UNIT - IV CURRENT ELECTRICITY

Electric current (i): The rate of flow of charge through a cross sectional area is called electric current. (or) the flow of charge per unit time through a cross sectional area. It is denoted by 'i'.

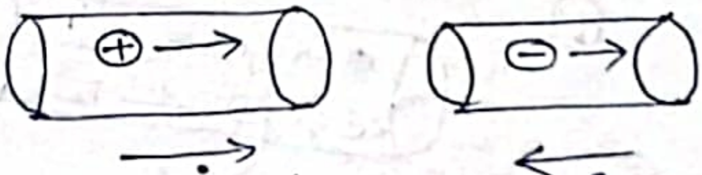
If a net charge 'Q' passes through any cross section of the conductor in time 't', then the average current is given by, $\boxed{i_{avg} = \frac{Q}{t}}$

Instantaneous current is given by $i = \lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t}$

$$\text{(or)} \quad i = \lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t} = \frac{dQ}{dt}.$$

Direction of current:

The direction of current is the direction of flow of positive charge (or) opposite to the direction of flow of negative charge.



A current is a fundamental physical Quantity.

S.I unit is Ampere (A).

Current has a direction but it is not a Vector. It is a Scalar Quantity as it does not obeys parallelogram law of Vectors.

→ 'i' varies with time 't'. The charge flowing in a time interval from t_1 to t_2 is given by the following way. W.K.T $i = \frac{dq}{dt}$

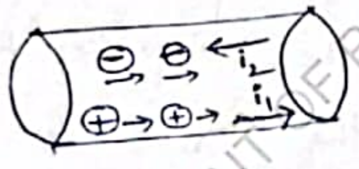
$\therefore dq = i\,dt \Rightarrow \int dq = \int_{t_1}^{t_2} i\,dt$

$\therefore \boxed{q = \int_{t_1}^{t_2} i\,dt}$

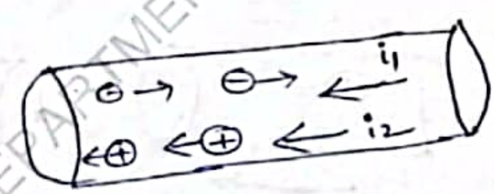
→ If 'n' charged particles passes through a cross-sectional area in a time 't', then $\boxed{i_{avg} = \frac{nq}{t}}$

→ In the above case if the charged particles are electrons, then $\boxed{i = \frac{ne}{t}}$.

→

(a) 

$i_{net} = i_1 \sim i_2$

(b) 

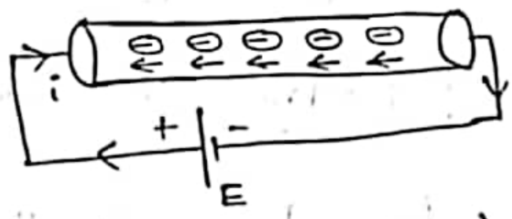
$i_{net} = i_1 + i_2$

→ If a point charge 'q' is moving in a circle of radius 'r' with uniform speed (v), frequency (f), angular frequency (ω), time period (t), then the current (i) is given by $i = \frac{q}{t} = qf = q\frac{\omega}{2\pi}$ $(\because \omega = 2\pi f)$

$\therefore \boxed{i = \frac{qv}{2\pi r}}$ $\left(\because \omega = \frac{v}{r}\right)$

Flow of electric charges in a metallic Conductor:

Consider a wire which is connected to the two termi-nals of a battery as shown. Then the wire becomes a metallic conductor.



when a P.D is applied across the conductor, then electrons will flow from '-ve' terminal of the cell towards the '+ve' terminal of the cell. Then current will flow from '+ve' terminal towards the '-ve' terminal of the cell. i.e flow of electrons and flow of current is always opposite to one another. This is the flow of current in a metallic conductor.

In any metallic Conductor the following points are to be noted.

(i) In a metallic Conductor, free electrons (having '-ve' charge) act as electric charge carriers.

(ii) The free $\bar{e}$s in a conductor are always in a state of random position with a velocity of the order of 10^{4} m/s. The net flow of charge in a conductor without application of P.D is zero.

(iii) The electric current flows from higher potential (+ve terminal of cell) to lower Potential (-ve terminal)

(iv) The direction of conventional current is opposite to the direction of flow of electrons.

(V) The net charge in a current carrying conductor is zero.

Electrical Resistance

Resistance is the opposition offered by a material for the flow of current.

It is defined as the ratio of potential difference 'V' across the conductor to the current (i) flowing through the conductor. $\therefore\ R = \frac{V}{i}$ volts/Ampere (or) ohm.

Its dimensional formula is $ML^2T^{-3}A^{-2}$

The resistance of a specimen is said to be one ohm if one volt P.D across it causes it a current of one Ampere to flow through it.

$$\frac{1\ \text{Volt}}{1\ \text{Ampere}} = 1\ \text{ohm}.$$

Resistance is a scalar quantity. It depends on the nature of the material of the specimen, dimensions of the specimen and physical conditions like temp., pressure and impurities.

Symbol:- 

(a) Fixed Resistor

(b) Variable Resistor.

Factors Effecting the Resistance of a Conductor

(i) Resistance 'R' is proportional to length of a conductor

$\therefore R \propto l$

(ii) $R \propto \frac{1}{A}$, where 'A' is area of cross section.

(iii) As temp. increases, Resistance of a Conductor ↑ses and that of Semiconductor ↓ses.

Conductance (G): The reciprocal of the resistance (R) is called Conductance of a Conductor. $G = \frac{1}{R}$

S.I unit is mho (or) Siemen. Dimension formula $[M^{-1} L^{-2} T^{3} A^{2}]$

Resistivity (ρ):

W.K.T, the resistance of a Conductor is directly proportional to its length and inversely proportional to its area of cross section. $\therefore R \propto \frac{l}{A} \Rightarrow R = \rho \frac{l}{A}$

Here 'ρ' is called Resistivity (or) Specific resistance.

if $l = 1m$, $A = 1m^2$, then $\rho = R$

The resistance of a conductor of unit length and unit area of cross section is called Resistivity of the material of the Conductor.

Conductivity (σ): It is the measure of ability of a material to Conduct electric current through it. It is reciprocal of resistivity. $\sigma = \frac{1}{\rho} = \frac{1}{RA}$ Siemen/m

Drift Velocity (V_d):

The average Velocity with which the free electrons in a conductor get drifted under the influence of external electric field applied across a Conductor is called Drift Velocity. It is denoted by $\vec{V_d}$.

It is of the order of 10^{-4} m/s.

Relaxation time (τ):

The short time, for which a free electron accelerates before it undergoes a collision with the +ve ion in the conductor is Known as Relaxation time τ.

The relation between drift Velocity and relaxation time (τ) is given by

$$\boxed{V_d = -\frac{Ee}{m}\tau}$$

$\left(\because V = u + at,\ u = 0,\ a = \frac{F}{m} = \frac{-Ee}{m},\ t = \tau \right)$

Current density (J):

The current passing through unit area of the conductor is called current density. It is denoted by J.

$$\therefore \boxed{J = \frac{I}{A}}$$

It is a Vector Quantity. S.I. unit is Ampere/m^2.

Mobility (μ): The average drift Velocity acquired by the free electrons per unit electric field is called mobility of the charged carriers. It is denoted by μ.

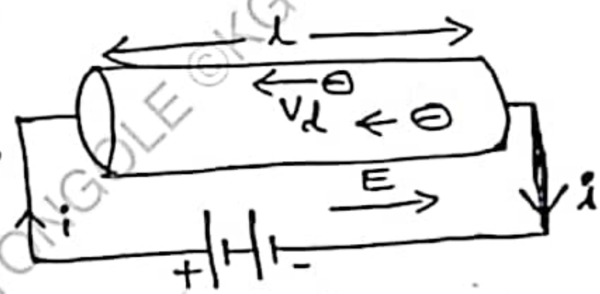
$$\mu = \frac{|V_d|}{E}$$

The mobility is '+ve' for both '+ve' and '−ve' charge carriers. S.I unit is $m^2 s^{-1} V^{-1}$ (or) $\frac{C-m}{N-S}$

Dimension formula is $\frac{L^2}{\frac{ML^2T^{-2}}{IT} \times T} = M^{-1}T^2I$

Mobility depends on pressure and temperature.

Relation between Current and Drift Velocity:



Consider a conductor of length 'l' and of uniform area of cross section 'A'.

$\therefore$ Volume of conductor $= Al$

Let 'n' be the no. of free electrons per unit volume, then The total number of free electrons in the conductor of volume 'Al' are 'N'. ie $N = n \cdot Al$

if 'e' be the charge of each electron, then the total charge of the conductor due to all electrons is 'q'.

ie $q = Alen$

Suppose when a P.D (V) is applied across the ends of the conductor with the help of a battery, then the electric field 'E' is set-up across the conductor.

$\therefore E = \frac{V}{l}$ (magnitude)

Due to this electric field the free $\bar{e}$s will begin to move with a drift velocity 'V_d' towards L.H.S.

$\therefore$ The time taken by the free $\bar{e}_s$ to cross the conductor is $t = \frac{l}{V_d}$.

Hence current $i = \frac{q}{t} = \frac{Alne}{l/V_d} = \frac{V_d\,Atne}{t}$

$$\therefore \quad i = V_d A ne \Rightarrow V_d = \frac{i}{Ane} = \frac{J}{ne}$$

$$\therefore \quad \boxed{V_d = \frac{J}{ne}} \Rightarrow \boxed{J = ne V_d}$$

but $V_d = \frac{Ee}{m}\tau$, hence the above equation can be written

as $\quad \frac{Ee}{m}\tau = \frac{i}{Ane} \Rightarrow \boxed{i = \frac{Ene^2A}{m}\tau}$

Ohm's law and V-I Characteristics:

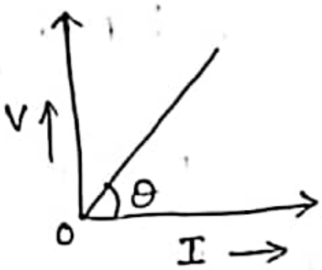
For a given conductor, at a given temperature the strength of the electric current through it is directly proportional to the potential difference applied across it. Let 'V' be the P.D applied across the conductor, 'i' be the current flowing through it.

According to ohm's law, $i \propto V$ (or) $V \propto i$

$\therefore \quad V = Ri$, where 'R' $\rightarrow$ electrical Resistance of conductor

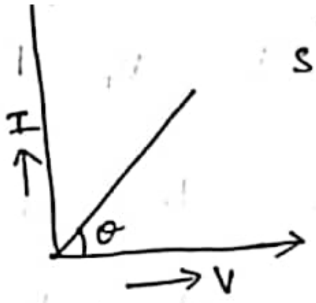
The conductors which obey ohm's law are called ohmic conductors. Ex:- Metals and Alloys.

For ohmic conductors 'I' Vs 'V' graphs are straight lines passing through origin. The slope of graphs are shown



slope $= \tan\theta = \frac{V}{I}$
$= R$

(a) Fig (a)

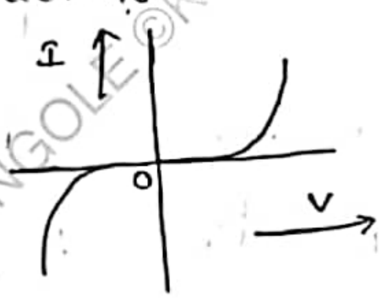
(b) 

slope $= \tan\theta$
$= \frac{I}{V}$
$= \frac{1}{R}$
$= G$

Fig (b)

It is observed that the slope of the Ohmic conductors gives Resistance and conductance.

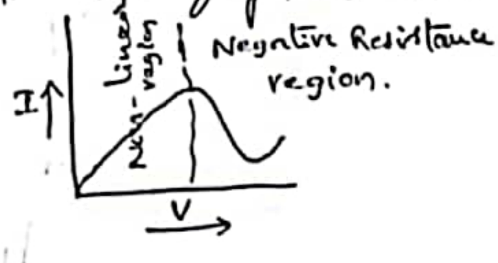
→ In Non Ohmic conductors like Vacuum diode, Semiconductor diode etc the V-I characteristics are as shown.



In Non-ohmic materials Ohm's law does not hold even for low values of current. ie V is not proportional to I and hence these are called Non-ohmic conductors. Ex:- Diode, Semiconductors, transistors, thermistor, electrolytes etc.

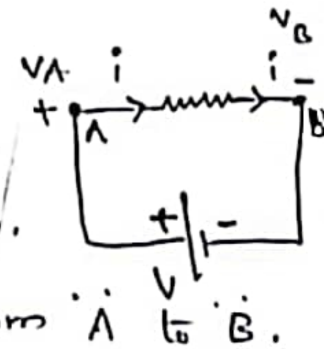
It should be noted that this type of behaviour is not unique in Non-ohmic materials. In 'Ga As' the graph is as shown.

∴ Ohm's law is not a Universal law.



Electrical Energy and Power:

Consider a conductor 'AB' in which a current 'i' is flowing from A to B.



Let 'q' be the charge flowing from A to B.

Let V_A, V_B be the Potentials at A and B respectively

Since the +ve terminal is having higher potential than at -ve terminal. Hence $V_A > V_B$.

$\therefore$ The P.D between the two points is $V_A - V_B$.

The work done to move the charge from 'A' to 'B' is given by $W = q(V_A - V_B)$

$$\therefore W = qV \quad (\because V_A - V_B = V)$$

power is defined as the ratio of work done to time of flow of charge. $\therefore P = \frac{W}{t}$.

It is also called as the rate of doing work.

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

$$\therefore \boxed{\text{Power} = V \cdot i}$$

$$P = iR \cdot i \quad (\because V = iR, \text{ Ohm's law})$$

$$\boxed{P = i^2 R}$$

(or) $$\text{power} = V \cdot \frac{V}{R} \quad (\because i = \frac{V}{R})$$

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

$$\therefore \boxed{\text{Power} = V \cdot i = \frac{V^2}{R} = i^2 R}$$

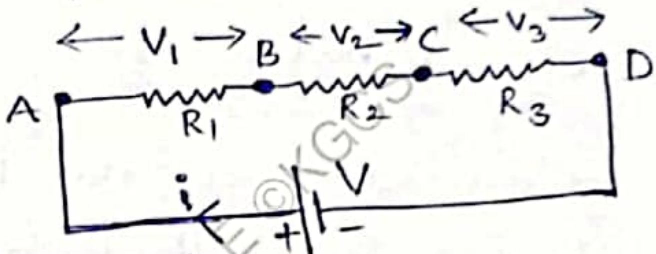
The S.I unit of power is Watt (or) Volts-Ampere

We know that power $= \frac{W}{t} \Rightarrow \boxed{W = P.t}$

This amount of work done is stored as the energy $E = P.t = i^2Rt = \frac{V^2}{R}t$

S.I unit of electrical energy is Joule (or) watt-Sec

Combination of Resistors in Series



Consider a number of resistors connected in Series by Joining them end to end Such that same current 'i' passes through all resistors. In figure three resistors R_1, R_2 and R_3 are connected in Series. This combination is connected to a battery of potential 'V' at the ends A and 'D'. Let 'i' be the current flows across the Series combination. Since the current flows of higher potential to lower potential, then 'A' is at higher Potential w.r.to B, B is at higher potential w.r.to C and 'C' is at higher potential w.r.to 'D'. Therefore, let V_1, V_2 and V_3 be the P.D's across the Resistors R_1, R_2 and R_3 respectively due to the passage of current 'i'.

Then $V_1 = iR_1$, $V_2 = iR_2$, $V_3 = iR_3$

W.K.T, the sum of V_1, V_2, V_3 is equal to 'V'.

$\therefore V = V_1 + V_2 + V_3 \Rightarrow iR = iR_1 + iR_2 + iR_3$

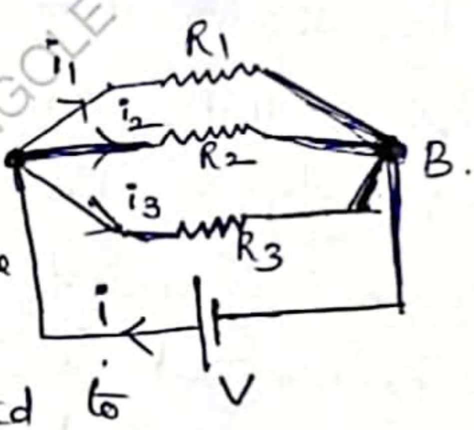
$\therefore$ $\boxed{R = R_1 + R_2 + R_3}$ $R \to$ Equivalent Resistance

$\therefore$ The equivalent Resistance of Series Combination is given by $\boxed{R = R_1 + R_2 + R_3}$

If this arrangement is extended for a number of resistors. Then, $\boxed{R = R_1 + R_2 + R_3 + \cdots + R_n}$

Combination of Resistors in Parallel

Consider a number of Resistors in parallel by Joining their one end at one point (A) and other end at another point (B). As shown in figure three Resistors R_1, R_2 & R_3 are connected in parallel.



This Combination is Connected to a battery of Voltage 'V'. Let 'I' be the current drawn from the battery. Let I_1, I_2, I_3 be the currents across R_1 R_2 and R_3 respectively.

Since the three resistors are Commonly connected to the battery of potential 'V', then same P.D (V) exist across all resistors.

If 'R' is the equivalent resistance, then the main current $i = \frac{V}{R}$, then $i = i_1 + i_2 + i_3$

$$\therefore \frac{V}{R} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

$$\Rightarrow \boxed{\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

Cell:- A device which converts chemical energy into electrical energy is called a cell.

Emf of a Cell:- The work done in moving a unit positive charge through the complete circuit including the charge flow inside the cell is called emf of a cell. $\therefore$ emf $(e) = \frac{W}{q}$

(or)

It is the P.D between the electrodes of a cell when the cell is not connected in a circuit.

Its unit is Joules/coloumb (or) Volt.

It is a scalar Quantity. Its dimensional formula is $[ML^2T^{-3}A^{-1}]$ $\left(\because e = \frac{W}{q} = \frac{FS}{IT} = \frac{ML^2T^{-2}}{AT}\right)$

* emf depends on nature of metal electrodes & independent of size of the cell. i.e area and distance between electrodes.

potential difference of a cell (or) Terminal P.D: The P.D between the electrodes of a cell when the cell is connected in a circuit.

Note:- (i) when the cell is open T.P.D = emf

(ii) emf of a cell is always greater than T.P.D

(iii) emf of a cell can be measured by Potentiometer and T.P.D can be measured by Volt meter.

(iv) T.P.D and emf are measured in volts.

Internal Resistance of a Cell: (r):

The resistance between the two electrodes of a cell is called Internal resistance. It is denoted by 'r'. It depends on nature and size of electrodes. It also depends on nature and concentration of electrolyte and the distance between the electrodes.

Internal resistance of a cell is very low and is of the order of 1 ohm. Internal resistance of an ideal cell is zero.

Back emf (or) Lost volts

The difference between emf and Terminal potential difference is called Back emf.

$\therefore$ Back emf (or) Lost volts = emf − T.P.D

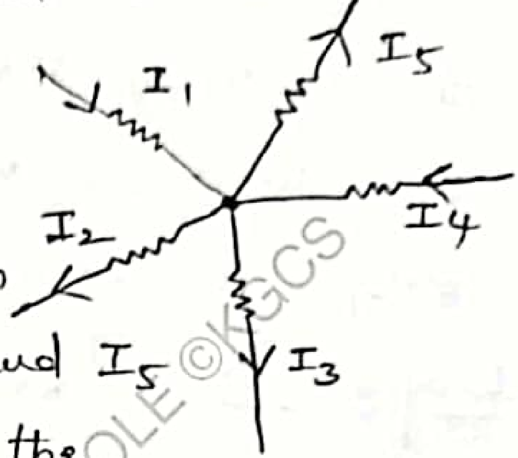
Kirchoff's laws:

Kirchoff's I st law (or) Current law:-

<u>Statement</u>: The algebraic sum of the currents meeting at a junction (at a point) in a circuit is zero. (or) the sum of the currents flowing into a junction

is equal to the sum of the currents flowing away from the junction.

Explanation: Consider five currents I_1, I_2, I_3, I_4 and I_5 meeting at a junction as shown in figure.



Here the currents I_1 & I_4 are flowing into the junction and the currents I_2, I_3 and I_5 are flowing away from the junction.

According to Kirchoff's Ist law,

Sum of currents flowing into the junction = Sum of currents flowing away from the junctio

$$\therefore I_1 + I_4 = I_2 + I_3 + I_5 \text{ (or)}$$

$$I_1 - I_2 - I_3 + I_4 - I_5 = 0$$

i.e the algebraic sum of the currents is zero. It can also be written as $\Sigma I = 0$

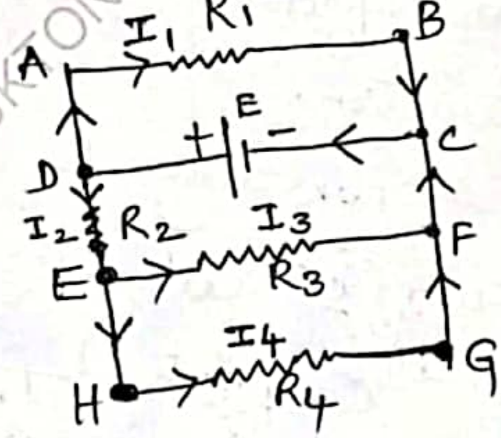
It is based on law of conservation of charge.

It is also called as junction law (or) point law.

Kirchoff's IInd law (or) Voltage law:

Statement:- In any closed circuit (or) loop, the algebraic sum of the P.D's of every branch is equal to zero. (or) In any closed circuit the sum of the products of the current and resistance of every branch is equal to the net emf in the circuit.

Explanation: Consider an electric circuit containing a cell and some resistors as shown below.



Applying Kirchoff's IInd law to closed loop ABCDA, we get $I_1R_1 = E$ (or)

$$I_1R_1 - E = 0$$

Applying IInd law to the loop CDEFC, we get $I_2R_2 + I_3R_3 = E$ (or)

$$I_2R_2 + I_3R_3 - E = 0.$$

Applying IInd law to the loop EFGHE, we get,

$$I_3R_3 - I_4R_4 = 0 \text{ (or) } I_3R_3 = I_4R_4$$

This law is also known as Mesh law (or) Loop law

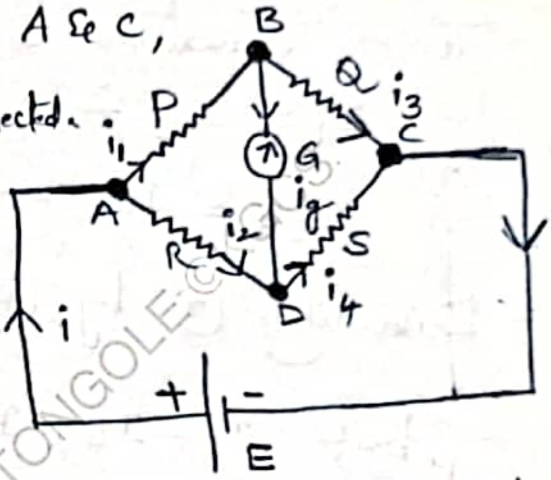
It is based on law of Conservation of energy.

This is an extension of Ohm's law.

Wheatstone bridge:

If four resistors P, Q, R and 'S' are arranged in the four arms of a circuit as shown in the figure, then it is known as a wheatstone bridge.

Between the opposite junctions A & C, a battery of emf 'E' is connected.



Between the other opposite junctions 'B' and 'D' a Galvanometer of resistance 'G' is connected.

Let 'i_1' be the strength of the current through the Resistor P, I_2 be the current through R, I_3 be the current through 'Q', I_4 be the current through 'S' and 'I_g' be the current through the galvanometer 'G'.

Applying Kirchoff's Ist law at the Point 'B', we get

$$i_1 = i_g + I_3 \rightarrow ①$$

Applying kirchoff's Ist law at the point 'D', we get

$$i_2 + i_g = i_4 \text{ — } ②$$

Applying kirchoff's IInd law to the loop ABDA, we get

$$i_1 P + i_g G - i_2 R = 0 \Rightarrow i_1 P + i_g G = i_2 R \text{ — } ③$$

Apply kirchoff's IInd law to the loop BCDB, we get

$$i_3 Q - i_4 S - i_g G = 0 \Rightarrow i_3 Q = i_4 S + i_g G \text{ — } ④$$

Balancing:- If the current passing through the galvanometer is '0' (or) If the galvanometer shows zero deflection, then the bridge is said to be balanced. $\therefore$ when the bridge is balanced $i_g = 0$

Then equations ①, ②, ③ and ④ becomes,

$I_1 = I_3$ — ⑤, $I_2 = I_4$ — ⑥, $I_1 P = I_2 R$ — ⑦

$I_3 Q = I_4 S$ — ⑧

Dividing ⑦ by ⑧, we get $\frac{I_1 P}{I_3 Q} = \frac{I_2 R}{I_4 S}$

but $I_1 = I_3$, $I_2 = I_4$, Hence, we have

$$\frac{I_1}{I_1}\frac{P}{Q} = \frac{I_2 R}{I_2 S} \Rightarrow \boxed{\frac{P}{Q} = \frac{R}{S}}$$

This is called Balancing Condition (or) Wheatstone bridge Principle.