only the frequency of the carrier wave is changed in accordance with the signal but the amplitude of the modulated wave (i.e. carrier wave amplitude) remains the same. The frequency variations of carrier wave depend upon the instantaneous amplitude of the signal. (Compare with amplitude modulation, in which the amplitude of the carrier wave varies, while the frequency remains constant.) It is used in radio, telemetry, radar and seismology. FM is widely used for broadcasting music and speech, two-way radio systems, magnetic tape-recording systems and some video-transmission systems.

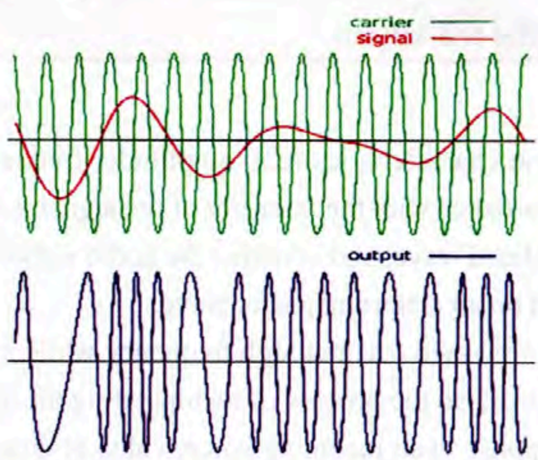


Figure 12.23 Frequency modulated signal

(iii) **Phase Modulation**

Phase modulation is a modulation pattern that encodes information as variations in the instantaneous phase of a carrier wave. It can be used for radio signals in a variety of radio communication applications. Unlike FM, phase modulation is not widely used for transmitting radio waves. It is used for signal and waveform generation in digital synthesizers (Figure 12.24).

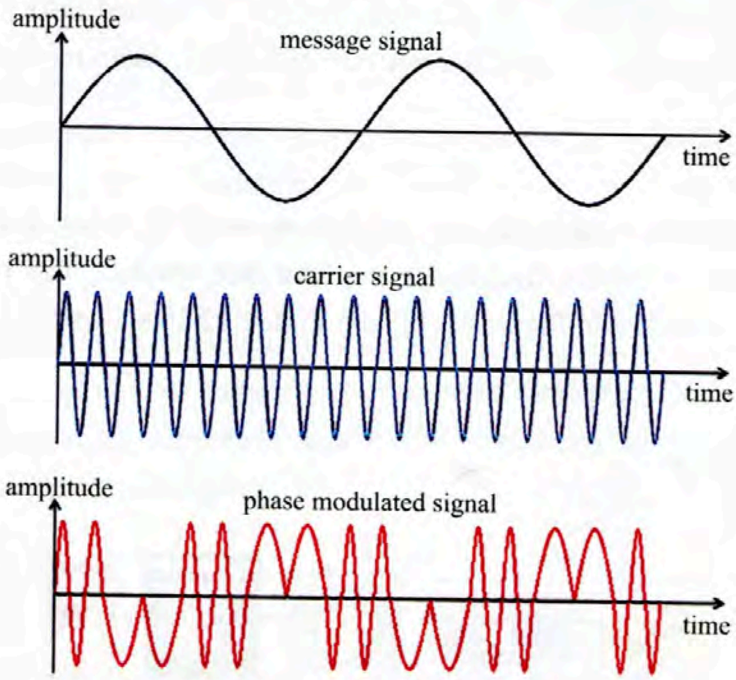


Figure 12.24 Phase modulated signal

Table 12.3 The comparison of frequency modulation (FM) and amplitude modulation (AM)

FM	AM
(i) The amplitude of carrier wave remains constant with modulation.	(i) The amplitude of carrier wave changes with modulation.
(ii) The carrier frequency changes according to the strength of the modulating signal.	(ii) The carrier amplitude changes according to the strength of the modulating signal.
(iii) The carrier frequency changes with modulation.	(iii) The carrier frequency remains constant with modulation.
(iv) FM radio ranges in a higher spectrum from 88 to 108 MHz. (or) 1200 to 2400 bits per second.	(iv) AM radio ranges from 535 to 1705 kHz (or) up to 1200 bits per second.

Demodulation

The process of recovering the audio signal from the modulated wave is known as demodulation or detection. At the broadcasting station, modulation is done to transmit the audio signal over longer distances to a receiver. When the modulated wave is picked up by the radio receiver, it is necessary to recover the audio signal from it. This process is accomplished in the radio receiver and is called demodulation. A demodulator is an electronic circuit (or computer program in a software defined radio) that is used to recover the information content from the modulated carrier wave.

As an example of communication system, the function of a simple radio receiver is described as follows.

Simple Radio Receiver

The radio receiver comprises roughly six pieces. They are antenna, tuner, rf (radio frequency) amplifier, diode detector, af (audio frequency) amplifier and speaker. The bolck diagram of a simple radio receiver is shown in Figure 12.25, and Figure 12.26 shows the circuit diagram of AM radio receiver.

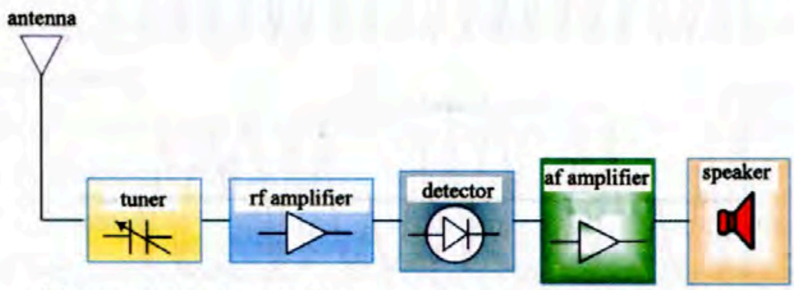
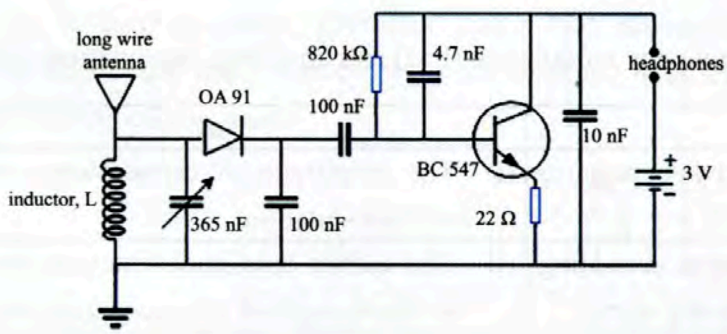


Figure 12.25 Block diagram of a simple radio receivers



(a)

(b)

(c)

Figure 12.26 (a) The circuit diagram of AM radio receiver
(b) Printed board of AM radio receiver
(c) Printed board of FM radio receiver

The receiving antenna picks up the radio signals which is coupled to tuning circuit (through the inductor L) and by adjusting a variable capacitor, a particular radio frequency can be selected. The weak signal is amplified and fed into the diode detector.

The input signal contains an *rf* (radio frequency) component, the carrier, and an *af* (audio frequency) component, the sound signal.

During each carrier cycle, the diode turns on briefly and charges the capacitor in the detection circuit to the peak voltage of the particular cycle. Between cycles, the capacitor would discharge through the resistor R. But, by making the time constant RC greater than the period of the carrier wave, there is a slight discharge between cycles.

Most of the carrier signal is thus removed and the output has the upper part of the modulated wave which is that of the original (modulating) sound wave.

The demodulated af signal is then amplified and converted back into sound by a speaker.

Reviewed Exercise

1. Give a short note on communication system.
2. Write short notes on the components of a simple radio receiver.

Key Words: modulation, amplitude modulation, frequency modulation, phase modulation, transmitters, receivers

SUMMARY

The branch of physics and technology concerned with the design of circuits using transistors, integrated circuits and microchips, and also with the behaviour and movement of electrons in a semiconductor, conductor or vacuum is known as **electronics**.

Digital electronics is a field of electronics involving the study of digital signals and the engineering of devices that use or produce them. This is in contrast to analog electronics and analog signals.

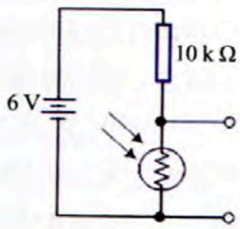
The process of changing some characteristics (e.g. amplitude, frequency or phase) of a carrier wave (e.g. radio wave) in accordance with the intensity of the signal is known as **modulation**.

The process of recovering the audio signal from the modulated wave is known as **demodulation** or detection.

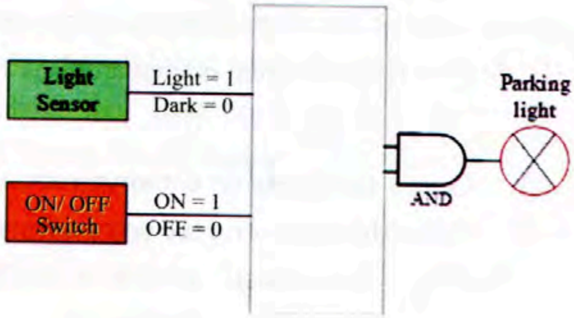
EXERCISES

1. Which electrical component is used to control the brightness of street lamps?
   (i) LED (ii) LDR (iii) thermistor

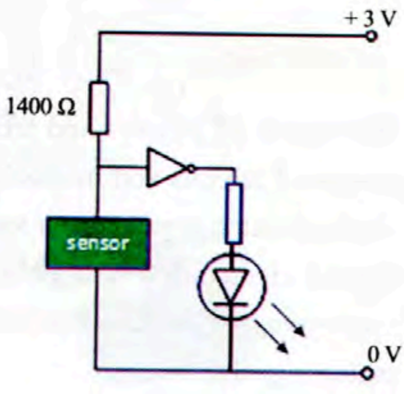
2. A potential divider consists of an LDR and a resistor connected to a 6 V battery in following figure. What should be the resistance of the LDR for the output to be 2.5 V?



3. A car may be fitted with an automatic parking light which switches ON when the car is parked at night. Figure shows an incomplete system for a parking light. Copy and complete the figure to show how a NOT gate can be used to make the parking light work. Use the correct symbol for a NOT gate.



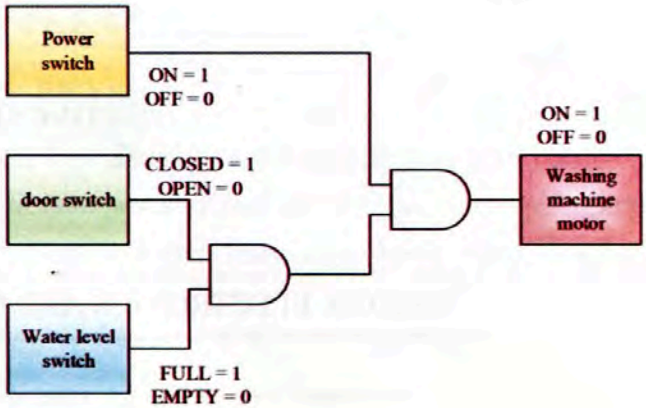
4. A student uses the sensor in the circuit shown in figure. The LED lights up when the temperature reaches 40 °C. Name a suitable temperature sensor and draw its circuit symbol.



5. In the giving table, *P*, *Q*, *R* and *S* are the outputs of four logic gates. Name the logic gate which represents each output.

input		output			
		P	*Q*	*R*	*S*
0	0	0	0	1	1
0	1	0	1	1	0
1	0	0	1	1	0
1	1	1	1	0	0

6. Figure shows a control system which may be fitted in an automatic washing machine. What conditions will (i) start (ii) stop the washing machine working?



7. Simplify the following expressions if possible:
   (i) $A + AB + A\bar{B}C$ (ii) $(\bar{A} + B)C + ABC$
8. Draw the logic circuit represented by each of the following expressions:
   (i) $A + B + C$ (ii) ABC (iii) $AB + C$ (iv) $AB + CD$
9. Construct a truth table for each of the followings:
   (i) $AB + BC$ (ii) $(A + B)C$ (iii) $(A + B)(\bar{B}+C)$
10. Find the value of X for all possible values of variables.
   (i) $X = (A + B)C + B$ (ii) $X = (\overline{A + B})C$ (iii) $X = A\bar{B}C + AB$
11. Apply De Morgan's theorems to the expression $\overline{\overline{ABC}}$ and $\overline{\bar{A} + \bar{B} + \bar{C} + \bar{D}}$.
12. Can sound travel very far? Why? Which device can be used to transmit sounds over long distance? What range of frequencies do the radio waves have?
13. What is meant by "AM and FM"?
14. What are the differences between FM and AM? Explain with illustrative diagrams?
15. Which range of frequency a radio telephone or walkie talkie is communicating? Also find the corresponding wavelength.

CONCEPT MAP

DIGITAL ELECTRONICS AND COMMUNICATION SYSTEMS

Electronic System

- zener diode
- light emitting diode (LED)
- photodiode
- light dependent resistor (LDR)
- thermistor
- liquid crystal display (LCD)

Digital Electronics

Combination of logic gates
- fire alarm system
- street lighting system

Boolean algebra
- basic laws
- basic rules

De Morgan's theorem

Electronic Communication System

Modes of Communication System
- analog communication
- digital communication
- wired (Line) communication
- wireless communication

Modulation
- amplitude modulation (AM)
- frequency modulation (FM)
- phase modulation (PM)

Demodulation

Simple radio receiver

CHAPTER 13

MODERN PHYSICS

This chapter describes nuclear physics, quantum mechanics and the special theory of relativity. Nuclear physics includes the radioactivity, radioisotopes and nuclear energy. Nature of matter wave will be learnt in quantum mechanics. Students will also learn some basic concepts of the special theory of relativity.

Learning Outcomes

It is expected that students will

- understand radioactivity, radioactive decays, alpha, beta, gamma rays and their properties.
- investigate activity and half-life of a radioactive substance.
- realize some application of radioisotopes.
- examine fission, nuclear energy, its peaceful use as a nuclear reactor and the environmental impacts.
- realize the de Broglie matter wave associated with wave particle dual nature and the quantization of angular momentum in theory of hydrogen atom.
- describe the experiments and scientific problems that led Albert Einstein to develop the special theory of relativity.
- understand the postulates on the special theory of relativity.
- describe the relativistic effects: time dilation, length contraction, and relativistic momentum.
- explain and perform calculations involving mass-energy equivalence.

13.1 RADIOACTIVITY AND USES OF RADIOACTIVITY


Henri Becquerel
(1852-1908)

In 1896, Henry Becquerel discovered that uranium salts emit radiations which affect photographic plates and cause ionization. The radiations are emitted from the nucleus of uranium atoms and are of three types; namely alpha, beta and gamma rays. This phenomenon is known as radioactivity.

Hence, the emission of some or all of alpha, beta and gamma rays from the nucleus of an unstable atom is called radioactivity. The term radioactivity is also known as radioactive decay, radioactive disintegration, nuclear decay, or nuclear disintegration.


Marie Curie
(1867-1934)

Of all 92 elements which exist in nature, only a few heavy elements with atomic number greater than 83 are radioactive or unstable. Some examples of radioactive elements (or radioactive substances) are uranium, thorium, radium, polonium and radon; of which radium and polonium were discovered by Marie Curie. Radioactive elements can also be artificially produced using nuclear reactors and particle accelerators.

1. **Alpha Decay, Beta Decay and Gamma Decay**

(i) **Alpha decay**

Alpha decay (α decay) is a process in which an atomic nucleus emits an alpha particle (helium nucleus) and transforms (or decays) into a different atomic nucleus, with mass number reduces by four and atomic number reduces by two as described by Eq. (13.1).

In symbols, $${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He \qquad (13.1)$$

where ${}^{A}_{Z}X$ = parent nucleus, ${}^{A-4}_{Z-2}Y$ = daughter nucleus, and ${}^{4}_{2}He$ = alpha particle.

An example of alpha decay is $${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

Note that atomic number and mass number are conserved in the decay process.

(ii) **Beta decay**

There are two types of beta decay: namely, β^- decay and β^+ decay.

β^- decay (beta-minus decay) is a process in which a neutron in an atomic nucleus changes to a proton with the emission of an electron (β^-) and an antineutrino ($\overline{\nu}_e$). The parent nucleus transforms into the daughter nucleus, with mass number remains unchanged but atomic number increases by one as described by Eq.(13.2).

In symbols, $${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e + \overline{\nu}_e \qquad (13.2)$$

where ${}^{A}_{Z}X$ = parent nucleus, ${}^{A}_{Z+1}Y$ = daughter nucleus,

${}^{0}_{-1}e$ = electron (β^- particle), $\overline{\nu}_e$ = antineutrino

An example of β^- decay is $${}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e + \overline{\nu}_e$$

β^+ decay (beta-plus decay) is a process in which a proton in an atomic nucleus changes to a neutron with the emission of a positron (β^+) and a neutrino (ν_e). The parent nucleus transforms into the daughter nucleus, with mass number remains unchanged but atomic number decreases by one as described by Eq. (13.3).

In symbols, $${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e + \nu_e \qquad (13.3)$$

where ${}^{A}_{Z}X$ = parent nucleus, ${}^{A}_{Z-1}Y$ = daughter nucleus,

${}^{0}_{+1}e$ = positron (β^+ particle), ν_e = neutrino

An example of β^+ decay is $${}^{11}_{6}C \rightarrow {}^{11}_{5}B + {}^{0}_{+1}e + \nu_e$$

Positron, the antiparticle of electron, has the same mass and same magnitude of electric charge as an electron; but positron is positively charged. The existence of positron was theoretically predicted by Dirac in 1931 and experimentally detected by Anderson in 1932.

Neutrino, a fundamental particle as an electron, has no charge and negligibly small rest mass ($< 2 \times 10^{-37}$ kg). There are three types of neutrino; called electron neutrino (ν_e), the muon neutrino (ν_μ) and the tau neutrino (ν_τ). Each neutrino is associated with an antineutrino: $\bar{\nu}_e$, $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$.

For a nucleus to be stable, there must be an appropriate ratio of protons and neutrons. If a nucleus has excess neutrons (e.g. $^{14}_{6}C$) β^- decay takes place. Conversely, a nucleus with excess protons (e.g. $^{11}_{6}C$) undergoes β^+ decay.

(iii) **Gamma decay**

In gamma decay (γ decay), the daughter nucleus resulting from alpha or beta decay is left in an excited state and it can then decay to a lower energy state by emitting a gamma ray photon. In gamma decay, the atomic number and mass number of the parent and daughter nuclei remain unchanged; only the parent nucleus releases energy in the form of electromagnetic radiation as described by Eq. (13.4).

In symbols,
$$^{A}_{Z}X^* \rightarrow {}^{A}_{Z}X + {}^{0}_{0}\gamma \qquad (13.4)$$

where $^{A}_{Z}X^*$ = parent nucleus (excited state),

$^{A}_{Z}X$ = daughter nucleus (ground state), $^{0}_{0}\gamma$ = gamma photon

For example, cobalt-60 undergoes β^- emission to an excited state of nickle-60, which in turn decays to the ground state by γ emission.

$$^{60}_{27}Co \rightarrow {}^{60}_{28}Ni^* + {}^{0}_{-1}e + \bar{\nu}_e, \qquad {}^{60}_{28}Ni^* \rightarrow {}^{60}_{28}Ni + {}^{0}_{0}\gamma$$

Hence, gamma decay takes place when a nucleus at an excited state deexcites to a lower excited state or to the ground state.

The photon is the quantum of the electromagnetic field including electromagnetic radiation such as light, X-rays and gamma rays. Photons are massless and move at the speed of light in vacuum. The energy of a photon is inversely proportional to the wavelength of the electromagnetic radiation associated with it.

α decay, β^- decay, β^+ decay and γ decay are illustrated in the following Figure 13.1.

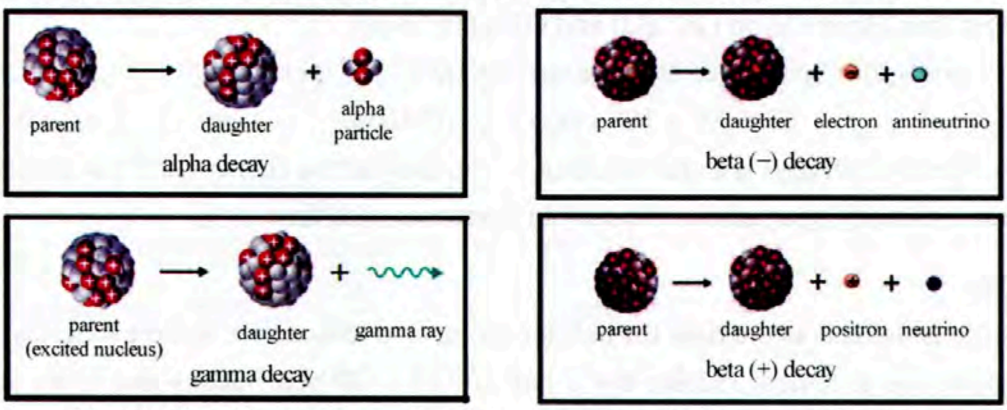


Figure 13.1 Illustrations of α decay, β^- decay, β^+ decay and γ decay

2. **Properties of alpha rays, beta rays and gamma rays**

(i) **Properties of alpha rays**

- Alpha rays consist of helium nuclei, positively charged particles. An α particle consists of two protons and two neutrons. The charge of an α particle is $+2\,e$ ($+\,3.2 \times 10^{-19}$ C).
- Alpha rays can be deflected by electric and magnetic fields.
- Alpha rays are the most ionizing of the three rays.
- Alpha rays are the least penetrating of the three rays.
- Alpha rays can be stopped by a thick sheet of paper.

(ii) **Properties of beta rays**

- Beta rays consists of either electrons (charge $= -\,e$) or positrons (charge $= +\,e$) moving with varying speeds.
- Beta rays can be deflected by electric and magnetic fields.
- Beta rays are less ionizing than alpha rays.
- Beta rays are more penetrating than alpha rays.
- Beta rays can be stopped by a few millimetres of aluminium.

(iii) **Properties of gamma rays**

- Gamma rays are electromagnetic waves like light and X-rays, but have much shorter wavelengths. Gamma rays are high energy photons. Gamma rays have no charge.
- Gamma rays cannot be deflected by electric and magnetic fields.
- Gamma rays are the least ionizing of the three rays.
- Gamma rays are the most penetrating of the three rays.
- Intensity of gamma rays can be greatly reduced by several centimetres of lead but they are never completely stopped.

3. **Activity**

The rate of decay of a radioactive sample is called activity. It is the rate at which alpha, beta particles or gamma rays are emitted.

SI unit for activity is becquerel (Bq). $1\text{ Bq} = 1\text{ event s}^{-1}$ (or 1 disintegration s^{-1})

Units larger than Bq are MBq (10^6 Bq) and GBq (10^9 Bq).

A unit of activity still being used today is curie (Ci).

$$1\text{ Ci} = 3.7 \times 10^{10}\text{ event s}^{-1} = 37\text{ GBq}.$$

The rate of decay (activity) is a characteristic of the radioactive element and it is unaffected by the temperature. Activity of a radioactive sample decreases with time.

4. **Half-life**

The half-life is defined as the time for half the atoms in a radioactive sample to decay.

For example, the statement radium has a half-life of 1620 year means that if we start with N_0

atoms of radium, then only $\frac{N_0}{2}$ atoms will remain after a time of 1620 years has elapsed. (After another 1620 years only $\frac{N_0}{4}$ atoms will remain and so on.)

Half-life of radioactive substances ranges from about femtosecond (10^{-15} s) to billions of year.

Graphical illustration of half-life

Consider radon of half-life $T_{½}$ is 3.8 days.

time (days)	mass of radon (g)
0.0	1
3.8	$\frac{1}{2}$
7.6	$\frac{1}{4}$
11.4	$\frac{1}{8}$

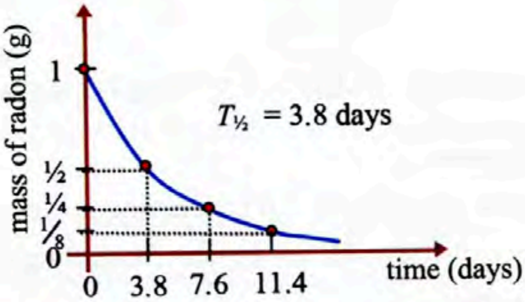


Figure 13.2 A graphical illustration of half-life or exponential nature of radioactive decay

$$\text{Amount left after n half-life} = \left(\frac{1}{2}\right)^n \times \text{initial amount.} \tag{13.5}$$

Radioactive decay is a statistical process: it is impossible to predict when a particular atom will decay, regardless of how long the atom has existed. However, for a significant number of identical atoms, the decay rate can be expressed as a decay constant λ or as half-life $T_{½}$. This leads to the exponential law of radioactive decay given by the relation as below.

$$N_t = N_0\, e^{(-\lambda t)} = N_0\, e^{\left(-\frac{0.693}{T_{½}}t\right)} \tag{13.6}$$

where N_t = number of radioactive atoms at time t,

N_0 = initial number of radioactive atoms,

$\lambda = \frac{0.693}{T_{½}}$ = decay constant, and $T_{½}$ = half-life

Example 13.1 Suppose there was 2 g of radon at $t = 0$ and its half-life is 3.8 days. How much would be left after 15.2 days?

Initial amount = 2 g , half-life $T_{½}$ = 3.8 days,

time elapsed = 15.2 days, number of half-life $n = \frac{15.2}{3.8} = 4$

Since amount left after n half-life = $(\frac{1}{2})^n$ × initial amount,

amount left after 15.2 days (4 half-life) = $(\frac{1}{2})^4 \times 2 = 0.125$ g

Example 13.2 A radioisotope has a half-life of 20 min. If there is initially 102.4 g of this isotope, how much time elapses for 12.8 g to be left?

Initial amount =102.4 g, amount left =12.8 g, half-life $T_{1/2}$ = 20 min,

$$\text{Since,} \qquad \frac{12.8}{102.4} = \frac{1}{8} = (\frac{1}{2})^3$$

$$\text{amount left} = (\frac{1}{2})^n \times \text{initial amount}$$

$$12.8 = (\frac{1}{2})^n \times 102.4$$

Therefore, number of half-life $n = 3$, time elapsed = $n \times T_{1/2} = 3 \times 20 = 60$ min = 1 h

Reviewed Exercise

1. Compare the ionizing and penetrating powers of alpha, beta and gamma rays.
2. Define half-life and draw a graph illustrating the half-life of radium which has a half-life of 1620 years.
3. Cobalt-60 (half-life = 5.25 years) is often used as a radiation source in medicine. How long after a new sample is delivered, will the activity have decreased to $\frac{1}{8}$ of its original value?
4. Suppose that initially there was 100 μCi of iodine-131 and its half-life is 8 days. How much would it be left after 24 days?

Key Words: radioactivity, α decay, β decay, γ decay, activity, half-life

5. **Uses of radioactivity (or) uses of radioisotopes**

A radioisotope (radioactive isotope or radionuclide) is an atom with an unstable nucleus which undergoes radioactive decay, resulting in the emission of alpha, beta and gamma rays. Radioisotopes with suitable half-lives play an important part in a number of technologies. Various uses of radioisotopes are described as (i) tracer (ii) radiotherapy (iii) industrial gamma radiography (iv) thickness monitor (v) radioactive dating and (vi) gamma irradiation of seeds and foods.

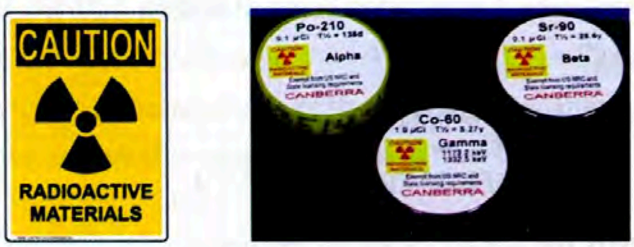


Figure 13.3 Radioactive material sign and some radioactive sources

(i) **Tracer**

A tracer is a small amount of radioactive isotope introduced into a system in order to follow the behaviour of some components of that system.

In medicine, radioactive tracers are effectively used in diagnostic procedures. For example, to check thyroid function, the patient drinks an iodine solution containing a small amount of radioactive iodine-131(gamma emitter). Over the next 24 hours, a gamma ray detector measures the activity of the iodine tracer to find out how qüickly it becomes concentrated in the thyroid gland. For tests like those above, artificial radioisotopes with short half-lives are used so that there is no detectable radiation after a few days.

In industry, small amounts of radioactive substances are added as tracers to materials in various processes to monitor fluid flow, detect leaks, and to study the rate of wear, erosion and corrosion of equipment.

In agriculture, radioisotope tracers are very useful in estimating the amount of fertilizers that should be supplied to soil. Fertilizers labelled with radioactive isotopes phosphorus-32 and nitrogen-15 have been used to study the uptake, retention and utilization of phosphate and nitrogen fertilizers.

(ii) **Radiotherapy**

Treatment with radiation is known as radiotherapy. Radioisotopes, such as cobalt-60 and cesium-137, are widely used to treat cancer in radiotherapy. Gamma rays from cobalt-60 can penetrate deep into the body and kill living cells. A highly concentrated beam from a cobalt-60 source can be used to kill cancer cells in a tumour as shown in Figure 13.4.

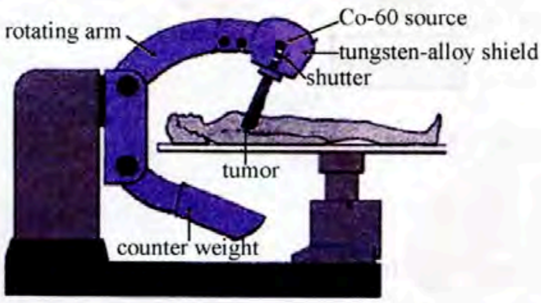


Figure 13. 4 Cobalt-60 radiotherapy

(iii) **Industrial gamma radiography**

In industrial gamma radiography, radioactive materials are used to inspect metal castings or welded joints. Radioactive gamma emitter in a sealed capsule is placed on one side of the object being screened, and photographic film is placed on the other side as shown in Figure 13.5.

The gamma rays pass through the object and create an image on the film which shows flaws in the object. Radioisotopes have the advantage that they can be taken to the site when an examination is required and no power is needed. However, they must be properly shielded when in use and also at other times.

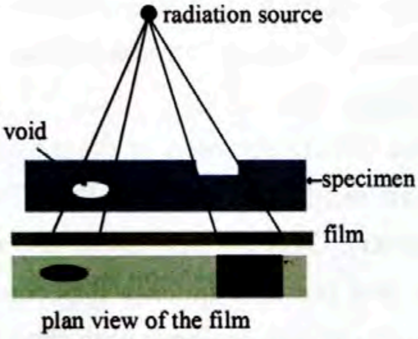


Figure 13.5 Industrial gamma radiography

(iv) **Thickness monitor**

The ability to use radioisotopes to accurately measure thickness is widely used as thickness monitoring system in the production of sheet materials, including metal, textiles, paper, plastics, and others.

In a thickness monitoring system shown in Figure 13.6, the moving band of tyre cord has a beta source on one side and a detector on the other. If, for example, the cord from the rollers becomes too thin, more beta radiation reaches the detector. Detector sends signal to the control unit which adjust the gap between the rollers.

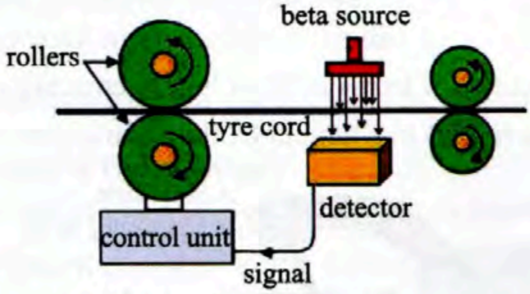


Figure 13.6 Thickness monitoring system

(v) **Radioactive dating**

Radioactive dating is a technique for estimating the age of an object by measuring the amounts of various radioisotopes present in it. Natural radionuclides are used in archaeology, geology, and paleontology to measure ages of fossil materials, rocks and minerals.

Carbon dating: Carbon dating is a technique, developed by Willard Libby, for estimating the age of the remains of plants and animals by measuring the activity of carbon-14 presents in the remains. Carbon is present in atmosphere and also in the bodies of plants and animals. A small proportion is radioactive carbon-14 (half-life 5730 years).

Although carbon-14 undergoes radioactive decay, it is also continually produced by cosmic rays entering the upper atmosphere. High energy neutrons of cosmic rays bombard nitrogen-14 atoms and produce carbon -14 atoms. Thus, the abundance of carbon-14 in the atmosphere is essentially constant. There is one carbon-14 atom in every trillion (10^{12}) of carbon-12 atoms.

When the plants and animals are alive, they absorb and give out carbon. There is equilibrium of carbon between the atmosphere and the bodies of plant and animals as shown in Figure 13.7. Thus, the amount of carbon-14 present in the living body is essentially constant.

However, when an animal or a plant dies carbon cycle stops and the carbon-14 in the remain gradually decreases by radioactive decay. By measuring the activity of carbon-14, the age of the remain can be estimated.

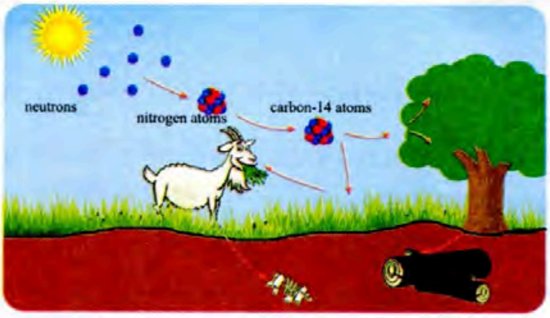


Figure 13.7 Accumulation of carbon-14 in plants and animals

Dating of rocks: The age of the rocks can also be estimated by radioactive dating technique. When rocks are formed, some radioisotopes become trapped in them. For example, potassium-40 (radioactive) is trapped in igneous rocks. As potassium-40 decays, more and more of its stable decay product, argon-40 is created as shown in Figure 13.8. Provided that argon has not escaped from the rock, the age of the rock can be estimated from the proportion of potassiun-40 to argon-40. Igneous rocks can also be dated by the proportion of uranium to lead isotopes. Lead is the stable final decay product of a series of decays that starts with uranium.

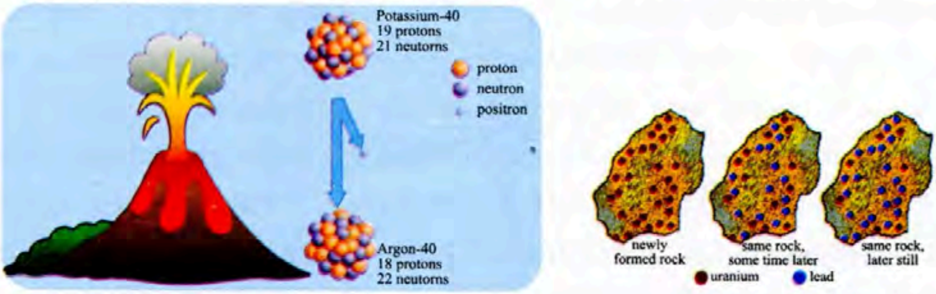
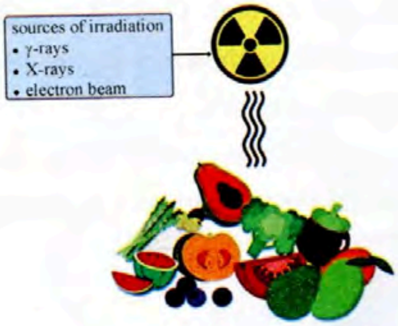


Figure 13.8 Radioactive dating of rocks

(vi) **Gamma irradiation of seeds and foods**

Gamma and neutron irradiation of seeds can be used to induce mutations to develop desired mutants that are resistant to disease, produce a higher yield and allow earlier ripening.

Radiation can also be used to destroy microbes in food and control insect and parasite infestation in harvested food. Irradiation of food has potential to produce safe foods with long shelf life. Certain seeds and canned food can be stored for longer periods by gently exposing them to radiations as shown in Figure 13.9.



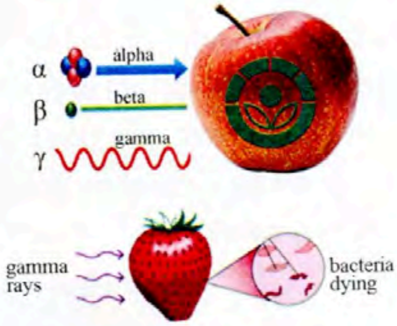


Figure 13.9 Irradiation of foods

Example 13.3 If a fossil has 10 % carbon-14 compared to a living sample, find the age of the fossil. (half-life of carbon-14 = 5730 years)

$\frac{N_t}{N_0} = 0.1,\ T_{1/2} = 5730$ years

We have the relation

$$N_t = N_0\, e^{(-\frac{0.693}{T_{1/2}}t)}$$

$$\ln\left(\frac{N_t}{N_0}\right) = -\frac{0.693}{T_{1/2}}t$$

$$\ln 0.1 = -\frac{0.693}{T_{1/2}}t$$

$$2.303\ \log_{10} 0.1 = -\frac{0.693}{T_{1/2}}t$$

$$-2.303 = -\frac{0.693}{5730}t$$

$$t = 19\,042 \text{ years}$$

Age of the fossil is 19 042 years.

Example 13.4 Potassium-40 has a half-life of 1300 million years. If the atomic ratio of potassium-40 to argon-40 in a rock sample is found to be 1:3, estimate the age of the rock. Assume that there was initially no argon in the rock and argon formed by the decay of potassium is trapped in the rock.

$T_{1/2} = 1300$ million years, the atomic ratio of potassium-40 to argon-40 in rock sample = $\frac{1}{3}$

Assume that there were N_0 atoms of potassium-40 when the rock was formed.

After n half-life, the number of potassium-40 atoms left = $(\frac{1}{2})^n N_0$

The number of argon-40 atoms formed = $N_0 - (\frac{1}{2})^n N_0 = N_0\,[1-(\frac{1}{2})^n]$

The atomic ratio of potassium-40 to argon-40 = $\dfrac{(\frac{1}{2})^n}{1-(\frac{1}{2})^n} = \dfrac{1}{2^n - 1}$

$$\frac{1}{3} = \frac{1}{2^n - 1}$$

Thus , $2^n - 1 = 3$ and $n = 2$, the age of the rock = 2 × 1300 = 2600 million years.

Reviewed Exercise

1. What is carbon dating? How does the proportion of the carbon-14 in the remains of dead plants and animals gives clues about their age? Can the age of living plants and animals be determined by carbon dating method?
2. Aluminium is rolled into sheets 1 mm thick. Of three types of radiations; alpha, beta and gamma, which radiation is suitable for checking the uniformity of thickness. Give the reason for your answer.

Key Words: tracer, radiotherapy, gamma radiography, thickness monitor, carbon dating

13.2 NUCLEAR ENERGY AND ITS ENVIRONMENTAL IMPACT

Of the various form of energy, nuclear energy now provides about 10 % of the world's electricity from about 450 nuclear power reactors. Nuclear power plants currently operate in some 30 countries.

1. Nuclear reaction

A nuclear reaction is a process in which a particle or a gamma radiation penetrate into a nucleus and changes its configuration. From energy point of view, there are two types of nuclear reactions: exothermic reaction and endothermic reaction. If the total mass before a nuclear reaction takes place is greater than the total mass after reaction, this mass defect is released as energy in a nuclear reaction according to Einstein's relation $E = m\,c^2$. This type of reaction is known as exothermic reaction.

On the other hand, if the total mass before a nuclear reaction takes place is less than the total mass after reaction, external energy must be provided for the reaction to take place. This type of reaction is known as endothermic reaction.

Nuclear fission reaction

The most important nuclear reaction from which considerable amount of nuclear energy can be extracted is nuclear fission reaction. When a neutron strikes and penetrates a nucleus of uranium-235, the nucleus becomes highly unstable and splits into two lighter nuclei, shooting out two or three neutrons as it does so. This splitting process is called fission, and the fragments are thrown apart as the energy is released as shown in Figure 13.10 (a).

An example of fission reaction is

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{92}_{36}Kr + ^{141}_{56}Ba + 3\ ^{1}_{0}n \qquad (13.7)$$

If the neutrons emitted from a fission reaction go onto split other uranium-235 nuclei and so on, the result is a chain reaction with a huge and rapid release of energy as shown in Figure 13.10 (b). For a chain reaction to be maintained, the uranium-235 has to be above a certain critical mass, otherwise too many neutrons escape and chain reaction cannot occur.

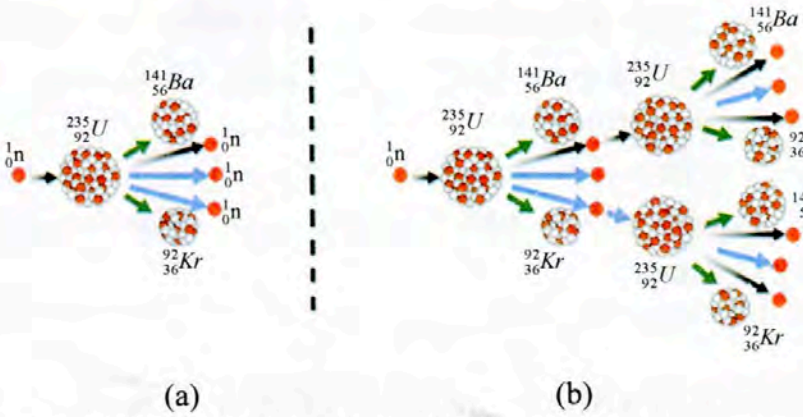


Figure 13.10 (a) Nuclear fission and (b) fission chain reaction

Energy released from a fission process

We will consider the reaction $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{92}_{36}Kr + ^{141}_{56}Ba + 3\ ^{1}_{0}n$

$$\text{total mass before reaction} = 235.043915 + 1.008665 = 236.052580 \text{ u}$$

$$\text{total mass after reaction} = 91.91972 + 140.910575 + 3 \times 1.008665$$

$$= 235.856290 \text{ u}$$

$$\text{mass defect} = 236.052580 - 235.856290 = 0.19629 \text{ u}$$

Since, atomic mass unit $1 \text{ u} = 931.5 \text{ MeV}$

$$\text{Energy released} = 0.19629 \times 931.5 = 182.84 \text{ MeV}$$

Note that the energy released per atom in a nuclear reaction is about a million times greater than the energy released per atom from a chemical reaction.

2. **Nuclear reactor**

Nuclear reactor is a device in which a fission chain reaction can be initiated, maintained and controlled. In a nuclear power station, the controlled chain reaction takes place in a nuclear reactor and thermal energy (heat) is released at a steady state. This heat energy is used to make steam for turbines which generates electricity, as in a conventional power station.

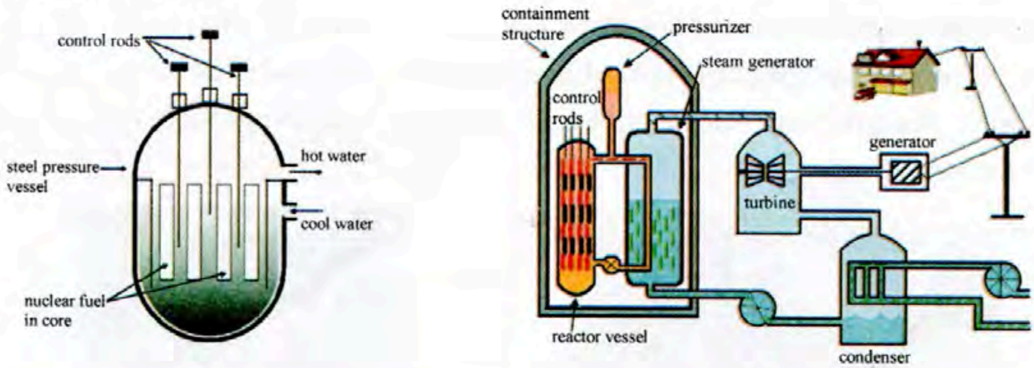
The essential elements of a nuclear reactor are fissionable nuclear fuel, moderator, coolant, control rods, reactor vessel and shielding.

Fissionable nuclear fuel is the material for fission reaction to take place. Uranium-235 or plutonium-239 can be used as fuel.

Neutrons released from a fission reaction are fast neutrons. They need to be slowed down to maintain a chain reaction. Moderator is a material to slow down fast neutrons released from a fission process. Graphite and ordinary water (H_2O) as well as heavy water (D_2O) are used as moderators.

Coolant is to extract the heat produced by fission fragments when they slow down and stop in the reactor material. Water and carbon dioxide CO_2 gas are used as coolant.

Control rods are used to control the rate of reaction by raising or lowering them from the core. Boron and cadmium (neutron absorbing materials) are used as control rods. Reactor vessel is to contain the reactor core, moderator, coolant and control rods. It is a pressurized steel vessel as shown in Figure 13.11(a).



(a) (b)

Figure 13.11 (a) Pressurized water reactor vessel (b) pressurized water reactor system

Shielding (or containment structure) is a protective barrier, usually a dense material. It reduces the passage of radiations from radioactive materials by absorbing them.

A schematic diagram of a pressurized water reactor system is shown in Figure 13.11 (b).

Radioactive waste

Materials which are radioactive and for which there is no further use are called radioactive waste. After three or four years in a reactor, spent fuel must be removed and replaced with a new one. The amount of uraniun-235 in it has fallen and the fission products has built up. Spent fuel are taken to a reprocessing plant where unused fuel and plutonium are removed. The remaining radioactive waste is sealed off and stored with thick shielding around it. Since some of the isotopes have long half-lives, safe storage will be needed for thousands of years.

Many of the fission products are radioactive and dangerous to be released into the environment. These include: strontium-90, iodine-131 and plutonium-239. Strontium becomes concentrated in bones and iodine in the thyroid gland. Plutonium is itself a nuclear fuel and is also used in nuclear weapons. It is highly toxic. If breathed in, a very small amount can kill a person.

Atomic bomb

In an atomic bomb, an uncontrolled chain reaction takes place so that an extremely large amount of energy is released in a short interval of time. In the first atomic bomb shown in Figure 13.12 (a), an uncontrolled chain reaction was started by bringing two lumps of pure uranium-235 together so that the critical mass was exceeded. In present day nuclear weapons, plutonium-239 is used for fission.

When completely fissioned, 1 kg (2.2 pounds) of uranium-235 releases the energy equivalently produced by 17 000 tons, or 17 kilotons of trinitrotoluene (TNT). The detonation of an atomic bomb releases enormous amounts of thermal energy, or heat, achieving temperatures of several million degrees Celsius. This thermal energy creates a large fireball, the heat of which can ignite ground fires that can incinerate an entire small city. Convection currents created by the explosion suck dust and other ground materials up into the fireball, creating the characteristic mushroom-shaped cloud of an atomic explosion is shown in Figure 13.12 (b). The detonation also immediately produces a strong shock wave that propagates outward from the blast to distances of several miles, gradually losing its force along the way. Such a blast wave can destroy buildings for several miles from the location of the burst.

(a)

(b)

Figure 13.12 (a) The atomic bomb (Little Boy), dropped on Hiroshima
(b) the mushroom-shaped cloud of atomic explosion

3. **Environmental impact of nuclear energy**

A major environmental concern related to nuclear power is the creation of radioactive wastes such as spent (used) reactor fuel and other radioactive wastes (such as strontium-90, iodine-131 and cesium-137). These materials can remain radioactive and dangerous to human health for thousands of years. Spent nuclear fuel storage is mostly a problem.

When managed correctly, nuclear power plants are capable of being more environmentally-friendly than other traditional energy generation options. The greenhouse gas emissions from nuclear fission power are much smaller than those associated with coal, oil and gas, and the routine health risks are much smaller than those associated with coal.

However, there is a catastrophic risk potential if containment fails, which in nuclear reactors can be brought about by overheated fuels melting and releasing large quantities of fission products into the environment. This potential risk could wipe out the benefits.

The 1979 Three Mile Island accident and 1986 Chernobyl disaster ended the rapid growth of global nuclear power capacity. A release of radioactive materials followed the 2011 Japanese tsunami which damaged the Fukushima I Nuclear Power Plant, resulting in hydrogen gas explosions and partial meltdown. The large-scale release of radioactivity resulted in people being evacuated from a 20 km exclusion zone set up around the power plant, similar to the 30 km radius Chernobyl Exclusion Zone still in effect.

Reviewed Exercise

- What device is a nuclear reactor? Give a brief description of the essential component of a nuclear reactor.

Key Words: nuclear reaction, nuclear fission, chain reaction, nuclear reactor, radioactive waste, environmental impacts of nuclear energy

13.3 WAVE-PARTICLE DUALISM

In Grade 11, wave-particle duality for light has been learnt. In 1905, German physicist Albert Einstein proposed that light, considered a form of electromagnetic waves, must also be thought of as particle or photon.

In 1923, French physicist Louis de Broglie extended the idea of the wave-particle duality. He proposed that the wavelength of a material particle would be related to its momentum. Louis de Broglie suggested that the momentum p of a particle and its associated wavelength λ are related by the following equation.

$$\lambda = \frac{h}{p} \qquad (13.8)$$

The wavelength λ associated with a moving particle (matter wave) is also called de Broglie wavelength.

If a particle is moving with a velocity v, the momentum $p = mv$ and its wavelength $\lambda = \frac{h}{mv}$.

All moving particles exhibit properties of both particles and waves nature.

Momentum p relates kinetic energy KE of the particle as follows.

$$KE = \frac{1}{2} mv^2 = \frac{p^2}{2\,m}$$

$$p = \sqrt{2\,m\,KE}$$

The de Broglie wavelength of a particle in terms of its kinetic energy is expressed as,

$$\lambda = \frac{h}{\sqrt{2\,m\,KE}} \qquad (13.9)$$

The existence of matter waves were first experimentally confirmed by Thomson's cathode ray diffraction experiment and the Davisson-Germer experiment for electrons. The de Broglie hypothesis has also been confirmed for other elementary particles. Furthermore, neutral atoms and even molecules have been shown to be wave-like. In electron microscope, the wave nature of electrons is used instead of light.

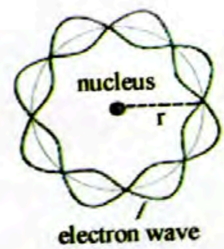
Interpretation of Bohr's Second Postulate Using de Broglie Hypothesis

Bohr's second postulate of hydrogen atom can be explained with matter waves concept of electrons as follows.

An integral number of de Broglie wavelengths associated with a revolving electron must fit in the circumference of an orbit.

Therefore, $2\pi r = n\lambda$ where $n = 1,2,3,4\ldots$

The de Broglie wavelength of electron, $\lambda = \dfrac{h}{p}$



Thus, $2\pi r = \dfrac{nh}{p}$

If the speed of electron in an orbit is v, its momentum $p = mv$

$$2\pi r = \frac{nh}{mv}$$

$$mvr = n\frac{h}{2\pi}$$

$$mvr = n\hbar$$

Where $\hbar = \dfrac{h}{2\pi}$, h = Planck's constant, and mvr = angular momentum of the electron.

As a result, de Broglie hypothesis proves Bohr's second postulate, which states that the angular momentum of the orbiting electron is quantized.

Example 13.5 Calculate the de Broglie wavelength of (i) a 0.65 kg basketball thrown at a speed of 10 m s^{-1}, (ii) a nonrelativistic electron with a kinetic energy of 1 eV.

(i) $m = 0.65$ kg , $v = 10$ m s^{-1}, $h = 6.63 \times 10^{-34}$ J s

The de Broglie wavelength associated with basketball,

$$\lambda = \frac{h}{mv}$$

$$\lambda = \frac{6.63\times10^{-34}}{0.65\times10} = 1.02 \times 10^{-34}\ \text{m}$$

(ii) $KE = 1$ eV $= 1.6\times 10^{-19}$ J

The de Broglie wavelength associated with electron,

$$\lambda = \frac{h}{\sqrt{2\, m\, KE}}$$

$$\lambda = \frac{6.63 \times 10^{-34}}{\sqrt{2 \times 9.1 \times 10^{-31} \times 1.6 \times 10^{-19}}} = 1.23 \times 10^{-9} \text{ m}$$

The de Broglie wavelength for basketball (macroscopic particle) is very much shorter than those of electron (microscopic particle). Hence, wave nature cannot be observed for basketball.

1 eV (electron volt) is the energy gained by an electron (a particle of charge e) when accelerated through a potential of one volt.

Reviewed Exercise

- How is the de Broglie wavelength of electrons related to the quantization of their orbits in atoms?

Key Words: de Broglie wavelength, matter wave, angular momentum

13.4 PRINCIPLE OF SPECIAL THEORY OF RELATIVITY

Frame of Reference and Speed of Light

We first have to learn some basic concepts and observations which lead to Einstein's development of his special theory of relativity. Firstly, we need to understand that motion is relative; and that observation and measurement of motion depends on the frame of reference. Galileo was the first to point out that all motion is relative. Motion is always measured with respect to a reference point (or place), which is called a frame of reference. The choice of the frame of reference is arbitrary. For example, the motion of a passenger in a moving bus can be viewed by two observers: (i) another passenger on the same bus (first observer), and (ii) a person standing on the sidewalk (second observer). For the first observer the passenger on the bus is at rest. On the other hand, for the second observer the passenger on the bus is moving with a velocity. Hence, frame of reference is an important concept in making observations and measurements.

Another important concept is the propagation and speed of light. During 19th century, it was generally believed that light could not travel across empty space. Most scientists believed that light, like all other types of energy that propagated as waves needed to travel through a material medium. It was considered that the space that light waves traveled through was filled with an invisible hypothetical material called ether (also spelled aether). So, it is expected that the speed of light measured by observers would depend on their relative motion with respect to ether.

In 1887, Albert Michelson and Edward Morley examined the existence ether by detecting the motion of the earth through ether. They designed an interferometer shown in Figure 13.13. A light beam is split into two perpendicular paths and then recombined. Recombining the light waves produces an interference pattern of bright and dark fringes. If the earth is moving through ether a shift in the fringes of interference pattern would have observed because the speed of light in two perpendicular directions would be different.

However, no fringe shift is observed which leads to two important conclusions: that there is no ether and that the speed of light is the same regardless of the relative motion of source and observer. This result is generally considered to be the first strong evidence against the prevalent ether theory, as well as initiating a line of research that eventually led to the special theory of relativity.

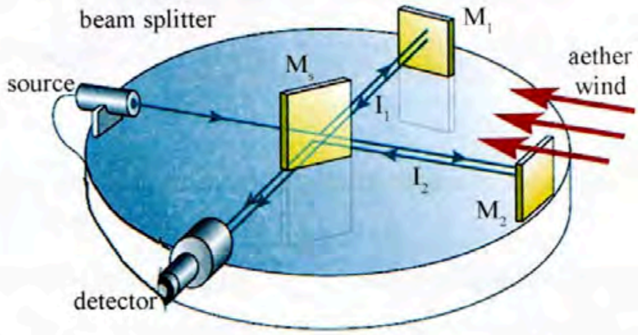


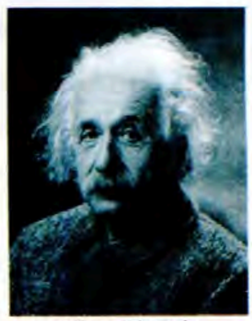
Figure 13.13 Michelson–Morley experiment

Einstein's Postulates

Einstein special theory of relativity is based on two simple postulates:

(i) The laws of physics are the same in all inertial frames of reference.

(ii) The speed of light in vacuum is the same in all inertial frames of reference and is not affected by the speed of its source.



Albert Einstein (1879–1955)

An inertial frame is a frame of reference that has no acceleration (where all objects follow Newton's first law of motion). That is, all inertial frames are in a state of constant, rectilinear motion (constant velocity) with respect to one another. For example, the inside of a car moving along a road at constant velocity and the inside of a stationary house are inertial frames of reference.

The consequences of Einstein special theory of relativity are:

1. Relativity of simultaneity.
2. Relativistic effects on time interval (time dilation).
3. Relativistic effects on length (length contraction).
4. Relativistic effects on mass, momentum and energy.

1. **Relativity of simultaneity**

Relativity of simultaneity states that two events that are simultaneous in one frame of reference may not be simultaneous in another frame moving relative to the first frame. There are many thought experiments to explain this concept. To understand this idea, consider a thought experiment

Train-and-platform, suggested by Daniel Frost Comstock in 1910 and Einstein in 1917.

It consists of one observer midway inside a speeding train car and another observer standing on a platform as the train moves past. A flash of light is sent off at the centre of the train car just as the two observers pass each other.

For the observer on board the train (first observer), the front and back of the train car are at fixed distances from the light source. According to this observer, the light will reach the front and back of the train car at the same time (i.e. simultaneously) as illustrated in Figure 13.14(a).

However, for the observer standing on the platform (second observer), the back of the train car is moving toward the point at which the flash was sent off, and the front of the train car is moving away from it. Hence, the light headed towards the back of the train car will have less distance to cover than the light headed for the front. Since the speed of light is finite and the same in all directions, the flashes of light will strike the ends of the train car at different times for the second observer as illustrated in Figure 13.14(b).

Thus, for the first observer, the light will reach the front and back of the train car simultaneously; while for the second observer, this will not be the case. That is, if one reference frame assigns precisely the same time to two events that are at different points in space, another reference frame that is moving relative to the first will generally assign different times to the two events (the only exception being when motion is exactly perpendicular to the line connecting the locations of both events).

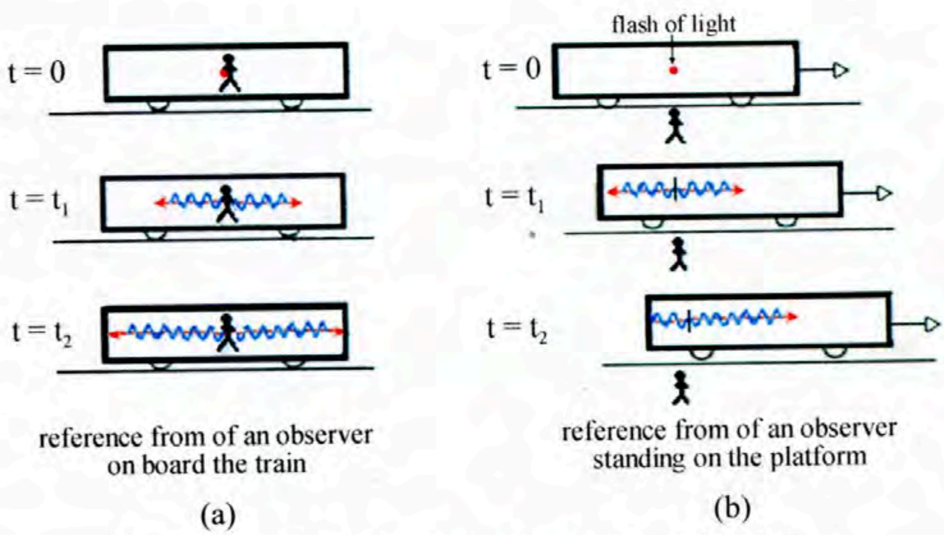


Figure 13.14 A thought experiment train and platform

2. **Relativistic effects on time interval (Time dilation)**

Time dilation is the phenomenon of time passing more slowly for an observer who is moving relative to another observer. That is, time dilation is the phenomenon of slowing down of time that occurs in a system in motion relative to an outside observer. This effect becomes apparent especially as the speed of the system approaches that of light.

Let us consider a thought experiment to explain time dilation. In Figure 13.15, an astronaut measures the time it takes for light to travel from the light source across the ship (space craft), bounce off a mirror, and return back. This time interval is obtained as Δt_0. The same time interval is measured by an earth-bound observer and obtained as Δt. It can be shown that time Δt_0 measured by the astronaut is smaller than the time Δt measured by the earth-bound observer.

The passage of time is different for the two observers because the distance 2 D, light travels in the astronaut's frame is smaller than the distance 2 S, light travels as observed by the earth-bound frame.

The time interval Δt_0 (known as the proper time) measured in the astronaut's frame is

$$\Delta t_0 = \frac{2D}{c}$$

The time interval Δt measured in the earth-bound observer's frame is

$$\Delta t = \frac{2S}{c}$$

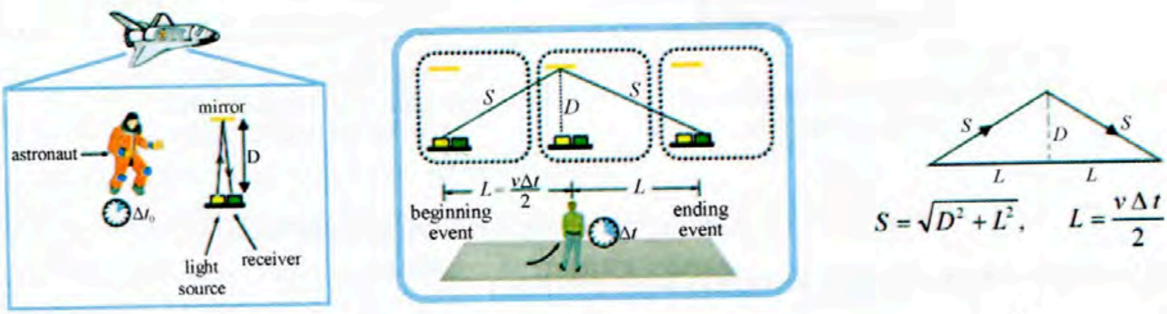
where $$S = \sqrt{D^2 + L^2}, \text{ and } L = \frac{v\Delta t}{2}$$

Therefore, $$\Delta t = \frac{2}{c}\sqrt{(\frac{c\Delta t_0}{2})^2 + (\frac{v\Delta t}{2})^2}$$

squaring and solving for Δt, we obtain

$$\Delta t = \frac{\Delta t_0}{\sqrt{1 - \frac{v^2}{c^2}}} \qquad (13.10)$$

Since $v < c$, $\Delta t > \Delta t_0$ (or) $\Delta t_0 < \Delta t$. Thus, each inertial observer determines that all clocks in motion relative to the observer run slower than that observer's own clock. We call this effect as time dilation.



(a) (b) (c)

Figure 13.15 (a) The time Δt_0 measured by astronaut (b) the time Δt measured by earth-bound observer (c) relation between distances travelled by light

Equation (13.10) can be expressed as $\Delta t = \gamma \Delta t_0$ (13.11)

where the relativistic factor γ is

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

When the velocity v is small compared to the speed of light c, then v/c becomes small, and γ becomes close to 1. When this happens, time measurements are the same in both frames of reference. Relativistic effects, meaning those that have to do with special relativity, usually become significant when speeds become comparable to the speed of light.

3. **Relativistic effects on length (length contraction)**

Like the time interval between two events depends on the observer's frame of reference, the length between two points also depends on the observer's frame of reference. Let L_0 is the proper length of an object measured by an observer who is at rest relative to the object. The length of the same object measured by another observer who is moving with a constant velocity v in a direction parallel to the length of the object is L. We can also show that L_0 and L are related by the expression

$$L = \frac{L_0}{\gamma} = L_0\sqrt{1-\frac{v^2}{c^2}} \quad (13.12)$$

Since $v < c$, $L < L_0$. That is, an object has a proper length L_0 when it is measured by an observer at rest with respect to the object. However, when the object is moving with speed v parallel to its length, its length is measured to be shorter according to Eq. (13.12).

4. **Relativistic momentum and mass**

Let us consider that a particle has mass m_0 measured when it is at rest relative to the observer. Hence, m_0 is known as rest mass. (We use the term material particle for a particle that has nonzero rest mass, like proton, neutron and electron.) In relativistic mechanics, law of conservation of momentum and Newton's second law of motion are valid if we introduce the relativistic momentum $\vec{p}$ as

$$\vec{p} = \gamma\, m_0\, \vec{v} = \frac{m_0\, \vec{v}}{\sqrt{1-\frac{v^2}{c^2}}} \quad (13.13)$$

where m_0 is the rest mass and $\vec{v}$ is the velocity of the particle as seen by a stationary observer. Eq. (13.13) for relativistic momentum is sometimes interpreted as a rapidly moving particle increases in mass. If a particle has mass m_0 when it is at rest, its relativistic mass m when moving with velocity $\vec{v}$ is

$$m = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}} \quad (13.14)$$

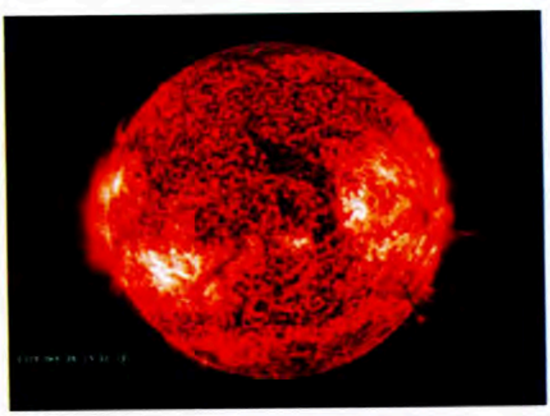
Relativistic Energy

Einstein showed that the law of conservation of energy is valid relativistically. A particle or object of rest mass m_0 moving at velocity v has relativistic energy given by

$$E = \gamma m_0 c^2 \quad (13.15)$$

This is the expression for the total energy of an object of mass m_0 at speed v and includes both kinetic and potential energy. When an object is at rest, v is 0 and the relativistic factor γ is 1. Then the rest energy, m_0, is $E_0 = m_0 c^2$.

There are many experimental evidences that rest energy really exists. The energy released in nuclear reactions and decay of radioactive nuclei are good examples of conversion of mass into energy. The energy generated by nuclear reactions (fusion reaction) in the sun is radiated to earth in the form of electromagnetic radiation, where it is then transformed into all other forms and is used in our daily life. In nuclear power plants, the energy from nuclear fission reactions is an example of peaceful use of nuclear energy. In each of these cases, the source of the energy is the conversion of a small amount of mass into a large amount of energy. Figure 13.16 shows some source of energy released from conversion of mass into energy.



(a)

(b)

Figure 13.16 Energy is released from conversion of mass into energy
(a) in the sun (b) in a nuclear reactor

Comparison between Einstein's special and general relativity theories

Table 10.1 Comparing special relativity and general relativity

Special Relativity	**General Relativity**
Published in 1905	Final form published in 1916
A theory of space-time	A theory of gravity
Applies to observers moving at constant speed (inertial frame)	Applies to observers that are accelerating (non-inertial frame)
Most useful in the field of nuclear physics	Most useful in the field of astrophysics
Accepted quickly and put to practical use by nuclear physicists and quantum chemists	Largely ignored until 1960 when new mathematical techniques made the theory more accessible and astronomers found some important applications

Also note that the theory of general relativity includes the theory of special relativity.

Example 13.6 A positron is a type of antimatter that is just like an electron, except that it has a positive charge. When a positron and an electron collide, their masses are completely annihilated and converted to energy in the form of gamma rays. If both particles have a rest mass of 9.11×10^{-31} kg, find the rest energy of each particle and the total energy of gamma rays in MeV.

$m_0 = 9.11 \times 10^{-31}$ kg, $c = 3 \times 10^8$ m s^{-1}

the rest energy of an electron or a positron is

$$E_0 = m_0 c^2$$

$$= 9.11 \times 10^{-31} \times (3 \times 10^8)^2 = 8.19 \times 10^{-14}\ \text{J}$$

Since (1 MeV = 1.6×10^{-13} J), $$E_0 = \frac{8.19 \times 10^{-14}}{1.6 \times 10^{-13}} = 0.511\ \text{MeV}$$

the total energy of gamma rays is

$$E = 2 \times 0.511 = 1.022\ \text{MeV}$$

Example 13.7 One stary night, an earth-bound observer looking up the stars sees an extra-terrestrial spaceship flashacross the sky. The ship is 50 m long and is traveling at 95 percent of the speed of light. What would the ship's length be when measured from earth-bound frame of reference?

proper length of the ship, $L_0 = 50$ m; velocity, $v = 0.95\,c$

observed length L of the ship using relativistic length contraction,

$$L = \frac{L_0}{\gamma} = L_0\sqrt{1-\frac{v^2}{c^2}}$$

$$= 50\sqrt{1-\frac{(0.95\,c)^2}{c^2}}$$

$$= 50\sqrt{1-(0.95)^2} = 15.61\ \text{m}$$

Example 13.8 How fast must a vehicle travel for 1 s of time measured on a passenger's watch in the vehicle to differ by 1 % for an observer measuring it from the ground outside?

$\Delta t_0 = 1\ s$ and $\Delta t = 1.01\ s$ (differ by 1 %)

$$\frac{\Delta t_0}{\Delta t} = \frac{1}{1.01}$$

The time dilation is given by $\Delta t = \gamma\, \Delta t_0 = \dfrac{\Delta t_0}{\sqrt{1-\dfrac{v^2}{c^2}}}$

$$\frac{\Delta t_0}{\Delta t} = \sqrt{1-\frac{v^2}{c^2}}$$

$$\left(\frac{\Delta t_0}{\Delta t}\right)^2 = 1-\frac{v^2}{c^2}$$

$$\frac{v^2}{c^2} = 1-\left(\frac{\Delta t_0}{\Delta t}\right)^2$$

$$\frac{v}{c} = \sqrt{1-\left(\frac{\Delta t_0}{\Delta t}\right)^2} = \sqrt{1-\left(\frac{1}{1.01}\right)^2}$$

$$= 0.14$$

$$v = 0.14\, c$$

Reviewed Exercise

1. Calculate the relativistic factor γ, for a particle traveling at 99.7 percent of the speed of light.
2. Calculate the relativistic factor γ, for an object traveling at 2×10^8 m s^{-1}.

Key Words: frame of reference, special relativity, general relativity, simultaneity, mass defect, length contraction, time dilation, proper length, relativistic factor

SUMMARY

The radiations are emitted from the nucleus of uranium atoms and are of three types; namely alpha, beta and gamma rays. This phenomenon is known as **radioactivity**.

The **half-life** is defined as the time for half the atoms in a radioactive sample to decay.

A **nuclear reaction** is a process in which a particle or a gamma radiation penetrate into a nucleus and changes its configuration.

The wavelength λ associated with a moving particle (matter wave) is also called **de Broglie wavelength**.

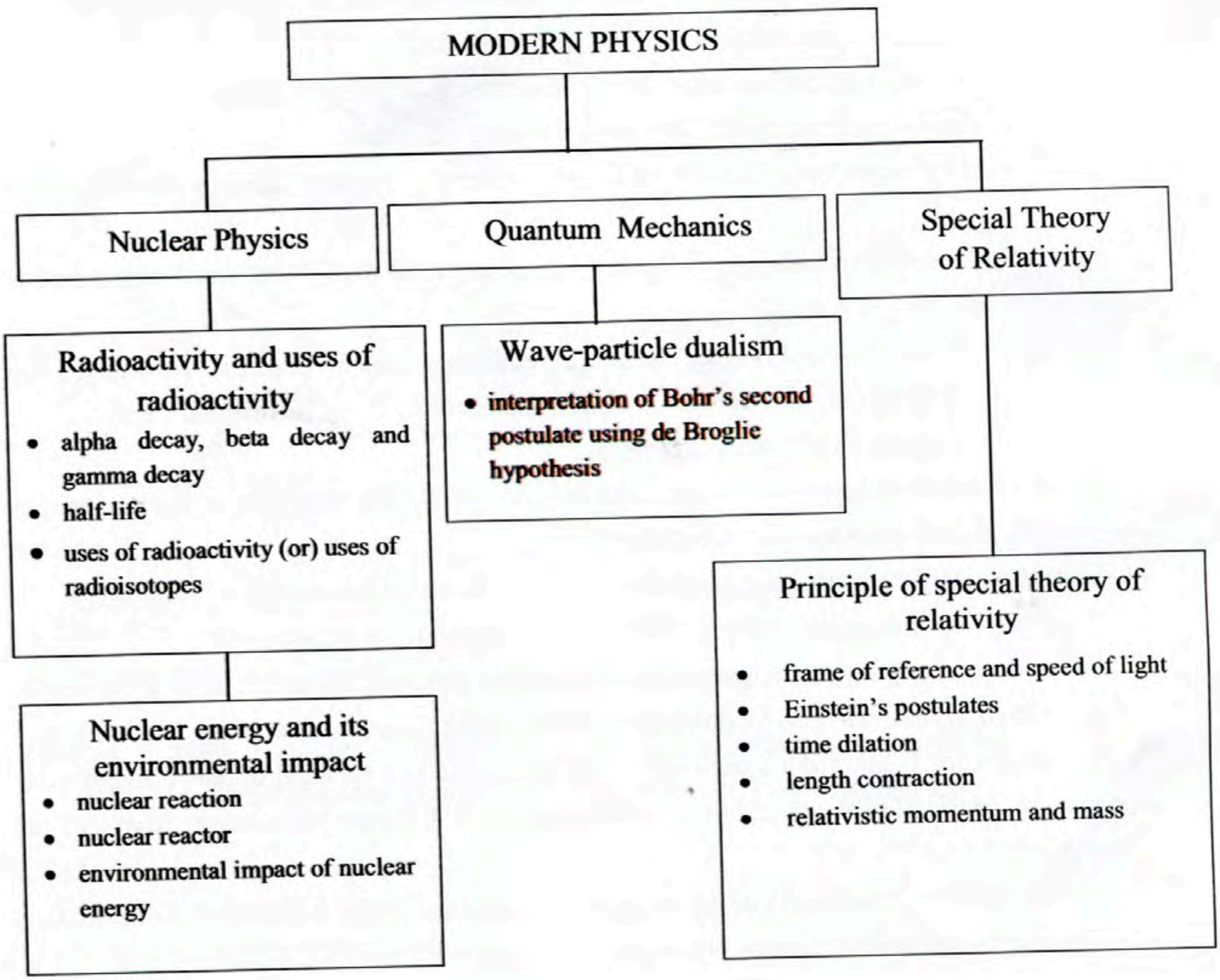
An **inertial frame** is a frame of reference that has no acceleration (where all objects follow Newton's first law of motion).

Time dilation is the phenomenon of time passing more slowly for an observer who is moving relative to another observer.

EXERCISES

1. What is radioactivity? Who discovered radioactivity? Name some radioactive elements.
2. Are all elements in nature radioactive? Can radioactive elements be produced artificially?
3. Briefly describe alpha decay, beta decay and gamma decay.
4. What are alpha, beta and gamma rays? Briefly describe their properties?
5. Explain the terms activity and half-life of a radioactive substance.
6. What is meant by radon has a half-life of 3.8 days? Draw a graph to illustrate the half-life of radon.
7. Suppose there was 8 g of radon at $t = 0$ and its half-life is 3.8 days. How much would be left after (i) 7.6 days (ii) 11.4 days?
8. Co-60 (half-life = 5.25 years) is often used as a radiation source in medicine. How long after a new sample is delivered, will the activity have decreased to $\frac{1}{8}$ of its original value?
9. What are radioisotopes? Give some examples.
10. What is a tracer? State some uses of radioactive tracers. Why is it important to use radioactive tracers with short half-lives in medical diagnosis?
11. Give two medical applications of radioisotopes.
12. What is meant by radioactive wastes? What is their impact on environment?
13. A proton and an electron are each accelerated through a potential difference of 1 kV from rest. What are their kinetic energies? Compare their de Broglie wavelengths. ($m_p = 1840\ m_e$)
14. In old days radios contained vacuum tubes that generated and speeded up electrons. A tube operates at 100 V. Find the speed of an electron and de Broglie wavelength. (mass of an electron = 9.1×10^{-31} kg)
15. Find the de Broglie wavelength of an electron in the ground state of hydrogen atom. Radius of the first orbit of hydrogen atom is 0.53 Å.
16. The distance between two points, called the proper length L_0 is 1 km. An observer in motion with respect to the frame of reference of the two points measures 0.8 km, which is L. What is the relative speed of the frame of reference with respect to the observer?

CONCEPT MAP


MODERN PHYSICS
Nuclear Physics
Quantum Mechanics
Special Theory of Relativity
Radioactivity and uses of radioactivity
• alpha decay, beta decay and gamma decay
• half-life
• uses of radioactivity (or) uses of radioisotopes
Wave-particle dualism
• interpretation of Bohr's second postulate using de Broglie hypothesis
Nuclear energy and its environmental impact
• nuclear reaction
• nuclear reactor
• environmental impact of nuclear energy
Principle of special theory of relativity
• frame of reference and speed of light
• Einstein's postulates
• time dilation
• length contraction
• relativistic momentum and mass

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