Course Title

Course Code PHS 102 / Department: PHYSICS

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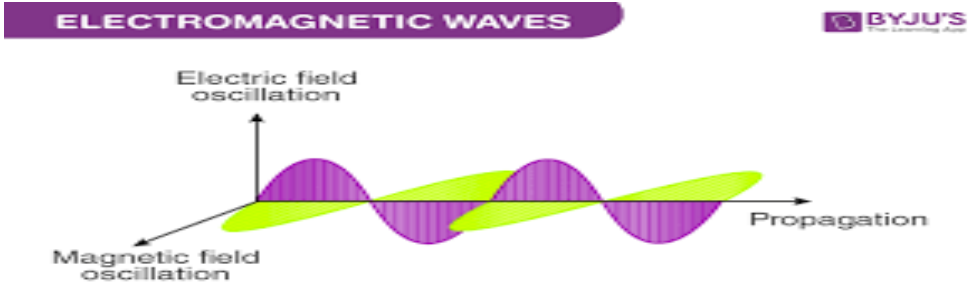
ELECTROMAGNETIC WAVES

Electromagnetic waves or EM **waves** are **waves** that are created as a result of vibrations between an electric field and a magnetic field. In other words, EM **waves** are composed of oscillating magnetic and electric fields



These are waves composed of undulating electrical fields and magnetic fields. The different kind of EM waves such as light and radio waves form the electromagnetic spectrum.

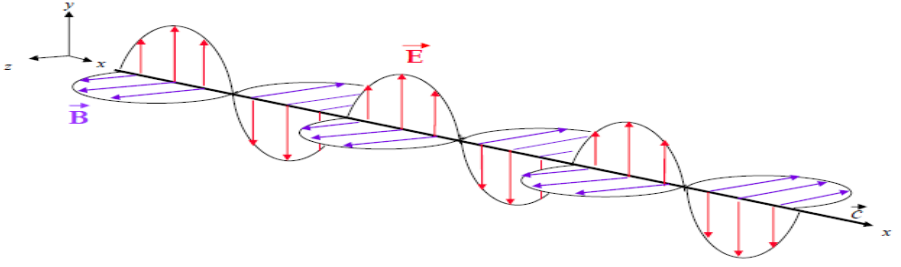
Note that all EM waves have the same speed in a vaccum (expressed by the letter c) and is equal to about 3×10^8m/s.

Maxwell's theory is a mathematical formulation that relates electric and magnetic phenomena. His theory, among other things predicted that electric and magnetic fields can travel through space as waves. He predicted that

(i) a changing electric field produces a magnetic field

(ii) an accelerating charges will radiate EM waves and that

(iii) the electric and magnetic fields in the wave are fluctuating. The figure below shows an EM waves in picture.



Properties of EM Radiation

Note that the Electric field due to a point charge q can be determined by applying Coulomb's law given as $\nabla . E = {}^{\rho}/_{\varepsilon_0}$ where $\rho = {}^{q}/_{v}$ is the electric charge density (charge per unit volume).

Electric fields originate on positive charges and terminate on negative charges while magnetic field lines always from closed loops (i.e they do not begin or end anywhere). This means that there are no magnetic monopoles.

This is given by Maxwells equation as $\nabla . E = O$ (the "zero" implying that there are no magnetic monopoles).

A varying magnetic field B induces an E.M.F and hence electric field (this is Faraday's law and is now re-expressed in Maxwell's form as $\nabla \mathrm{X}\, E = \frac{-\partial B}{\partial t}$.

Also magnetic fields are generated by moving charges (or current). This is Ampere's law and is re-expressed in Maxwell's form as $\nabla \mathrm{X}\, B = \mu_0 J$.

EM waves (i.e radiation) propagate at a velocity given by $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 2.99792 \times 10^8 m/s$

EM waves are emitted from oscillating electric charges i.e An oscillating electric charges produces an Electric field that varies in time, which produces a B-field that also varies in time, which produces a new E-field that varies in time and so on.

EM waves also behave like particles, planck called a packet of electromagnetic radiation a photon in the early 1900s.

EM waves are transverse waves, since the electric and magnetic fields are perpendicular to the direction of propagation of the wave and to each other.

EM waves carry both energy and momentum (despite have no mass) hence the energy is proportional to frequency and inversely proportional to wavelength. The energy is given by $E = hv = \frac{hc}{\lambda}$ where v is the frequency of an EM waves

In summary, these are properties of EM waves

EM waves all travel speed of light c where $c^2 = \frac{1}{\mu_0 \varepsilon_0}$

The E and B fields are perpendicular to each other

The E and B fields are in phase (both reach a maximum and minimum at the same time).

The E and B fields are perpendicular to the direction of travel (transverse waves) i.e. perpendicular E and B propagate through space in direction of E X B.

The magnitude of E and B in empty space are related by the expression $\frac{E}{B} = C$

Example: An EM wave in a vacuum has an electric field amplitude of 220v/m. calculate the amplitude of the corresponding magnetic field.

Solution: Note that the ratio of the maximum magnitude of the E-field to the maximum magnitude of the B-field of an EM wave is

$$\frac{Emax}{Bmax} = C \;\therefore Bmax = \frac{Emax}{C} = \frac{220v/m}{3x10^8 m/s} = 7.33\ \mathrm{X}10^{-7}T = 733nT$$

Electromagnetic waves are produced by_____

ANSWER: An accelerated charge

The direction in which electromagnetic waves propagate is the same as that of

ANSWER: $\vec{E} \times \vec{B}$

ELECTROMAGNETIC SPECTRUM

The EM spectrum is defined to be the intensity of an EM wave as a function of wave length, frequency or energy. EM waves can be generated in different frequency bands. The continuous EM spectrum is split into different regimes. Below is the list of EM spectrum from shortest to longest wavelength with distinct wavelength dividng lines.

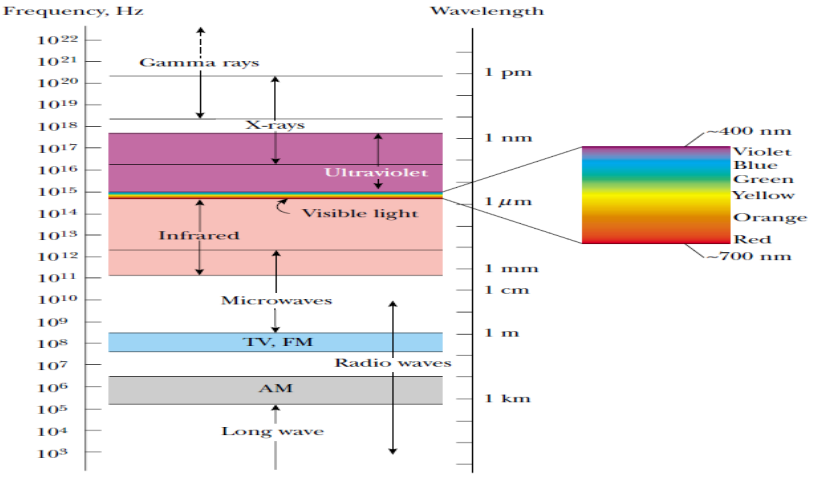
Gamma rays → X-rays → UV → Visible light → Intra Red → Micro waves → Radio waves.

Radio waves: wavelengths range from more than 10^4m to about 0.1m. They are the result of charges accelerating through conducting wires. They are generated by such electronic devices such as LC oscillators and are used in radio and television communication systems.

Microwaves: wavelengths range from 0.3m to 10^{-4}m and are also generated by electronic devices. They are used in radar system and for studying the atomic and molecular properties of matter.

Infra Red waves: wavelengths ranging from 10^{-3}m – 7 x 10^{-7}m. They are used in physical therapy, IR photography and vibrational spectroscopy.

Visible light: wavelengths range from 4 x 10^{-7}m– 7 x 10^{-7}m. The sensitivity of the human eye is a function of wavelength, being maximum at a wavelength of about 5.5 x 10^{-7}m.



(Note: visible light ranges than from 400mm – 700mm (4000Å - 7000Å)

Note: 1Å = 10^{-10}m.

Some spectral regions are sub-divided into smaller bands. In case of visible spectrum between 500 – 570nm which is also the wavelengths where the sun emits the peak of its intensity in the EM spectrum (natural selection at work!).

Example: The eye is most sensitive to light of wavelength 5.5 x 10^{-7}m which is in the G-Y region of the visible spectrum. Calculate the frequency of this light?

Solution: $v = \frac{C}{\lambda} = \frac{3\times10^{8}m/s}{5.5\times10^{-7}m} = 5.45 \times 10^{14}Hz$

The Doppler Effect for EM radiation

The spectrum of an object will be blue shifted if it is approaching the observer

The spectrum of an object will be red shifted if it is receding from an observer.

The wavelength shift in a spectral line is given by $\frac{\Delta\lambda}{\lambda_0} = \frac{Vr}{C}$ $\therefore \frac{\Delta\lambda c}{\lambda_0} = \frac{0.37Å}{6562.85Å}\left(3 \times \frac{10^{8}m}{s}\right)$

$$= (-5.638 \times 10^{-5})\left(3 \times \frac{10^{8}m}{s}\right)$$

= -1.69 X 10^{4}m/s = -16.9 km/s.

i.e Polaris is moving towards as (-ve sign and the line was blue shifted at 16.9km/s).

ENERGY CARRIED BY EM WAVES

EM waves carry energy, and as they propagate through space, they can transfer energy to objects placed in their path.

The rate of flow of energy in an EM wave is described by a vector S called the Poynting vector defined by the expression $S \equiv \frac{E \times B}{\mu_0}$. The magnitude of S represents power per unit area (i.e the rate at which energy flows through a unit surface area) perpendicular to the direction of propagation.

For a plane EM wave where $|E \times B| = EB \;\therefore S = \frac{EB}{\mu_0},\; from\; B = \frac{E}{C}$, we can also express S as $S = \frac{E^2}{\mu_0 C} = \frac{c}{\mu_0} B^2$.

The average value of S (the intensity of the wave) is given by

$$I = S_{av} = \frac{E_{max}\, B_{max}}{2\mu_0} = \frac{E^2{}_{max}}{2\mu_0 c} = \frac{cB^2{}_{max}}{2\mu_0}$$

$$I = cU_{av}\,, \qquad where\; U_{av} = \frac{1}{2}\mathcal{E}_0 E^2{}_{max} = \frac{B^2{}_{max}}{2\mu_0}$$

The intensity of an EM wave equals the average energy density multiplied by the speed of light.

Note: The instantaneous energy density U_E associated with an Electric field is given by $U_E = ½ E_0 E^2$ and that associated with magnetic field $U_B = \frac{B^2}{2\mu_0}$.

$$U_B = \frac{\left(\frac{E}{C}\right)^2}{2\mu_0} = \frac{\varepsilon_0 \mu_0 E^2}{2\mu_0} = \frac{1}{2}\varepsilon_0 E^2 \quad \therefore \quad U_B = U_E = \frac{1}{2}\varepsilon_0 E^2 = B^2/2\mu_0$$

.: The energy density U of an EM wave is given by

$$E = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2}\mu_0 B^2 = \varepsilon_0 E^2 = \frac{1}{\mu_0} B^2$$

<u>Example:</u> The Electric field in an EM wave is described by

$$E_y = 100 sin\,(1.00 \times 10^7 x - wt)$$

Find the amplitude of the corresponding magnetic field oscillations

The wavelengths ʌ and (c) the frequency f

Solution:

Using $B = \frac{E}{C} \therefore B = \frac{100\, v/m}{3 \times 10^8 m/s} = 3.33 \times 10^{-7} T = 0.333 \mu T$

$$\lambda = \frac{2\pi}{K} = \frac{2\pi}{1 \times 10^7 m^{-7}} = 0.628 \mu m$$

$$f = \frac{C}{\Lambda} = \frac{3 \times 10^8 m/s}{628 \times 10^{-7} m} = 4.77 \times 10^{14} Hz$$

Example: How much energy per cubic metre is contained in sunlight, if the intensity of the sunlight at the Earth surface under a fairly clear sky is 1000w/m^2?

Solution: $S = I = \frac{U}{At} = \frac{Uc}{V} = UC = IV \;\; \therefore \frac{U}{V} = \frac{I}{C} = \frac{1000 w/m^2}{3 \times 10^8 m/s} = 3.33 \mu J/m^3$

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Diffraction is the deviation of light from a straight line path when the light passes through an aperture or around an obstacle. Diffraction is due to wave nature of light.

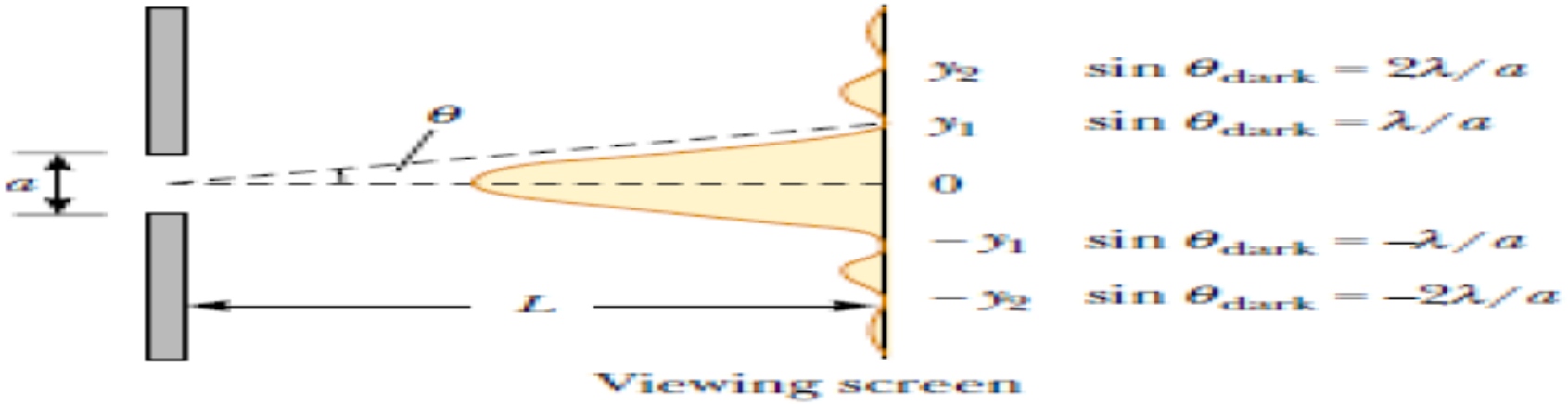
In physics of single slit diffraction experiment, the single slit is of width 'a' as two slit each with a width of $^{a}/_{2}$. Waves from one side of the slit when $^{a}/_{2}$ Sinθ = $^{\lambda}/_{2}$ where both λ and **a** are of the same unit or $\sin\theta = \frac{\lambda}{a}$, θ is the angle subtended from the normal line of the slit into four parts instead of two, then $\sin\theta = \frac{2\lambda}{a}$, θ now giving the angle to the second dark band, or six parts instead of four, $\sin\theta = \frac{3\lambda}{a}$, with θ giving the angle to the third dark band e.t.c

.: The general condition for destructive interference for a single slit of width 'a' is

$$\sin\theta_{dark} = \frac{m\lambda}{a}, \quad m = \pm 1, \pm 2, \pm 3 \ldots\ldots\ldots\ldots$$

This equation gives the values of θ_{dark} for which the diffraction pattern has zero light intensity i.e when a dark fringe is formed.

The general feature of intensity distributions are shown in figure below

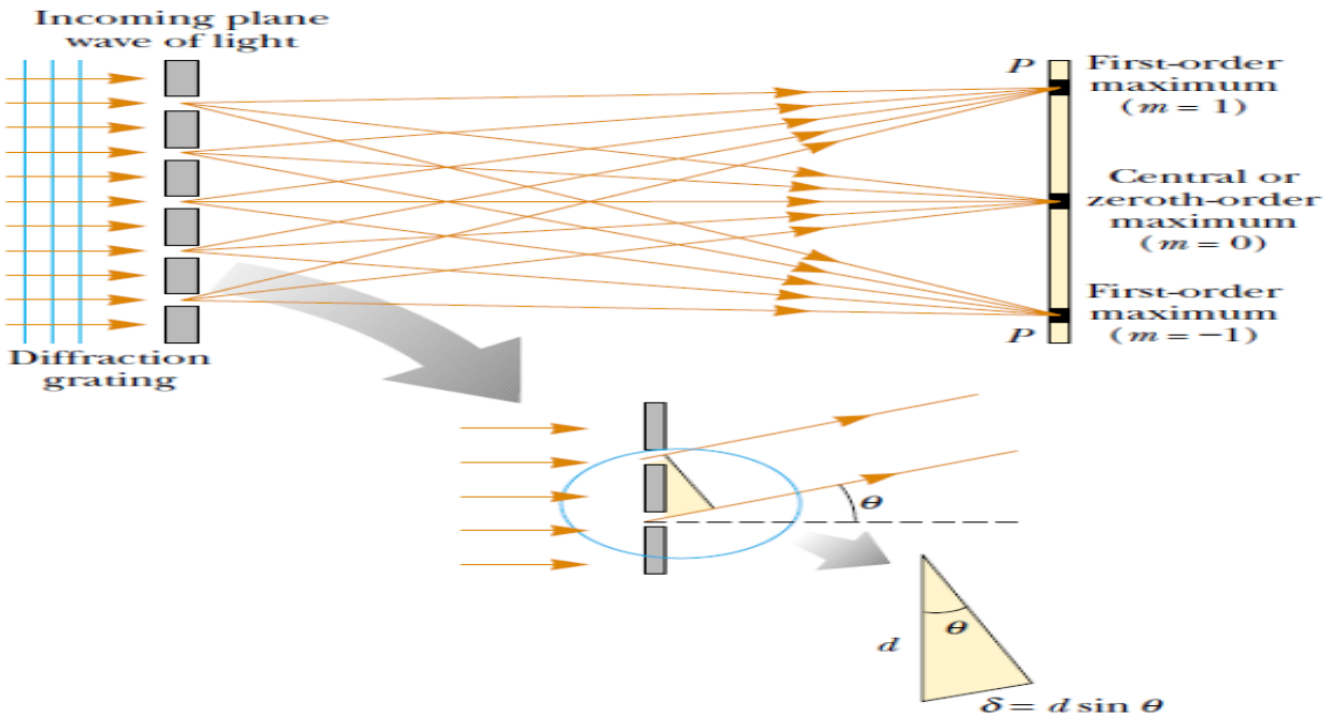


DIFFRACTION GRATING

Note that diffraction will occur either for light passing through narrow slits, or for light travelling around thin obstacles. It is this second type of diffraction that is used to construct diffraction gratings.

Diffraction grating is a useful device for analyzing light sources, it consists of a large number of equally spaced parallel slits. A section of a diffraction grating is shown in

Incoming plane



A plane wave is incident from the left, normal to the plane of the grating. The pattern observed on the screen is the result of the combined effects of interference and diffraction. Each slit produces diffraction, and the diffracted beams interfere with one another to produce the final pattern. The waves from all slits are in phase as they leave the slits but must travel different path

lengths before reaching the screen. If the path difference δ between rays from any two adjacent slits equals one wavelength or some integral multiple of wavelength, a bright fringe is observed. The condition for maxima in the interference pattern at the angle θ_{bright} is

$d \sin\theta_{bright} = m\lambda$, $m=0, \pm1, \pm2, \pm3, \ldots\ldots\ldots\ldots\ldots$ where d is the grating spacing.

Example

Example

Light of wavelength 600nm falls on a 0.40nm wide slit and forms a diffraction pattern on a screen 1.5m away.

(a) Find the position of the first dark band on each side of the central maximum

(b) Find the width of the central maximum.

Solution:

Dark bands will occur where $\sin\theta = m\left(\frac{\lambda}{a}\right)$

For the first dark band, m =1

From $y_1 = L\,tan\theta \approx L\,sin\theta = L\left(\frac{\lambda}{a}\right)$

$$\therefore y_1 = 1.5m\left(\frac{600\times10^{-9}m}{0.4\times10^{-3}m}\right) = 2.25\times10^{-3}m = 2.3mm$$

The width of the central maximum is just $2y_1 = 2(2.25mm) = 4.5mm$

Example: Monochromatic light from a helium-neon Laser (λ=632.8nm) is incident normally on a diffraction grating containing 6000 grooves per centimeter. Find the angles at which the first and second-order maxima are observed.

Solution: Slit separation $(d) = \frac{1}{no\ of\ grooves\ per\ cm} = \frac{1}{6000}\,cm$

$$= 1.667 \times 10^{-4} cm = 1667nm$$

For the first-order maximum (m=1) , $sin\theta_1 = \frac{\lambda}{d} = \frac{632.8nm}{1667nm} = 0.3796$

$$\therefore sin\theta_1 = 0.3796$$

$$\theta_1 = 22.31^o$$

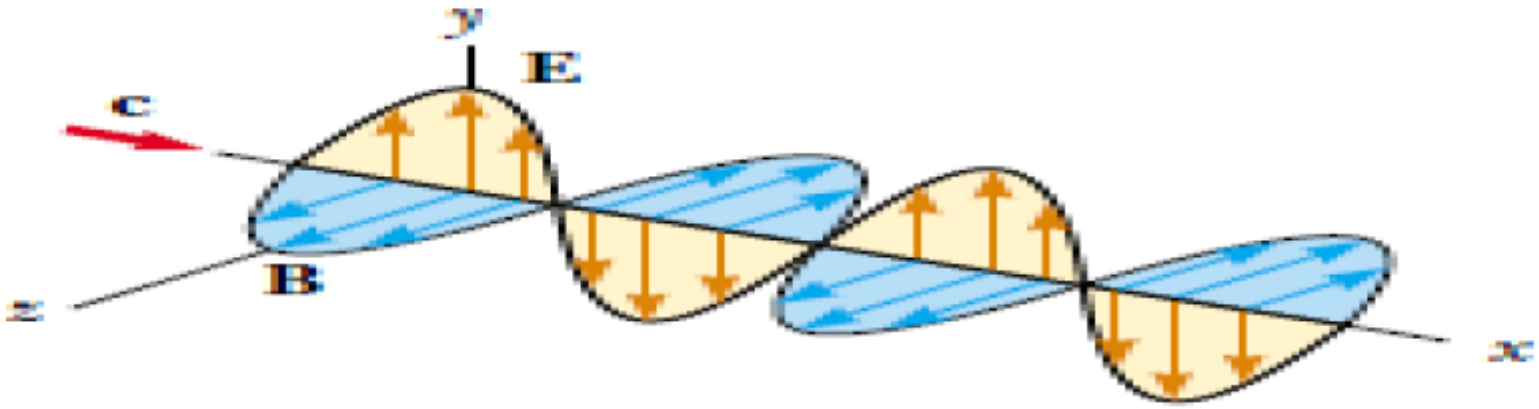
For the second-order maximum (m=2), we find $sin\theta_2 = \frac{2\lambda}{d} = \frac{2(632.8nm)}{1667nm}$

$$sin\theta_2 = 0.7592$$

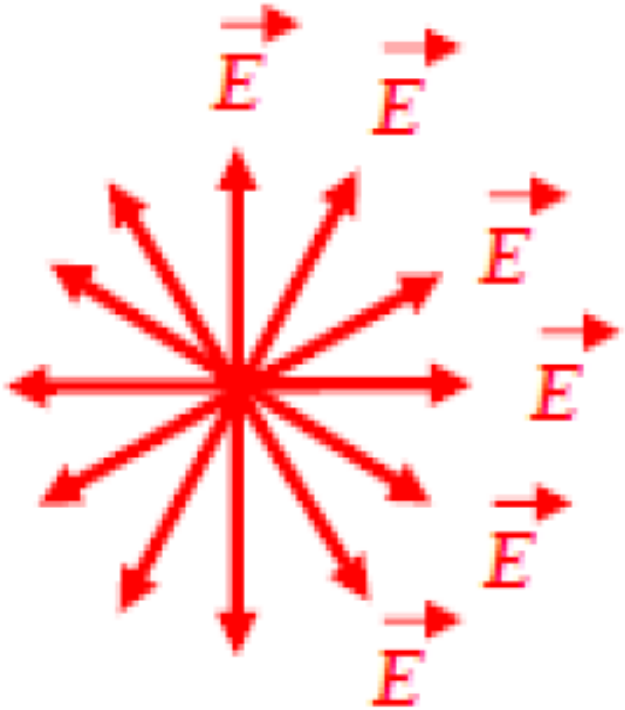
$$\therefore \theta_2 = 49.39^o$$

POLARIZATION

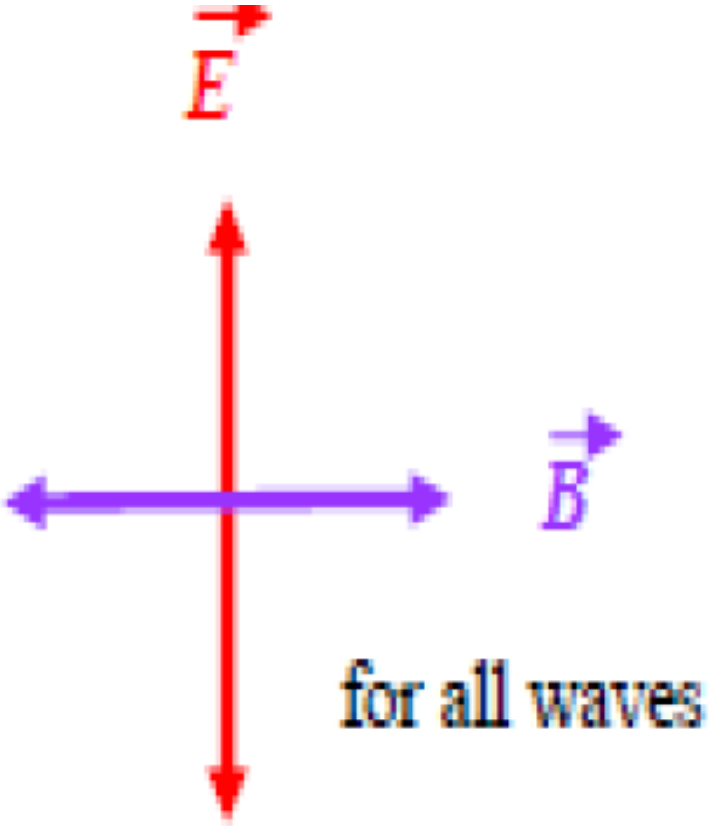
An ordinary beam of light consists of a large number of waves emitted by the atoms of the light source. The direction of polarization of each wave is defined to be Electric field $\vec{E}$ direction which lie along y axis. However, an individual EM wave could have its E vector is the yz plane, making any possible angle with the y-axis. This is shown in below



When light is polarized, the electric field $\vec{E}$ always points in the same direction but if the electric field pointing along all directions perpendicular to the direction of propagation, the resulting light is unpolarized. A wave is said to be linearly polarized if the resultant E field vibrates in the same direction at all times at a particular point. Such a wave is often reffered to as being plane polarized as shown below.



Unpolarized



Linearly polarized

Unpolarized light can be changed into a polarized light by passing the light through or reflecting off of a special material called a Polarizer. In 1932, E.H. Land discovered such a transmitting material called a POLAROID that polarized light through selective absorption by molecules oriented in a specific manner in the material as unpolarized light passed through it.

POLARIZATION BY SCATTERING

When light is incident on any material, the electrons in the material can absorb and reradiate part of the light. Such absorption and re-radiation of light by electrons in the gas molecules that make up air is what causes sunlight reaching an observer on the earth to be partially polarized.

For example, the N_2 and O_2 molecules in the Earth atmosphere are very effective at polarizing the sun's light through a process known as Rayleigh Scattering. The amount of Rayleigh Scattering that an atom or a molecule will perform is proportional to $\frac{1}{\lambda^4}$. This is why the sky is blue as the blue light from the sun is scattered much more efficiently than red light.

Malus's law gives the intensity **I** after light goes through polarizers/Analyzers. (Note: Polarizer is used when input is unpolarized light and Analyzer when input is polarized light (it gives direction of polarization).

The polarizer output is polarized light with amplitude E_0 while the Analyzer output is component of E_0 along analyzer transmission axis. The Amplitude of analyzer output is $E_0 \cos\theta$.

But Intensity **I** is proportional to $|E|^2$ $\therefore I_{trans} = I_0 \cos^2\theta$.

If $\theta = 90^0$, then there is no transmission through the analyzer.

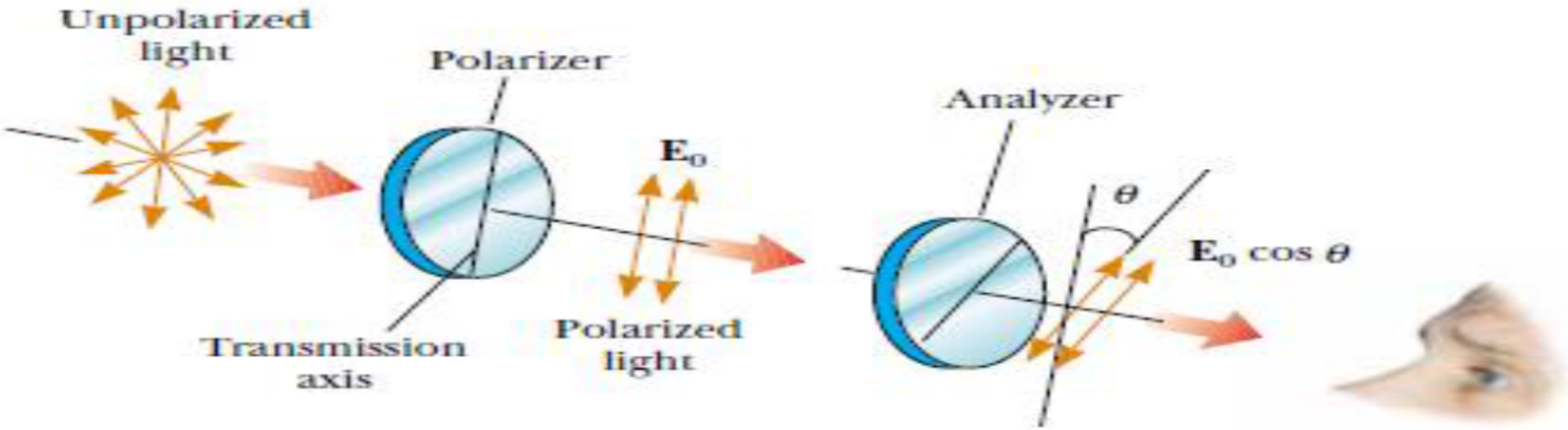
LEARNING MANAGEMENT SYSTEM LMS

.: The intensity of the polarized beam transmitted through the analyzer varies as $I = I_{max} Cos^2\theta$

or $I_{trans} = I_0 Cos^2\theta$

Where I_{max} rep the intensity of the polarized beam incident on the analyzer.

The figure below represent an unpolarized light beam incident on the polarizer while the transmitted beam (polarized) is being intercepted by the analyzer.

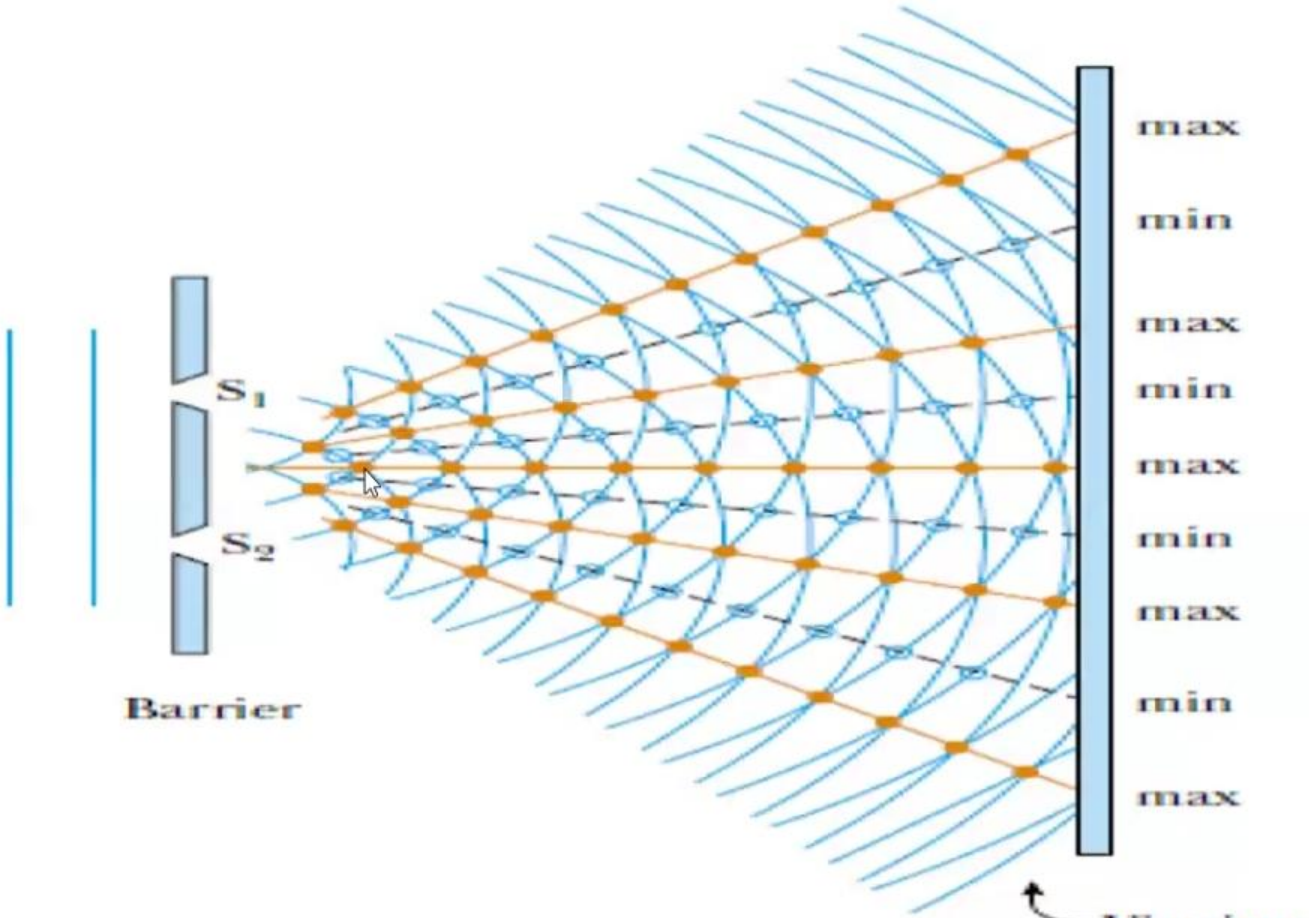


BASIC PHENOMENA OF PHYSICAL OPTICS FOR ILLUSTRATION (INTERFERENCE, DIFFRACTION, POLARIZATION)

INTERFERENCE

The interaction of two or more waves is called interference. Constructive interference occurs if the waves are in phase with each other. This process lead to a large amplitude resultant wave which is the sum of the amplitudes of the individual waves. Destructive interference occurs if the waves are out of phase with each other resulting in a wave of zero amplitude. For the two types of interference, these conditions must be met (i) the waves from the sources must be coherent. This means that the waves they emit must maintain a constant phase with respect to

each other. (ii) The sources of waves should be monochromatic i.e of single wavelength and (iii) the waves must have identical wavelengths to be coherent. A laser (light amplification of stimulated emission of radiation) is a good source of coherent radiation. Most ordinary light sources produce a continuos spectrum, hence produce incoherent light. Incoherent light can be converted to a coherent light through the use of two "pinholes" or "slits" at a specific separation. Thomas young in 1801 demonstrated interference in light waves from two sources produced from a single source of light passing through two pinholes in a screen as shown below.


max
min
max
min
max
min
max
min
max
S_1
S_2
Barrier
Viewing screen

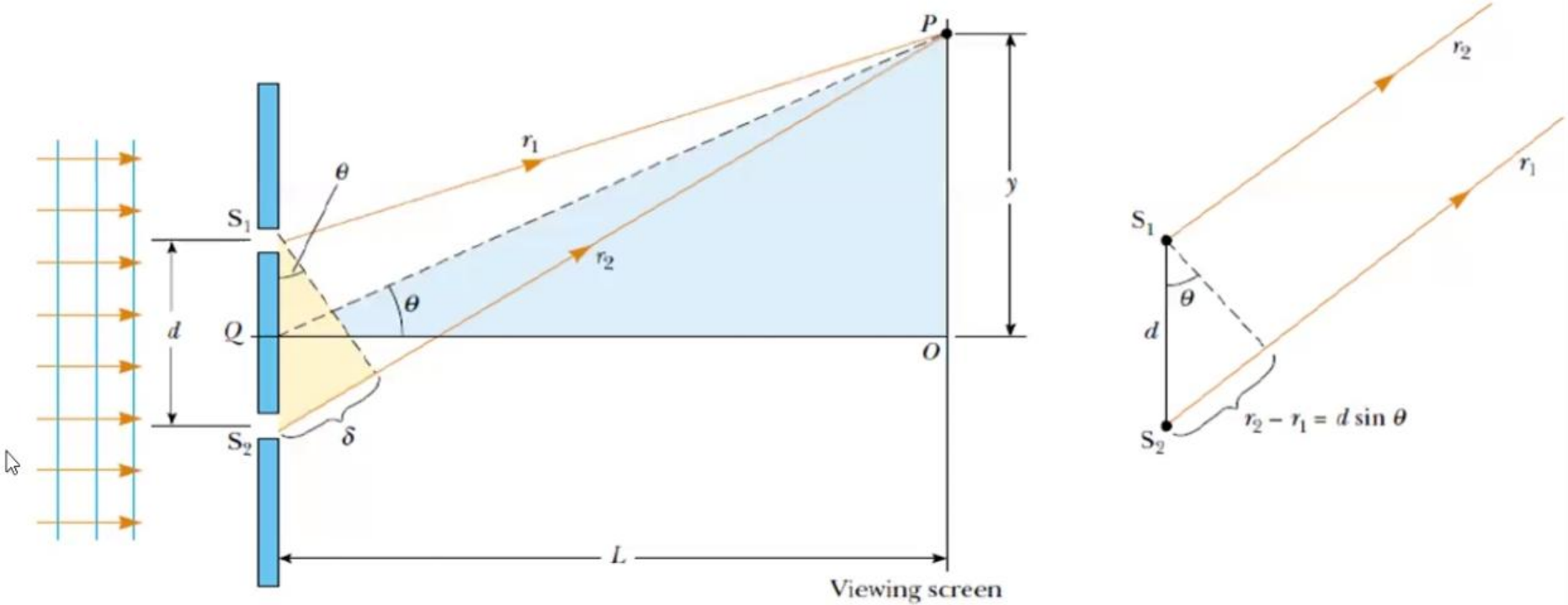
(a)

The experiment showed that the resulting wavefronts from the two slits produced as series of bright and dark parallel bands called fringes.

In order for the wavefront (i.e wave crests) of the light from the two different slits to arrive on a **projection screen at the same time at the same place, the following equation must be true**

$$\delta = r_2 - r_1 = d \sin \theta$$

where r_1 is the distance that the wave front travelled from slit1, r_2 the distance travelled slit2, δ is the path difference between r_2 and r_1, d is the distance between the slits, and θ i angle shown in the figure below (b)



The "bright" fringes correspond to regions of constructive interference. This will occur at a position on the viewing screen when $\delta = \pm m\lambda$ i.e. $\delta = \sin\theta_{bright} = m\lambda$, $m=0, \pm1, \pm2$ ..... where **m**, is called the order number. The central bright fringe at $\theta_{bright} = 0$ is called the zeroth-order maximum. The first maximum on either side where $m= \pm1$ is called the first-order maximum, and so forth.

The "dark fringes" correspond to regions of destructive interference. This will occur at a position on the viewing screen when the waves are 180^0 out of phase (i.e when δ is an odd multiple of $\frac{\lambda}{2}$).

The condition for dark fringes or destructive interference at point P is $\delta = d \sin \theta_{dark} = \left(m + \frac{1}{2}\right) \lambda,\ m = 0, \pm 1, \pm 2, \ldots \ldots \ldots$

Here, the first dark fringe occurs at m=0 giving a path difference of $\frac{\lambda}{2}$, the second dark fringes occurs at m=1 giving a path difference of $\frac{3\lambda}{2}$ and so on.

Let L be the distance between the "slit plane" and the viewing screen and y be the distance that a fringe is away from the zeroth-order maximum on the viewing screen. Then, if L>>d and d>>λ, which is typically the case in this type of experiment. Under these conditions θ is small, thus $\sin\theta \approx \tan\theta$, so that $\sin\theta \approx \frac{y}{L}$.

So from d Sin $\theta_{bright} = m\lambda$, we get $d\frac{y_{bright}}{L} = m\lambda$

.: Using this approximation, we find that the positions of the bright fringes measured from the zeroth-order bright fringe is

$$y_{bright} = \frac{m\lambda L}{d}, m = 0, \pm 1, \pm 2 \ldots\ldots\ldots$$

Also,

$$y_{dark} = \frac{\lambda L}{d}\left(m + \frac{1}{2}\right)$$

(Note: Young's double-slit experiment provides a method for measuring the wave length of light)

The intensity at a point in the double-slit interference pattern

If the two slits represent coherent sources of sinusoidal waves such that the two waves from the slits have the same angular frequency w and constant phase difference $\emptyset$. The total magnitude of E at point P on the screen is the superposition of the two waves.

Assuming that the two waves have the same amplitude E_o. The magnitude of the electric field at P due to each wave is $E_i = E_o \sin wt$ and $E_2 = Eo \sin (wt + \emptyset)$

Although, the waves are in phase at the slits, their phase difference θ at P depends on the path difference $\delta = r_2 - r_1 = d \sin \theta$

A path difference for constructive interference corresponds to a phase difference of 2πrad. Using the ratio $\frac{\delta}{\lambda} = \frac{\emptyset}{2a}$, this gives $\phi = \frac{2\pi\delta}{\lambda} = \frac{2\pi}{\lambda} d \sin\theta$

The magnitude of the resultant electric field E at P is $E_p = E_1 + E_2 = E_0(\sin wt + \sin(wt + \emptyset)) = 2E_0 \, Cos\left(\frac{\emptyset}{2}\right) Sin\left(wt + \frac{\emptyset}{2}\right)$.

If $\emptyset$ is even i.e if $\emptyset = 0, 2\pi, 4\pi$, Ep is $2E_o$ corresponding to the condition for maximum constructive interference. Likewise if $\emptyset$ is odd i.e $\emptyset = \pi, 3\pi, 5\pi, \ldots$ then E_p is zero and this is for total destructive interference.

Since intensity of a wave is proportional to the square of the resultant electric field at that point

$$\therefore I \alpha {E_p}^2 = 4E_0^2 \cos^2\left(\frac{\emptyset}{2}\right) \sin^2\left(wt + \frac{\emptyset}{2}\right).$$

The time averaged value of $\sin^2\left(wt + \frac{\emptyset}{2}\right)$ over one cycle is ½ .: we can write the average light intensity at P as $I = I_{max} \, Cos^2\left(\frac{\emptyset}{2}\right)$ where I_{max} is the maximum intensity on the screen. By substituting $\emptyset = \frac{2\pi}{\lambda}$ d Sinθ into equation above, we get $I = I_{max} \, Cos^2\left(\frac{\pi \, d \, sin}{\lambda}\right)$

Or since Sin θ ≈ $\frac{y}{L}$ for small values of θ

$$\therefore I \approx I_{max} \, Cos^2\left(\frac{\pi d y}{\lambda L}\right)$$

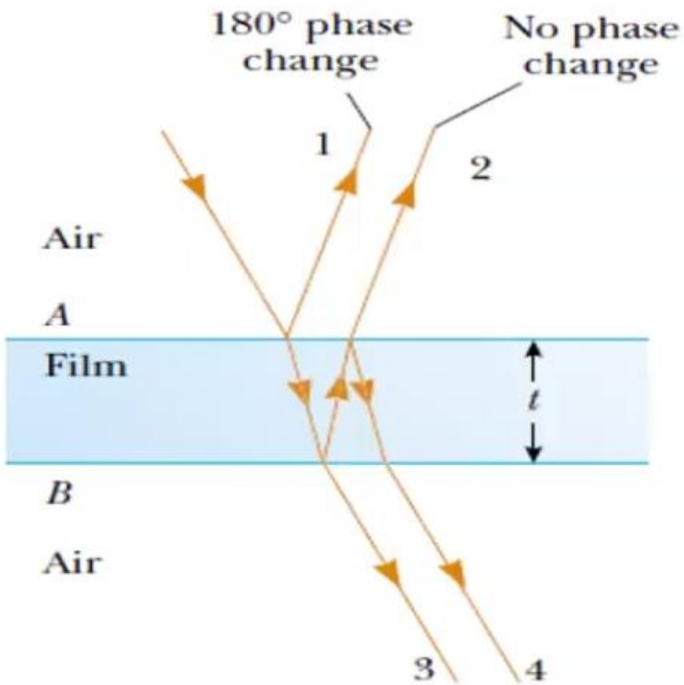
Interference in Thin Films

Interference effects are commonly observed in thin film, such as thin layers of oil on water or the thin surface of a soap bubble. The varied colours observed when white light is incident on such films result from the interference of waves reflected from the thin surfaces of the film.

Consider light reflected off a surface. Let n_1, be the index of refraction of the incident side of the surface and n_2 be the index of refraction on opposite side. With this set up, we can write the rules of phase change of reflected light as:

(a) If $n_2 > n_1$, any light reflected off of this surface will undergo a 180^0 phase change upon reflection.

(b) If $n_2 < n_1$, any light reflected off this surface will experience no phase change upon reflection.



Now consider a thin film (film of uniform thickness t) with an index of refraction n. Let A and B be the top and bottom side of the film surface respectively, on either side of this film, we assume that air is the medium and hence $n_{outside} = n_{air} = 1$

An incident beam passes through air and interacts with surface A. Part of the beam get reflected (Ray 1) where the reflected ray has an 180^0 phase change. Since $n_{film} > n_{air}$, and part of the ray is reflected into the medium (film).

In the medium of refractive index (n),the waves length of light changes to $\lambda_n = \frac{\lambda}{n}$ *where* λ is the wavelength of light in a vacuum (and in air since we have assumed that $n_{air}=1$). The refracted beam in the medium then interacts with surface B. Once again, part of the beam get reflected, but this time the reflected ray has no phase change since $n_{film} < n_{air}$, and path of the ray is transmitted (and once again refracted) into the air on the other side of the thin film following a path that is parallel to the original incident beam. This surface B reflection then once again interacts with surface A and get refracted such that it is following a path parallel to the 180^0 out of phase surface A reflected beam (Ray 1). We will label this second ray 2. However, Ray 2 travels an extra distance 2t before the waves recombine in the air above surface A. Suppose these two rays are completely out of phase with each other, we will get constructive interference (bright reflection) when $2t = \left(m + \frac{1}{2}\right)\lambda_{,} m = 0,1,2, \ldots\ldots$ using $\lambda_n = \frac{\lambda}{n}$, we get

$$\frac{2t}{\lambda_n} = \frac{2nt}{\lambda_{vac}} = \left(m + \frac{1}{2}\right) \therefore 2nt = \left(m + \frac{1}{2}\right)\lambda, m = 0,1,2, \ldots..$$

Likewise if the extra distance 2t that Ray 2 takes is a multiple of λ_n, the two waves combine out of phase resulting in destructive interference. Destructive interference (dark reflection) occur if

$$\frac{2nt}{\lambda_{vac}} = m \;\; or \; 2nt = m\,\lambda_{vac} \; or \; 2t = m\,\lambda \; (\text{note } \lambda = \lambda_{vac})$$

Example: A pair of narrow, parallel slits separated by 0.25mm is illuminated by the green component from a mercury vapour lamp (^= 546.1 nm). The interference pattern is observed on a screen 1.20m from the parallel slits. Calculate the distance (a) from the central maximum to the first bright region on either side of the central maximum and (b) between the first and second dark bands in the interference pattern.

Solution

Here ^=546.1nm, L=1.20m, d= 0.25mm = 0.25×10^{-3}m

The distance between the central maximum and the first order bright fringe can be determined with the use of equation.

$$y_{bright} = \frac{\lambda Lm}{d}$$

$$\therefore\ \Delta y = y_{bright}|_{m=1} - y_{bright}|_{m=0} = \frac{\lambda L.1}{d} - 0$$

$$= \frac{\lambda L}{d} = \frac{546.1 \times 10^{-9} \times 1.20}{0.25 \times 10^{-3}} = 2.62 \times 10^{-3} m = 2.62 mm$$

(b) The distance between the first and second dark bands can be determined by

$$y_{dark} = \frac{\lambda L}{d}\left(m + \frac{1}{2}\right)$$

$$\Delta y = y_{dark}|_{m=1} - y_{dark}|_{m=0}$$

$$= \left[\frac{\lambda L}{d}\left(1 + \frac{1}{2}\right)\right] - \left[\frac{\lambda L}{d}\left(0 + \frac{1}{2}\right)\right]$$

$$= \frac{3\lambda L}{2d} - \frac{\lambda L}{2d} = \frac{\lambda L}{d} = 2.62 \times 10^{-3} m = 2.62 mm$$

Example 2: A transparent oil with index of refraction 1.29 spills on the surface of water (n= 1.33), producing a maximum of reflection with normally incident orange light (wavelength 600nm in air). Assuming the maximum occurs in the first order, determine the thickness of the oil slick.

Solution:

Since $n_{air} < n_{oil} < n_{water}$, light reflection from both top and bottom surfaces of the oil film experiences phase reversal, resulting in zero net phase difference due to reflections. Therefore the condition for constructive interference for reflective light will be given by $2n_{oil} \lambda t = m \lambda$ $or\ t = m\left(\frac{\lambda}{2n_{oil}}\right)$.

Since we are told that the first order will produce the maximum intensity m=1 and the thickness of the oil slick is $t = 1\left(\frac{600nm}{2(1.29)}\right) = 233nm$

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The Bohr Model of Hydrogen

The hydrogen atom has a diameter of about 0.1nm. It consists of a proton as the nucleus (with radius of about 10^{-15}m) and a single election.

The first effective model of the atom was introduced by Bohr (1913). The earliest version of the Bohr model pictured electrons in circular orbits around the nucleus. He further assumed that there is no radiation as long as an election remains in one orbit but that energy is absorbed by the atom when the election is moved from an orbit of lower energy to one of higher energy and emitted when the electron moves in the reverse direction.

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The centripetal force needed to hold the electron in its circular orbit is supplied by the electrostatic (Coulomb) force of attraction toward the nucleus.

Hence, $\frac{mV_n^2}{r_n} = \frac{Ke^2}{r^2}$, simultaneous solution of this equation gives the radii of stable orbits as r_n = 0.053nm)n^2.

for hydrogen atom, $\frac{mV^2}{r} = \frac{Ze^2}{(4a\varepsilon_0)r^2}$,..... (1)

for hydrogen, Z = 1

For the electron's de Broglie wave to "resonate" or "fit" in an orbit of radius r, the following must be true i.e. $mV_n r_n = \frac{n\lambda}{2\pi}$.

The speed of the electron may be written as $V_n = \frac{nh}{2\pi mr}$

from equ (1) the K.E of the electron is $\frac{1}{2}mv^2 = \frac{Ze^2}{(4\pi\varepsilon_0)2r}$

Elimination of v from the last two equations gives the radius of an orbit to be $r = \frac{n^2h^2(4\pi\varepsilon_0)}{4\pi^2mZe^2}$.

The assumption that radiation is emitted only for an orbital transition and that the energy of the photon is given by $h\nu = W_i - W_f$.

This leads to an expression of the frequency of a spectrum line. A transition from an upper level m to a lower level n will radiate a photon at frequency

$$\nu_{mn} = cR_AZ^2\left(\frac{1}{n^2} - \frac{1}{m^2}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (B)$$

Where the velocity of light c = 2.997925 x 10^{10}cm/s, Z is the effective charge of the nucleus (Z_H =1, Z_{He} = 2, etc) and the atomic Rydberg constant, R_A is given by $R_A = R_\infty\left(1 + \frac{Me}{Ma}\right)^{-1}$

R_A = 1.0974 x $10^7 m^{-1}$.

Equ (B) can also be expressed in terms of wavelength (vacuum) by the following

$$\frac{1}{\lambda_{mn}} = R_A Z^2 \left(\frac{1}{n^2} - \frac{1}{m^2}\right)$$

The spectral lines emitted by excited isolated hydrogen atoms occur in series. Lines that originate from (or terminate to) the same level in a hydrogen like atom/ion are said to belong to the same series. Transitions out of (or into) the ground state (n = 1) are lines of the Lyman Series, n = 2 corresponds to the Balmer Series, and n =3 the Paschen Series.

i.e Lyman: $\frac{1}{\lambda} = R\left(\frac{1}{1^2} - \frac{1}{n^2}\right)$ $n = 2,3, \ldots$

Balmer: $\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$ $n = 3,4, \ldots$

Paschen: $\frac{1}{\lambda} = R\left(\frac{1}{3^2} - \frac{1}{n^2}\right)$ $n = 4,5, \ldots$

For each series, the transition with the longest wavelength is called the alpha (α) transition, the next blueward line from α is the β line followed by the γ line, etc

Lyman α is the $1 \leftrightarrow 2$ transition, Lyman β is the $1 \leftrightarrow 3$ transition, Lyman γ is the $1 \leftrightarrow 4$ transition etc.

Balmer or Hα is the $2 \leftrightarrow 3$ transition, Hβ is the $2 \leftrightarrow 4$ transition, H γ is the $2 \leftrightarrow 5$ transition etc.

An atom in its ground state can absorb a photon in a process called <u>resonance absorption</u> only if that photon will raise the atom to one of its allowed energy level. Lines that go into or come out of the ground state are referred to as resonance lines.

Example: Calculate the wavelength of the first line in the visible (Balmer) series of the hydrogen spectrum.

Solution:

$$\frac{1}{\lambda} = R\left(\frac{1}{n^2} - \frac{1}{m^2}\right) = 1.0974 \times 10^{-3}\text{Å}^{-1}\left(\frac{1}{2^2} - \frac{1}{3^2}\right)$$

$$= 1.52 \times 10^{-4}\text{Å}^{-1}$$

$$\lambda = 6{,}560\text{Å}$$

The lowest energy state (E=0) is called the ground state. States above the ground are said to be excited.

Bohr also determined that the distance that a state is from the nucleus (i.e a proton in the case of hydrogen) can be determined in a semi-classical approach by setting the angular momentum L of a mass in a circular orbit to an integer multiple of ħ.

i.e $L_n = M_e V_n r_n = n\hbar$

Bohr also determined that the distance that a state is from the nucleus (i.e a proton in the case of hydrogen) can be determined in a semi-classical approach by setting the angular momentum L of a mass in a circular orbit to an integer multiple of ħ.

$r_n = (0.053nm)n^2 = n^2a^0$. The radius of the ground state is a_0 which is called the Bohr radius. a_0 is given by $a_0 = \frac{\hbar^2}{m_e K_e e^2} = 0.0529nm$.

for a hydrogen like ion, the radii of each quantum orbit is

$$r_n = \frac{n^2\hbar^2}{Zm_e K_e e^2} = \frac{n^2 a_0}{Z} = \frac{n^2(0.0529nm)}{Z}$$

(Note: for hydrogen atom $r_n = \frac{n^2\hbar^2}{m_e K_e e^2} = n^2 a_0 = n^2(0.0529nm)$

Example

For a hydrogen atom in its ground state, use the Bohr model to compute

(a) The orbital speed of an electron

(b) The kinetic energy of an electron and

Solution

(a) With electrical force supplying the centripetal acceleration

$\frac{m_e V_n^2}{r_n} = \frac{K_e e^2}{r_n^2}$, giving $V_n = \sqrt{\frac{K_{ee^2}}{m_e r_n}}$ where $r_n = n^2$ (0.0529nm)

$\therefore$ Thus $V_1 = \sqrt{\frac{K_{ee^2}}{m_e r_1}} = \sqrt{\frac{(8.99\times10^9 N\, m^2/C^2)(1.60\times10^{-19}C)^2}{(9.11\times10^{-31}kg)(0.0529\times10^{-9}m)}}$

$$= 2.19 \times 10^6 m/s$$

(b) $K.E_1 = \frac{1}{2}m_e V_1^2 = \frac{1}{2}m_e\left(\frac{K_e e^2}{m_e r_1}\right) = \frac{K_e e^2}{2r_1}$

$$= \frac{8.99 \times 10^9 \times (1.60 \times 10^{-19}C)^2}{2(0.0529 \times 10^{-9}m)} = 2.18 \times 10^{-18}\left(\frac{leV}{1.60 \times 10^{-19}J}\right)$$

$$= 13.6eV$$

The P.E is $P.E_1 = \frac{K_e(-e)e}{r_1} = \frac{8.99\times10^9\times(-1.60\times10^{-19})(1.60\times10^{-19})}{(0.0529\times10^{-9})}$

$$= -4.35 \times 10^{-18}J\left(\frac{leV}{1.60 \times 10^{-19}J}\right) = -27.2eV$$

Example: An electron is in the first Bohr orbit of hydrogen. Find

(a) The speed of the electron

(b) The time required for the electron to circle the nucleus, and

(c) The current in amperes corresponding to the motion of the electron

Solution

Using $L_n = M_e V_n r_n = n\hbar$, solving for V_n and set n= 1 for ground state, we get $M_e V_n r_n = n\hbar$

$$V_n = \frac{n\hbar}{m_e r_n} \quad \therefore V_1 = \frac{\hbar}{m_e r_1} = \frac{\hbar}{2\pi m_e a_0}$$

$$= \frac{6.63 \times 10^{-34} J.s}{2\pi(9.11 \times 10^{-31} kg)(0.0529 \times 10^{-9} m)} = 2.19 \times 10^{6} m/s$$

(b) This velocity V= 2.19 x 10^6 m/s just represent the path taken per one cycle. Since the path is the circumference of a circle, C= 2πr

.: The amount of time it will take to complete one orbit (i.e, cycle) is

$$V_1 = \frac{C_1}{\Delta t} = \frac{2\pi r}{\Delta t} \quad \therefore \Delta t = \frac{2\pi r_1}{V_1} = \frac{2\pi(0.0529 \times 10^{-9} m)}{2.19 \times 10^6 m/s}$$

$$\therefore \Delta t = 1.52 \times 10^{-16} s$$

(c) $I = \frac{\Delta Q}{\Delta t} = \frac{|e|}{\Delta t} = \frac{1.6\times10^{-19}C}{1.52\times10^{-16}S} = 1.05 \times 10^{-3} A = 1.05 mA$

For each series, the transition with the longest wavelength is called the alpha (α) transition, the next blueward line from α is the β line followed by the γ line, etc

Lyman α is the $1 \leftrightarrow 2$ transition, Lyman β is the $1 \leftrightarrow 3$ transition, Lyman γ is the $1 \leftrightarrow 4$ transition etc.

Balmer or Hα is the $2 \leftrightarrow 3$ transition, Hβ is the $2 \leftrightarrow 4$ transition, H γ is the $2 \leftrightarrow 5$ transition etc.

An atom in its ground state can absorb a photon in a process called <u>resonance absorption</u> only if that photon will raise the atom to one of its allowed energy level. Lines that go into or come out of the ground state are referred to as resonance lines.

Example: Find the energy of the electron in the ground state of doubly ionized lithium, which has atomic number of z = 3 (b) find the radius of its ground state orbit.

Solution

The principal (n) level have energies of

$$E_n = \frac{-2\pi^2 m e^4 z^2}{n^2 h^2} = (-13.6eV)\frac{z^2}{n^2}$$

Where Z = charge of the nucleus

Using $E_n = (-13.6eV)\frac{z^2}{n^2} with\ n = 1\ and\ z = 3$

$$E_1 = (-13.6eV)\frac{z^2}{n^2} = (-13.6eV)\frac{3^2}{1^2} = -1.22eV$$

(b) Using $r_n = \frac{n^2 a_0}{z}\ with\ n = 1\ and\ z = 3$

$$\therefore\ r_1 = \frac{n^2 a_0}{Z} = \frac{1^2(0.0529m)}{3} = 1.76 \times 10^{-11} m$$

Example: A photon is emitted as a hydrogen atom undergoes a transition from the n=6 to the n= 2 state. Calculate (a) the wave length (b) the energy(c) the frequency of this photon and (d) to which series in the hydrogen spectrum does this photon belong?

Solution

The solution to (a) can be easily derived from the solution to (b)

(a) Using $E = \frac{hc}{\lambda} = \frac{(6.63\times10^{-34}Js)\times(3\times10^{8}m/s)}{4.1029\times10^{-7}m} = 4.85\times10^{-19}J = 3.03eV$

(b) Using $\frac{1}{\lambda} = R_A Z^2\left(\frac{1}{n^2}-\frac{1}{m^2}\right) \Rightarrow \frac{1}{\lambda} = R_H(1)^2\left(\frac{1}{2^2}-\frac{1}{6^2}\right)$

$$= 1.096776\times10^{5}cm^{-1}\left(\frac{1}{4}-\frac{1}{36}\right) = 2.43728\times10^{4}cm^{-1}$$

$$\therefore \lambda = 4.1029\times10^{-5}cm\left(\frac{1nm}{10^{-7}cm}\right) = 410.29nm$$

Example: Find the energy of the electron in the ground state of doubly ionized lithium, which has atomic number of z = 3 (b) find the radius of its ground state orbit.

Solution

The principal (n) level have energies of

$$E_n = \frac{-2\pi^2 m e^4 z^2}{n^2 h^2} = (-13.6eV)\frac{z^2}{n^2}$$

Where Z = charge of the nucleus

Using $E_n = (-13.6eV)\frac{z^2}{n^2}$ $with\ n = 1\ and\ z = 3$

$$E_1 = (-13.6eV)\frac{z^2}{n^2} = (-13.6eV)\frac{3^2}{1^2} = -1.22eV$$

(b) Using $r_n = \frac{n^2 a_0}{z}$ $with\ n = 1\ and\ z = 3$

$$\therefore\ r_1 = \frac{n^2 a_0}{Z} = \frac{1^2(0.0529m)}{3} = 1.76 \times 10^{-11} m$$

If the probability of α-particles of energy 10 MeV to be scattered through an angle greater than θ on passing through a thin foil is 10^{-3}, what is it for 5 MeV protons passing through the same foil?

SOLUTION

Since the atomic number and foil thickness and angles are the same, the probability for scattering will be inversely proportional to the square of energy and directly proportional to this square of the charge of the particle. Hence the probability for scattering of 5 MeV α-particles will be $\frac{2^2}{10^2} \times \frac{5^2}{1^2} \times 10^{-3} = 10^{-3}$

Course Title

Course Code 102 / Department: PHYSICS

RADIATION AND PHOTONS

Name of Presenter: OLURIN 'SEUN T.

RADIATION AND PHOTON

All the various forms of electromagnetic radiation, including light have a dual nature, they behave like waves when travelling through space but when interacting with atoms and molecules, they act like a stream of quantized energy or photon.

They energy E of each photon of frequency f and wavelength λ is given by $E = hf = \frac{hc}{\lambda}$ where

h=6.626 x 10^{-34} Js (Planck's Constant)

PHOTOELECTRIC EFFECT

When electromagnetic radiation is incident upon the surface of certain metals, electrons may be ejected. A photon of energy hf penetrates the material and is absorbed by an electron. If enough energy is available, the electron of the metal will be raised to the surface and ejected with some kinetic energy ½ mv^2. Let w be the energy required for an electron to break free of the surface, (work function). The maximum kinetic energy which the electron can have when it leaves the surface is therefore $E_{k,max} = hf - w$. This is called Einstein's Photoelectric equation.

The energy of the ejected electron may be found by determine what potential difference must be applied to stop its motion. Then for most energetic electron, $eV_s = hf - w$ where V_s is the stopping potential.

The minimum frequency of light that will liberate electrons from the particular metal is known as threshold frequency. At this threshold frequency f_0, the photon delivers just enough energy to enable the electron to get out of the metal, with $E_k = 0$ $\therefore hf_0 = w$.

i.e. At the threshold frequency, the photon's energy just equals the work function.

The Momentum of a Photon

$E^2 = m^2c^4 + p^2c^2$, when $m=0$, $E = pc$

$$\therefore E = pc = hf \qquad \therefore p = \frac{hf}{c} = \frac{h}{\lambda}$$

$\therefore$ The momentum of a photon is $p = \frac{h}{\lambda}$

The Compton effect

Compton allowed a beam of monochromatic X-rays to fall on a scattering material, he observed that the scattered radiation have the same wavelength as the incident beam. But in addition Compton observed a scattered wavelength λ' greater than that of the original beam. The shift in wavelength $\Delta\lambda = \lambda' - \lambda$ was found to become larger as the scattering angle θ was increased. This scattering with an increase in wavelength is called the Compton effect. This effect is explained by photon picture of electromagnetic radiation. A photon can collide with a particle having mass

e.g. electron. When it does so, the scattered photon can have a new energy and momentum. Suppose a photon of initial wavelength λ collides with a free, stationary electron of mass Me and is deflected through an angle θ with a new scattered wavelength λ'. Then the scattered wavelength λ' is given by $\lambda' = \lambda + \frac{h}{m_e C}(1 - cos\theta)$ which fits the experimentally measured wavelength shift as a function of scattering angle θ.

Example

Calculate the energy of a photon of blue light of wavelength 450nm

Solution

$$E = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} J.s \times 2.998 \times 10^{8} m/s}{450 \times 10^{-9} m}$$

$$= 4.42 \times 10^{-19} J = 2.76 eV$$

Example 2

The work function of a group 1 metal is 2.3eV. What is the longest wavelength light that can cause photoelectron emission from this metal?

Solution:

At threshold, the photon energy equals the energy required to tear the electron loose from the metal. In other words, hf = w (i.e. the electron's K.E = 0) .: hf = w $\therefore w = \frac{hc}{\lambda}$

$$\therefore (2.3eV)\frac{(1.602 \times 10^{-19})}{1.00\ eV} = \frac{6.63 \times 10^{-34} J.s \times 2.998 \times 10^{8} m/s}{\lambda}$$

$$\lambda = 5.4 \times 10^{-7} m$$

Example 3

Calculate the work function of sodium metal if the photoelectric threshold wavelength is 680nm?

Solution

$$hf = w \qquad \therefore w = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} J.s \times 3 \times 10^{8} m/s}{680 \times 10^{-9} m}$$

$$\therefore w = \frac{6.63 \times 3 \times 10^{-26}}{6.8 \times 10^{-7}} = \frac{19.89 \times 10^{-26}}{6.80 \times 10^{-7}}$$

$$\therefore w = 2.925 \times 10^{-19} J.$$

In eV $\therefore w = \frac{2.925 \times 10^{-19}}{1.6 \times 10^{-19}} = 1.82 eV$

De Broglie Wavelength

A particle of mass m in moving with momentum p has associated with it a de Broglie wavelength given by $\lambda = \frac{h}{p} = \frac{h}{mv}$. A beam of particles can undergo both diffraction and interference phenomenon. These wavelike properties of particles can be computed by assuming the particles to behave like wave (de Broglie waves) having the de Broglie wavelength.

RADIOACTIVITY

Radioactivity is defined as the spontaneous disintegration of unstable nuclei: Nuclei found in nature with atomic number Z greater than that of lead, (Z = 82) are unstable or radioactive. A radioactive nucleus spontaneously ejects one or more particles in the process of transforming into a different nucleus. Early result on radioactive materials shown that they emit three kind of rays. These are α, β, and γ ray. Later experiments on radioactive material showed α rays to be positively charged helium atoms, β rays to be electrons and gamma (γ) rays to be electromagnetic radiation of short wavelength.

STATISTICAL LAW OF RADIOACTIVE DECAY

The activity of a radioactive sample (i.e the number of distingerations per second) is an experimental (or logarithmic) function of time. This means that the activity decreases with time.

A simple relation that exists between the number N of atoms of radioactive material present and the number ΔN that will decay in a short time Δt is given by $\Delta N = \lambda N \Delta t$ where λ is called the distingeration /decay constant. It represents the fractional number of radioactive atoms decaying per unit time.

$$\lambda = \frac{\Delta N}{N \triangle t}$$

One can express the number N of radioactive atoms remaining after time t in time of number N_0 originally present at time t = 0 as: $N = N_0 e^{-\lambda t}$

The time at which the number of radioactive atoms remaining is just one-half the original number is called the half-life ($t_{½}$). it is related to decay constant through $\lambda t_{½} = 0.693$

Note $\frac{N}{N_0} = \frac{1}{2} = e^{-\lambda t_{\frac{1}{2}}}$ $\therefore t_{\frac{1}{2}} = \frac{ln2}{\lambda} = \frac{0.693}{\lambda}$. λ has a unit of S^{-1}

$\frac{\Delta N}{\Delta t}$ is the rate of distingerations (activity of the sample) and it is equal to λN. The S.1 unit of activity is the Becquerel (B_q) where $1B_q = 1$ decay/s

GAMMA DECAY

A nucleus in an excited state ${}^{A}_{Z}X^{*}$ may go to a state of lower energy by emitting the difference in energy as a photon.

i.e ${}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + h\nu$

the gamma (γ) decay does not cause a charge in the atomic number or the mass number of the nucleus.

Note: Study of γ radiation gives important information about the initial and final states of the nucleus undergoing a γ transition. The observed energies of emitted photons give consistent results for the nuclear energy levels as $h\nu = E_i - E_f$.

ALPHA DECAY

When an α particle is ejected from the nucleus, the original nucleus loses 2 protons and 2 neutrons. Its mass number decreases by 4 unit while its atomic number decreases by 2.

i.e. ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He + Q$. Where Q is the distingeration energy.

$$Q = E_{k,d} + E_{k,\propto} = (m_p - m_d - m_\propto)c^2$$

Example 1: Find the Q value for the distingeration of ${}^{144}_{60}N \rightarrow {}^{4}_{2}He + {}^{140}_{58}Ce$

Solution:

from tables of isotope masses ${}^{4}_{2}He = 4.00387$, ${}^{140}_{58}Ce = 139.94977$ and ${}^{144}_{60}Ne = 143.95556$

$$\therefore \quad m = 143.95556 - (4.00387 + 139.94977)$$

$$\therefore \quad m = 143.95556 - 143.95364 = 0.00192$$

$$\therefore \quad Q = mc^2 = 0.00192c^2 = 1.79MeV$$

BETA DECAY

There are high energy electrons that are created by a rearrangement of the original nucleus into a state of lower energy. There are two different types of β- decay: (a) β^- decay, in which an electron is emitted from the nucleus and β^+ decay, in which a positron is emitted.

$$ {}^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + {}_{-1}^{0}e + Q $$

$$ {}^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + {}_{+1}^{0}e + Q $$

For β^- decay to occur, the mass of the decaying nucleus must be greater than the mess of the product nucleus plus the mass of an electron. The condition for β^+ decay is slightly more complicated where $Q = (m_x - m_y - 2me)\, c^2$ where m_e is the rest mass of an electron.

NUCLEAR REACTIONS

We may consider a general notation for a nuclear reaction in which a particle or nucleus x strikes a nucleus X and results in the emission of particle y, leaving a nucleus Y.

$X + x \rightarrow Y + y$ The notation is often abbreviated as X (x,y) Y where X is the struck nucleus, (x, y) stand for the incoming and outgoing particles respectively and Y represents the residual nucleus. For example, the nuclear reaction

$$^{14}_{7}N + ^{1}_{1}H \rightarrow ^{11}_{6}C + ^{4}_{2}He$$

can be written according to the notation above as $^{14}_{7}N + ^{1}_{1}H \rightarrow ^{11}_{6}C + ^{4}_{2}He$ or ^{14}N(p, α) ^{11}C

others are $^{27}_{13}Al + ^{1}_{0}n \rightarrow ^{27}_{12}Mg + ^{1}_{1}H$ or ^{27}Al (n, p) ^{27}Mg

$^{10}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}He$ or ^{10}B (n, α) ^{7}Li

Example

The half-life of radon is 3.80 days. After how many days will only one – sixteenth of a radon sample remain?

Solution

Using $\lambda = \frac{ln2}{t_{\frac{1}{2}}} = \frac{0.693}{3.80d} = 0.182/d$

$$\therefore {}^{N}/_{N_0} = \frac{1}{16} = e^{-\lambda t} = e^{-0182/dt} = e^{-0.182t}$$

$$\therefore -0.182t = \ell\mathrm{n}\left(\frac{1}{16}\right) = -2.77$$

$$\therefore t = 15.2d$$

Example 2: Find the activity of a 1g sample of radium ($^{226}_{88}Ra$) whose half-life is 1620 years.

Solution: $\lambda = \frac{0.693}{1620yrs} = 4.28 \times 10^{-4}/yr = 1.36 \times 10^{-11}/s$

1 gram of ^{226}Ra contains a number of atoms equal to

$$N = \frac{6.025 \times 10^{23} atom\ per\ mole\ \times 1.0g}{226g/mole} = 2.7 \times 10^{21} atoms$$

Hence Activity = λN

= (1.36 x 10^{-11}/s) × (2.7 x 10^{21}atoms)

= 3.6 x 10^{10} distingerations per second

= 3.6 x $10^{10}S^{-1}$

= 0.97 Ci

Note: 1 Curie = 3.7×10^{10} distingerations/S

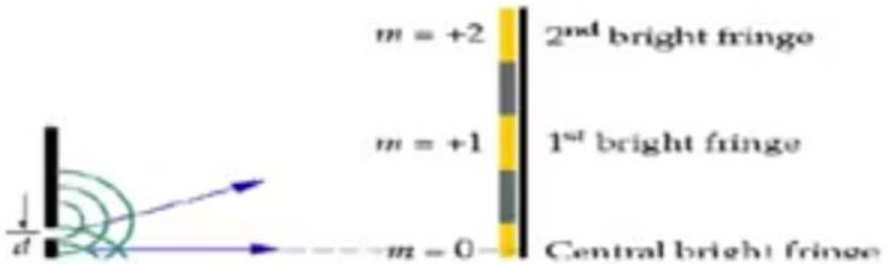
$1ci = 3.7 \times 10^{10}$ distingeration/s

$x = 3.6 \times 10^{10}$

$= 0.97C_1$

QUESTION ONE

Picture the Problem: The figure shows a double slit that produces the first bright fringes at angles of ±35° when laser light of wavelength 670 nm illuminates the slits.



Solution: Find d for $m = 1$:

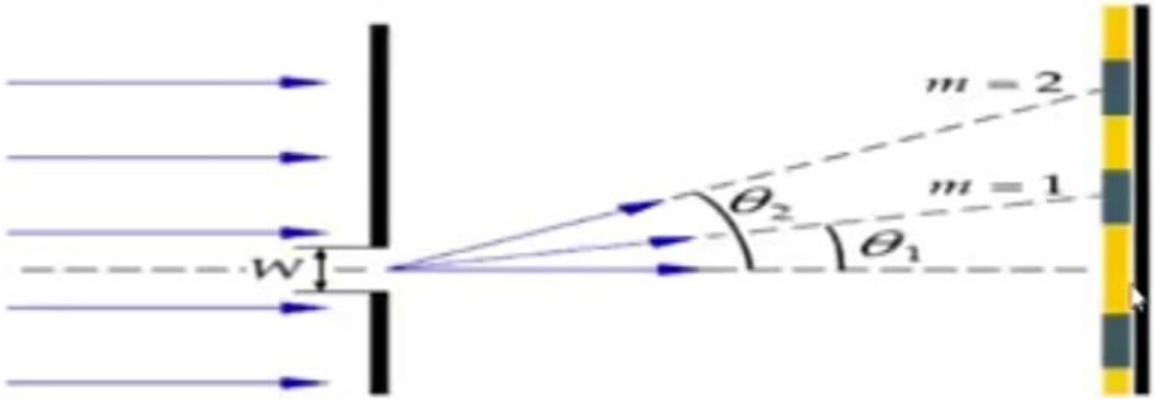
$$\sin\theta = m\frac{\lambda}{d}$$

$$d = \frac{m\lambda}{\sin\theta} = \frac{1(670\text{ nm})}{\sin 35^\circ} = \boxed{1.2\ \mu\text{m}}$$

QUESTION TWO

The light that has a wavelength of 626nm

passes through a 7.64-μm slit to a screen that is 1.85 m away. The center of the first bright fringe is a distance y above the central maximum.



SOLUTION

Solution: 1. Calculate the angle to the first bright fringe:

$$\theta_{1.5} = \sin^{-1}\frac{1.5\lambda}{W}$$

$$= \sin^{-1}\frac{1.5\left(626\times10^{-9}\ \text{m}\right)}{7.64\times10^{-6}\ \text{m}} = 7.06°$$

2. Calculate the distance y:

$$y = L\tan\theta_{1.5} = (1.85\ \text{m})\tan(7.06°) = \boxed{22.9\ \text{cm}}$$

QUESTION THREE

A viewing screen is separated from a double-slit source by 1.2 m. The distance between the two slits is 0.030 mm. The second-order bright fringe ($m = 2$) is 4.5 cm from the center line.

(A) Determine the wavelength of the light.

(B) Calculate the distance between adjacent bright fringes.

SOLUTION

4.5×10^{-2} m, $L = 1.2$ m, and $d = 3.0 \times 10^{-5}$ m:

$$\lambda = \frac{y_{\text{bright}} d}{mL} = \frac{(4.5 \times 10^{-2}\ \text{m})(3.0 \times 10^{-5}\ \text{m})}{2(1.2\ \text{m})}$$

$$= 5.6 \times 10^{-7}\ \text{m} = \boxed{560\ \text{nm}}$$

which is in the green range of visible light.

$$y_{m+1} - y_m = \frac{\lambda L}{d}(m+1) - \frac{\lambda L}{d} m$$

$$= \frac{\lambda L}{d} = \frac{(5.6 \times 10^{-7}\ \text{m})(1.2\ \text{m})}{3.0 \times 10^{-5}\ \text{m}}$$

$$= 2.2 \times 10^{-2}\ \text{m} = \boxed{2.2\ \text{cm}}$$

QUESTION FOUR

Calculate the minimum thickness of a soap-bubble film that results in constructive interference in the reflected light if the film is illuminated with light whose wavelength in free space is $\lambda = 600$ nm.

Solution The minimum film thickness for constructive interference in the reflected light corresponds to $m = 0$ in Equation 37.16. This gives $2nt = \lambda/2$, or

$$t = \frac{\lambda}{4n} = \frac{600 \text{ nm}}{4(1.33)} = 113 \text{ nm}$$

QUESTION FIVE

A laser beam ($\lambda = 632.8$ nm) is incident on two slits 0.200 mm apart. How far apart are the bright interference fringes on a screen 5.00 m away from the double slits?

QUESTION FIVE

$$\Delta y_{\text{bright}} = \frac{\lambda L}{d} = \frac{(632.8 \times 10^{-9})(5.00)}{2.00 \times 10^{-4}} \text{ m} = \boxed{1.58 \text{ cm}}$$

Course Outline

Electric charges, Electric Fields, Potential, Coulomb's Law. Direct Current and Measuring Instruments; the Potentiometer method. Chemical, Thermal and Magnetic effects of Current

Selected References:

- *Physics for Scientists and Engineers", 8th Edition, by Serway and Jewett*
- *University Physics: Fredman and Young*
- College Physics by Frederick, J Beuche and Eugene Hecht
- University Physics W. Sears
- Fundamentals of Physics by J. Walker
- Advance level Physics by Nelkon and Parker
- *College Physics : Twelveth Edition, by Eugene Hecht*

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Section 1.0: Electric Charges

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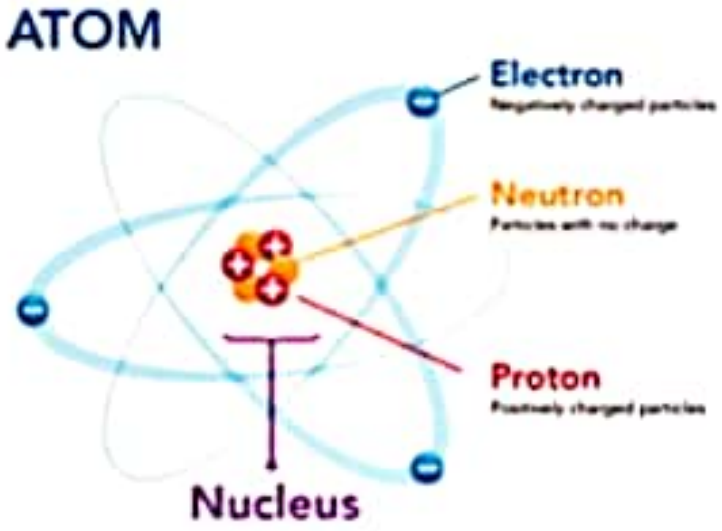
Electrical Charge

- Atoms have a **positively charged nucleus** made of (+) protons and neutral neutrons and are surrounded by (-) electrons. Matter is made of protons, neutrons and electrons.
- When a body **gains electrons**, the body **becomes negatively** charged, while the body becomes **positively charged** when it **loses electrons**.
- When the **positive** charge **equals** the **negative** charge the atom is said to be **neutral**.



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Electric Charge (Q) - The quantity of Electricity a body possesses; it is the amount by which the negative particles in a body exceed or less than the positive particles in it.

$$Q = nq_e = nq_p$$

Where: n - no. of excess electrons or excess protons

q_e - Charge of an electron = (-) 1.6×10^{-19} coulomb

q_p - Charge of a proton = 1.6×10^{-19} coulomb

Q - Total amount of charge in Coulomb

All free charges, those that can be isolated and measured, are integer multiples of q_e, where $q_e = 1.602\,18 \times 10^{-19}$. ***This confirms that <u>charge is quantized.</u>***

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- Electric charge is a property of matter that can cause attraction or repulsion.
- The fundamental quantity in electrostatics is the electric charge.
- The study of charges that **are stationary** is called Electrostatics.
- Charges of the ***same sign repel*** each other; charges of *opposite sign attract.*
- Something is said to *be charged* when it has an *unequal amount of positive/negative charges*.
- **Charge is conserved**; meaning the *total charge in an isolated system is constant.* The *algebraic sum* of the **charges** in the universe is constant.

When a particle with charge $(+e)$ is created, a particle with charge $(-e)$ is simultaneously created in the immediate vicinity.

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- The positive protons and electrically neutral neutrons in an atom are bound together by the nuclear force;

- the negative electrons surround the nucleus at distances much greater than the nuclear size.

- Electric interactions are chiefly responsible for the **structure of atoms**, molecules and solids.

- Conductors are materials that allow electric charge to move easily within them e.g most metals are good conductors.

- Insulators do not allow electrons to move about freely in them, e.g Plastics. rubber, glass, cloth, wood etc. Most non metals are insulators.

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Section 2.0: Coulomb's Law *and Electric Fields*

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Coulomb's Law *and Electric Fields*

- Coulomb's Law is the basic **law of interaction** for point electric charges.

Coulomb's Law also applies to charged conducting spheres and spherical shells, as well as to uniform spheres of charge. This is true provided that these are all small enough, in comparison to their separations, so that the

- It states that for charges q_1 and q_2 separated by a distance r, the ***magnitude of the force*** on either charge is proportional to the product q_1 q_2 and inversely proportional to the square of the distance between them.
- Because charge can be positive or negative, the force can be **positive (repulsive)** or **negative (attractive)**.

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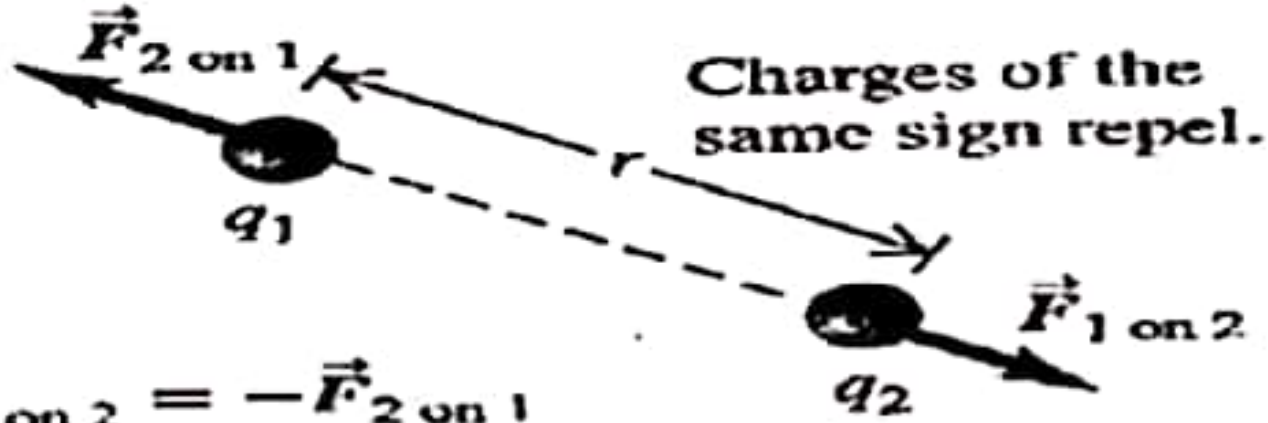
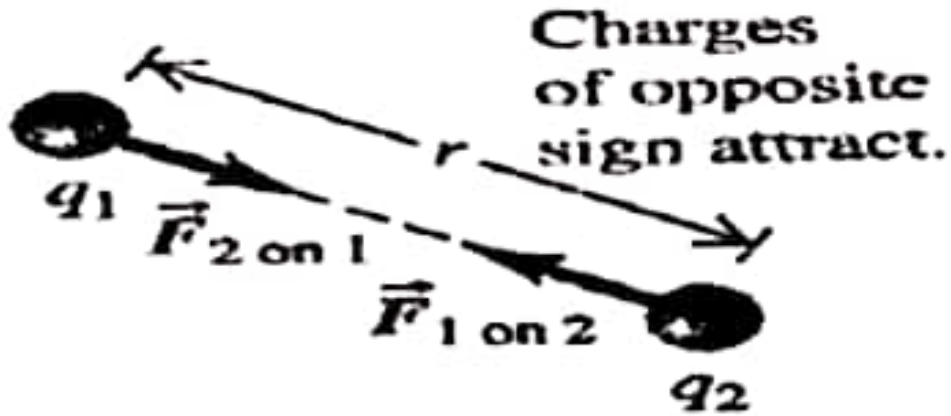
$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2} \quad where \quad \frac{1}{4\pi\varepsilon_0} = 8.988\ x10^9 N.m^2/C^2$$

where $\varepsilon_0 = 8.85 \times 10^{-12}\ C^2/N \cdot m^2$ **(permittivity of free space)**. But when the surrounding medium is not a vacuum, then (ε) of the material is used.



$$\vec{F}_{1\ on\ 2} = -\vec{F}_{2\ on\ 1}$$

$$F_{1\ on\ 2} = F_{2\ on\ 1} = k\frac{|q_1 q_2|}{r^2}$$



- The **force on each charge** is *along the line joining* the two charges - **repulsive** if q_1 and q_2 **have the same sign** and **attractive** if they have **opposite signs**.

- The forces form an ***action- reaction pair*** and obey Newton's third law.

- In S.I Units, the unit of electric charge is the coulomb, abbreviated C and that of the force is Newton (N).

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Example

- Two point charges +3.37 μC and -8.21 μC attract each other with a force of 0.0626 Newton. Determine the separation distance between the two of them ($k = 9.0 \times 10^9$ N•m²/C²).

Solution:

Given:

$Q_1 = +3.37\ \mu C = +3.37 \times 10^{-6}$ C

$Q_2 = -8.21\ \mu C = -8.21 \times 10^{-6}$ C

$F_{elect} = -0.0626$ N (**NOTE:** use a ***-ve force*** value since it is **attractive**),

Find d =?

$$F_{elect} = k \cdot Q_1 \cdot Q_2 / d^2$$

$$d^2 = k \cdot Q_1 \cdot Q_2 / F_{elect}$$

$$d = SQRT(k \cdot Q_1 \cdot Q_2) / F_{elect}$$

$$d = SQRT\ [(9.0 \times 10^9\ N{\bullet}m^2/C^2) \cdot (-8.21 \times 10^{-6}\ C) \cdot (+3.37 \times 10^{-6}\ C) / (-0.0626\ N)]$$

$$d = Sqrt\ [\ +3.98\ m^2\ ]$$

d = +1.99 m

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Electrical and Gravitational Forces

- Electrical force and gravitational force are examples of non-contact forces

- Coulomb's law equation for ***electrical force*** has a strong resemblance to ***Newton's equation for universal gravitation***

$$F_{elect} = \frac{k * Q_1 * Q_2}{d^2}$$

$(k = 9.0 \times 10^9\ N{\cdot}m^2/C^2)$

$$F_{grav} = \frac{G * m_1 * m_2}{d^2}$$

$(G = 6.67 \times 10^{-11}\ N{\cdot}m^2/kg^2)$

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- The two equations show that the force is directly proportional to the product of the quantity that causes the force;
- For the electrical force – (the charge, For the gravitational force the mass).
- There is an inverse square relationship between force and separation distance in the two cases.

- ***Differences*** between these two forces. (1): Gravitational forces are only attractive forces while electrical forces can either be attractive or repulsive. (2): The Coulomb's law constant (k) is significantly greater than Newton's universal gravitation constant (G).

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Example

An α particle is the nucleus of a helium atom. It has mass $m = 6.64 \times 10^{-27} kg$ and charge $q = 2e = 3.2 \times 10^{-19} C$. Compare the force of the electric repulsion between two α particles with the force of gravitational attraction between them.

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Solution:

$$F_e = \frac{1}{4\pi\varepsilon_0}\frac{q^2}{r^2}, \qquad F_g = G\frac{m^2}{r^2}$$

Therefore, the ratio of the electric force to the gravitational force is

$$\frac{F_e}{F_g} = \frac{1}{4\pi\varepsilon_0 G}\frac{q^2}{m^2} = \frac{9.0\,x10^9\,N.m^2/C^2}{6.67\,x\,10^{-11}N.m^2/kg^2}\,\frac{(3.2\,x10^{-19}C)^2}{(6.64\,x\,10^{-27}kg)^2}$$

$$= 3.134 \text{ x } 10^{35}$$

This very large number shows that the gravitational force is negligible in this case as compared to the electric force.

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Example

Two point charges, $q_1 = +25nC$ and $q_2 = -75nC$, are separated by a distance of 3.0 cm. Find the magnitude of (a) the electric force that q_1 exerts on q_2; and (b) the electric force that q_2 exerts on q_1.

Solution:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$$

$$= 9.0\ x\ 10^9 N.m^2/C^2 \frac{(+25\ x\ 10^{-9}C)(-75\ x\ 10^{-9}C)}{(0.03m)^2}$$

$$F_{q_1 \text{ on } q_2} = 0.019N$$

(b) Newton's third law also applies to the electric force. **Despite the fact that the charges have different magnitudes**, the *magnitude of the force that q_1 exerts on q_2 is same* as that *exerted by q_2 on q_1*. therefore Magnitude of Force q_1 on q_2 = Magnitude of Force q_2 on q_1 = 0.019N

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Superposition of forces

The principle of superposition of forces states that **when two or more charges exert a force** on *a charge*, the **total force on that charge** is the ***vector sum of the force*** exerted by the **individual charges**

Example

Two point charges are located on the positive x–axis of a coordinate system. Charge q_1 = 1.0nC is 2.0cm from the origin, and charge q_2= -3.0nC is 4.0 cm from the origin. What is the total force exerted by these two charges on a charge q_3 =5.0nC located at the origin? Gravitational forces are negligible.

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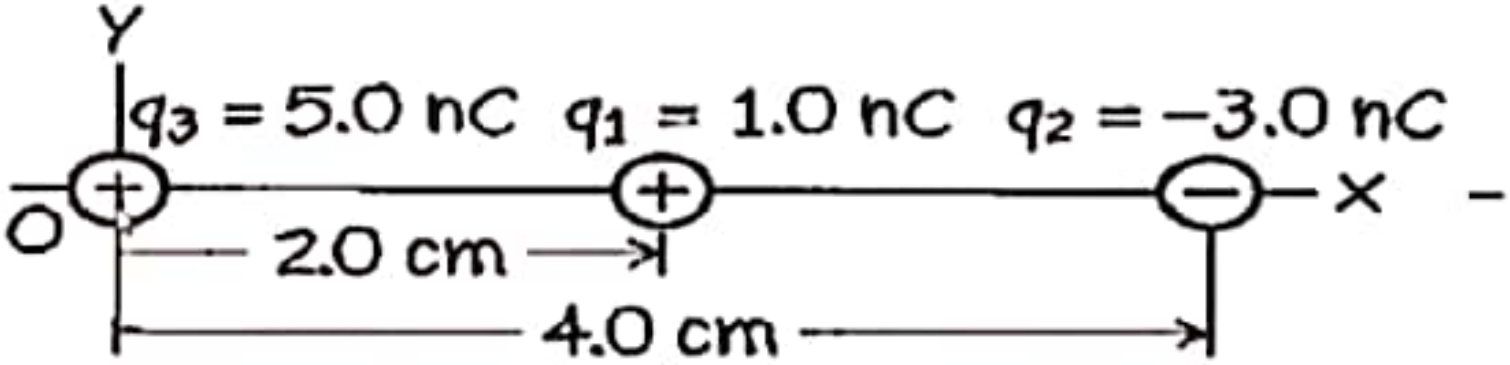
Solution:



We first find the magnitude $F_{1\,on\,3}$ of the force of q_1 on q_3.

$$F_{1\,on\,3} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_3}{r^2} = 9.0x10^9 N.m^2/C^2 \frac{(1.0\,x\,10^{-9}C)(5.0\,x\,10^{-9}C)}{(0.02m)^2}$$

$$F_{1\,on\,3} = 1.12\,x\,10^{-4}\,N = 112\mu N$$ **In the –ve direction (repulsion)**

This force has a negative x-component because q_3 is repelled (that is, pushed in the negative x- direction) by q_1.

The magnitude $F_{2\,on\,3}$ of the force of q_2 on q_3 is

$$F_{2\,on\,3} = \frac{1}{4\pi\varepsilon_0}\frac{q_2 q_3}{r^2} = 9.0x10^9 N.m^2/C^2 \frac{(3.0\,x\,10^{-9}C)(5.0\,x\,10^{-9}C)}{(0.04m)^2}$$

$$F_{2\,on\,3} = 8.4\,x\,10^{-5}\,N = 84\mu N$$ In the +ve x –direction (attraction)

This force has a positive x-component because q_3 is attracted (that is, pulled in the positive x-direction) by q_2 .The sum of the x-components is

$$F_x = -112\mu N + 84\mu N = -28\mu N$$

There are no y- or z-components. Thus the total force on q_3 is directed to the left, with magnitude $28\mu N = 2.8\,x\,10^{-5}N$.

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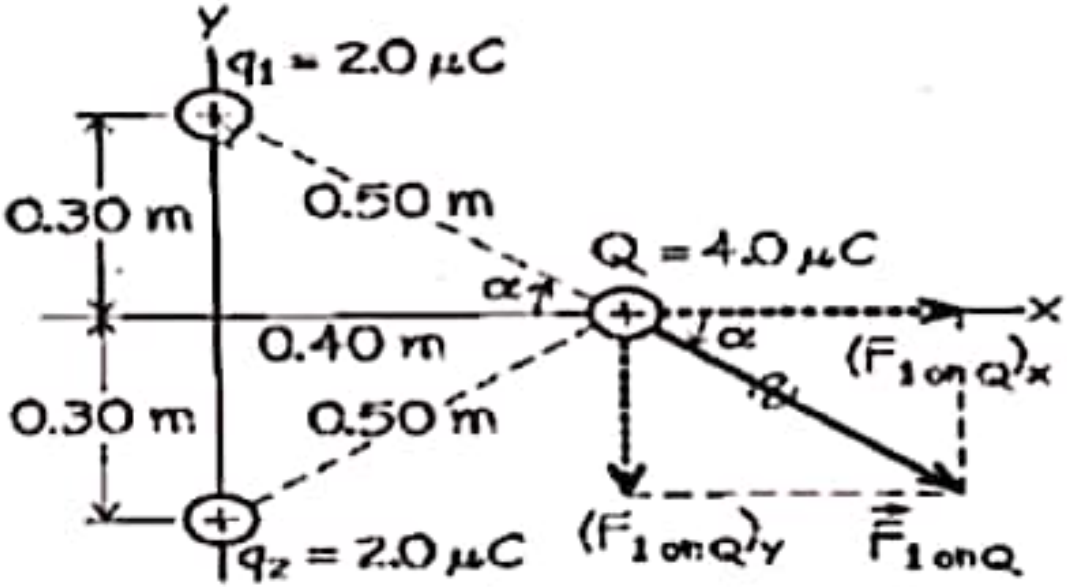
Example

Two equal positive point charges $q_1 = q_2 = 2.0\mu C$ are located at x = 0, y = 0.30m and x =0, $y = -0.30m$, respectively. What are the magnitude and direction of the total (net) electric force that these charges exerts on a third point charge $Q = 4.0\mu C$ at $x = 0.40m, y = 0$?



Solution

The magnitude of force q_1 on Q is

$$F_{1\ on\ Q} = \frac{1}{4\mu\varepsilon_0}\frac{q_1 Q}{r^2}$$

$$= 9.0x10^9 N.m^2/C^2 \frac{(4.0\ x\ 10^{-6}C)(2.0\ x\ 10^{-6}C)}{(0.5m)^2}$$

$$= 0.29N$$

The angle α is below the x –axis, so the components of this force are given by :

$$(F_{1\ on\ Q})_x = (F_{1\ on\ Q})cos\alpha = (0.29N)\frac{0.4m}{0.5m} = 0.23N$$

$$(F_{1\ on\ Q})_y = -(F_{1\ on\ Q})sin\alpha = -(0.29N)\frac{0.3m}{0.5m} = -0.17N$$

The lower charges q_2 exerts a force with the same magnitude but at an angle α above the x – axis. From symmetry we see that its x – component is the same as that due to the upper charge, but its y – component has the opposite sign. So the components of the total force $\vec{F}$ on Q are:

$$F_x = 0.23N + 0.23N = 0.46N$$

$$F_y = -0.17N + 0.17N = 0$$

The total force on Q is the + x – direction, with magnitude 0.46N.

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Electric Field

An Electric Field is said to exist at any point in space when a test charge, placed at that point, experiences an electrical force. The direction of the electric field at a point is the same as the direction of the force experienced by a *positive* test charge placed at the point.

- Electric field is the region in which an electric charge placed on it experiences a force.

- The electric field produced by a point charge is directed radially away from or towards the charge.

Electric field lines can be used to sketch electric fields. The line through a point has the same direction at that point as the electric field. Where the field lines are closest together, the electric field is largest. Field lines come out of positive charges (because a positive charge repels a positive test charge) and come into negative charges (because they attract the positive test charge).

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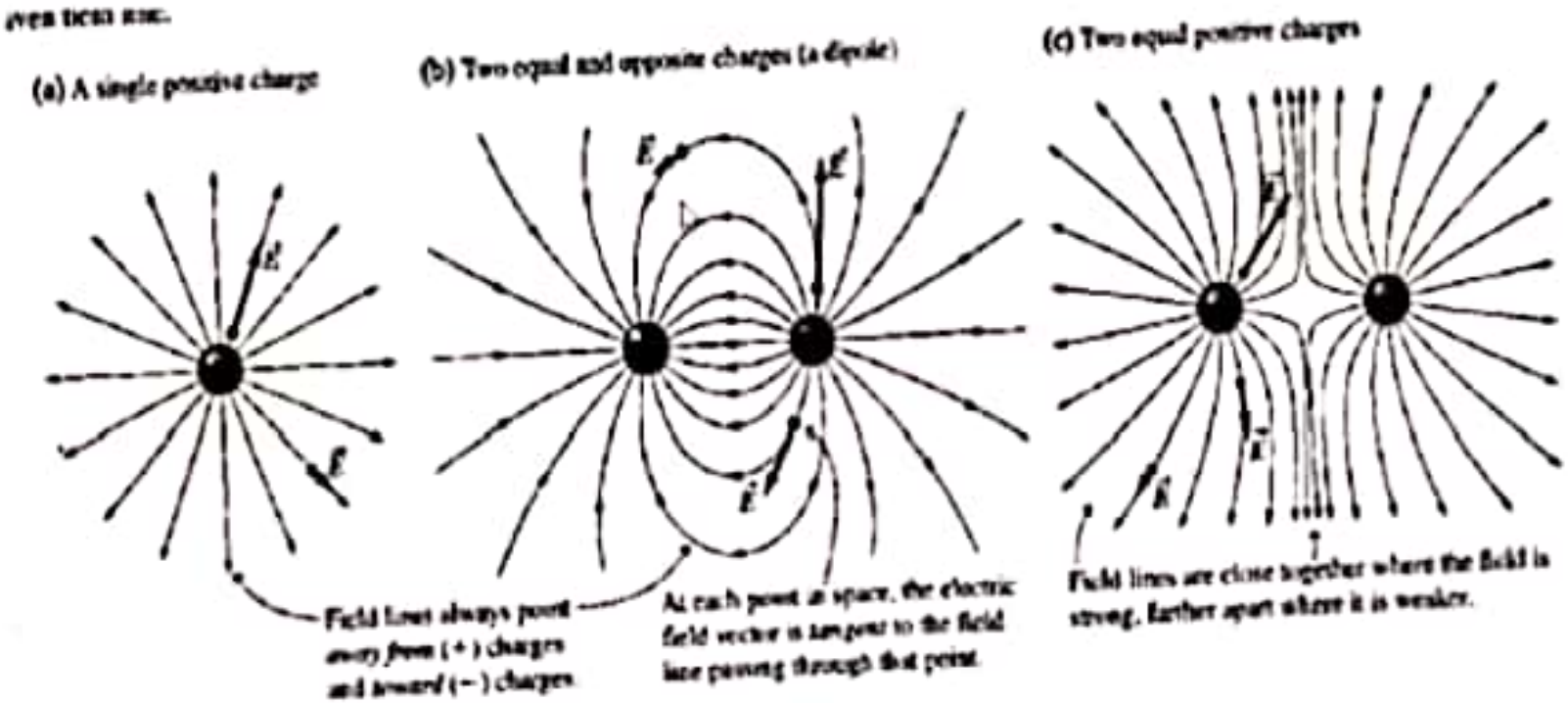
Field lines provide a graphical representation of electric fields.

At any point on a field line, the tangent to the line is in the direction of E at that point. The number of lines per unit area (perpendicular to their direction) is proportional to the magnitude of E at the point.



The actual field vectors have been drawn at several points in each pattern. Notice that in general, the magnitude of the electric field is different at different points on a given field line; a field line is not a curve of constant electric –field magnitude!

Electric lines of force directed away from a positive charge

Electric Lines of force directed towards a negative charge

Electric Field Intensity (E)

- The measure or strength of an electric field. It is the force (F) exerted by an electric field per unit positive test charge (q) place on it.

$E = F/q$

Where: F – force exerted by the field
q – test charge (unit charge)

- It is a vector quantity **(E)**: since it is the ***force per unit charge*** exerted by a test charge at any point provided the test charge is small enough that it does *not disturb the charges that cause the fields*. The unit of electric field intensity E is N/C.

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Magnitude of Electric Field Intensity (E) Due to a Point Charge

If a point charge q'_o is placed at a distance r from the charge q_o, it will experience a force

$$F_E = \frac{1}{4\pi\varepsilon}\frac{q_o q'_o}{r^2} = q'_o\left(\frac{1}{4\pi\varepsilon}\frac{q_o}{r^2}\right) \qquad (*)$$

(*) Using Coulomb's law

But if a point charge q'_o is placed at a position where the electric field is E,

then the force on q'_o is

$$F_E = q'_o E \qquad (**)$$

From (*) and (**), the magnitude of the electric field intensity E of a point charge is:

$$E_o = \frac{1}{4\pi\varepsilon}\frac{q_o}{r^2}$$

The same relation applies at points outside of a small spherical charge q.

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Example

What is the magnitude of the electric field at a field point 2.0m from a point charge q = 4.0nC?

Solution:

$$E = \frac{1}{4\pi\varepsilon_0}\frac{|q|}{r^2} = 9.0\,x10^9 N.m^2/C^2 \frac{4.0x10^{-9}C}{(2.0m)^2}$$

$$E = 9.0N/C$$

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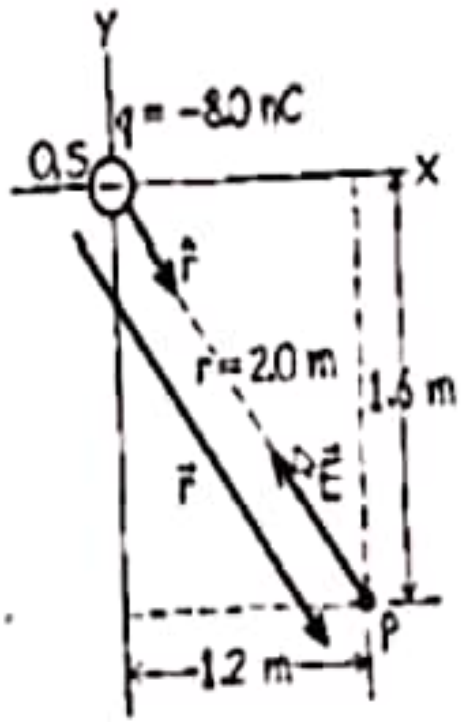
Example:

A point charge q = -8.0.nC is located at the origin. Find the electric - field vector at the field point x = 1.2m, y= -1.6m.



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Solution

First find the distance from the charge at the source s, (origin) to the field point P

$$r = \sqrt{x^2 + y^2} = \sqrt{(1.2m)^2 + (-1.6m)^2} = 2.0m$$

The unit vector r is directed from the source point to the field point. This is equal to the displacement vector r from the source point to field point, divided by its magnitude r;

i.e $\quad \hat{r} = \frac{\vec{r}}{|r|} \quad \rightarrow \quad \hat{r} = \frac{\vec{r}}{r} \frac{x_{i+y_j}}{r}$

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$$\hat{r} = \frac{\vec{r}}{r} \frac{x_{i+y_j}}{r} = \frac{(1.2m)_i + (-1.6m)_j}{2.0m} = 0.60_i - 0.80_j$$

Hence the electric – field – field vector is

$$\vec{E} = \frac{1}{4\pi\varepsilon_0} \frac{q}{r^2} \hat{r}$$

$$= (9.0 \, x \, 10^9 N. \frac{m^2}{C^2} \frac{(-8.0 \, x \, 10^{-9} C)}{(2.0m)^2} (0.60_i - 0.80_j)$$

$$= (-11N/(C)i) + (14N/C)j$$

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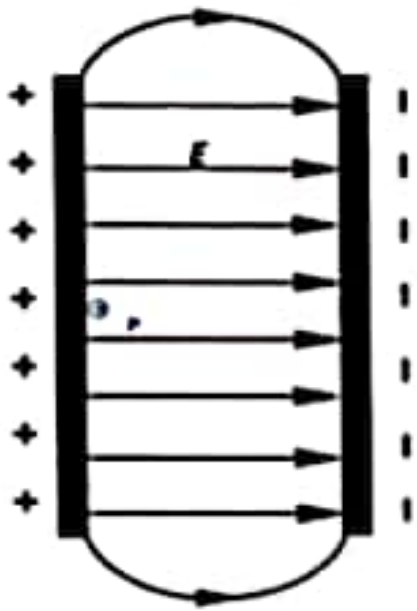
Electric Potential Energy

Recall: an object held above the Earth's surface has a gravitational potential energy associated with its position.

Similarly: a charge placed in an electric field will have an electrical potential energy associated with its position.

Electric Potential Energy in a Uniform Electric Feld

The electric field between two parallel plates is an example of a uniform electric field.



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A positive charge placed at Point P will feel an electrical force directed towards the negative plate.

Due to its location in the field the charge has electrical potential energy.

If the charge is released, it will accelerate towards the negative plate. The $PE_{electric}$ at the positive plate is transferred to kinetic energy (motion)

- Electric potential is the energy associated with a charged particle due to its position relative to a source of electric force.

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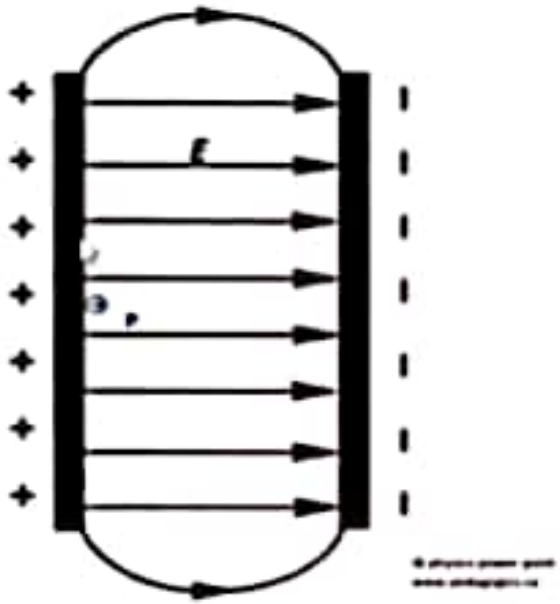
The change in potential energy for a positive charge placed at Point P if it moves to the negative plate can be expressed as: $\Delta PE_{elec} = -Eq\Delta x$

The negative sign indicates that the amount of PE is decreasing. Work is being done on the charge by field.

This equation only applies to a uniform electric field.



Electric Potential Difference

Electrical potential difference **is defined as the work done per unit of charge (Joules per Coulomb) while moving the charge between two points in an electric field. It can also be thought of as the change in PE per unit of charge between two points in an electric field.**

$$\Delta V = \frac{Work}{q} = \frac{-Eq\Delta x}{q} = -E\Delta x$$

written as $E = -\frac{\Delta V}{\Delta x}$

The negative sign indicates that the direction of decreasing potential is the same as the field direction.

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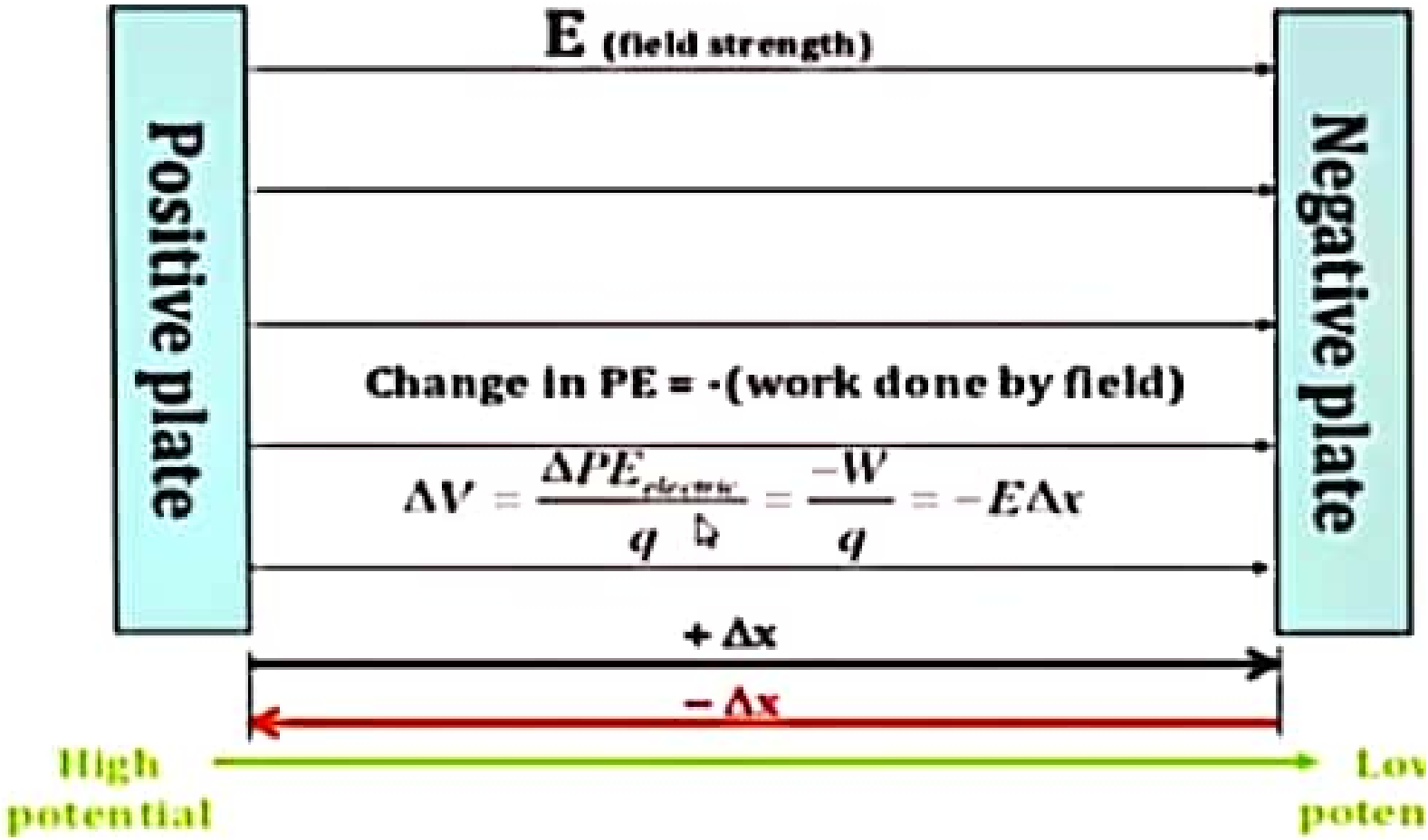
The potential difference between the positive and negative plates depends on the field strength and separation. Potential difference is measured in vol 1 JC^{-1}).



Example

How far apart must two parallel charged plates be situated so that a potential difference of 1.50×10^2 V across the plates produces an electric field strength of 1.00×10^3 NC^{-1}?

$$\Delta x = \frac{\Delta V}{E}$$

$$\Delta x = \frac{150}{1000}$$

$$\Delta x = 0.150 \text{ m}$$

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Current, Resistance, and Ohm's Law

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Current (I) in Amperes

- When a net electric charge is moved from one point to another in a particular region, then Current of electricity exists in that region.
- Suppose the charge (q) is moving through a wire.
- If a charge *q (Coulomb's)* is transported through a given cross section of the wire in a time *t (sec)*, then the current through the wire is

$$I = \frac{q}{t} \rightarrow \quad I = \frac{\Delta q}{\Delta t}$$

the direction of the current is taken to be in the direction of flow of positive charge.

Resistance (Ω) in ohms

- The Resistance of an object is the measure of its potential difference (V) that must be impressed across the object to cause a current one amperes to flow through

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

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Battery

A Battery is a source of electrical energy.

- The ***potential difference (V) between the terminals of a battery*** is known as the electromotive force (emf) (inVolts) of the battery ***if and only if*** there is **no loss of internal energy** in the battery.
  - The ***Terminal potential difference*** (or Voltage) of a battery, whenever it delivers a current I, it is ***related to its electromotive force*** (ε) and the ***internal resistance*** (r) as shown below:
  - When it is **discharging** i.e (delivering current)

$$\text{Terminal voltage} = (\text{emf}) - (\text{Voltage drop in internal resistance})$$

$$V = \mathcal{E} - Ir$$

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When receiving current **i.e (Charging)**

Terminal voltage = emf + (Voltage drop in internal resistance)

$$V = \mathcal{E} + Ir$$

When no current exists:

Terminal voltage = emf of battery

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Ohm's Law

Ohm's law is a statement of voltage – current relationship for an object whose resistance is constant. It is usually written as

$$V = IR$$

- **The law states that electric current is proportional to voltage and inversely proportional to the resistance if only the temperature and other physical factors are constant.**

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Resistivity

The Resistance of a piece of wire depends on the length of the wire.

The **size of the wire** and the material from which the wire is made.

The resistance of an object having a uniform cross section made out of an ohmic materials is given by $R \alpha \frac{L}{A}$. $R = \frac{\rho L}{A}$.....(10)

ρ is the resistivity of the material.

Materials that have high conductivities, such as copper and silver, are called conductors while materials having small conductivities, such as glass, are called insulators.

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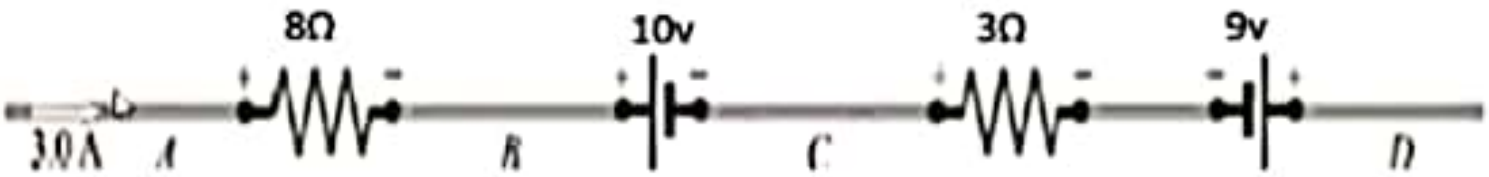
Example

A current of 3.0 A flows through the wire shown **What**

will a voltmeter read when connected from (*a*) *A* to *B*, (*b*) *A* to *C*, (*c*) *A* to *D*?



Solution

Put plus and minus signs on all of the resistors given that the current flows from left to right. Label each battery, as ever, with the + on the long side of the symbol.

(*a*) Point-*A* is at the higher potential because current always flows "downhill" through a resistor (+ to −). There is a potential drop

Of IR = (3 A) x (8Ω) = 24v from point A to B. The voltmeter will therefore ***read – 24 v***

(*b*) In going from *B* to *C*, one goes from the positive to the negative side of the battery; hence, there is a potential drop of ***10v*** from *B* to *C*. The drop adds to the drop of **24v** from A to *B*, found in (*a*), to give a **34v** drop from *A* to *C*. The voltmeter Will read ***-34*** from A to C.

(C) From C to D, there is a potential drop of IR = (3A) x (3Ω) = 9v through the resistor. Afterwards, since one has to go from negative to the positive terminal of the 9 v battery, then there is a potential rise of 9v through the battery.

Therefore the connection from A to D reads:

- 24v - 10 -9 +9 = - 34 v

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Example

A wire has length 4m and radius 9×10^{-3}m. Calculate the resistance of the wire, given the resistivity of the wire as $1.56 \times 10^{-8}\ \Omega$m.

Solution

The cross -sectional area of a wire A is the area of a circle of radius r, or of diameter d = 2r

$A = \pi r^2$

$$R = \rho \frac{L}{A} = (1.56 \times 10^{-8}\ \Omega m) \frac{4}{\pi(9x10-3)^2}$$

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Direct Current Circuits

- In a simple circuit, the battery provides **direct current** **i.e** a current flowing in only one direction.

- A direct current circuit is a circuit that has its electric current flowing through in one direction.

- A direct Electric current flows only when the circuit is closed but stops completely when the circuit is open.

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Resistors in Series

when one and only one terminal of a resistor is connected directly to one and only one terminal of another resistor, the two are in **series and the same current passes through both.**

There are no nodes between circuit elements (such as capacitors, resistors, and batteries) that are **connected in series.**

The equivalent resistance in series is always greater than the largest of the individual resistances.

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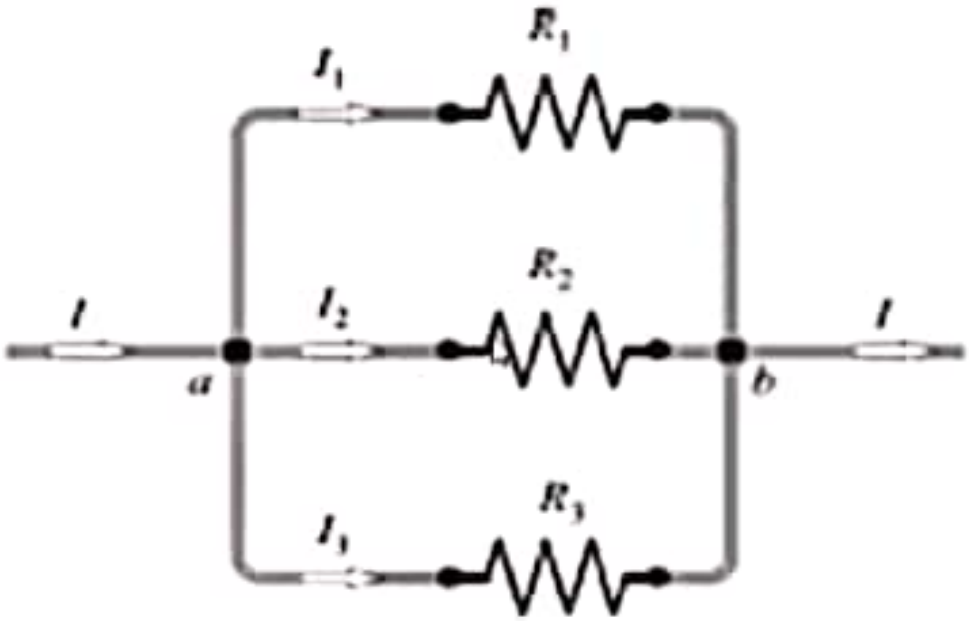
Resistors in Parallel

Several resistors are connected in **parallel** between

two nodes if one end of each resistor is connected to one node and the other

end of each is connected to the other node.

The equivalent resistance in parallel is always less than the smallest of the individual resistances..



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When several resistors $R_1, R_2, R_3 \ldots$, are connected in series, the equivalent resistance R_{eq} is the sum of the individual resistances. The same current flows through all the resistors in a series connection. When several resistors are connected in parallel, the reciprocal of the equivalent resistance R_{eq} is the sum of the reciprocals of the individual resistances. All resistors in a parallel connection have the same potential difference between their terminals.

(resistors in series). $R_{eq} = R_1 + R_2 + R_3 + \cdots$ (i)

(resistors in parallel). $\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$ (ii)

Four different ways of arranging three resistors

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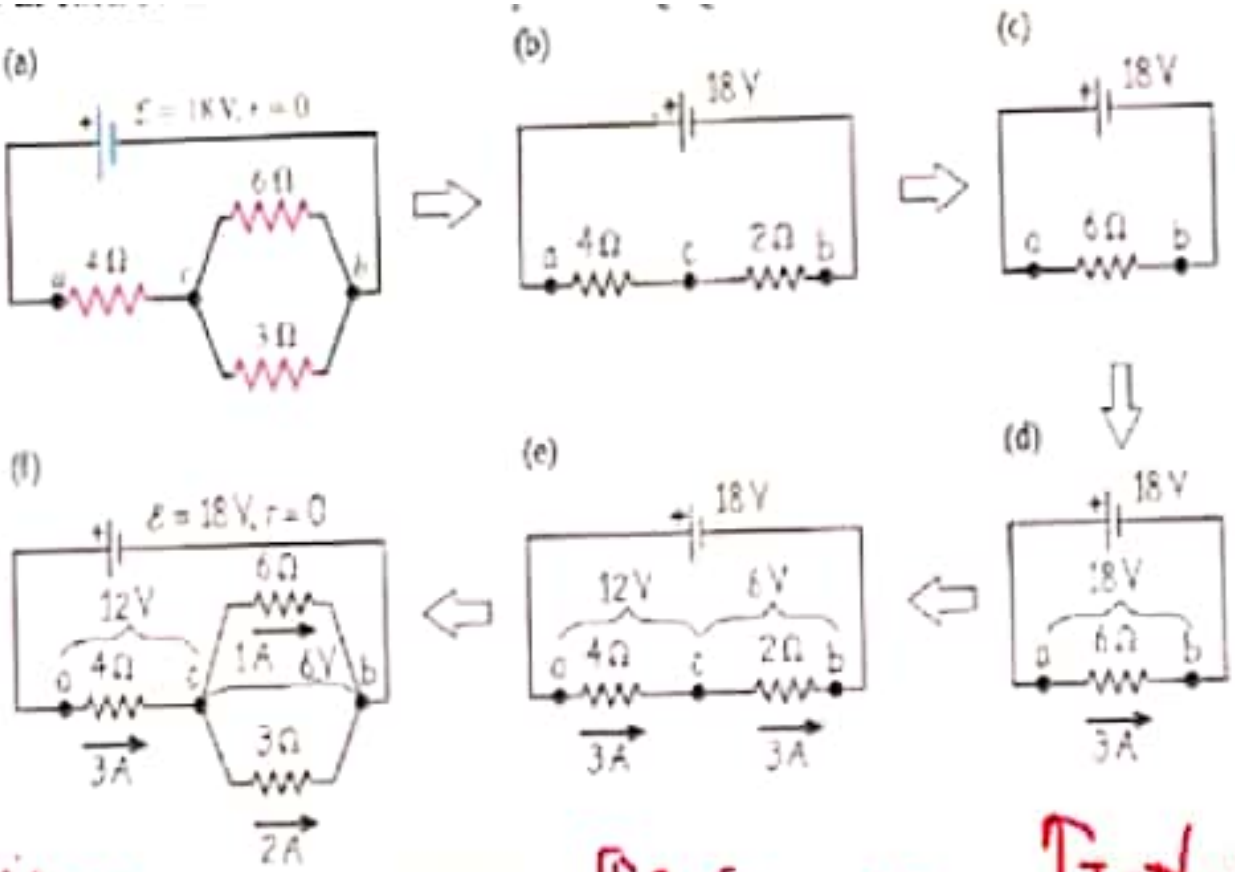

1. ∥ = Same V
2. Share I

① ↑ Same I = 3A

② V = IR (Series)

↑ I = V/R = 18/6 = 3A

Solution

Figures *b* and *c* show successive steps in reducing the network to a single equivalent resistance. From equation (ii) the 6Ω and 3Ωresistors in parallel in figure *a* are equivalent to the single 2Ω resistor in figure *b*.

$$\frac{1}{R_{eq}} = \frac{1}{6\Omega} + \frac{1}{3\Omega} = \frac{1}{2\Omega}. \quad R_{eq} = 2\Omega$$

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From equation (i) the series combination of this 2 Ω resistor with the 4 Ω resistor is equivalent to the single 6 Ω resistor in figure c.

To find the current in each resistor of the original network. we reverse the steps by which we reduce the network. In the circuit shown in figure d. the current is

$$I = \frac{V_{cb}}{R} = \frac{18V}{6\Omega} = 3A.$$

So the current in the 4 Ω and 2 Ω resistors in figure e is also 3A. The potential difference V_{cb} across the 2 Ω resistor is therefore $V_{cb} = IR = (3A)(2\Omega) = 6V$. This potential difference must also be 6V in figure f. Using $I = \frac{V_{cb}}{R}$, the currents in the 6 Ω and 3 Ω Resistors in figure f are $\left(\frac{6V}{6\Omega}\right) = 1A$ *and* $\left(\frac{6V}{3\Omega}\right) = 2A$ *respectively.*

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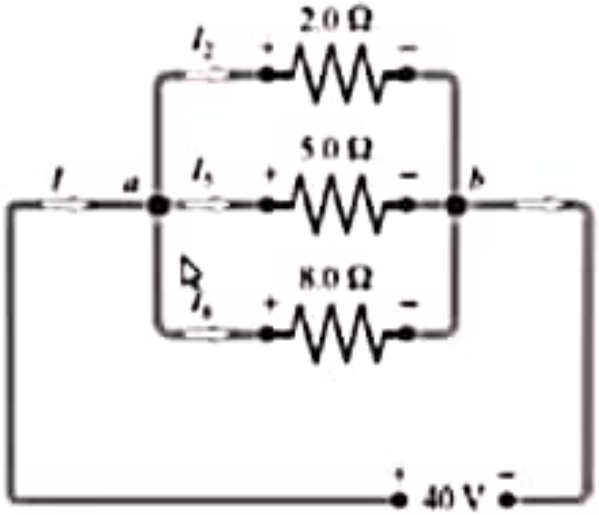
Example



find the current in each resistor and the current drawn from the 40-V source.

Solution

The potential difference between parallel resistors is same across point a and b.

Notice that the p.d. from a to b is 40 V. Therefore, the p.d. across each resistor is 40 V. Then,

Note that the current will be shared amongst the three parallel resistors.

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$$I_2 = \frac{40\ \text{V}}{2.0\ \Omega} = 20\ \text{A} \qquad I_5 = \frac{40\ \text{V}}{5.0\ \Omega} = 8.0\ \text{A} \qquad I_8 = \frac{40\ \text{V}}{8.0\ \Omega} = 5.0\ \text{A}$$

b. Since I splits into three currents:

Then,

$$I = I_2 + I_5 + I_8 = 20\ \text{A} + 8.0\ \text{A} + 5.0\ \text{A} = 33\ \text{A}$$

OR

- Find the equivalent resistance of the parallel resistors (1.2 Ω) then, Find the current across the potential difference between point a and b (40v).
  - I = (40/1.2) =33 A

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Kirchhoff's Rules

- **Kirchhoff's rules** can be used to analyze closed circuit, be it simple or complex.

- When the **simplification of circuits to a combination** of parallel and series connections is impossible, the analysis of the circuit to determine the parameters of the circuits is possible with ***Kirchhoff's laws/rules***.

Kirchhoff's junction rule

- Kirchhoff's junction rule (***KCL)*** is based on ***conservation of charge***.
- It states that the **algebraic sum of the currents into any junction/ node is zero.** i.e $\sum I = 0$
- **A junction is any point in a circuit where two or more circuit paths come together.**

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• *Kirchhoff's loop (KVL)*

- ***It is based on conservation of energy and conservative nature of electrostatic fields.***

- states that at any given instant, the ***algebraic sum of the voltages*** in any closed loop or closed path ***in a circuit is zero***

- That is the ***algebraic sum of potential drops or rises around any closed loop in a circuit is zero.***

$$\sum V = 0$$

- Careful use of consistent sign rules is essential in applying Kirchhoff's rules.

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KVL SIGN RULES

i. If the imaginary loop around the circuit enters a source of e.m.f (battery, power supply, etc) at the negative terminal and leaves at the positive terminal, use a +ve voltage. If the loop enters at the +ve terminal, use a negative voltage.

ii. If the loop going through a resistor is in the same direction as the current, use – IR. If the loop goes in the opposite direction as the current, use +IR

iii. If there are two (or more) currents identified in a resistor, use the sum of the voltage drops with the sign given as in item 2 above.

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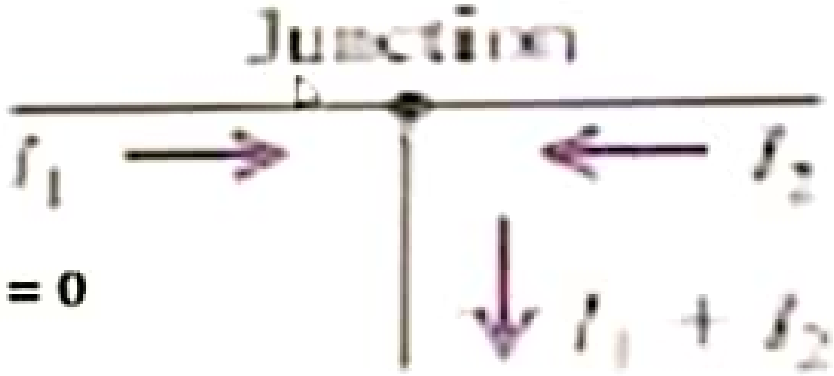
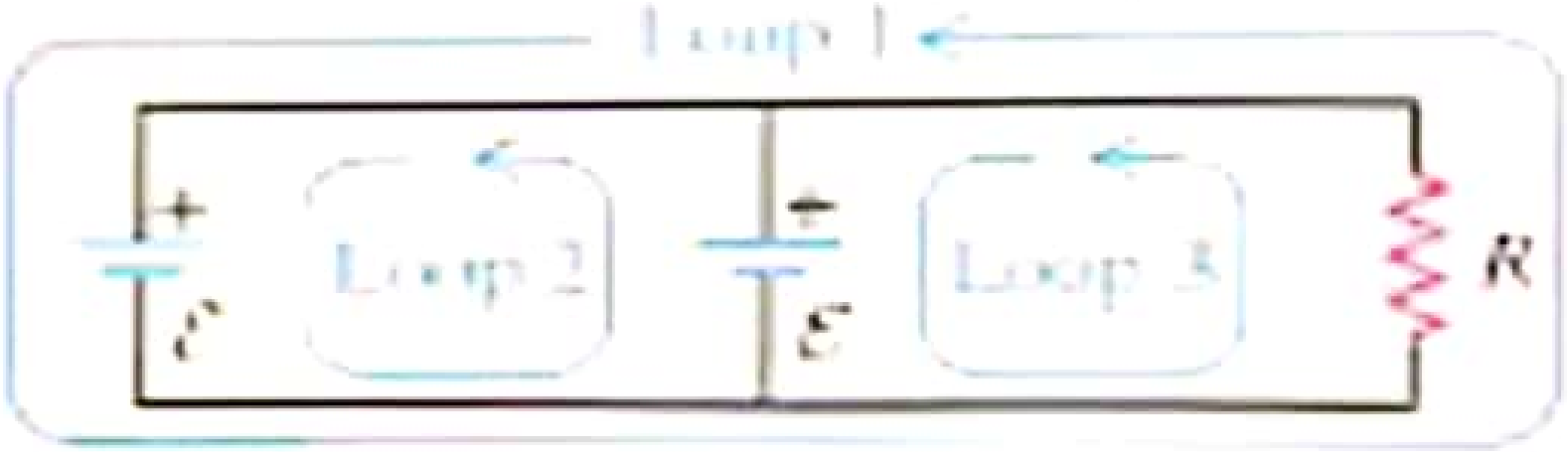
At any junction:
$\Sigma I = 0$



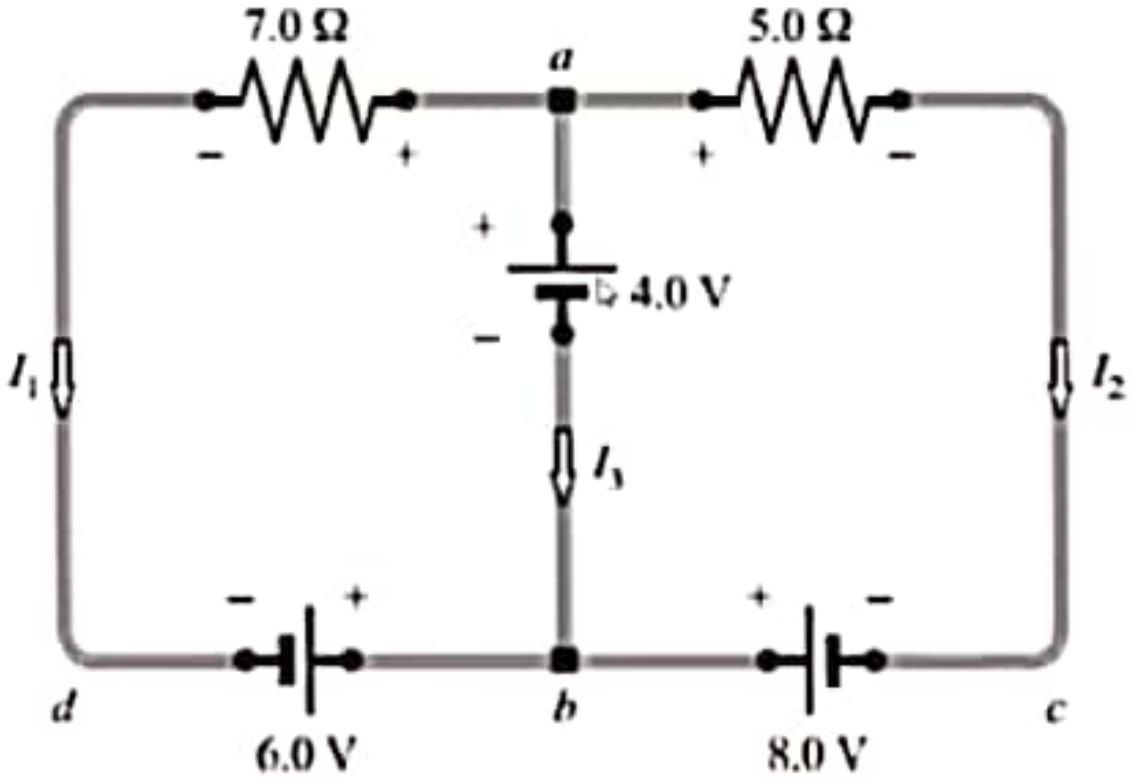
$$\sum I = 0$$



Around any loop: $\Sigma V = 0$

$$\sum V = 0$$

Example Find the currents in the circuit shown



Solution

Notice that the signs of the voltage drops have been provided in the circuit diagram. it's a good habit to put them in as a first step.

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- The next step is to reduce the circuit by replacing all series and parallel resistors with their equivalent resistors.

- But This circuit cannot be reduced further because it contains no resistors in simple series or parallel combinations. We therefore revert to Kirchhoff's rules.

- Generally, one MUST be CAREFUL when assigning the current directions.

- Although those chosen in a wrong direction will JUST give ***negative*** Numerical ***Values***.

- If the currents had not been labeled and shown by arrows, that would be the **first thing to do.**

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Next apply the loop rule to loop abda in Volts

$$-6 - 4 + 7I_1 = 0 \quad \text{OR} \quad I_1 = \frac{10}{7}\,A$$

- Then apply the loop rule , (KVL) to loop (acba) in Volts.

$$+4 + 8 - 5I_2 = 0 \quad \text{OR} \quad I_2 = \frac{12}{5}\,A$$

- **Let us go back to the KCL equation (*) to find the last unknown (** The minus sign tells us that I_3 is opposite in direction to that shown in the figure.
- **From (*),** $(I_3) = -(I_1) - (I_2)$

$$(I_3) = -\frac{10}{7} - \frac{12}{5} \rightarrow (I_3) = -\frac{134}{35} \rightarrow (I_3) = -3.8\ A$$

- The minus Sign shows that I_3 is opposite in direction to that used

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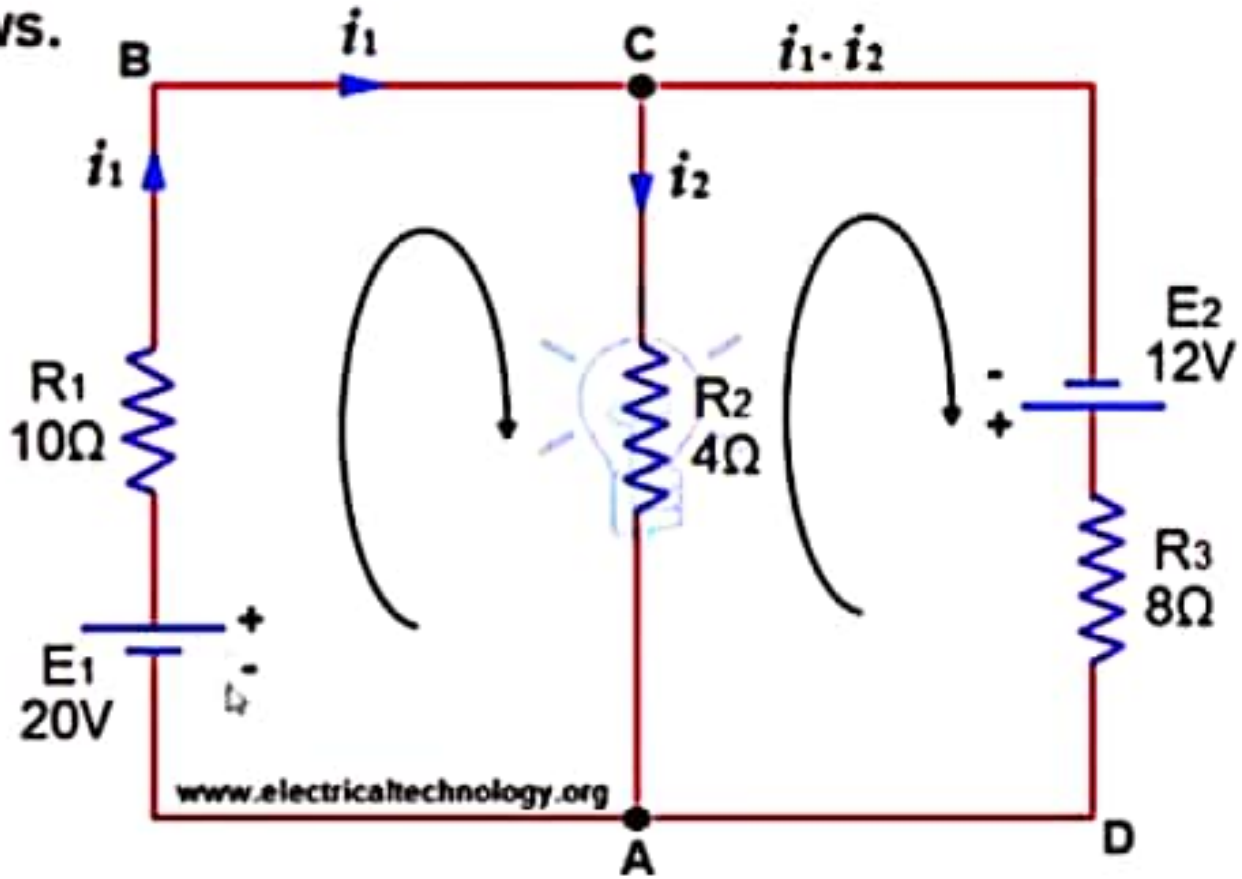
Example

Resistors of $R_1 = 10\Omega$, $R_2 = 4\Omega$ and $R_3 = 8\Omega$ are connected up to two batteries (of negligible resistance) as shown. Find the current through each resistor using Kirchhoff's laws.



Solution

- Assume that currents flow in the directions indicated by arrows. Identifying the currents in the circuits i.e:
- Current in mesh **ABC** = i_1
- Current in mesh **CA** = i_2
- Then current in mesh **CDA** = $i_1 - i_2$
- Now, Apply **KVL on Mesh ABC**, we get;

$$20 - 10i_1 - 4i_2 = 0$$

$$10i_1 + 4i_2 = 20 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

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- In mesh ACD,

$$-8(i_1 - i_2) + 4i_2 + 12 = 0$$

$$8(i_1 - i_2) - 4i_2 = 12$$

$$8i_1 - 8i_2 - 4i_2 = 12$$

$$8i_1 - 12i_2 = 12 \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

- Solving for the unknowns, we can use different metods, Crammer's rule, elimination method, substitution method etc.

  - Multiplying equation (1) by 3; we have

$$30i_1 + 12i_2 = 60 \quad \ldots\ldots\ldots\ldots\ldots (3)$$

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- Solving for i_1

$$30i_1 + 12i_2 = 60 \quad ..(3)$$
$$8i_1 - 12i_2 = 12 \quad ..(4)$$

$$38i_1 = 72$$

Add eqns (3) and (4) to get I_1

- $i_1 = 1.895$ A → Current in the 10 Ohms resistor
- Substituting this value in (1), we get:
  $10(1.895) + 4i_2 = 20$

$4i_2 = 20 - 18.95$

- $i_2 = 0.263$ A → Current in the 4 Ohms Resistors
- Now,
- $i_1 - i_2 = 1.895 - 0.263 = 1.632$ A

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D'Arsonval Galvanometer

- Potential difference (Voltage), Current or resistance can be measured through the use of a d'Arsonval Galvanometer.
- A *pivoted coil of fine wire* is placed in the *magnetic field of a permanent magnet*.
- A spring is attached to this coil.
- The pointer is at Zero, when **there is no current in the coil** which is the *equilibrium position*.

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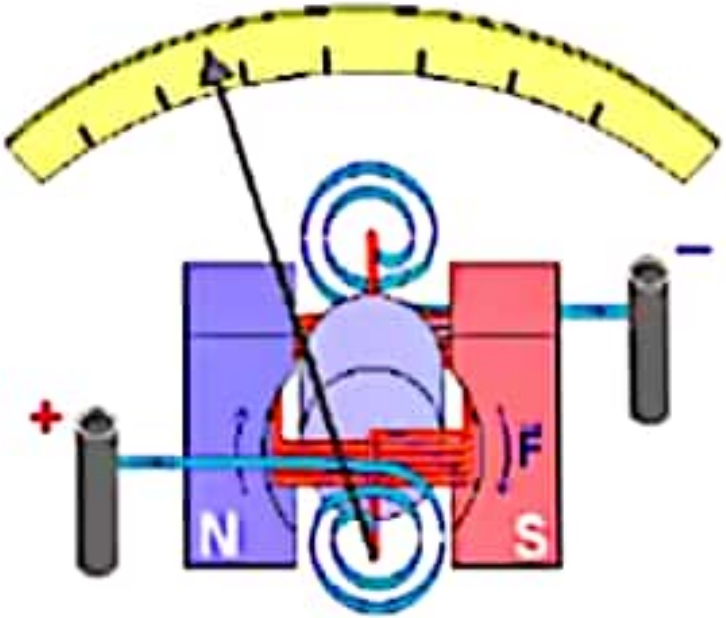
- But **when *there is current in the coil***, then the *magnetic field exerts a torque on the coil* which is ***proportional to the amount of current.***

- When **the coil turns,** then the **spring exerts a restoring torque** that is **proportional to the angular displacement.**



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Thus, the angular deflection of the coil and pointer is directly proportional to the coil current, and the device can be calibrated to measure current.

For a larger current range, a shunt resistor is added, so some of the current bypasses the metre coil. Such an instrument is called an ammeter. If the coil and any additional series resistance included obey ohm's law, the meter can also be calibrated to read potential difference or voltage. The instrument is then called a voltmeter. A good ammeter has very low resistance; a good voltmeter has very high resistance.

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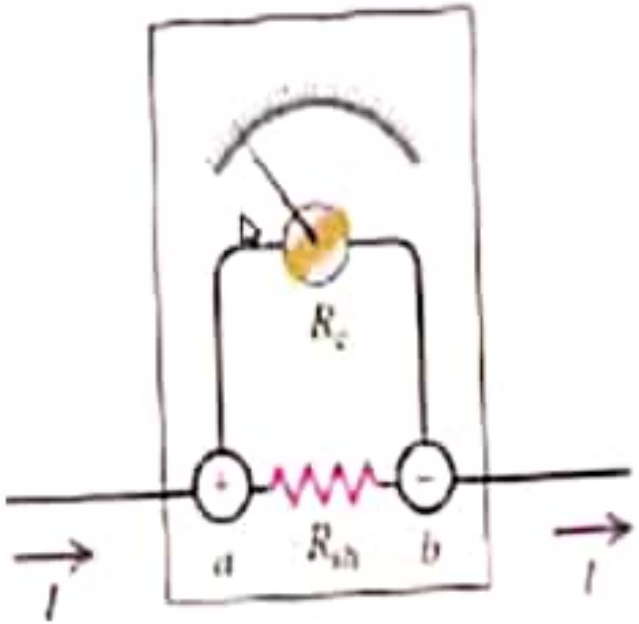
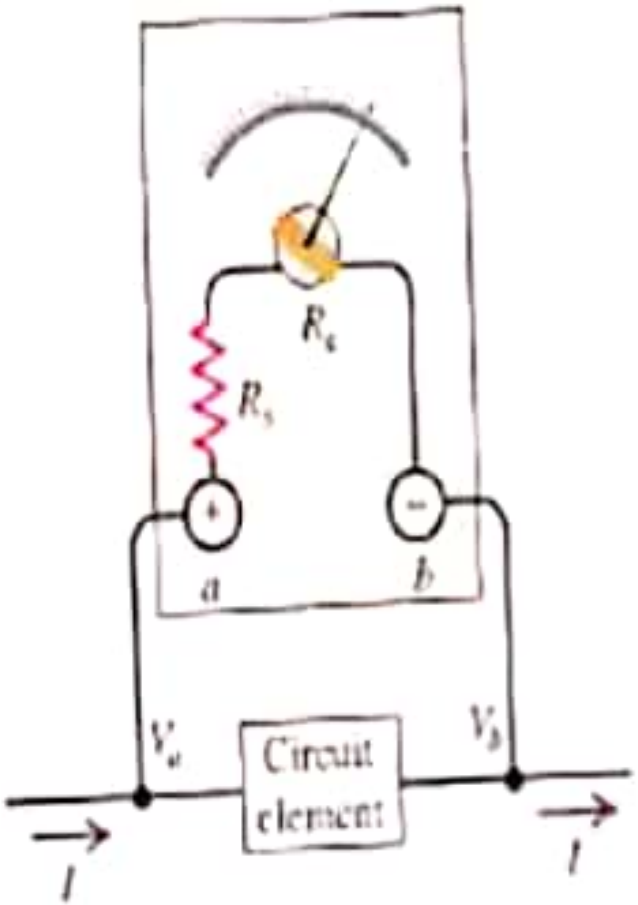
(a) A moving-coil ammeter



(b) A moving-coil voltmeter



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Example 2.4

What shunt resistance is required to make the 1.00mA, 20.0Ω meter into an ammeter with a range of 0 to 50mA?

Solution

We want to make the ammeter to be able to handle a maximum current $I_a = 50mA = 50 \times 10^{-3}A$. The resistance of the coil is $R_c = 20\Omega$, and the meter shows full-scale deflection when the current through the coil is

$$I_{fs} = 1.00 \times 10^{-3}A. Using\ eq. I_{fs}R_c = (I_a - I_{fs})R_{sh}$$

$$R_{sh} = \frac{I_{fs}R_c}{I_a - I_{fs}} = \frac{(1.00 \times 10^{-3}A)(20\Omega)}{(50 \times 10^{-3}A) - (1.00 \times 10^{-3}A)} = 0.408\Omega$$

I_{fs} = Full Scale I of the galvanometer

I_a = Ammeter

Rc = Coil Resistance

R_s = Shunt resistance

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Example 2.5

How can we make a galvanometer with $R_c = 20\Omega$ *and* $I_{fs} = 1.00mA$ into a voltmeter with a maximum range of 10.0V?

Solution By series connection of the Series resistance R_s

The maximum allowable voltage across the voltmeter is $V_v = 10.0V$. We want this to occur when the current through the coil (of resistance $R_c = 20\Omega$) is $I_{fs} = 1.00mA$. We find the series resistance R_s using equation $V_v = I_{fs}(R_c + R_s)$.

$$I_{fs} = \frac{V}{R_C + R_S}$$

$$R_s = \frac{V_v}{I_{fs}} - R_c = \frac{10.0V}{0.001A} - 20\Omega = 9980\Omega$$

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Potentiometer

- A **potentiometer** is a three – terminal resistor with a sliding contact that makes an adjustable Voltage divider.
- Potentiometers consist of a resistive element, a sliding contact that moves along the element, making good electrical contact with one part of it,
- electrical terminals at each end of the element, a mechanism that moves the sliding contact from one end to the other
- and a housing containing the element and sliding contact.
- The Potentiometer is an instrument that can be used to measure the electromotive force (emf) of a source without drawing any current from the source.

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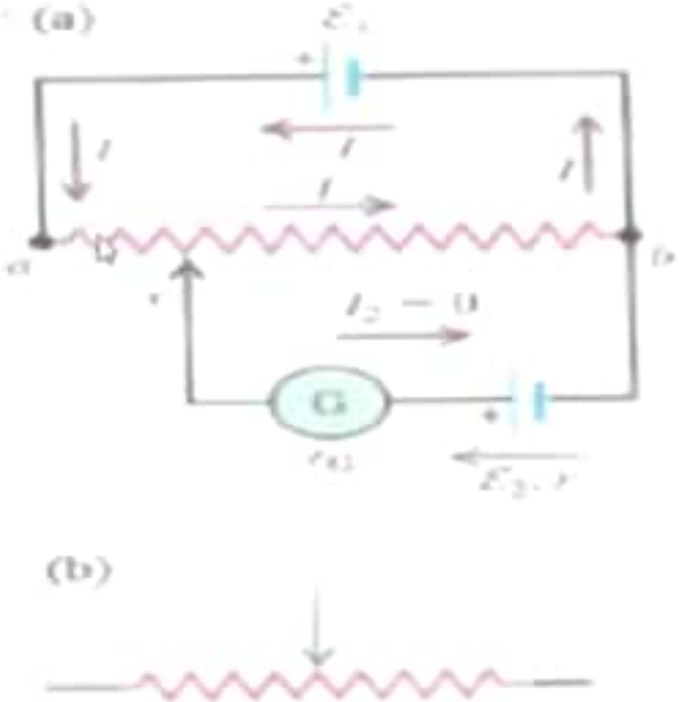
- It balances an unknown potential difference against an adjustable, measurable potential difference.

The Principle of a Potentiometer

- From the diagram below, A resistance of wire AB of total resistance R_{ab} is permanently connected to the terminals of a source of known emf ε_1 .



- A slide contact C is connected through the galvanometer G to a second Source whose emf ε_2 is to be measured.

- As contact c is moved along the resistance wire, the resistance R_{cb} is proportional to the length of the wire between c and b.

- To determine the value of ε_2, ***contact c is moved until a position is found*** at which the galvanometer shows no deflection and this corresponds to the zero current passing through ε_2.

With $I_2 = 0$,

Kirchhoff's loop rule gives $\varepsilon_2 - IR_{cb} = 0 \quad \rightarrow \quad \varepsilon_2 = IR_{cb}$

The potentiometer works on the principle that potential difference across any two points of uniform current carrying conductor is directly proportional to the length between the two points i.e.

$$V \propto l$$

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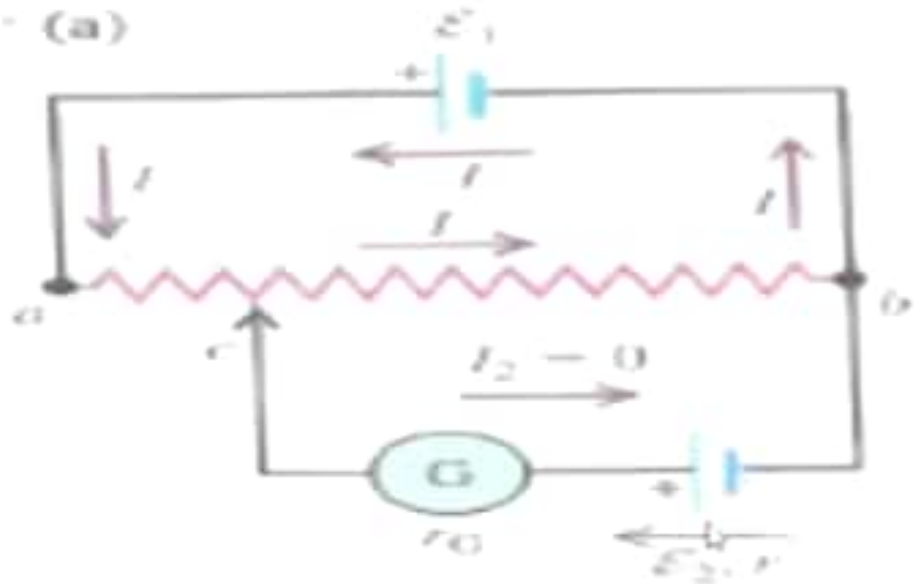
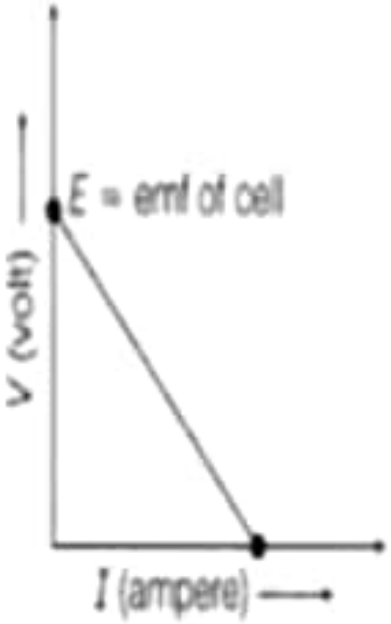
With $I_2 = 0$, the current I produced by the *emf*, has the same value no matter what the value of the *emf* ε_2. We calibrate the device by replacing ε_2 by a source of known *emf*; then any unknown *emf* ε_2 can be found by measuring the length of wire cb for which $I_2 = 0$. Note that for this to work, V_{ab} must be greater than ε_2.



'. The variation of terminal voltage changes with the current drawn from the cell is shown graphically.

$$\therefore \qquad V = E - Ir$$



The slope of the curve gives negative of value of current and intercepts on Y-axis gives emf of cell.

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Potentiometer It is an electrical device which can

(*i*) measure the potential difference with greater accuracy.

(*ii*) compare the emfs of two cells.

(*iii*) measure the emf of a cell.

(*iv*) be used to determine the internal resistance of a primary cell.

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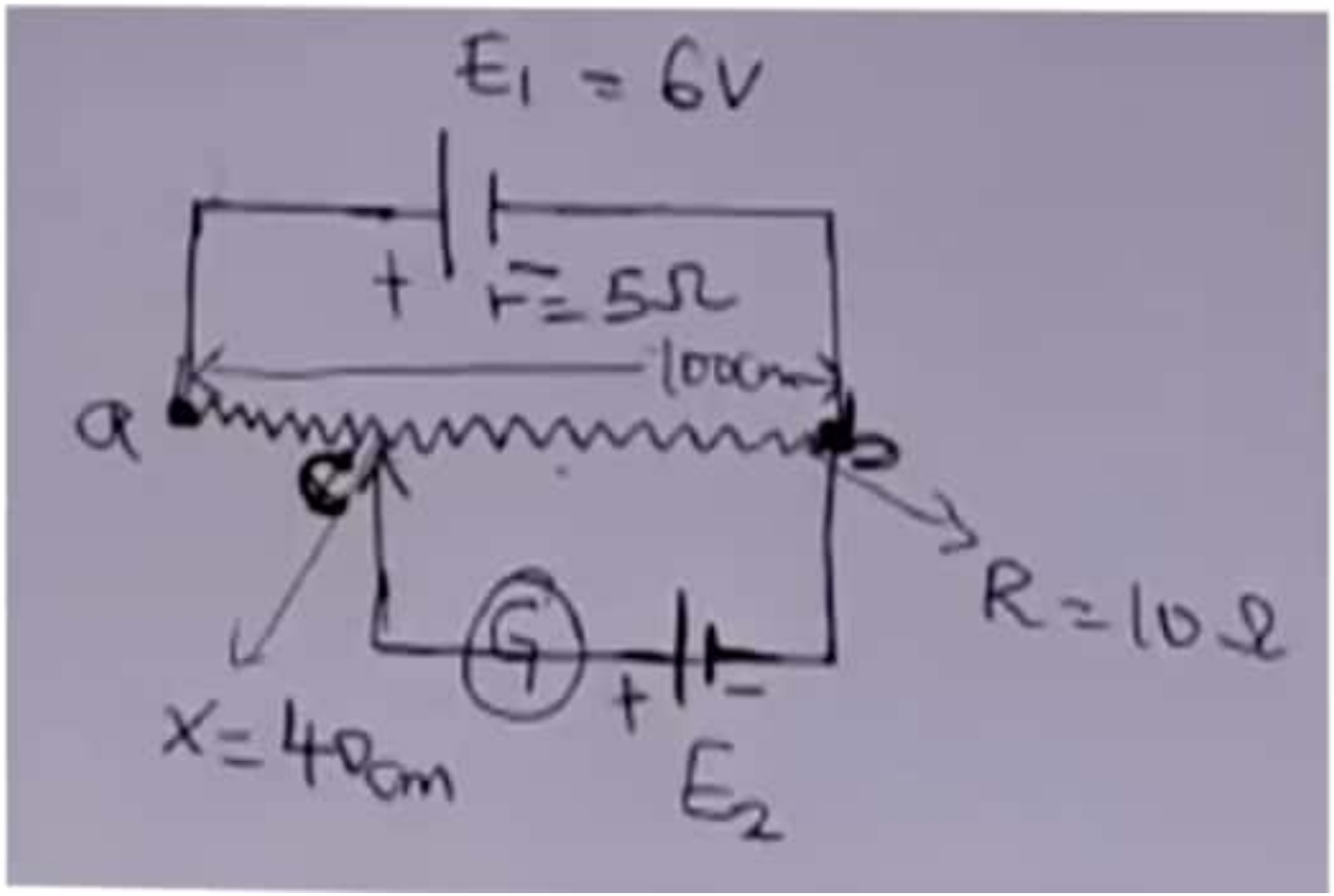
EXAMPLE

A potentiometer of length 1m has a resistance of 10 Ω. It is connected to a 6v battery in series with a resistance of 5 Ω. Determine the e.m.f of the primary cell which gives a balance point at 40 cm.

Solution :



Solution :- Given, length of wire $L = 1m = 100cm$

Resistance of wire $R = 10\Omega$

Emf of battery, $E_1 = 6V$

Internal resistance $r = 5\Omega$

Balance point $x = 40cm$

$\therefore$ Current $= I = \dfrac{E_1}{R+r}$ $\longrightarrow$ In series

$$I = \frac{6}{10+5} = \frac{6}{15} A$$

But V_{AB} = Potential difference across ab per length

$$\frac{V_{AB}}{\text{length}} = \frac{IR}{\text{length}} = \left(\frac{6\times10^{-2}}{15}\right)\cdot\text{length} = \left(\frac{60}{15}\right)/\text{length}$$

$$= 4/\text{length} = 4/100\ \text{V/cm}$$

The potentiometer works on the principle that potential difference acro points of uniform current carrying conductor is directly proportional to between the two points i.e.

$$V \propto l$$

$\therefore$ Emf of the Primary cell $= \frac{V_{AB}}{L} \times x$

$$= \frac{4}{100}\,(\text{Vcm}^{-1}) \times 40\,(\text{cm}) = \frac{16}{10} = 1.6\text{V}$$

Example

- A potentiometer wire is 15m long and a potential difference of 7.5 v is maintained between its end. i. Find the potential drop per centimeter of the wire. ii. Find the emf of a cell which balances against a length of 190 cm of the wire.

Solution

- Given: length of potentiometer wire l_{AB} = 15m =1500 cm.
- Pot. diff. across potentiometer wire V_{AB} = 7.5 v
- Balancing length l = 190 cm.
- Find pot drop per cm =? , e.m.f of cell =?
- Potential drop per cm = V_{AB}/l_{AB} in cm = (7.5 /1500) = $0.005 vcm^{-1}$

  e.m.f of cell = potential drop per cm X balancing length in cm

  = (0.005 X 190) = 0.95v

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Example

A potentiometer wire has a length of 4m and a resistance of 14ohms . It is connected in series with a cell of e.m.f 6v and internal resistance of r = 8 ohms. i. Find the potential gradient on the wire. ii. Find where a cell of e.m.f 2v will balance on the wire.

Solution

- Given: length of potentiometer wire l_{AB} = 4m.
- Resistance of potentiometer wire R_{AB} = 14 ohms
- e.m.f of cell E = 6v
- Internal resistance of cell r = 8 ohms.
- e.m.f of cell e = 2v
- $I = E/(R_{AB} + r) \rightarrow 6/(14 + 8) = (6/22) = I = 0.27$ A
- $V_{AB} = IR_{AB} = 0.27 \times 14 = 3.8$v
- Potential gradient = $V_{AB} / l_{AB} \rightarrow (3.8 / 4) = 0.95 vm^{-1}$
- e.m.f of cell = (potential drop X Balancing length) $\rightarrow 2 = (0.95 \times l_{AB}) \rightarrow l_{AB} = (2/0.95)$
- Balancing length (l_{AB}) = 2.1 m

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Effects of Electric Current

1. Heating Effect (Thermal Effect)

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- Heating effect of current is one of the widely used effects in the world.

- When electric current is passed through a conductor, it generates heat due to the ***resistance it offers*** to the ***current flow***.
- The work done in overcoming the resistance is generated as heat.

- When electric current is supplied to a ***purely resistive conductor***, the **energy of electric current is dissipated in the form of heat** and as a result, **the resistor gets heated up**.

- The heating of resistor due to dissipation of electrical energy is commonly known as ***Heating Effect of Electric Current***.

- The **electric current in a conductor** is **due to the motion of electrons**.

- During their motion, **electrons collide with the oscillating positive ions** in the conductor and *impact part of their energy to them*.

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- **Ions oscillate faster** and their increased energy is manifested as heat. Some **examples** are as follows:

- When **electric energy is supplied** to an **electric bulb, the filament g heated and as a result, it gives light.**

The heating of electric bulb happens because of heating effect of electric current.

- When an ***electric iron is connected to an electric circuit,*** the ***element of electric iron gets heated because of dissipation o electric energy,*** which then ***heats the electric iron***.

- The element of electric iron is a purely resistive conductor. This happ because of heating effect of electric current.

Joule heat is used in domestic appliances such as electric iron, toaster, oven, kettle, **Room heater etc.**

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(a)

(b)

(c)

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- **All of these have a heating element in them. Heating elements are generally made of specific alloys like, nichrome, manganin, constantan etc**

Joule's Law of Heating:

Let: an electric current I flowing through a resistor having resistance equal to R.

The potential difference through the resistor is equal to V.

The charge Q flows through the circuit for the time t.

$W = E$

Thus. work done in moving a charge Q of potential difference $V = VQ$

Since. this charge Q flows through the circuit for time t

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Joule's law of heating contd.

Therefor: power input (P) to the circuit can be given by following equation:

$$P = V \times \frac{Q}{t} - - - - - - - (i)$$

since W = VQ, P = (VQ)/t , P = W/t , P = E/t

We know, electric current I = Q/t

Substituting Q/t = I in equation (i), we get;

P = VI .....(ii)

Since the electric energy is supplied for time t, thus after multiplying both sides of equation (ii) by time t, we get

P x t = VI x t = VIt .....(iii)

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Or, $H = VIt$ .....(iv)

We know: according to Ohm's law: $V = IR$

By substituting this value of V in equation (iv), we get:

$H = IR \times It$

Or, $H = I^2Rt$ .....(v)

The expression (v) is known as Joule's Law of Heating, which states that the heat produced in a resistor is directly proportional to the square of current given to the resistor, directly proportional to the resistance for a given current and directly proportional to the time for which the current is flowing through the resistor.

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Example 1: If an electric heater consumes electricity at the rate of 500W and the potential difference between the two terminals of electric circuit is 250V. calculate the electric current and resistance through the circuit.

Solution: Given, power input (P) = 500 W

Potential difference (V) = 250 V

Electric current (I) =?

Resistance (R) through the circuit =?

We know that power (P) = VI

Or, 500 W = 250 V x I

Or, I = 500 W ÷ 250 V = 2 A

We know, resistance R = V/I

Or, R = 250 V ÷ 2 A = 125 Ω

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Example 3: An electric heater having resistance equal to 5Ω is connected to electric source. If it produces 180 J of heat in one second, find the potential difference across the electric heater.

Solution: Given, Resistance (R) = 5 Ω, Heat (H) produced per second by heater = 180 J, time 't' = 1 s

Potential difference (V) =?

To calculate the potential difference, we need to calculate electric current (I) first.

We know that $H = I^2Rt$

Or, $180\ J = I^2 \times 5\ \Omega \times 1\ s$

Or, $I^2 = 180 \div 5 = 36$

Or, $I = 6\ A$

Now, potential difference $V = IR$

Or, $V = 6\ A \times 5\ \Omega = 30\ V$

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Example

Calculate the energy used in joules by a hairdryer of power 1kW in 1 hour.

$E = I \times V \times t$ **Since Power = Energy divided by time**

but electrical power $P = I \times V$

and so: $E = P \times t$

= 1 kW x 1 hour

= 1000 W x 3 600 seconds

Electrical Energy used = 3 600 000 J or 3.6 MJ

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Example

An electric heater of resistance 10 Ω connected to 220 V power supply is immersed in the water of 1 kg. How long the electrical heater has to be switched on to increase its temperature from 30°C to 60°C. (The specific heat of water is $s = 4200\ J\ kg^{-1}$)

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Solution

- According to Joule's heating law $H = I^2 Rt$

- The current that passed through the electrical heater = 220V/10Ω = 22 A

- The ***heat produced*** in one second by the electrical heater $H = I^2 R$

The heat produced in one second $H = (22)^2 \times 10 = 4840$ J = 4.84 k J.

- **NOTE:** That the **power rating** of this electrical heater **is 4.84 k W.**

- The ***amount of energy to increase*** the **temperature of 1kg** water from ***30°C to 60°C*** is

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- $Q = ms\,\Delta T$ → (Quantity of heat)

Here $m = 1$ kg,

$s = 4200\ J\ kg^{-1}$, → (Specific heat capacity of water)

$\Delta T = 30$,

- so $Q = 1 \times 4200 \times 30 = 126$ kJ

The time required to produce this heat energy

- $t = Q / I^2R = 126 \times 10^3 / 4840$ **≈ 26 .03 s**

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0:02

CHEMICAL EFFECTS OF ELECTRIC CURRENT

- One of the ways of showing the chemical effects of electricity is through Electrolysis.

- The process of carrying out non-spontaneous reactions under the influence of electric energy is termed electrolysis.

- The purpose of electrolysis is mainly to convert reactants in non-spontaneous reactions into more useful products.

- Electrolytic cells use electrical energy to drive non-spontaneous chemical reactions i.e those reactions for which $\Delta G \geq 0$ (G = Gibb's free energy).

Electrolysis

Behaviour of substances to the passage of electric current through them can be classified into two categories:

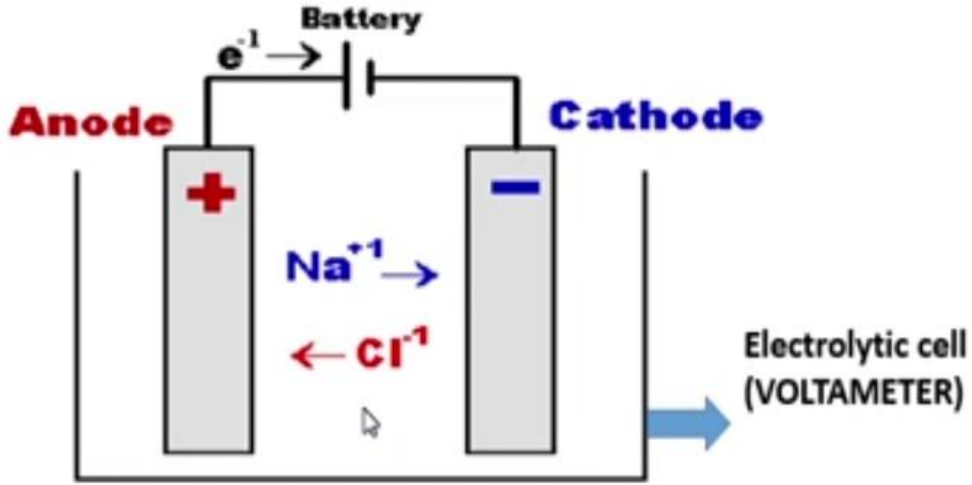
(a) Substances which do not decompose due to the passage of electric current.

Example: Pure metals whether they are in solid or liquid form

(b) Substances which decompose due to the passage of electricity.

Example: Solution of copper sulphate, sodium chloride, etc. Such substances are called electrolytes.

The process of decomposition of electrolytes by the passage of electric current through them is called electrolysis.



The process of electrolysis is carried Out in a vessel called voltameter.

The electrolyte is put into the voltameter. A source of e.m.f is connected across two conducting plates dippedinto electrolyte.

The plates are called electrodes. The plate A connected with positive terminal of the source is called anode whereas the plate 'C' connected with negative terminal is called cathode.

- When an external electric current flows into the cathode of the electrolytic cell,

- The resulting negative charge attracts the dissociated positive ions present in the electrolyte.

- This results in the deposition of the positively charged ions onto the cathode.

- At the same time, the negatively charged ions flow towards the anode, which is positively charged.
- Through this, the chemical effects of current can be noticed. It also has several applications which would be discussed later.
- There are basically two useful laws in electrolysis.

Faraday's Laws of Electrolysis

Faraday gave the following two laws:

- **The first Law**

(a) The *mass* of ion deposited on an electrode in the process of electrolysis, is *proportional to the quantity of charge* that has passed through the electrolyte.

If 'm' is the mass of ion deposited on an electrode due to passage of charge 'q', then,

$m \propto q$

But $q = it$

Here, 'i' is the current which flows for a time t.

So, $m \propto it$

Or, $m = zit$ ..... (1)

Here '*z*' is the *constant of proportionality* and it is known as *electro-chemical equivalent (e.c.e.)* of the substance.

If $i = 1$ A, $t = 1$ s, $m = z$.

- **NOTE THIS:** Therefore, *electro – chemical equivalent of a substance* is numerically *equal to the mass of ion* deposited when *a charge of 1 C* (or a current of 1 A passes through it for 1 s);

e.c.e. varies from one substance to the other. *Its unit* = gC^{-1}.

Example

What is the electrochemical equivalent of Silver, when 16 g was deposited durin electrolysis by passing 24 A current through the electrolyte in 10 mins?

Solution:

- Given: I = 24Amperes
  t = 10 mins = 10 x 60 sec = 600 secs
  Silver deposited = 16 grams.
- But the electrochemical equivalent of a substance (silver) is the mass deposited when a charge of 1C passes through it.
- Therefore, to know the amount of charge that deposited 16 g of silver,
  $q = I \times t \rightarrow 24 \times 600 = 14400$ C.
- The amount of silver deposited by 14400 C = 16g.
- The amount of silver deposited by 1C = $\frac{16}{14400} = 1.11\ x10^{-3}$
- **Therefore, electrochemical equivalent of Silver** = $1.11\ x10^{-3}$g/C.

➢ The Second Law

(b) When *same current* passes through *several electrolytes* for the *same time*, the *masses of various ions* deposited at each of the electrodes are *proportional to their chemical equivalents* (equivalent weights).

If *certain current* passes through *two electrolytes A and B for the same time*,

weight of A deposited / weight of B deposited = chemical equivalent of A / chemical equivalent of B.....2nd law

- *Note:* that *chemical equivalent of an element is defined as the ratio of its atomic weight to its valence.*

i.e Chemical equivalent = atomic weight/valence

Let same charge 'q' be passed through two electrolytes having (electo- chemical equivalences (e.c.e.'s) z_1 and z_2. Let m_1 and m_2 be the masses of ions liberated.

<u>According to Faraday's first law,</u>

$m_1 = z_1 q$

$m_2 = z_2 q$

or $m_1/m_2 = z_1/z_2$ ..... (2)

<u>According to Faraday's second law,</u>

$m_1/m_2 = E_1/E_2$ ..... (3)

Here, 'E_1' and 'E_2' are the chemical equivalents of two electrolytes.

From equations (2) and (3), we get,

$E_1/E_2 = z_1/z_2$ or $E_1/z_1 = E_2/z_2$ **so, $E \alpha Z$**

Important That is, E/z = constant = F (say) ..... (4)...combination of 1st and 2nd laws

'F' is known as a 'faraday'.

from equation (1), $z = m/it = m/q$

Substituting in (4), we get,

$F = E / (m/q) = Eq/m$ that is, $F = \frac{Eq}{m}$

If $m = E$, $F = q$

Thus, a faraday is the amount of charge required to liberate one gram equivalent of a substance during electrolysis.

For copper E = 31.5 g

$z = 0.000329\ gC^{-1}$

Substituting in equation (4), we get,

$F = 31.5\ g / 0.000329\ gC^{-1} = 96500\ C$

Thus, a faraday represents a charge 96500 C.

So, 96500 C is the amount of charge needed to liberate one gram equivalent of copper during electrolysis.

Question 1

According to Joule's law of heating, heat produced in a resistor is

(a) directly proportional to the square of current,

(b) inversely proportional to resistance

(c) directly proportional to the square of the time for which the current flows through

Question 2

The S.I. unit of a power is,

(a) Henry

(b) Coulomb

(c) watt

(d) watt - hour

Question 3

The filament of an electric bulb is made of

(a) carbon

(b) aluminum

(c) tungsten

(d) nickel

Question 4

The rating of a fuse wire is always expressed in

(a) ampere-hours

(b) ampere-volts

(c) kWh

(d) amperes

Example

A current of 0.5 ampere was passed through a solution of $AgNo_3$ for 193 sec. depositing 0.108 g of silver. Find the equivalent weight of silver.

Solution:

- Given: mass = 0.108g

  I = 0.5 A

  t = 193 s

  From $\frac{E}{Z} = F$ [**E = chemical equivalent (equivalent weight) , Z = electrochemical equivalent, F = Faraday (96500 C)**]

- $\frac{Eq}{m} = F$ but q = It and Z = m/q

- $E = \frac{m \, x \, F}{I \, x \, t}$ → $E = \frac{0.108 \, x \, 96500}{0.5 x \, 193}$ → 108 g is the equivalent weight of silver

Galvanic/Voltaic cell

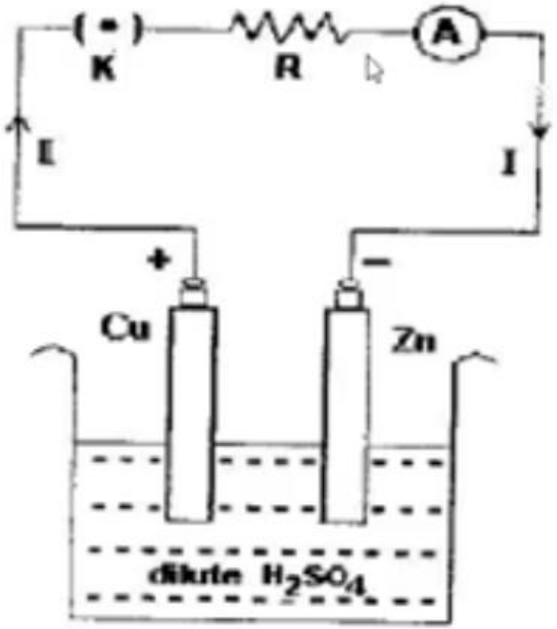
The device used to convert chemical energy into electrical energy is called a (Galvanic) electrochemical cell.

When a metal plate (electrode) is immersed into an electrolyte, positive or negative ions from the electrolyte move towards it and a net *e.m.f.* is developed between it and the

electrolyte. When two electrodes of different metals are immersed into the electrolyte, a net e.m.f. is generated between them. The electrode at higher electric potential is called the positive electrode and the one having lower potential is called the negative electrode.

Steady electric current flows on completing the electric circuit by connecting the two electrodes with a conducting wire. Such a device is called an electrochemical cell(**Voltaic**).

Dilute H_2SO_4 is used as an electrolyte. Positive charge deposits on copper electrode and negative charge on zinc electrode. So copper electrode is at a higher potential that the zinc electrode.



Calculate the mass of silver deposited from silver nitrate solution by a current of 2A flowing for 30 minutes

Solution:

Given:

I = 2A, t =30 minutes.

but

Molar Mass of Ag = 108 g/mol and 1F = 96500 C mol^{-1}

We know that $F = \frac{E}{Z}$ (*) and $m = ZIt$

Substitute for Z in (*) and make m subject of the formula.

$$Z = \frac{\text{Equivalent weight}}{96500} = \frac{108}{96500}$$

$$t = 30 \text{ min} = 30 \times 60 \text{ seconds}$$

$$\therefore m = \frac{108}{96500} \times 2 \times 30 \times 60$$

$$\therefore m = 2.01 \text{ g}$$

Electrolysis of dilute aqueous Nacl solution was carried by passing 10mA current. The time needed to liberate 0.01 moles of H_2 gas at the cathode is what?

Solution

- The hydrogen ions are reduced by electron e- gain to form hydrogen molecules at the negative electrode which attracts positive ions.

$$2H^+ (aq) + 2e^- \rightarrow H_2$$

- 0.01 moles of H_2 will need 2 x 0.01 = 0.02 moles of electrons or 0.02 Faradays.

NOTE: one Avogadro's number of electron = charge of 1 Faraday = 96500 C = 96500 amperes Sec = 1 equivalent mass deposited/ reacted.

Therefore,

- one Faraday is defined as the charge carried per unit mole of electrons.

Note: 10mA = 10/1000 = 0.01 A

i.e

$1F = \frac{Q}{mole} = \frac{I \times t}{mole}$ but since it is 0.02 moles of electron used

Then, $96500 = \frac{0.01 \times t}{0.02}$ $t = \frac{96500 \times 0.02}{0.01}$ $t = 193000$ sec

Primary and Secondary Cells

Electrochemical Cells are of two types:

- **Primary cells** are basically use-and-throw **galvanic cells.**

- The ***electrochemical reactions*** that take place in these cells are ***irreversible in nature***. Hence, the reactants are consumed for the generation of electrical energy and the **cell stops producing an electric current** once the **reactants are completely depleted**.

- **Secondary cells** (also known as *rechargeable batteries*) are electrochemical cells in which the cell has a **reversible reaction**, i.e. the cell **can function** as a ***Galvanic cell as well as an Electrolytic cell***.

- **Rechargeable batteries**: **electrolysis** is used to **recharge rechargeable batteries** : The batteries operate as **Voltaic cells when powering** devices BUT as **electrolytic cells during recharge**.

- Most of the **primary batteries** (multiple cells connected in series, parallel, or a combination of the two) are considered **wasteful and environmentally harmful devices**.

- This is because they require about **50 times the energy** they contain in **their manufacturing process**.

- They also contain **many toxic metals** and are considered **to be hazardous waste**.

NOTE the differences in Galvanic -electrochemical cells and ***electrolytic type of Electrochemical cells***.

- A **Galvanic** Electrochemical cell is a device which converts chemical energy into electrical energy.

- On the other hand, ***electrolytic cell type is a device which converts*** **electrical energy into chemical energy.**

- The two cells also differ significantly with respect to the **charges on the electrodes.** For example, in **Galvanic -*electrochemical cell, anode is negative*** whereas in ***electrolytic cell, the anode is positive.***

- Similarly, **cathode is positive in electrochemical** cell whereas it is **negative in the electrolytic** cell.

  - **USE THIS TO REMEMBER** for ***electrolytic cells***

  - [don't ''PANIC''-Positive ANODE Negative Is CATHODE], reverse is the case for **Galvanic -**Electrochemical cells.

- Electrolytic cells are used for electroplating metals, recharging batteries and separating pure metals from metallic compounds.
- Electrolytic cells converts the electrical energy from external source due to non-spontaneous redox reaction to generate chemical energy, (ΔG) > or =0. e.g when charging a used battery.
- Electrons Electrolytic cells originate from an external source (such as a battery).
- **Galvanic/Voltaic Electrochemical cells** are the primary cells (batteries), non rechargeable, that are used to power our domestic devices

- **A Galvanic/Voltaic cell, an example of electrochemical cell** induces a spontaneous redox (oxidation-reduction) reaction to create a flow of electric charges or electricity (Pry. Battery- non rechargeable)

- i. e it converts the chemical potential energy due to spontaneous redox reaction to generate electrical energy.
- The electrons originate from the species that undergoes oxidation.

- A reaction is spontaneous when the change in Gibb's free energy (ΔG) <0.

Magnetic Effects of Electric Current

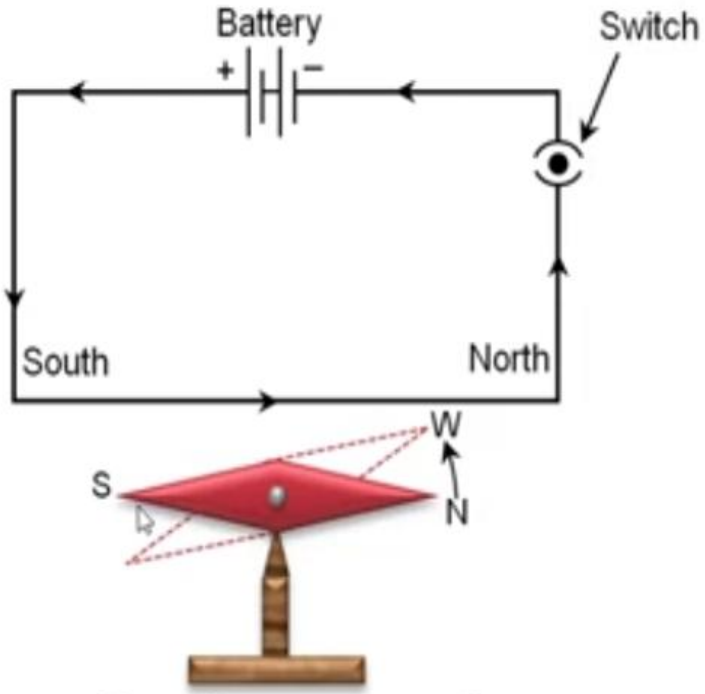
Magnetic Effects of Electric Current

The **magnetic effect of electric current** is known as electromagnetic **effect**.

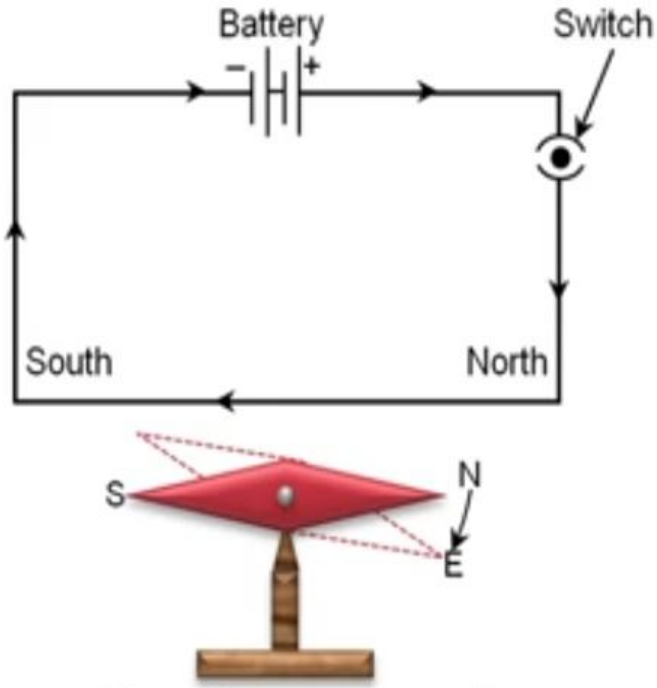
It is observed that when a compass is brought near a **current** carrying conductor the **needle of a compass** gets *deflected* because of flow of **electricity**.

This shows that **electric current** produces **magnetic effect**.

This concept actually **means that the flow of an electric current** through a **conductor produces a magnetic field around** it.



Magnetic compass needle

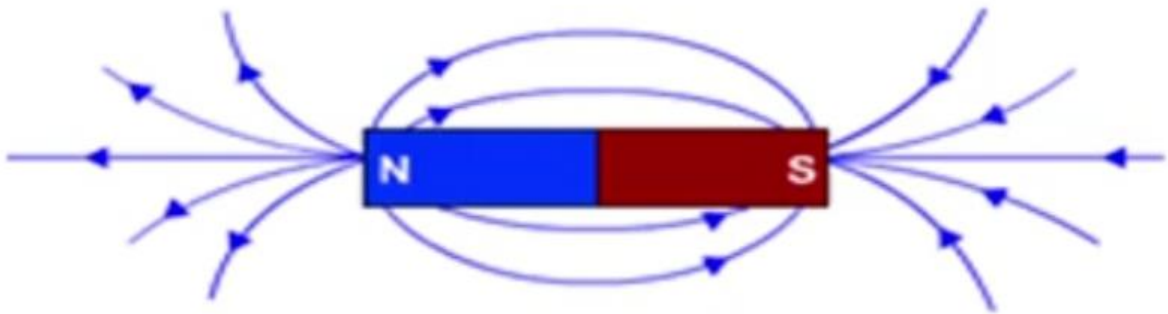


Magnetic compass needle

The Basic Concepts

- **Electric Current** is the flow of electric charge (a physical property of the matter that experiences a force when placed around an electromagnetic field)
- Magnetic field is the area around a magnet where the ***magnetic force is experienced***.

- The imaginary lines of magnetic field around a magnet is called Magnetic Field Lines.



MAGNETIC FIELD LINES

Magnetic Field Lines

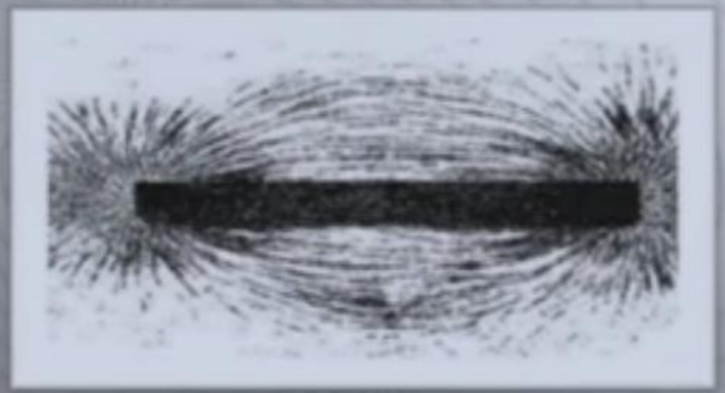
Magnetic field lines are the paths around a magnet along which the north pole of a magnetic compass needle tends to move.

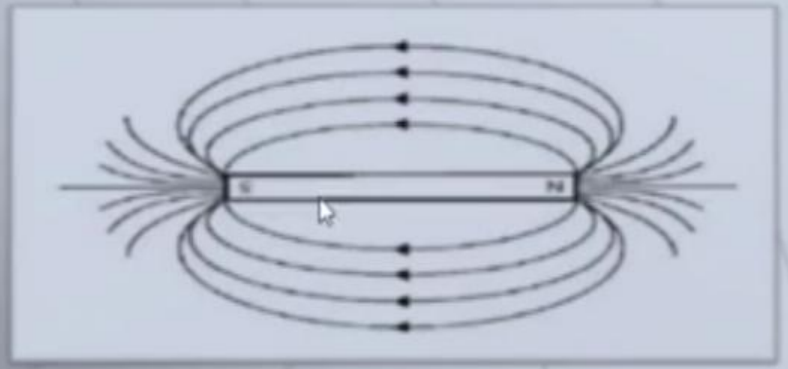
The magnetic field lines around a magnet can be observed by sprinkling iron filings around a magnet. It can also be observed by moving a magnetic compass around a magnet.

i) The magnetic field lines emerge at the north pole and merge at the south pole.

ii) The magnetic field lines are closer at the poles.

iii) The magnetic field lines do not intersect each other.





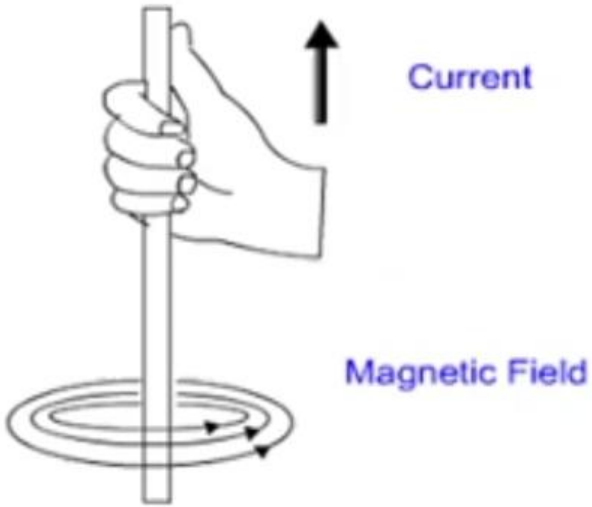
The Right-Hand Thumb Rule

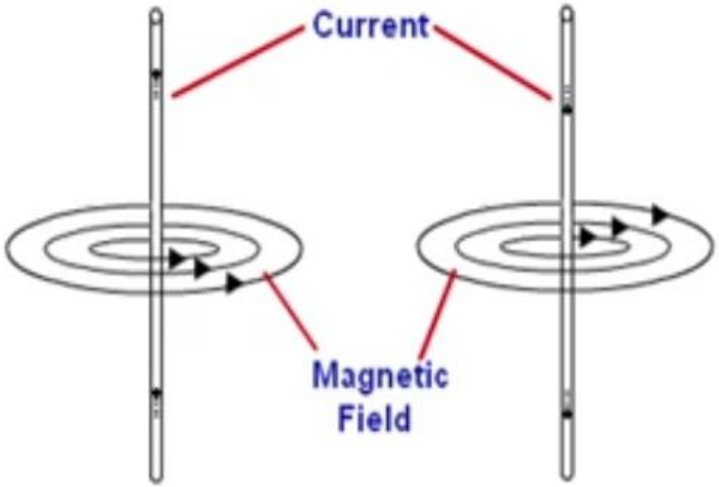
- The Right-Hand Thumb Rule or Maxwell's Corkscrew Rule ***shows the direction of magnetic field*** in **relation to the direction of electric current through a straight conductor.**

- It states that if a current carrying conductor is held by the right hand with the thumb straight up

- and the *electric current is flowing in the direction of the thumb,*

- then ***the direction of the magnetic field can be shown by the direction of wrappings of the other fingers.***





Current is from down to top (S to N)

Current is from TOP to DOWN (N to S)

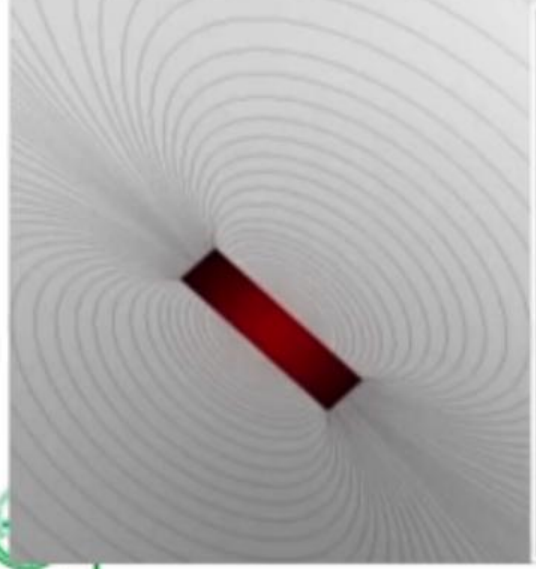
This means that in a **vertically suspended current** carrying conductor **if the direction of the current is from south to north then** the ***magnetic field will be in an anticlockwise direction***. But **if it is vice-versa which means that the direction of the current is flowing from north to south** then ***the magnetic field will be in clockwise direction.***

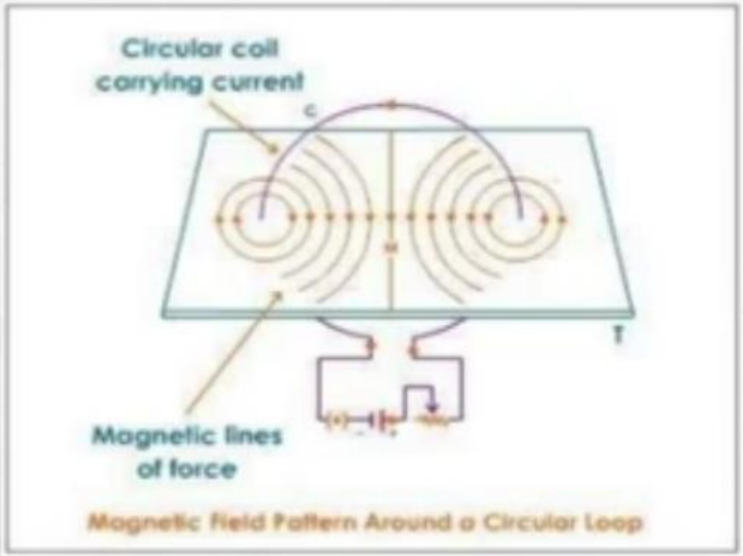
Current Flowing Through a Circular Loop

- Similarly, as in the observation above, **if the electric current carrying** conductor ***is circular in shape instead of a straight current conductor***,
- the magnetic field is also generated in the same manner ***(Concentric circles near the conductor).***
- This is because ***as the*** **electric current carrying conductor exerts a force** ***when a magnetic needle is placed near it,*** in a ***similar manner a*** ***magnet also exerts an equal and opposite pressure on the electric carrying conductor.***

Magnetic Field Due to Current in Circular Loop

When current is passed through a circular conductor (loop) the magnetic field produced is in the form of concentric circles around the conductor. Towards the centre the arcs of the circles become larger and appears as straight line.





- Here ***it is observed that with the change in direction of the flow of current,***

- **the force of the magnet on the conductor also changes**.

- **NOTE**: In a **circular loop, the strength of the magnetic field will be more than that of the straight conductor,**

- **because in this case, the magnetic fields are very close to the current carrying conductor.**

Magnetic Field Due To a Solenoid

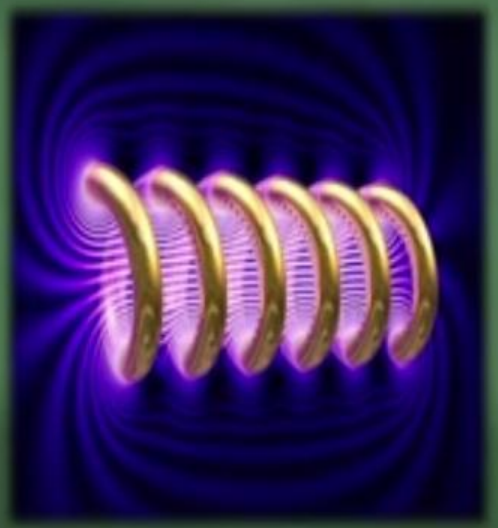
- A Solenoid is the coil with many circular turns of insulated copper wire wrapped closely in the shape of a cylinder.

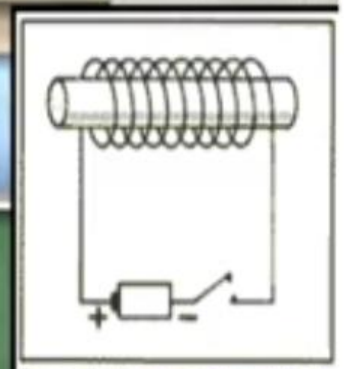
- A **solenoid behaves like a magnet**, ***one end of a solenoid behaves as the north pole and the other end behaves like the south pole.***

- **In this case, the magnetic field lines are parallel inside the solenoid, which is similar to a magnet and this proves that *magnetic field is the same at all points* inside a solenoid.**

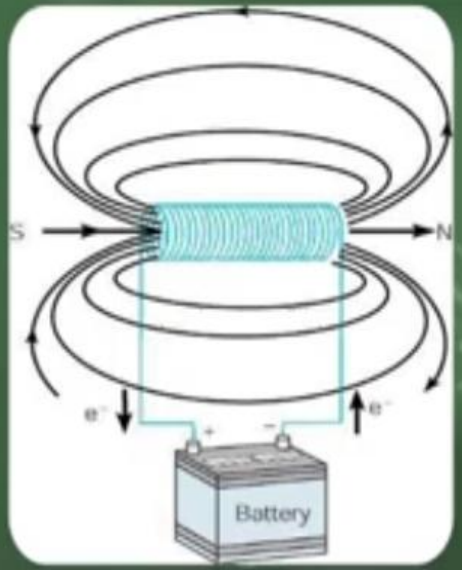
- *Magnets formed by producing a magnetic field inside a* ***solenoid is called electromagnet.***

Solenoid





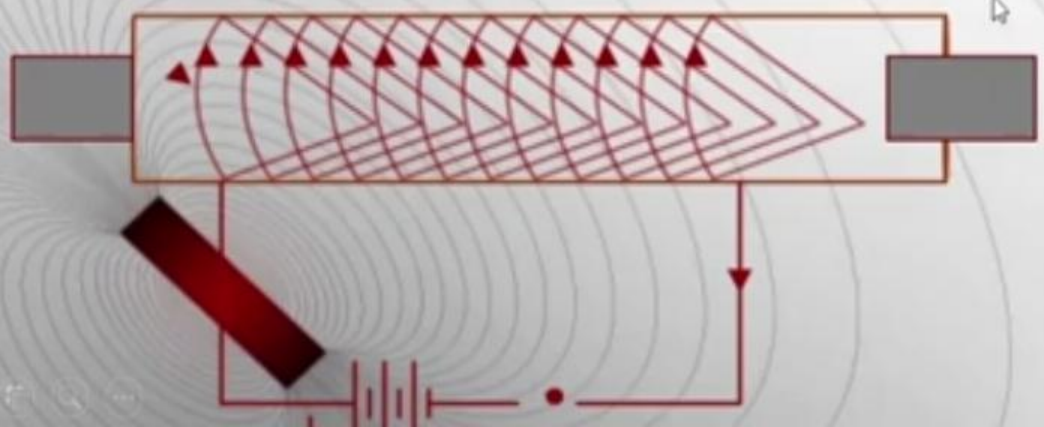
Power off, no current, no magnetic field

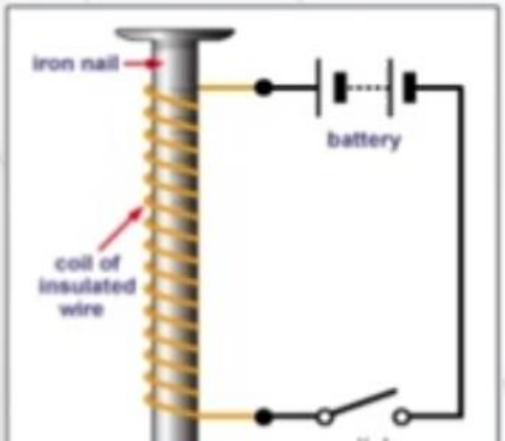


Electromagnet

A strong magnetic field inside a solenoid can be used to magnetise a piece of magnetic material like a soft iron when placed inside the coil. Such a magnet is called an electromagnet.

If electric current is passed through a wire wound around a piece of soft iron, it behaves like a magnet. Such a magnet is called an electromagnet.





FORCE ON A CURRENT CARRYING CONDUCTOR IN A MAGNETIC FIELD

- A **current carrying conductor exerts a force** when a magnet is placed in its vicinity;

- likewise, **a magnet also exerts equal and opposite force on the current carrying conductor**.

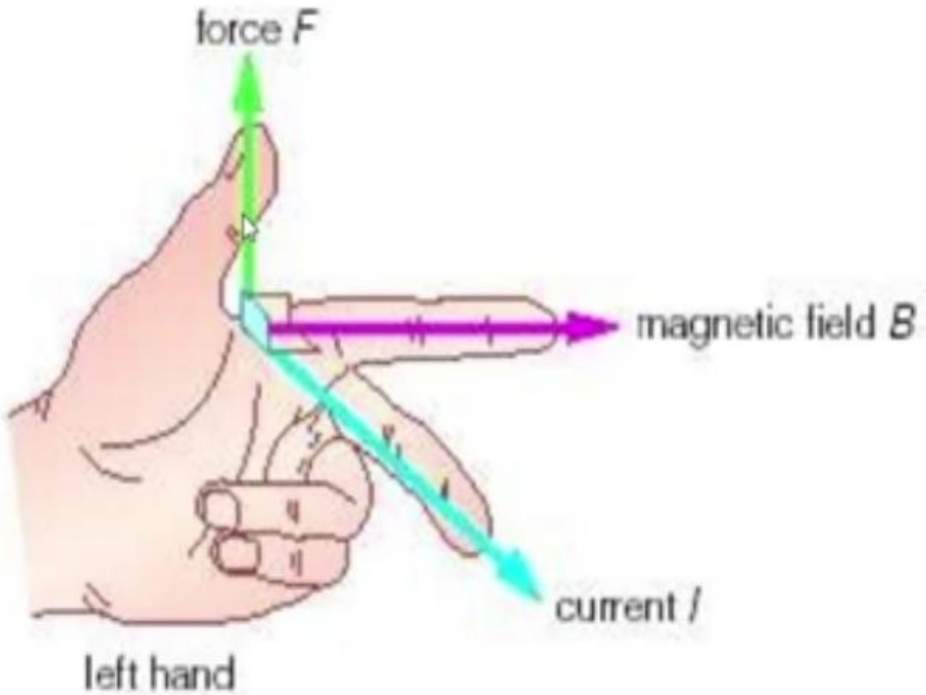
- It is observed that ***with the change in direction of the flow of current,*** **the direction of force of the magnet on the conductor also changes.**
- It is noticed that ***the magnitude of force is highest when the direction of current is at right angle to the magnetic field.***

Fleming's Left-Hand Rule

- According to Fleming's Left-Hand Rule, if the direction of flow of the electric current is perpendicular to the magnetic field, the direction of its force is also perpendicular to it.

- ***It states that if the forefinger, thumb, and the middle finger of the left hand is stretched in a way that they are right angles to each other, then the forefinger and middle finger show the direction of magnetic field and direction of electric current respectively and the thumb shows the direction of motion or force acting on the current carrying conductor.***

- Applications such as electric motor, Electric generators, loudspeakers etc. works on Flemings left hand rule.

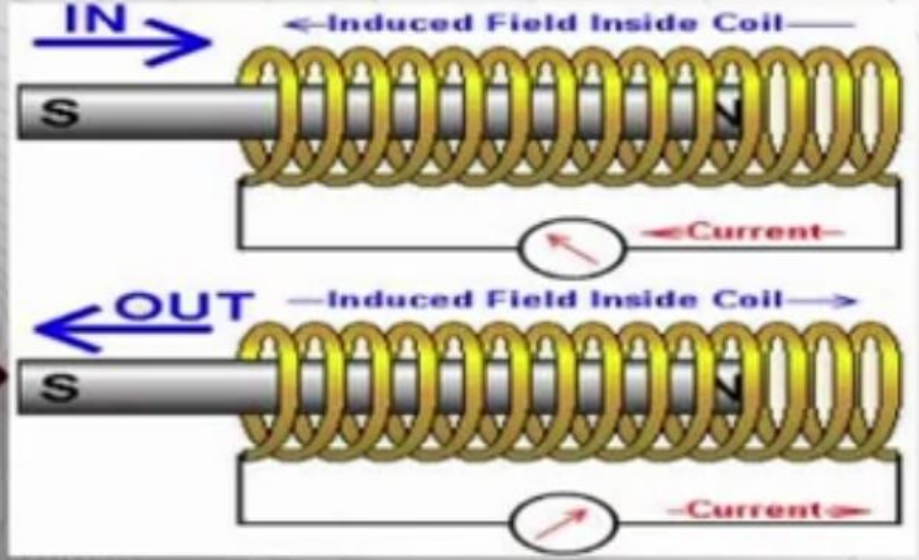

force F
magnetic field B
current I
left hand

Electromagnetic Induction (Faraday)

The motion of a magnet with respect to a coil or a change in the magnetic field induce a potential difference in the coil and produces induced current. This is called electromagnetic induction.

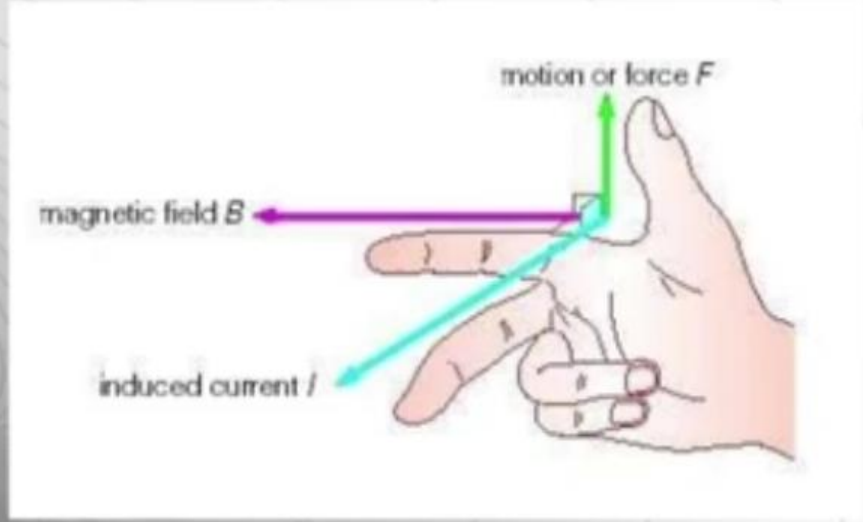
i) Motion of a magnet with respect to a coil produces induced current :-

If a magnet is moved towards or away from a coil of wire connected to a galvanometer, the galvanometer needle shows a deflection. This shows that current is induced in the coil due to the motion of the magnet.



FLEMINGS RIGHT HAND RULE (For the Direction of the Induced Current)

The direction of induced current is given by Fleming's Right Hand Rule. It states that ' If the thumb, fore finger and middle finger of the right hand is held perpendicular to each other such that the thumb points in the direction of motion of the conductor, the fore finger points in the direction of the magnetic field, then the middle finger shows the direction of induced current '.



DOMESTIC ELECTRIC CIRCUIT

Household electric supply consists of 3 types of wire. Live wire (red insulation cover), neutral wire (black insulation cover) and earth wire (green insulation cover)

The potential difference between neutral and live wire is 220V.

In household circuit system, two type of circuit are used. One of 15 A for appliances with higher power ratings and the other of 5 A ratings for bulbs etc.

In domestic circuit, different appliances are connected in parallel combination. This ensures that if one appliance is switched 'on' or 'off', the others are not affected.

The earth wire is used as a safety measure, especially for those appliances that have a metallic body.

Short circuit

- It means that the two wires live and neutral have come in contact with each other. This may happen either due to their insulation have been damaged or due to a fault in the appliance. In such a case, the resistance of the circuit decreases to a very small value. According to Ohm's law, the current increases enormously. It may results in spark at the place of short circuit, which may even cause fire. Sometimes, the current also increase due to overloading of the circuit.

Overloading

- It is a situation when too many appliances are connected in the same circuit such that the overall current (sum of all the current used by all appliances) exceeds the current carrying capacity of the connecting wires. The wires cannot withstand such a high current and melt and may cause fire.

The electric fuse

- Electric fuse is used as safety device for the protection of electric circuits and appliances due to short circuiting or overloading of the circuit.. The electric fuse is a piece of wire having a very low melting point and high resistance.When a high current flows through the circuit due to short circuit or overloading, the fuse wire gets heated and melts. The circuit is broken and current stops flowing thus saveithe electric circuit and appliance ~~form~~ from damage.

Capacities of fuse wire

- The fuse for domestic purposes are rated as 1A, 2A, 3A, 5A, 10A and 15A.

Characteristics of fuse wire

- 1. Low melting point
  2. High resistance

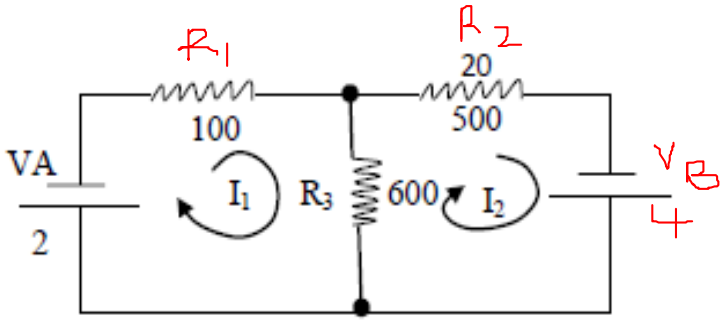
Fuse wiresare made up of pure tin or made of an alloy of copper and tin.

General Physics II

Phs 102 (A)/ Physics

I. C. OKEYODE

EXAMPLES TO PLAY WITH



solve the worked example using mesh equation method.

$$-V_A - I_1 (R_1 + R_3) \quad + I_2 R_3 = 0$$

$$V_B \quad + I_1 R_3 \quad - I_2 (R_2 + R_3) = 0$$

Re-writing these in standard form gives

$$I_1 (R_1 + R_3) \quad - I_2 R_3 \quad = -V_A$$

$$-I_1 R_3 \quad + I_2 (R_2 + R_3) = V_B$$

Hence $\quad 700I_1 - 600I_2 = -2$

$$-600 I_1 + 1100 I_2 = 4$$

$$\frac{-2200+2400}{770000-360000} = \frac{200}{410000}$$

$$= 4.88\times10^{-4}$$

$$I_1 = \frac{\begin{vmatrix} -2 & -600 \\ 4 & 1100 \end{vmatrix}}{\triangle} = \frac{\begin{vmatrix} -2 & -600 \\ 4 & 1100 \end{vmatrix}}{\begin{vmatrix} 700 & -600 \\ -600 & 1100 \end{vmatrix}} = \frac{200}{410{,}000}$$

$$= 0.488\text{mA}$$

$$I_2 = \frac{\begin{vmatrix} 700 & -2 \\ -600 & 4 \end{vmatrix}}{\triangle} = \frac{1600}{410{,}000} = 3.90\text{mA}$$

Thus the current through R_1 is I_1, and that through R_2 is I_2, whereas the current through R_3 is the difference of I_2 and I_1, or 3.412mA [redacted]

What is the magnitude of electric force F between two charges of 5.0pC seperated by 1.0mm?

Solution:-

$$F = \frac{kQ_1Q_2}{r^2} = \frac{8.9\times10^{9}\,Nm^2}{C^2} \times \frac{5\times10^{-12}\,C \times 5\times10^{-12}\,C}{(1.0\times10^{-3}\,m)^2}$$

$$= 2.2\times10^{-7}\,N$$

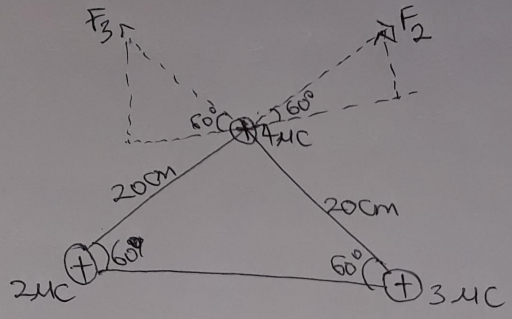
* A helium nucleus has a charge $+2e$ and a neon nucleus $+10e$. Find the repulsive force exerted on one by the other when they are at a distance of 3nm from each other (Assume the system to be in vacuum).

Solution:- $F = \frac{Kq_1q_2}{r^2}$

$$= \frac{8.9\times10^{9}\times2\times1.6\times10^{-19}\times10\times1.6\times10^{-19}}{(3\times10^{-9}\,m)^2}$$

$$= 5.1\times10^{-10}\,N \equiv 0.51\,nN$$

* Find the force on the 4 μC charge due to the other two charges as shown in the diagram below.



Solution :- from Coulomb's law

$$F_2 = \frac{8.9\times10^{9} \times 2\times10^{-6} \times 4\times10^{-6}}{(0.2)^2} = 1.8N$$

In like manner,

$$F_3 = \frac{8.9\times10^{9}\times 3\times10^{-6}\times4\times10^{-6}}{(0.2)^2} = 2.7N$$

The resultant force on charge 4μC has component

$$F_x = F_2\cos60^\circ - F_3\cos60^\circ = (1.8-2.7)\times0.5 = -0.45N$$

$$F_y = F_2\sin60^\circ + F_3\sin60 = (1.8+2.7)\times0.866N = 3.9N$$

$\therefore$ Resultant force $F = \sqrt{F_x^2+F_y^2}$

$$= \sqrt{(0.45)^2+(3.9)^2}$$

$$= 3.9N$$

* Two point charges lie 1.5m apart and carry identical charges, find the amount of charge on each if a point charge experience a force of 2N?

Solution:- $F = \frac{KQq}{r^2} \Rightarrow Qq = \frac{Fr^2}{K}$

$$= \frac{2 \times (1.5)^2}{9 \times 10^9 \, Nm^2/C^2} = 5 \times 10^{-10} C^2$$

but since $Qq = 5 \times 10^{-10} C^2$, the amount on each point charge is $q = Q = 2.5 \times 10^{-5} C$

* Find the electric field for a point charge $Q = 10\mu C$ at a distance $r = 1.0m$

Solution :-

$$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2} \equiv E = \frac{kq}{r^2}$$

$$= 8.9\times10^{9}\frac{Nm^2}{C^2}\times\frac{10^{-6}C}{1^2m^2}$$

$$E = 8.99\times10^{3}\,N/C$$

* What is the absolute potential at a distance of $r = 10cm$ from a charge of $2.0\mu C$.

Solution: $V = \frac{KQ}{r} = \frac{9\times10^{9} Nm^2/C^2 \times 2\times10^{-6}}{0.1}$

$= 1.8\times10^{5} V$

*How much charge does a 120 μF capacitor store if the voltage btw the terminal is 240V?

Solution:-

for a capacitor

$Q \propto V$

$Q = CV \Rightarrow 120\,\mu F \times 240 = 28800\,\mu C$

$= 0.029\,C$

* Suppose $A = 1\,m^2$ and $d = 0.1\,mm$ of a parallel plate capacitor, find the value of C?

Solution:- For a parallel plate capacitor, the

$$C \propto \frac{KA}{d} \Rightarrow C = \frac{K\varepsilon_0 A}{d} = \frac{8.85\times10^{-12}\times1}{0.1\times10^{-3}}$$

dielectric constant $\Rightarrow (8.85\times10^{-12})$

$K = 1$ for vacuum

$$= 8.85\times10^{-8}\,F$$

$$\therefore C = 0.0885\,\mu F$$

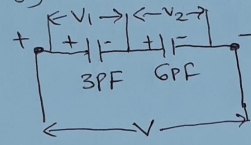
Consider a series combination of two capacitors connected across 1000V as shown in the figure below.

Calculate (a) equivalent capacitance of the combination

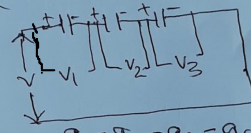
(b) magnitude of the charges on the capacitors

(c) The potential difference across the capacitors

(d) energy stored in the capacitors.



(Hints: series combinations) *A

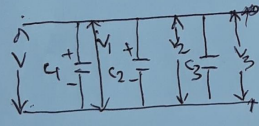


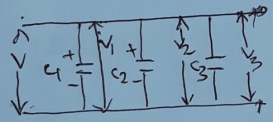
$$q = q_1 = q_2 = q_3$$

$$V = V_1 + V_2 + V_3$$

$$\therefore \frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

(Parallel combination) *B





$$\therefore \frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

$$q = q_1 + q_2 + q_3$$

$$V = V_1 = V_2 = V_3$$

$$\therefore C_{eq} = C_1 + C_2 + C_3$$

So, solution is $\Rightarrow$ (a) $\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} = \frac{1}{3pF} + \frac{1}{6pF} = \frac{1}{2pF} \Rightarrow C_{eq} = 2pF$

(b) for series combination, each capacitor carries same charge which is the charge on the combination

i.e $q = C_{eq} V = (2 \times 10^{-12} F) \times 1000V = 2nC$

$\therefore q_1 = q_2 = q = 2.0nC$

c) $V_1 = \frac{q_1}{C_1} = \frac{2\times10^{-9}C}{3\times10^{-12}} = 667\ V = 0.67kV$

$V_2 = \frac{q_2}{C_2} = \frac{2\times10^{-9}C}{6\times10^{-12}F} = 0.33kV$

d) Energy in $C_1 = \frac{1}{2}q_1V_1$ since energy of a capacitor $= \frac{1}{2}qV = \frac{1}{2}CV^2 = \frac{1}{2}\frac{Q^2}{C}$

$\therefore C_1 = \frac{1}{2}(2\times10^{-9}\times0.67\times10^{3}V) = 67\times10^{-7}J = 0.67\mu J$

Energy in $C_2 = \frac{1}{2}q_2V_2$

$= \frac{1}{2}(2\times10^{-9}\times0.33\times10^{3}V) = 0.33\mu J$

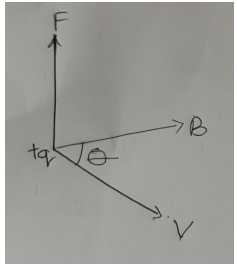
~~Energy in $C_3 = \frac{1}{2}q_3V_3$~~

Energy in combination $= (0.67+0.33)\mu J$

$= 1.01\mu J$

More Examples

Ideally, the magnetic force on a charged particle moving in a magnetic field B has this expression **F_B = q V X B (v= Velocity of charge, q= charge and B = mag field)**



The magnitude of F_B = /q / VB sin θ

Note that F_B is *Zero when V is parallel or anti parallel to B*, i.e when θ = 0^0 or 180^0 and F_B is maximum when V is perpendicular to B i.e θ = 90^0)

DIFFERENCES BETWEEN ELECTRIC FORCE AND MAGNETIC FORCE

- **Electric force acts along the direction of the electric field while magnetic force acts perpendicular to the magnetic field**

- **Electric force acts on a charged particle *whether stationary or in motion* while Magnetic force acts on a charged particle ONLY *when the particle is in motion***

Example: Calculate the magnetic force on an electron moving towards cathode tube with a speed of $8x10^6$ m/s, if there is a magnetic field of magnitude 0.025T directed at an angle of 60^0 to the x- axis?

Solution:

$$F_B = /q / VB \sin\theta = 1.6x10^{-19} x\ 8x10^6\ x\ 0.025x \sin 60^0$$

$$= 2.8x10^{-14} N$$

NOTE : ***For a solenoid, B = μ_0 nI, where n =number of windings per unit length and I is the current in the winding.***

EXAMPLE: A Proton travels with a speed of $3x10^8$ m/s at an angle of 37^0 with the direction of a magnetic field of 0.3T in the +y direction, calculate (a) the magnitude of the magnetic force on the proton, (b) Its acceleration (mass of proton = $1.67x10^{-27}$kg)

SOLUTION:

(a) $F_B = qVB \sin\theta$

$= 1.6x10^{-19} \text{ x } 3x10^8 \text{ x} 0.3x\sin 37^0$

$F_B = 8.67x\ 10^{-12}N$

(b) $F = ma \rightarrow a = {}^{F}/_{m} = \dfrac{8.67x\ 10-1^2N}{1.67x10^{-27}kg}$

$= 5.19x10^{15}m/s^2$

EXAMPLE: An electron is accelerated through 2400 v from rest and then enters a uniform 1.7T magnetic field. What are (a) the max (b) min values of the magnetic force this charge can experience?

SOLUTION:

Kinetic energy $E = {}^{1}/_{2}mv^2$ *also* $K.E = {}^{1}/_{2}mv^2 = eV$

so $2eV = mv^2$

$v^2, = \frac{2eV}{m}$, *therefore vel* $v, = \frac{\sqrt{2eV}}{m}$

$$v = \sqrt{\frac{2x\ 1.6x10^{-19}\ x2400}{9.11\ x10^{-31}kg}} = 2.9x10^7 m/s$$

(a) $F_{B\ max} = qvB$, *since* $\theta = 90^0$ *and* $\sin 90^0 = 1$ *when v is perpendicular to B. therefore,* $F_{B\ max} = qvB$

$= 1.6x10^{-19} x\ 2.9x10^7 x1.7T = 7.9x10^{-12}N$

(b) $F_{B\ min} = 0$ *, this happens when v is pararell or antiparallel to B , i.e* $\theta = 0^0$ *or* 180^0

EXAMPLE: A proton moving at $4x10^6$ m/s through a magnetic field of 1.7T experiences a magnetic force of magnitude $8.2\ x10^{-13}$ N. find the angle between the proton's velocity and the field.

SOLUTION:

$$F_B = qVB \sin\theta$$

$$8.2x10^{-13} N = 1.6x10^{-19} x4x10^6 x1.7x \sin\theta$$

$$\sin\theta = 0.7540$$

$$Therefore, \theta = \sin^{-1}(0.7540)$$

$$\theta = 48.9^0$$

EXAMPLE: A proton moves with a velocity of v = (2i-4j+k)m/s in a region in which the magnetic field is B=(i+2j-3k)T. What is the magnitude of the magnetic force that this charge experiences?

SOLUTION: from $F_B = qVXB$ *and*

$$VxB = \begin{vmatrix} i & j & k \\ +2 & -4 & +1 \\ +1 & +2 & -3 \end{vmatrix}$$

= i(12-2) –j(-6-1)+k(4+4)

= i(10) +j6+j+8k → ***10i +7j+8k***

therefore the magnitude of VxB i.e **/vxB/**

$$= \sqrt{10^2 + 7^2 + 8^2} = 14.6\text{Tm/s}$$, **so the magnitude of the force /F_B/= q/VxB/= 1.6x10^{-19}x 14.6**

= ***2.34x10^{-18}N***

EXAMPLE: A steady current of 0.5A flows through a wire in 1min, how much charge pass through the wire?

SOLUTION :

$$I = \frac{\Delta Q}{\Delta t} = \frac{Q}{t} \quad but\ \Delta Q = I\Delta t \rightarrow 0.5 \times 60 = 30sec$$

EXAMPLE:

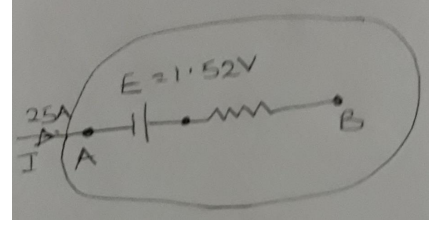
A dry cell has an e.m.f of 1.52 volts, its terminal potential drops to zero, when a current of 25 A passes through it. Find its internal resistance.

SOLUTION*: From the question, the p.d from A to B is zero i.e from the formula* $V = E - Ir$ *therefore*

$$0 = 1.52V - (25r)$$

so, $1.52 = 25r$

$$\rightarrow r = 0.061\ \Omega$$



Note: The voltage of a battery or generator when it delivers a current I is related to the e.m.f E and the internal resistance r by

(a)Terminal voltage = emf –(voltage drop in internal resistance)

i.e ***V= E – Ir*** { when delivering current i.e on discharging}

(b)Terminal Voltage ***V = E + Ir*** {when receiving current i.e on charging}

(c) Terminal Voltage ***V = emf of battery E*** {when no current exists}

Current always flow from high to low potential through a resistor.

Example: The resistance of a coil of copper wire is 3.35 Ω at 0^0C . What is the resistance at 50 ^{0}C if α (temperature coefficient of the resistance of the material of the wire) = $4.3x10^{-3}$ ($^0C^{-1}$).

Solution:

Using $R= R_o+ \alpha R_o(T-T_o)$

R= ? , R_0 = 3.35 Ω, T = 50 ^{0}C and T_0 =0^0C

$$R= 3.35\ \Omega + (4.3x10^{-3})x3.35(50-0)$$
$$= 4.1\ \Omega$$

A 100 W, 110 V lamp is connected in series with an electrolytic cell containing CdSO4 solution. Calculate the mass of Cd that will be deposited by the current flowing for 10 hrs.

SOLUTION:

FROM FARADAY 1ST LAW,

MASS m of copper deposited = ZIt

P = IV → $I = \frac{100}{110}$ **= 0.909A**

Quantity of charge Q= It = 0.909x10x3600

Q = ***32727.3C ….(**)***

The cathode reaction is Cd^{2+} **+2e →**Cd

Therefore mass of cd deposited = Zit i.e

m = ZQ

But recall that F= $\frac{E}{Z}$ **….(*) , F= Faraday ≅ 96500c,**

Z = electrochemical equivalent, E= chemical equivalent,

(E= $\frac{atomic\ weight}{valency}$ **). So from (*), Z =** $\frac{E}{F}$

= $\{\frac{112.4}{2x96500}\}$ →Z but ***m***=ZIt **≅ ZQ →** $\{\frac{112.4}{2x96500}\}$**x*32727.3* = *19.05g***

Example: If 0.2964g of copper was deposited when current 0.5A passes through a $cuso_4$ solution for 30 mins, calculate the atomic mass of copper Cu (1F =96500c)

Solution:

Q=It = 0.5x30x60 = 900C

Since 900C deposited 0.2964g of cu

96500 C deposited Xg

$$x = \frac{96500x0.2964}{900} = \frac{28602.6}{900} = 31.78g \cong equivalent\ mass$$

Therefore,

atomic mass = equivalent mass x valency

= 31.78 x 2= 63.56 g

Note: to get the ***number of mole of electrons*** obtained from a coulomb of electricity, ***use Q = n(e⁻)F*** {q=quantity of charge, F =faraday, n(e⁻) no. of mole of electron} example: Calculate the no. of mole of electrons obtained from 250C of electricity.

Solution: $Q = n(e^-)F \rightarrow n(e^-) = \frac{Q}{F} = \frac{250}{96500} = 2.59x10^{-3}\ mol$

EXAMPLE: An electric iron of resistance 20Ω takes a current of 5 A. Calculate the thermal energy in joules developed in 30 sec.

SOLUTION:

Energy H = I^2 R t = 5^2 x 20 x30=15KJ = 15000 J

EXAMPLE: *An electric heater of resistance 8* Ω draws15 A from the service mains, what is the cost of operating the heater, for a period of 4hrs at 10 naira per kwh?

Solution:

P = I^2R = 15^2 x 8 = 1800 = 1.8 kw

therefore,

cost = 1.8kw x 4 x10 = 72 Naira

Example

Calculate the cost of using an electric heater of power 2kW for 5 hours if each kWh costs 12cts.

kilowatt-hours = kilowatts x hours

= 2kW x 5 hours

= 10 kWh

cost in pence = kilowatt-hours x cost per kWh

= 10 kWh x 12cts

= 120cts