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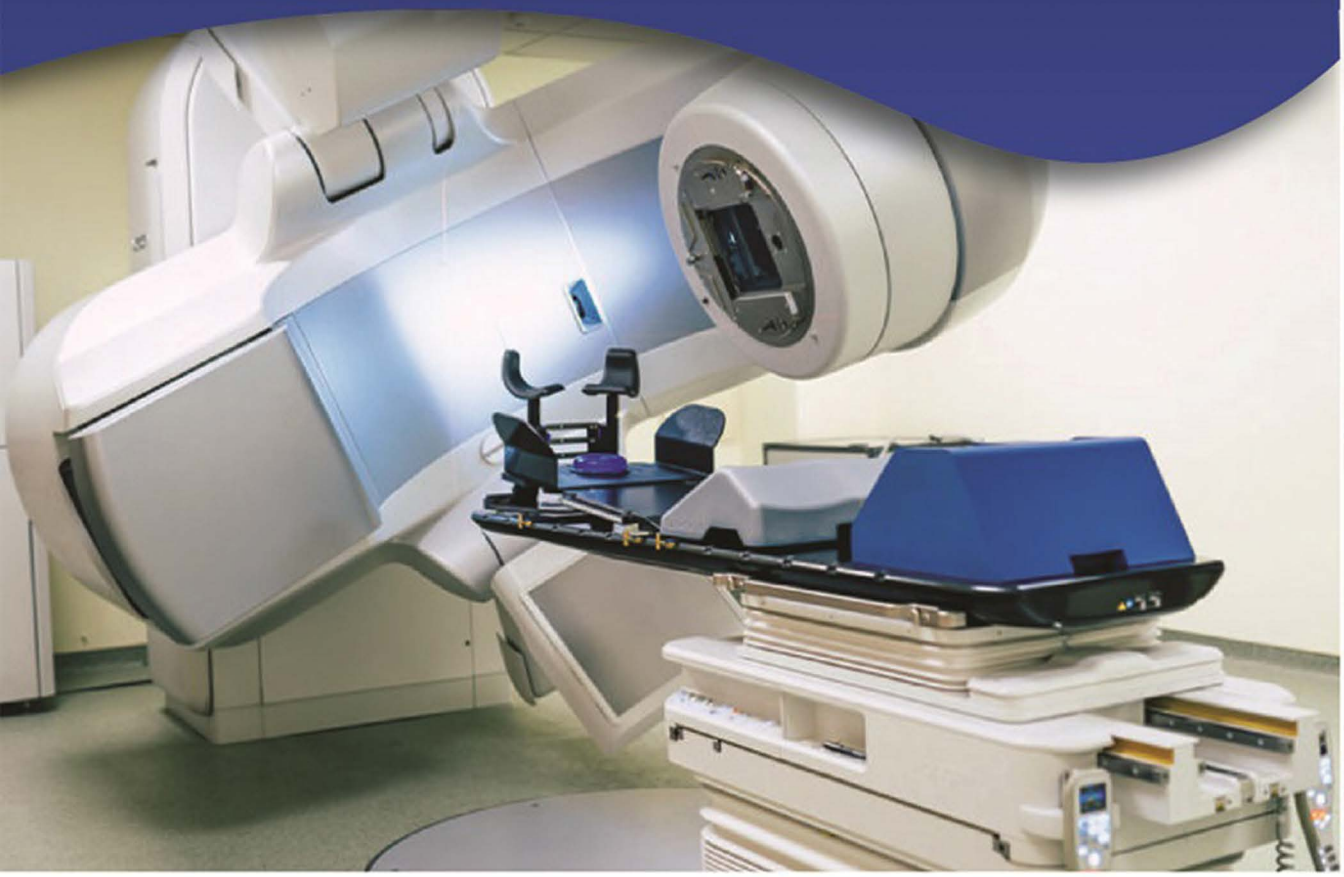
The Physics of Radiation Oncology



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Foreword
GK Rath

JAYPEE

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Chapter

2 Electromagnetic Induction

INTRODUCTION

The term electric is derived from the Greek word *electron*. Any solid rubbed with suitable materials will attract light objects, e.g., an *ebonite rod rubbed with animal fur, or a glass rod rubbed with silk cloth* attracts small pieces of leaves and dusts. Charged glass rod and animal fur attract each other, whereas two charged animal fur or glass rods repel each other. The agency which is responsible for this property is called *electricity* and the bodies are said to possess electric charge. **Benjamin Franklin** stated the existence of two types of charges in the universe, namely—(1) *positive* and (2) *negative charge*. If the charge is zero, then the object is said to be neutral.

ELECTRIC CHARGE

In an atom, the number of protons is equal to the number of electrons and the atom is always neutral. When a glass rod is rubbed with silk, some of its negative charges are transferred to the silk. Now the glass rod has lesser number of electrons and become positively charged. Similarly, when an ebonite rod is rubbed with fur, the ebonite rod gets some extra negative charges from the fur. Hence, the ebonite becomes negatively charged, and the fur becomes positively charged. Thus, when two bodies are rubbed with each other there is a redistribution of charges and no creation of charges. The body which loses the negative charges is positively charged and the other which gains negative charge is negatively charged. The electric charge is denoted by the letter q.

Charges can neither be created nor be destroyed, and the total amount of charge in a system does not change, which is called the *law of conservation of charges. It states that the total electric charge in the universe is constant*. In any physical process the net charge is zero.

Coulomb's Law

Coulomb (1786) found a relation for the force between two stationary point charges in vacuum. Electrostatic force is directly proportional to the product of magnitudes of two-point charges and inversely proportional to the square of the distance between point charges and lies always along a line joining the charges. This force may be attractive or repulsive force. Consider two charges q_1 and q_2, separated by a distance r, then force (F) between two charges are as follows:

$$F = k\frac{q_1 q_2}{r^2} \qquad \text{...(2.1)}$$

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where, k is a constant = $1/4\ \pi\varepsilon_0 = 9 \times 10^9\ Nm^2C^{-2}$, ε_0 is *permittivity* of free space = $8.854 \times 10^{-12}\ C^2\ N^{-1}\ m^{-2}$. If two charges of one coulomb separated by one meter, then the force is estimated as, $F = 9 \times 10^9\ N$. Coulomb's law is true only for point charges, and it is applicable to two charged objects whose sizes are much lesser than the distance between them. If one of the charges is a unit positive charge (say $q_2 = 1$), then force is, $k\ (q_1 \times 1)/r^2 = kq/r^2$.

The unit of charge is *coulomb (C) and one coulomb is defined as the quantity of charge which when placed at a distance 1 m in air or vacuum from an equal and similar charge, experiences a repulsive force of* $9 \times 10^9\ N$. The amount of charge in an electron is equal to 1.6029×10^{-19} coulombs.

Electric Field

A space surrounding an electric charge in which another charge experiences a force is called an *electric field* (**Faraday**). Electric field strength or intensity at a point is the force experienced by a unit positive charge kept at that point. It is a *vector quantity* and has a magnitude and direction. If F is a force experienced at a point by a charge q, then electric field (E) is given by:

$$E = F/q\ NC^{-1} \qquad ...(2.2)$$

The above relation is valid only for point charges. If an electric charge is positive, then electric field points away from charge. If electric charge is negative then field points towards the charge. There are two kinds of electric field, namely—(1) *uniform* and (2) *nonuniform electric field*. Uniform electric field will have the same direction and constant magnitude. Nonuniform electric field will have different direction or different magnitude or both.

Electric Lines of Force

Line of force in an electric field is an imaginary line to visualize an electric field vector **(Fig. 2.1)**. The path followed by a unit positive charge in an electric field is represented by *lines of force.* It is drawn in such a way that, the tangent drawn to it at any point gives direction of electric field at that point. The lines of force are generally curved and never intersect each other. The number of lines of force which cross an unit area perpendicular to the field, indicate magnitude of electric field strength at that point.

They start from a positive charge and terminate on negative charge or infinity. They follow certain rules—(i) electric field lines are denser in a region where the electric field has larger magnitude, and less dense in a region where the electric field magnitude is smaller, (ii) no two electric field lines intersect each other, and (iii) number of electric field lines that emanate from a positive charge or end at a negative charge is directly proportional to the magnitude of the charges.

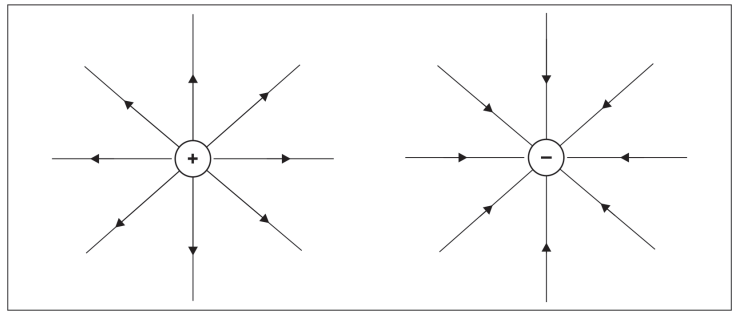

Fig. 2.1: Electric lines of force.

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Electric Dipole

Two equal and opposite charges separated by a small distance constitute an *electric dipole*, e.g., water, ammonia, carbon dioxide, and chloroform. These molecules behave like electric dipoles, because the centers of positive and negative charge do not coincide and are separated by a small distance. If two-point charges +q and –q are kept at distance 2d, then *dipole moment (C)* is the product of magnitude of one of charges and the distance between them:

$$C = q \times 2d \quad \text{...(2.3)}$$

The dipole moment is a *vector quantity*.

ELECTROSTATIC POTENTIAL

The charge configuration can be given potential energy since Coulomb force is a conservative force. Electric potential at a point in an electric field is equal to the work done by an external force to bring a unit positive charge with constant velocity from infinity to that point. The potential is a *scalar quantity* and the potential of earth is taken as zero.

The unit of electric potential is *Joule per coulomb = volt*, after **Alessandro Volta**. Potential difference between two points is also expressed in volt. *One volt is the potential difference between two points, if the work done in carrying one coulomb of positive charge from one point to another is 1 J against electrical forces*: 1 kilo volt (kV) = 1,000 or 10^3 volts and 1 mega volt (MV) = 10^6 volts.

Electron Volt

Definition of volt tries to define Joule in terms of coulomb units which is derived from Joule. Hence, instead of moving one coulomb, movement of electron charge is recommended. The charge of electron is small, compared to 1 coulomb charge and the energy involved is lesser than one Joule. Thus, unit *electron volt (eV)* is arrived, useful in radiation physics, where it deals with microscopic objects. *One electron volt is the kinetic energy imparted to an electron, accelerated across a potential difference of one volt*:

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J} = 1.602 \times 10^{-12} \text{ ergs} = 4.4 \times 10^{-26} \text{ kWh} \quad \text{...(2.4)}$$

In practice, kiloelectron volt (keV) and million electron volts (MeV) are used as units: 1 keV = 1000 eV, and 1 MeV = 10^6 eV. The electron volt describes potential as well as kinetic energy. The binding energy of an electron in an atom is a form of potential energy and it is expressed in keV.

Electric Flux

The number of electric field lines crossing a given area normal to electric field lines is called *electric flux*. It is usually denoted by the Greek letter Ψ and its unit is $Nm^2\ C^{-1}$. It is a *scalar quantity*, either positive or negative, and is calculated by *Gauss's law*.

ELECTROSTATIC INDUCTION

Electrostatic induction is a phenomenon in which a body is charged without actual contact. Positive and negative charges are accumulated or separated in a substance when a charged body is brought nearer to it. For example, consider a conductor **bc** which is electrically neutral

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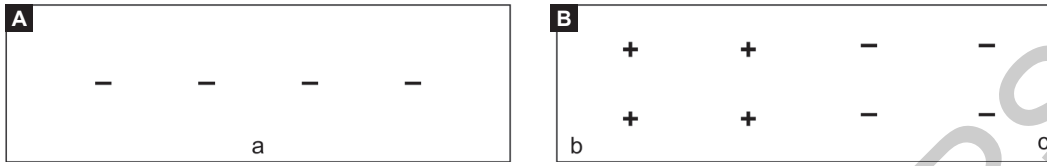

Figs. 2.2A and B: Electrostatic induction.

(Figs. 2.2A and B). Free electrons are uniformly distributed on the surface. When a negatively charged body, **a** is brought nearer to a conductor **bc**, near end **b** acquires positive charge, and far end **c** acquires negative charge. This means that negative charges in **a** repell the electrons in **bc** to far end. As a result, positive charges are induced in the near end. The amount of charge in **a** and in **bc** is equal in magnitude. If **a** is positively charged, **bc** will have the opposite effect. This method of charging a body is known as *electrostatic induction* and is used in electrostatic machines and capacitors, e.g., *electrophorus, lighting arrester, and van de Graaff generator.*

If the conductor **bc** is earthed, all electrons flow to the earth, while positive charges remain in the conductor. After removing the earthing wire, if the rod a is moved away, positive charges in **bc** will be uniformly distributed on the surface of conductor. Though the conductor **bc** is previously a neutral conductor, now becomes positively charged.

Dielectrics

A dielectric or insulator is a nonconducting material and has no free electrons. The electrons in a dielectric are tightly bound to the nucleus of the atoms, e.g., *ebonite, glass, oil, and mica*. When an external electric field is applied, electrons are not free to move anywhere, but they are realigned in a specific way. A dielectric is made up of either *polar molecules* or *nonpolar* molecules.

Polar Molecules

In polar molecules, the centers of positive and negative charges are separated even in the absence of an external electric field. They have permanent dipole moment, due to thermal motion, direction of each dipole moment is oriented randomly. Hence, net dipole moment is zero in the absence of an external electric field, e.g., H_2O, N_2O, HCl, and NH_3. When an external electric field is applied, the dipoles inside the material tend to align in the direction of electric field. Now the dielectric is said to be polarized by an external electric field.

When the external electric field applied to a dielectric is much larger, it tears the atoms apart so that the bound charges become free charges. Then dielectric starts to conduct electricity, is referred as *dielectric breakdown*. The maximum electric field that the dielectric can withstand before breakdown is called *dielectric strength*.

Nonpolar Molecules

A nonpolar molecule is one in which centers of positive and negative charges coincide. As a result, it has no permanent dipole moment, e.g., *hydrogen (H_2), oxygen (O_2), and carbon dioxide (CO_2)*. When an external electric field is applied, the centers of positive and negative charges are separated by a small distance which induces dipole moments along the direction of external electric field. Now the dielectric is said to be polarized by an external electric field.

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Capacitance

The property of a conductor to store electric charge and electrical energy is known as *capacitance*. The device that provides capacitance is called a *capacitor*. The capacitance is defined as ratio of magnitude of charge on either of the conductor plates to potential difference existing between them. If q is the charge in the conductor of potential V, then the capacitance C is given by $C = q/V$.

The unit of capacitance is *coulomb per volt = farad (F)*, after **Michael Faraday**. *One farad is the capacitance of a capacitor, which requires one coulomb electric charge to raise its potential by one volt.* Hence, one farad = one coulomb per volt. In practice, microfarad and picofarad are used as units: 1 microfarad (μF) = 10^{-6} farads, and 1 picofarad = 10^{-12} farads.

Capacitor Principle

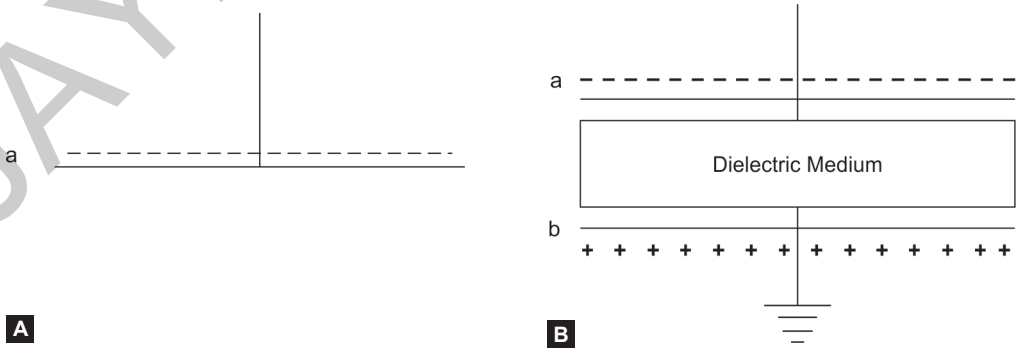
A capacitor consists of two conductors (plates), which are separated by a distance. One plate is charged, and the other is earthed. The space between the plates is filled with *dielectric material*. When plate **a** is negatively charged, there is a rise in negative potential, and its capacitance is much small **(Fig. 2.3A)**. When a second similar conductor **b** is brought very nearer to **a**, positive charges are induced in **b** by electric induction **(Fig. 2.3B)**. This positive charge decreases negative potential on **a**. For the same charge q, potential V, decreases and capacitance of the first conductor increases, since $C = q/V$.

Capacitors are available in various shapes (*cylinder and disks*) and types (*tantalum, ceramic, and electrolytic*). A commonly used capacitor is the *parallel plate capacitor* of area A and separation d, and its capacitance is given by the relation:

$$C = \varepsilon_o \frac{A}{d}, \text{ where } \varepsilon \text{ is } \textit{permittivity} \text{ of free space} = 8.85 \times 10^{-12}\ C^2N^{-1}m^{-2} \quad ...(2.5)$$

Capacitance of a capacitor depends on several factors—(i) area of overlap between two plates; higher the area, more will be capacitance, (ii) distance between plates; lesser the distance, more will be capacitance, and (iii) nature of dielectric medium.

Capacitors are used—(i) in digital cameras for taking photographs (flash capacitor), (ii) in the ignition system of automobile engines to eliminate sparking, (iii) to reduce power fluctuations in power supplies and to increase efficiency of power transmission, and (iv) during cardiac arrest; *heart defibrilla*tor is used to give a sudden surge of a large amount of electrical energy to patient's chest to retrieve normal heart function.



Figs. 2.3A and B: (A) Charge distribution in a single plate; (B) Parallel plate capacitor principle.

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Van de Graaff Generator

Robert Van de Graaff (1929) designed Van de Graff generator which produces large amount of electrostatic potential difference, up to several million volts. It is basically an *electrostatic accelerator* which accelerates only charged particles. It works on the principle of *electrostatic induction and action of points*.

A large hollow *spherical dome* is fixed on an insulating stand. A *pulley* is mounted at the center of a spherical dome and another pulley is fixed at bottom. A *belt* made up of insulating materials like *silk* or *rubber* runs over both pulleys. The bottom pulley is driven continuously by an *electric motor*. Two comb-shaped metallic conductors are fixed near the pulleys **(Fig. 2.4)**. The upper comb is called a *charge collector*, which is connected to the inner side of the *hollow metal sphere*.

The lower comb is called *charge sprayer*, which is maintained at a potential of 104 V, by a power supply. Due to high electric field near charge sprayer, the air between belt and comb gets

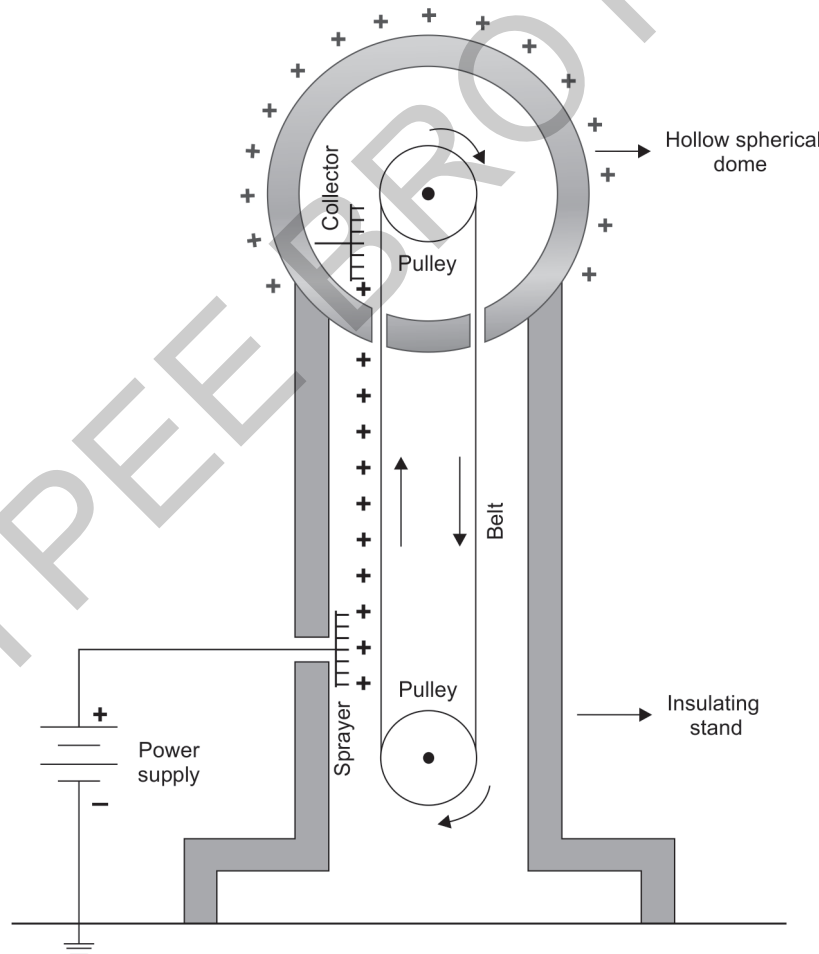

Fig. 2.4: Van de Graaff generator.

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ionized by *action of points (corona discharge).* Negative charges in air move toward the comb and positive charges are repelled. Thus, positive charges are sprayed onto the belt by charge sprayer. The moving belt carries these positive charges to top, where it is removed by the charge collector. Due to electrostatic induction, comb acquires negative charges and spherical dome gets positive charges. Acquired positive charges are distributed uniformly on the outer surface of the sphere.

As a result, high potential is developed between the metal sphere and earth. When the belt descends, it has almost no net charge. At bottom, it again gains large positive charge and the process repeats. This process continues until the outer surface produces a potential difference of order 10 MV, which is the limiting value. This potential is applied across an *X-ray tube,* where electrons strike the target and produce X-rays. X-ray tube has series of *metal rings* apart from *filament and target*. These rings are connected to the series of *resistors* to offer uniform drop of potential from lower to upper value.

Van de Graaff generator cannot store charges beyond 10 MV limit since extra charge starts leaking to surroundings due to ionization of air. Hence, insulation is provided by a mixture of *nitrogen and* CO_2. The generator is enclosed in a *steel tank-filled with gas mixture* at a pressure of 20 atm, to reduce leakage of charges. This generator was used for radiotherapy and become obsolete today.

ELECTRIC CURRENT

Atoms have valence electrons, which are less bound and free to move. Substance which has abundance of free electrons are called *conductors*. Free electrons move randomly throughout the conductor at a given temperature, such movement of electric charge in a conductor is called an *electric current*. There is no actual transfer of charges from one end to the other end and the net current is zero. When a potential difference is applied by the battery across the ends of a conductor, free electrons drift toward positive terminal of battery, producing a net electric current. Positive charge flows from the region of higher electric potential to region of lower electric potential, and negative charge flows from region of lower electric potential to region of higher electric potential.

Electric current is quantified by the amount of charge flowing in 1 second and the unit of current is *ampere (A). Electric current through a wire is called one ampere, if one coulomb of charge flows through the wire in 1 second.* Hence, 1 A = 1 C/s. It is found that 1 A current consists of 6.25×10^8 electrons. In practice, milliampere (mA) and microampere (μA) are also used as units, 1 mA = 10^{-3}A, and 1 μA = 10^{-6} A.

Current Flow in Metals

A metal consists of a large number of free electrons moving in random directions. Though free electrons move in all directions, there cannot be any net motion of electron in a particular direction. Hence, there is no flow of current. When an electric field is applied, electrons at the conductor ends experience a force (F = eE), in a direction opposite to the electric field. Electron gets accelerated and make collision with each other as well as with positive ions. Due to collisions, a backward force acts on the electrons and they are slowly drifted and move with a constant average velocity, in a direction opposite to the electric field referred as *drift velocity*.

Drift velocity is defined as the velocity with which free electrons get drifted toward positive terminal when an electric field is applied. The constant average velocity of electron is responsible

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for flow of current. Drift velocity of electron is proportional to the electric field intensity, of the order of 0.1 cm s^{-1}. *Current density (J)* at a point is defined as the quantity of charge passing per unit time through unit area, taken perpendicular to direction of flow of charge at that point, i.e., J = I/A. It is a *vector quantity*, and its unit is Am^{-2}.

Conventional Current

Initially physicists thought that current is due to flow of something from positive end to negative end. They used arrow heads to indicate the direction of flow of current in a circuit. By convention arrowhead refers to the flow of current in the circuit from a positive to negative terminal of battery referred as *conventional current*.

After the discovery of electrons, it is found that charge flow is nothing but electrons, which is responsible for current. Electron flows from negative terminal to the positive terminal of the battery. As a result, flow of electrons and direction of conventional current are in opposite direction. However, still conventional current is used in practice, hence, the *direction of conventional current is always opposite to real electron flow*.

Ohms Law

Ohms law states that a steady current flowing through a metallic conductor is proportional to potential difference between its ends, provided temperature remains constant. If *I* is current in ampere and *V* is potential difference in volts, then $I \propto V$, at constant temperature, i.e., $I \propto V/R$ where, *R* is a constant known as the *resistance* of the conductor.

Resistivity

Resistance is the property of a conductor by which it opposes flow of current. It is defined as ratio between potential difference and current of the conductor, i.e., $R = V/I$. The device, which offers resistance to flow of current is called *resistor* and it is represented by zigzag lines. The resistor with variable resistance is called *rheostat*.

The unit of resistance is *ohm (Ω)*. *One ohm is the resistance of a conductor through which a steady current of 1 A flows, when a potential difference of one volt exists across it.* In practice, kiloohm (KΩ) and megaohm (MΩ) are used as units, i.e., 1 KΩ = 1,000 Ω, and 1 MΩ = 10^6 Ω. Resistance of a material is influenced by—(i) shape of material, (ii) type of material, and (iii) temperature of material.

Resistance of a resistor at a given temperature depends upon the material and its dimensions. The resistance (R) of a resistor is directly proportional to its length (L) and inversely proportional to its area of cross section (A):

$$R \propto \frac{L}{A} = \frac{\rho L}{A} \text{ or } \rho = \frac{RA}{L} \qquad \text{...(2.6)}$$

where, ρ is called *resistivity* or *specific resistance*. Thus, electrical resistivity of a material is defined as resistance offered to current flow by a conductor of unit length having unit area of cross section. The SI unit of ρ is *ohm-meter (Ωm)*. Based on resistivity, materials are classified as *conductors, insulators, and semi-conductors.* The conductors have lowest resistivity, insulators have highest resistivity and semiconductors have resistivity greater than conductors but less than insulators. The above relation reveals that resistance of a thick wire would be lesser than

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that of a thin wire. The resistance is greater if length is greater. The reciprocal of the resistivity ($1/\rho$) is called the *conductivity* (σ).

Superconductivity

At much lower temperatures, resistivity of some materials (metals, compounds, or alloys) becomes zero. Materials in such state are called *superconductors*. In general, conductors become superconducting at certain temperatures, referred as superconducting *transition temperature* (T_c). During transition temperature, electrical resistivity drops to zero, conductivity become infinity, and the material excludes its magnetic flux lines.

Current in a ring-shaped superconducting material has been observed to flow for years in the absence of a potential difference, with no measurable decrease. Superconductors are mainly used for generating much strong magnetic fields, since it has the ability to withstand large magnetic fields and carry large currents. A material in a superconducting state requires no power to carry large currents. Since resistance of material in superconducting state is zero, no thermal losses are associated with passage of large currents.

Metal alloys like *niobium-titanium* become a superconductor below 10 K. It is used in *magnetic resonance imaging (MRI)* equipment but requires *liquid helium* as a coolant system. *Ceramic metal oxide compounds* become super conductors at higher temperatures, e.g., *yttrium barium copper oxide* at 93 K and *thallium calcium bismuth copper oxide* at 125 K. Since they operate at higher temperatures, *liquid nitrogen* is used as effective coolant, which is cheaper than helium.

Super conductors have the following applications—(i) they form the basis of energy saving power systems, namely superconducting generators, which are smaller in size and weight, in comparison with conventional generators, (ii) since current in a superconducting wire can flow without any change in magnitude, it can be used for transmission lines, (iii) they can be used as a memory or storage elements in computers, (iv) superconducting magnets have been used to levitate trains above its rails; they can be driven at high speed with minimal expenditure of energy, (v) superconducting magnetic propulsion systems may be used to launch satellites into orbits directly from earth without use of rockets, and (vi) high-efficiency ore separating machines may be built using superconducting magnets, which can be used to separate tumor cells from healthy cells, by high gradient magnetic separation method.

Electric Power

Electric power (P) is the rate at which energy is expended. It is equal to the product of potential difference (V) and current (I), i.e., $P = VI$. The unit of electric power is *Joules per second* = *watt*. In practice, kilo watt and *kilowatt-hour (kWh)* are used as units of electric power.

Electric Cell and Battery

An electric cell converts chemical energy into an electrical energy to produce electricity. It contains two electrodes, namely *carbon* and *zinc*, immersed in an *electrolyte* such as *sulfuric acid*. Two or more electric cells are connected to form a *battery*. When a battery is connected to a circuit, electrons flow from the negative terminal to positive terminal. By using chemical reactions, battery produces potential difference across its terminals which provides energy to move the electrons through the circuit.

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The term *electromotive force (emf)* is a misnomer since it does not really refer to force but describes a potential difference in volts. The emf of a battery is the voltage provided by the battery when no current flows in an external circuit. It refers to the amount of work that a battery does, to move certain amount of charge around the circuit. An ideal battery has zero internal resistance and potential difference (terminal voltage) across the battery is equal to its emf. In practice, the battery is made of electrodes and electrolyte, there is resistance to flow of charges within the battery, referred as *internal resistance*. For a real battery, terminal voltage is not equal to emf of the battery.

Heating Effect of Electric Current

When electric current flows through a conductor having resistance, certain amount of electrical energy is converted into heat energy. This will raise the temperature of the conductor. This heat is produced by free electrons as they move through metal. On their way, they collide frequently with atoms and give some of their kinetic energy to atoms. The atoms which gain kinetic energy and generate heat in the conductor.

Joule's Law of Heating

Heat (H) developed in a current carrying conductor is directly proportional to—(i) square of the current passing through the conductor (I), (ii) resistance of the conductor (R), and (iii) time of flow of current (t), i.e., $H = I^2 Rt J$. If current is doubled, the heat generated is four times higher. This concept is applied in fuse wires, as current goes to higher value, heat generated in the circuit is sufficient to melt the fuse wire. Therefore, melting point of fuse material is much critical for material selection. The fuse wires are basically an alloy of *lead (37%)*, and *tin (63%)*. It is connected in series in an electric circuit and it has high resistance and low melting point.

Electric iron, heater, and *toaster* works on the principle of heating effects of current. *Nichrome, an alloy of nickel and chromium* is used as heating elements. It has high melting point, high specific resistance and not easily oxidized. Electric bulb with tungsten filament, electric arc, and electric welding are also working on the above principle.

MAGNETISM

Magnetism is a fundamental property of matter, and it is produced by motion of electrical charges. The word magnetism is derived from the ore *magnetite*. As we are aware that electrons are in random motion in materials. The atoms and molecules that have paired electrons, cancel their magnetic fields and net magnetic field is zero. However, atoms with unpaired spinning of electrons in different shells, present net magnetic field.

A magnet has two poles namely, *north pole and south pole* **(Fig. 2.5A)**. The term "pole" refers to end of a magnet in which entire magnetism appears to be concentrated. The pole that points north under the influence of earth's magnetic field is called *north pole* and the other is called *south pole*. As in the case of electric charge, like poles repel and unlike poles attract each other. Magnets are divided into *natural* and *artificial magnets*. Strength of natural magnets are very weak with irregular shape, e.g., *iron, cobalt*, and *nickel,* whereas artificial magnets are made to have a desired shape and strength. Simplest magnet at atomic level is magnetic dipole. A magnet in the shape of rectangle or circular is called *bar magnet*.

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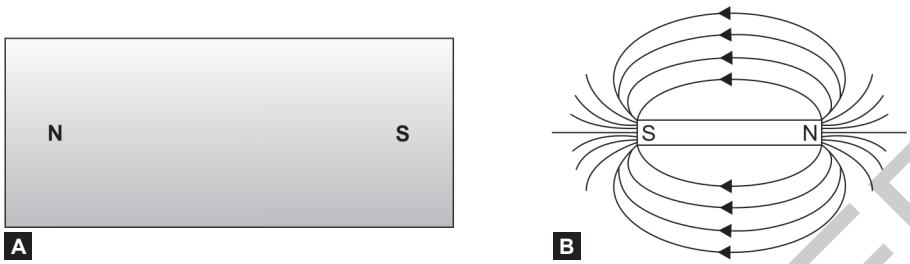

Figs. 2.5A and B: (A) Magnetic dipole; (B) Magnet and magnetic lines of force.

A magnet has the following properties, (i) freely suspended bar magnet will always point along north-south direction, (ii) magnet attracts or repels another magnet or magnetic substances toward itself; the attractive or repulsive force is maximum near the end of a bar magnet; when a bar magnet is dipped into iron-filling, they cling to the ends of the magnet, (iii) when a magnet is broken into pieces, each piece behaves like a magnet with poles at its ends, (iv) two poles of a magnet have equal pole strength, and (v) length of a bar magnet is called *geometrical length* and length between two magnetic poles in a bar magnet is called *magnetic length*. The magnetic length is always slightly smaller than geometrical length.

Coulomb's Inverse Square Law

Force of attraction or repulsion (F) between two magnetic poles is directly proportional to product of their pole strengths and inversely proportional to square of the distance between them:

$$F = \frac{q_{m1}\, q_{m2}}{4\pi \mu r^2} \qquad ...(2.7)$$

where, q_{m1} and q_{m2} are pole strengths of two magnetic poles which are separated by distance r, and μ is *absolute permeability* of the medium.

Magnetic Field and Lines of Force

Space around a magnetic pole in which another pole experiences a force is called *magnetic field (H)*. It is a *vector quantity,* and its SI unit is Am^{-1}. Magnetic fields can be visualized by magnetic lines of forces which are imaginary lines **(Fig. 2.5B)**. A line of force can be defined as the path taken by an independent north pole, moving from the north pole of magnet to the south pole.

Characteristics of magnetic lines of force are—(i) continuous closed curves; direction of magnetic field lines is from the north pole to south pole outside the magnet, and from the south pole to north pole inside the magnet, (ii) direction of magnetic field at any point on the curve is known by drawing tangent to magnetic field lines at that point, (iii) magnetic field lines never intersect each other; otherwise, magnetic compass needle would point towards two different directions, which is not possible, and (iv) degree of closeness of field lines determines relative strength of magnetic field. Magnetic field is strong where magnetic field lines are crowded, and weak where magnetic field lines are well separated.

There are uniform and nonuniform magnetic fields. Magnetic field is said to be uniform if it has same magnitude and direction at all the points for a given region. Magnetic field is said to be nonuniform if the magnitude or direction or both vary at different points in a region.

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Magnetic Flux and Flux Density

Number of magnetic field lines crossing an area is called the *magnetic flux* and its unit is *weber (Wb)*. The term *magnetic flux density (B)* is defined as the magnetic field lines crossing per unit area kept normal to the direction of the lines of force, its unit is Wbm^{-2}. The SI unit of magnetic flux density is *Tesla (T)* and $1\ T = 1\ Wbm^{-2}$. The older unit is *gauss (G)*, and 1 T is equal 10,000 G. Earth's magnetic field has both horizontal and vertical components and its strength varies from 0.5 to 1.0 G, which is in the order of microtesla. However, the magnets used in MRI is in the range of 0.3–3 T.

Intensity of Magnetization

Electrons in atoms are randomly oriented due to orbital motion. Since they are charged particle, have magnetic moment and net magnetic moment is zero per unit volume of material. When such material is kept in an external magnetic field, atomic dipoles are induced which will try to align partially or fully along the direction of external field. Net magnetic moment per unit volume of material is known as *intensity of magnetization (M)*. It is a *vector quantity*, and its SI unit is Am^{-1}.

Magnetic Permeability

Magnetic permeability (μ) is a measure of ability of a material to allow passage of magnetic field lines through it or degree of penetration of magnetic field through the substance. *Relative permeability* (μ_r) is defined as ratio between absolute permeability of medium to permeability of free space:

$$\mu_r = \frac{\mu}{\mu_0} \qquad ...(2.8)$$

where μ_0 is the permeability of free space = $1.26 \times 10^{-6}\ WbA^{-1}m^{-1}$ or henry per meter (Hm^{-1}).

Magnetic Susceptibility

Magnetic susceptibility (K) is a property which describes the extent to which a material becomes magnetized when placed in a magnetic field. It measures how easily and strongly a material can be magnetized. It is defined as the ratio of intensity of magnetization induced in the material to magnetizing field.

Magnetic Induction

If a material is placed in a magnetic field, magnetism may be induced in that material by magnetizing force. Atoms of the material tend to align with the direction of magnetizing force and induce a magnetic flux within material. If H is the magnetizing force that induces a magnetic flux B in material, then $B = \mu H$, where μ is *permeability of the medium* and unit of magnetic induction is tesla.

Classification of Magnetic Materials

Magnetic properties of materials are determined by atomic and molecular structures relative to its electron behavior. Based on the magnetic *susceptibility* of material, it can be classified as diamagnetic, paramagnetic, and ferromagnetic substances.

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