Chp-3: Current Electricity

- Flow of electrically charged particles (Charge-carriers) from electric current.

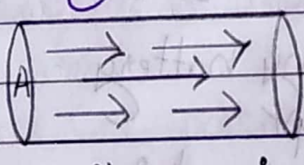
* How current flows:

- Current flows through circuit.
- Strength of current (i) - Electric strength passing through a cross-sectional area in unit time.

$$i = \frac{\text{charge}}{\text{time}} = \frac{Q}{t} = \frac{dQ}{dt}$$

- Unit of electric current is amphere (A).
- If in a circuit one coulomb charge flows in one second then intensity of current is one amphere.
- Electric current is a scalar quantity because it follows addition laws of scalar quantities and not a vector quantity.

* Current density:



- Current per unit area is a vector quantity cause it depends on direction

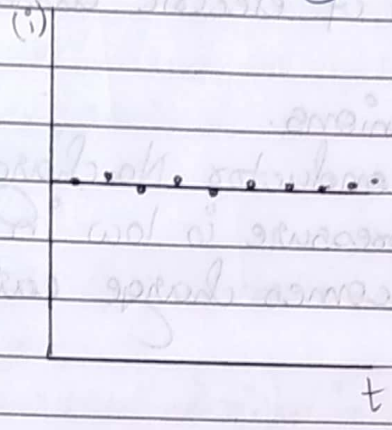
$\cancel{V = \frac{i}{A}}$ o $J = \frac{i}{A}$

$i = j \cdot A \cos\theta$

$i = \vec{j} \cdot \vec{A}$

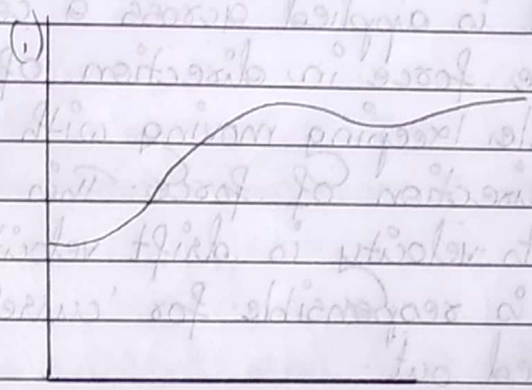
* Types of current:

1) Direct current (steady current):



Current value is constant as time passes and does not change its direction.

2) Variable current:



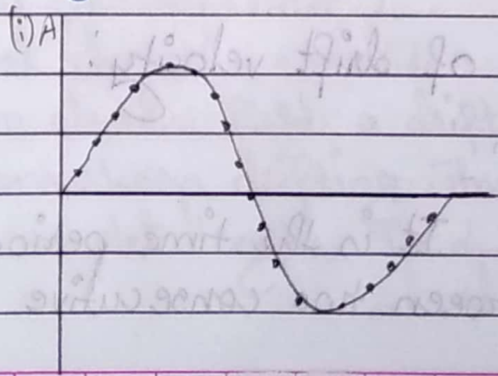
Magnitude is not same.

3) Instantaneous current:

- Current for an instant

(i) Charging current & (ii) Discharging current.

4) Alternating current (AC):



Don't have same value at every instant and can change direction.

* Charge carriers:

- Charge carriers are the particle which carry charge and move during flow of electric current.
- Metals: Electrons
  Electrolytes: Cations & anions.
  Gases: Gases are bad conductor. No charge carriers.
- Special condition: When pressure is low in gas electrons leave the atom and becomes charge carrier.

* Drift velocity:

- When electric field is applied across a conductor free electrons experience force in direction of higher potential and while keeping moving with thermal velocity drift in direction of force. This phenomena is drifting and its velocity is drift velocity.
- This drift velocity is responsible for 'current' because this is not cancelled out.
- This drift velocity is very small to the order of 10^{-1} mm/s but still it is effective to make current because the number of electron carrying in same direction is very very less. $i = \frac{ne}{t}$

~~* Deriving~~

* Deriving expression of drift velocity:

- Relaxation time 'τ' -
  It is the time period for electron elasped between two consecutive collision

$\tau = \frac{T_1 + T_2 + T_3 \ldots T_n}{n}$ (Temperature decrease τ decreases)

$V = u + at$

If $u = 0$

$V = at$

$a = \frac{F}{m} = \frac{-e \cdot E}{m}$

$V_1 = \frac{-e \cdot E}{m} \cdot T_1$ & $V_{av} = \frac{-e \cdot E}{m} \cdot \tau$

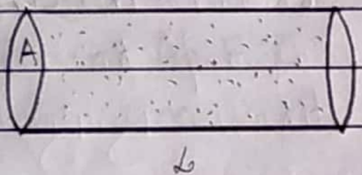
- This average velocity is due to application of E in one direction. Hence this is drift velocity.

$V_d = \frac{-e \cdot E}{m} \cdot \tau$

Vd depends upon E & τ.

If temperature increases τ decreases therefore Vd decreases.

* Electric current and drift velocity:



A conductor has length L area of cross-section 'A'.

'n' is electron density per unit volume.

$\therefore$ Total electron $= nAL$

$\therefore$ Total charge $q = -enAL$.

- Due to electric field a drift velocity vd is set up and electrons keep drifting. Time period for all electron to drift complete length. $T = \frac{L}{v_d}$.

- Now current $(i) = \frac{q}{t}$ or $i = \frac{-enAl}{\frac{l}{v_d}}$

$= -neAv_d$.

-ve sign shows that direction of electric current is taken as opposite direction of v_d of electron.
Magnitude for the charge $\therefore i = neAv_d$.

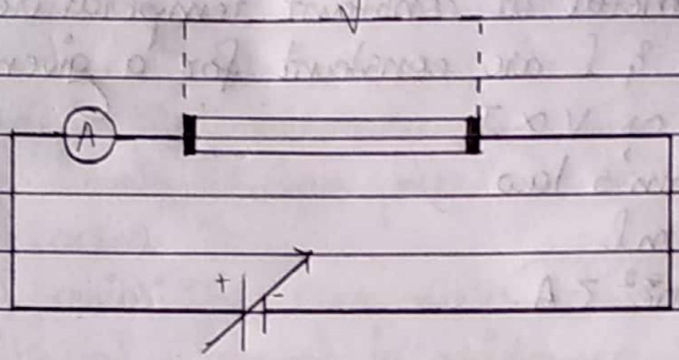
* Mobility:

- Mobility of a charge carrier in a particular medium is drift velocity developed when electric field applied is unity.
Mobility $\mu = \frac{v_d}{E}$ $\frac{ms^{-1}}{Vm^{-1}} = m^2 s^{-1} V^{-1}$ } Unit
- Dimensions: $LAT T^{-1} M^{-1} L^{-1} T^{+2} = AM^{-1}T^2$.
- Drift velocity $(\mu) = \frac{-qE\tau}{Em} = \frac{-q\tau}{m}$.
- Mobility of electron $\mu_e = \frac{-e\tau}{m}$.
- Mobility of hole $\mu_h = \frac{e}{m_h}\tau$.

- Eg,

	Material	Mobility e^-	Mobility holes
1.	Diamond	1800 $cm^2 V^{-1} s^{-1}$	1200
2.	Silicon	1350 $cm^2 V^{-1} s^{-1}$	480
3.	Gallium Arsenic	8000 $cm^2 V^{-1} s^{-1}$	300

* Ohm's law:



- Potential difference applied across a conductor is directly proportional to current flowing in it. Provided all the physical condition (temperature & pressure) remains same.

$$V \propto I \qquad V = RI$$

$\therefore R = \frac{V}{I}$ (Ratio of voltage to current)

R = resistance.

* Proof of Ohm's law:

$I = n \cdot e \cdot A \cdot v_d$

$I = \frac{-ne A e E \tau}{m}$

$= \frac{-ne^2 A E \tau}{m}$

$E = \frac{dv}{dr}$. Here $E = \frac{V}{l}$

$\therefore I = \frac{-ne^2 A \tau V}{ml}$

Here, e and m are constant of electron n is constant for given metal at constant temperature, τ is constant. A & l are constant for a given sample.

$\therefore I \propto V$ or $V \propto I$

This is Ohm's law

$\therefore \frac{V}{I} = R = \frac{ml}{ne^2 \tau A}$

* Resistivity or specific resistance :

1) $R \propto l$ 2) $R \propto \frac{1}{A}$

After combining

$R \propto \frac{l}{A}$

$R = \rho \frac{l}{A}$ $\therefore \rho = \frac{R \times A}{l}$

ρ - Resistivity or specific resistance

If A = 1 and l = 1.

$\therefore \rho = R$.

We know that $R = \frac{ml}{ne^2 \tau A}$

but l and A = 1 and then $R = \rho$

$\therefore \rho = \frac{m}{ne^2 \tau}$ And ρ is dependent on metal.

- Resistivity is equal to resistance of a block of conductor across two opposite faces which have area of cross-section in unity and distance between them as one unit.

- Unit of resistance = ohm Ω

1 Ohm resistance :-

If $V = 1$ and $I = 1$ then $R = 1\,\Omega$

One Ohm is that resistance in which current of one ampere develops when potential difference of 1V is applied across it.

- Unit of resistivity = Ohm-meter = Ωm
- Resistivity of a metal is resistance between two opposite faces of a unit cube of that metal.

Q What is resistance?

Ans Resistance is opposition faced by charges while moving in a conductor. Basic cause of resistance is collision.

* Conductance & Conductivity:

- $G = \dfrac{1}{R}$

$$\text{Conductance} = \frac{1}{\text{Resistance}}$$

- Property of conductor is conductance and conductivity.

$$\sigma = \frac{1}{\rho}$$

where,

σ - conductivity

ρ - resistivity

$$\sigma = \frac{1}{\Omega m} = \Omega^{-1} m^{-1}$$

* Microscopic form of Ohm's law:

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

$jA = \frac{E \times l}{\frac{\rho l}{A}}$

where, j is current density and ρ is resistivity.

$j = \frac{E}{\rho}$

$\vec{j} = \sigma \cdot \vec{E}$

"σ" is current conductivity of a material".

Q When wire is drawn to ~~to~~ double length, then what is the change in resistance?

→ $\rho = R\frac{A}{l}$

$R = \rho\frac{l}{A}$

Here ρ constant, l and A changes volume does not change.

$V = A_1 L_1$ ∴ $A_1 L_1 = A_2 L_2$

$V = A_2 L_2$

$\frac{A_1}{A_2} = \frac{l_2}{l_1}$ — (i) $l_2 = 2l_1$ — (ii)

$R_1 = \frac{\rho l_1}{A_1}$

So, $\frac{R_2}{R_1} = \frac{l_2 A_1}{l_1 A_2} = \frac{A_1^2}{A_2^2} = \left[\frac{2}{1}\right]^2 = 4$

$\therefore R_2 = 4R_1$

* General formula:

- l increases n times
  A decreases n times
  $R_1 = \rho \frac{l}{A}$ — (i) $R_2 = \frac{\rho l n}{A/n}$

$\therefore R_2 = \frac{\rho l n^2}{A}$

From eq (i)

$\boxed{R_2 = n^2 R_1}$ — General formula.

* Effect of temperature on resistivity:

1.) Metal (conductors):

Temperature increases, resistivity increases.

Reason -

Temperature increases → Thermal velocity increases → Relaxation period decreases → Number of collision per second increases → Resistance increases.

Thermal co-efficient of resistivity -

This is increase in resistance (α) of a sample material whose resistance is in ohm and its temperature increases by 1°C.

Eg: $R_0 \rightarrow$ heat $\rightarrow \Delta T \rightarrow R$

Increase per unit resistance $= \frac{R - R_0}{R_0 \Delta T} = \alpha$

$\alpha = \frac{R - R_0}{R_0 \Delta T}$ Unit of $\alpha = K^{-1}$

Dimension: T^{-1}

$R = R_0 + \alpha R_0 \Delta T$

$R = R_0 (1 + \alpha \Delta T)$

2) Alloy:

Show very small (negligible) value of α

Resistance do not change with temperature in alloys.

Due to this property alloys are used as standard resistance in lab.

3) Electrolyte:

(Liquid) temperature increases $\rightarrow$ resistance decreases

Reason -

At higher temperature the density decrease (becomes thin) so for ions it is easier to move, that is resistance decreases.

4) Semiconductor:

Temperature increases $\rightarrow$ Resistance decreases

Resistivity $(\rho) = \frac{m}{ne^2 \tau}$

Reason -

Due to temperature increase number of free electron (population) increases very rapidly, therefore resistance decreases.

The effect of decrease of τ is not that strong hence negligible.

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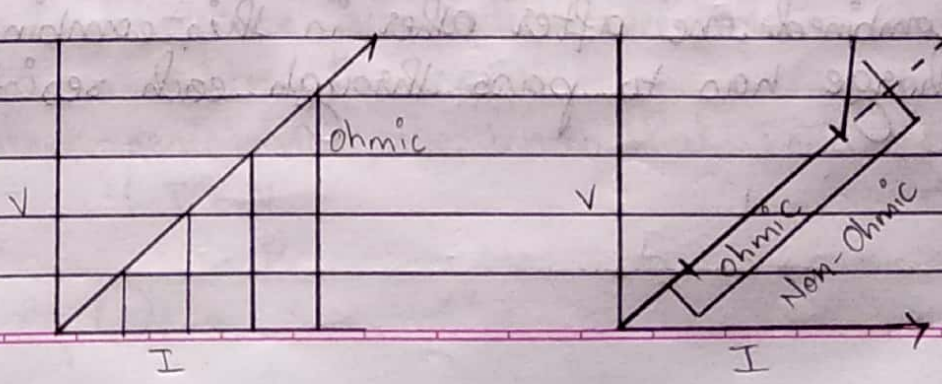
5) Insulators:
Temperature increases → Resistance decreases.
Reason-
At very high temperature electrons are ejected out of atoms becomes free electrons. Conductivity increases and resistance decreases. Finally it is breakdown of insolutions.

6) Thermistors:
Their resistance changes very rapidly with temperature for this property they are used in thermometer.

7) Superconductor:
These are the materials whose resistance is zero. Super conductors are made at very low temperature. The lower temperature of which a material becomes super conductor is called critical temperature.

Material	Critical temp	Applications
Lead	4.2k	Make strong electromagnet
Mercury	7.25k	Research high energy particle
$Bi_2Ca_2Sr_2Cu_3O_{10}$	105k	High speed computer
$Tl_2Ba_2Cu_3O_{10}$	125k	Transmission of electric power.

* Non-Ohmic resistor or non-Ohmic behaviour:



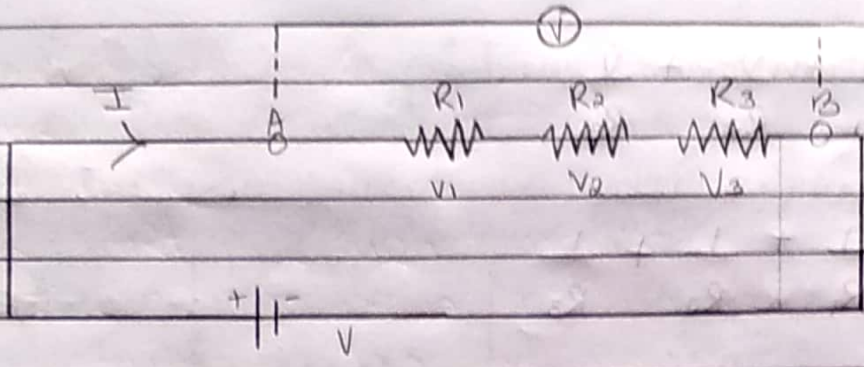
The circuits and components which do not follow Ohm's law. $V \propto I$ are called Non-Ohmic circuit. This non-Ohmic ~~circuit~~ linear behaviour is non-ohmic behaviour
Eg: Meter at high current, semiconductor, etc.

* Carbon - resistor:

Colour	Number	Multiplier	Tolerance	
Black	0	$10^0 = 1$		
Brown	1	10^1		
Red	2	10^2		
Orange	3	10^3		
Yellow	4	10^4		
Green	5	10^5		
Blue	6	10^6		
Violet	7	10^7		
Grey	8	10^8		
White	9	10^9		
Gold		10^{-1}	5%	No colour = 20%
Silver		10^{-2}	10	

* Combination of resistors:

1.) Series combination:
Combined one after other in this combination, charge has to pass through each resistor.



- $V = V_1 + V_2 + V_3$ (Potential difference is divided)
- Current I is same through all resistor in series.
- Equivalent resistance between A & B is.

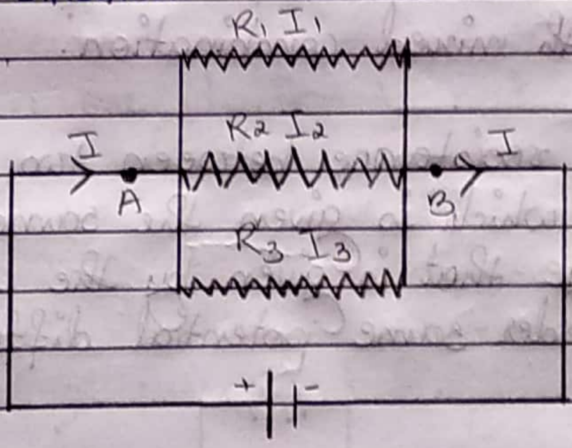
$$R_{AB} = \frac{V_{AB}}{I_{AB}} = \frac{V_1}{I_{ab}} + \frac{V_2}{I_{AB}} + \frac{V_3}{I_{AB}} = R_1 + R_2 + R_3$$

- In series resistance increases.

n Resistance in series $\longrightarrow nR$.

- Current in circuit $I = \dfrac{V}{R_1 + R_2 + R_3}$

2) Parallel combination.



- Current is divided: $I = I_1 + I_2 + I_3$
- Potential difference across the resistor is same as that across battery (source) V.
- Equivalent resistance, we know that $I = I_1 + I_2 + I_3$ —(i)

$Re = \dfrac{V}{I}$ $\therefore I = \dfrac{V}{R}$

So in eq (i)

$$\frac{V}{R_e} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

$$= \frac{1}{R_e} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

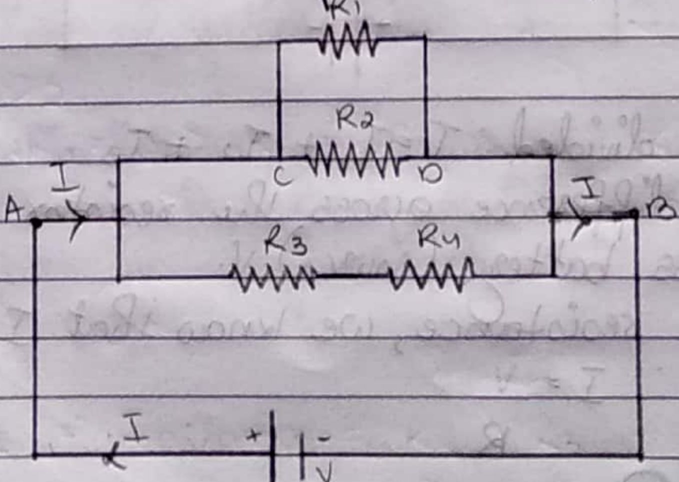
$$\therefore R_e = \left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right]^{-1}$$

- In parallel combination resistance decreases. The equivalent resistance is less than the smallest resistance.
- For 2 resistance, R_1 & R_2 $\therefore R_e = \frac{R_1 \times R_2}{R_1 + R_2}$

For 'n' similar resistor in parallel $R_e = \frac{R}{n}$

* Circuit with mixed combination:

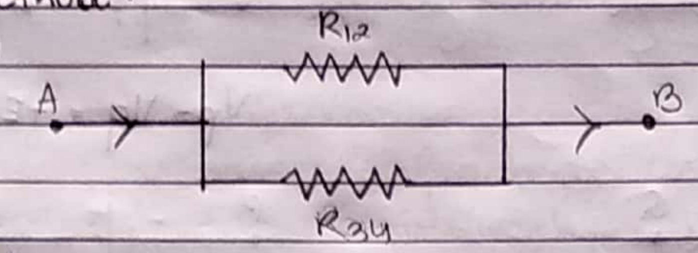
Equivalent resistance between two point is that resistance which is given the same value of current and voltage that is given by the combination of resistor, under same potential difference.



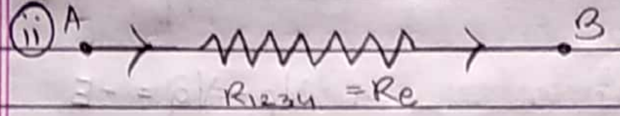
$I = \frac{V}{R_e}$ (Only for 2 point or 1 resistor).

Method:

(i)



(ii)



* Kirchoff's rules:

⇒ Junction rule or current rule:

Junction is a point in a circuit which has more than 2 lines meet.
Branch is a current path from one junction to next.
Current from one junction to next current throughout is same.

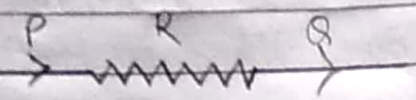
Loop-
A closed path of current.

Junction rule:
(1) The sum of all current at the junction is zero.
$\Sigma i = 0$.
(2) Current approaching in a function is equal to current leaving out.

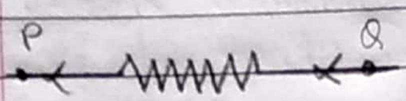
⇒ Loop rule or voltage rule:

In a closed loop the sum of potential across element is zero $\Sigma V = 0$.

Calculation

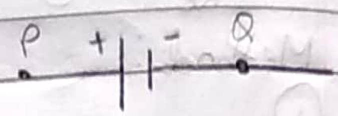


$V_p - V_q = +ve$.

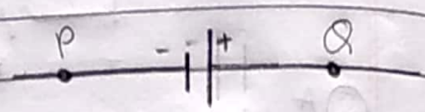


$V_p - V_q = -ve$

Calculation

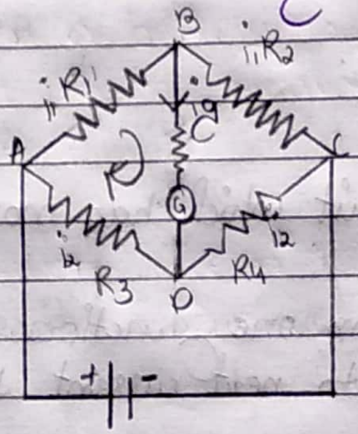


$V_p - V_q = +E$



$V_p - V_q = -E$

* Wheat-stone bridge:



Unbalanced: When there is current in galvanometer $V_B \neq V_A$.

Balanced: When there is no current in galvanometer $V_B = V_A$.

Applying Kirchoff's law:

Loop ABAA =>

$i_1R_1 - i_2R_3 = 0 \Rightarrow i_1R_1 = i_2R_3$ or $\frac{i_1}{i_2} = \frac{R_3}{R_1}$ — (i)

Loop BODB,

$i_1R_2 - i_2R_4 = 0 \Rightarrow i_1R_2 = i_2R_4$ or $\frac{i_1}{i_2} = \frac{R_4}{R_2}$ — (ii)

By eq (i) & (ii)

$\frac{R_3}{R_1} = \frac{R_4}{R_2}$ => rearrange => $\frac{R_1}{R_2} = \frac{R_3}{R_4}$

It is possible only when $i_g = 0$ or bridge is balanced.

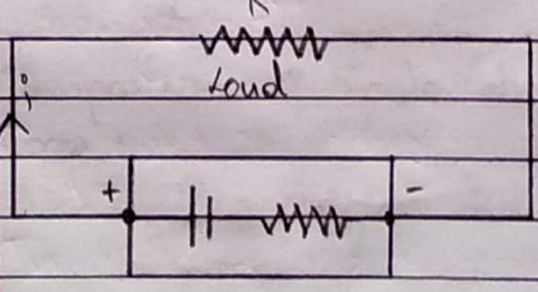
* Cell:

- Internal resistance -
  Resistance created by electrolyte to the moving ions inside cell 'r'.
- Factors on which internal resistance depends:
  ① Distance between electrode increases r.
  ② Larger dipping of electrode decreases 'r' cause area increases.
  ③ Temperature increases 'r' decreases cause electrolyte becomes thin.

* EMF:

- EMF of a cell is amount of work done in rotating one unit charge through complete cycle. Symbol - (ε)
- Terminal potential difference -
  Work done by a unit charge while moving from one terminal of battery to other in outer current. Symbol 'v' unit volt.

* Relation between EMF 'E' & terminal potential difference 'v':



Current in the circuit

$$i = \frac{\varepsilon\,(EMF)}{R + r} \quad \text{—— (i)}$$

Terminal potential diffence, $V = iR$ — (ii)

Condition 1:

Battery discharging work getting done from eq (i)

$E = iR + ir$

$\varepsilon = V + ir$

$V = \varepsilon - ir$ (Terminal potential difference V is always smaller than EMF 'ε')

Condition 2:

Circuit open No use of battery then $i = 0$

$V = \varepsilon$.

Condition 3:

When a battery is getting recharged, ~~they~~ during that time terminal potential difference is more than EMF 'E'.

* Relation between terminal potential difference and internal resistance:

$V = \varepsilon - ir$

$ir = \varepsilon - V$

$r = \dfrac{\varepsilon - V}{i}$

$r = \dfrac{\varepsilon - V}{\frac{V}{R}}$

$r = R\dfrac{\varepsilon - V}{V}$

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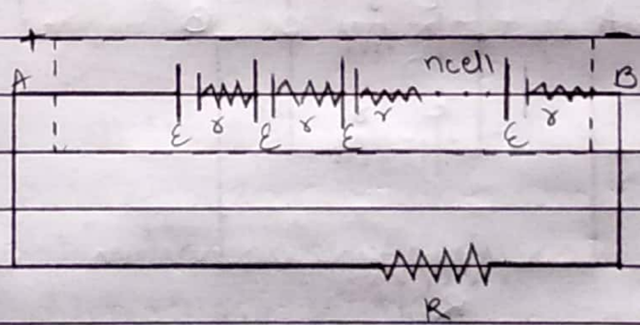
$$r = R\left(\frac{\varepsilon}{V} - 1\right)$$

Here r is the iternal resistant.

- In our household supply when load increases the current increases according to relation $V = \varepsilon - ir$. When the current increases, the terminal potential difference 'V' decreases. Therefore the potential difference in the main line decreases. Therefore all bulb and other equipments experience lower voltage.

* Combinations of cells:

1) Series combination:



Net EMF = nE

Total resistance = $nr + R$

Current = $\dfrac{n\varepsilon}{nr + R}$

For a single cell current = $\dfrac{\varepsilon}{R + r}$

Comparison of single cell and combined cell:

Case 1:

$R >> r$, then current due to cell is $\dfrac{\varepsilon}{R}$.

Current in series $= \frac{n\varepsilon}{R}$

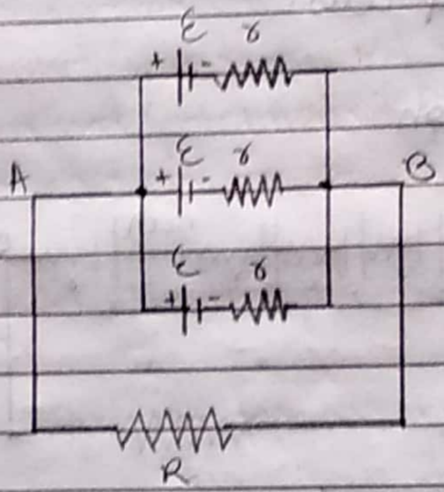
∴ Current increases

Case 2:

$R << r$ Current due to single cell $= \frac{\varepsilon}{r}$

Current in series is $= \frac{n\varepsilon}{nr} = \frac{\varepsilon}{r}$

2) Parallel combination:



EMF Net $= \varepsilon$

Resistance $= \frac{r}{n} + R$

$= \frac{nR + r}{n}$

Current $= \frac{\varepsilon}{\left(\frac{nR+r}{n}\right)} = \frac{n\varepsilon}{nR + r}$

$\therefore i_p = \frac{n\varepsilon}{nR + r}$

Comparing single cell and combination in parallel

For single cell $= \frac{\varepsilon}{R+r}$

Case 1:

$R \gg r$

$i_p = \frac{n\varepsilon}{nR+r}$ (neglecting r)

$= \frac{\varepsilon}{R}$

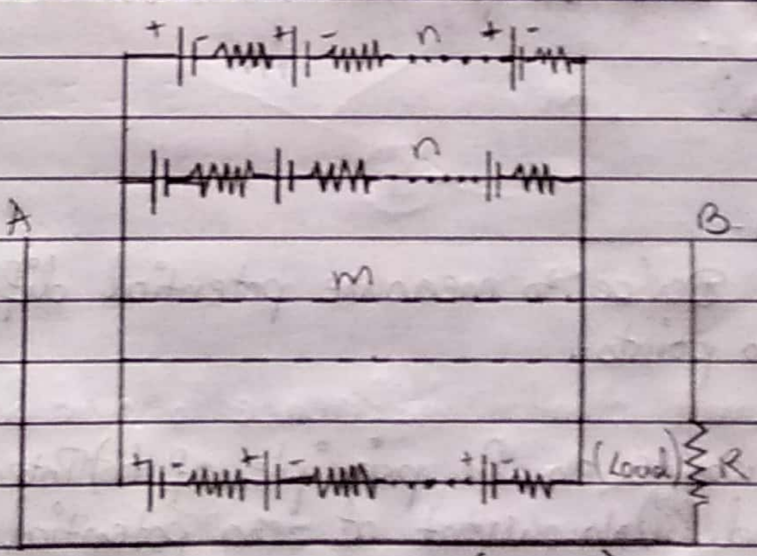
For single cell $i = \frac{\varepsilon}{R}$

Case 2:

$i_p = \frac{n\varepsilon}{r}$ (neglected r).

For single cell $i = \frac{\varepsilon}{r}$

3) Mixed combination:



EMF across one row: $n\varepsilon$ (series)

EMF across parallel rows remain unchanged.

∴ EMF across AB $= n\varepsilon$.

In one row series resistance $= nr$.

$\therefore$ A to B $R_{AB} = \frac{nr}{m} + R$

Current in circuit $i = \frac{nE}{\frac{nr + R}{m}} = \frac{m \times nE}{nr + mR}$

Condition for maximum current

$i = \frac{m \times nE}{nr + mR}$

Current will be maximum when $nr + mR$ is smallest

condition for $nr + mR$ to be small

W.K.T

$(nr + mR)^2 = (nr - mR)^2 + 4mrnR$.

Condition for $nr + mR$ to be minimum is $nr - mR = 0$.

$\therefore nr = mR$.

$\therefore \frac{n}{m} = \frac{R}{r}$.

This is the condition for maximum current.

* Potentiometer:

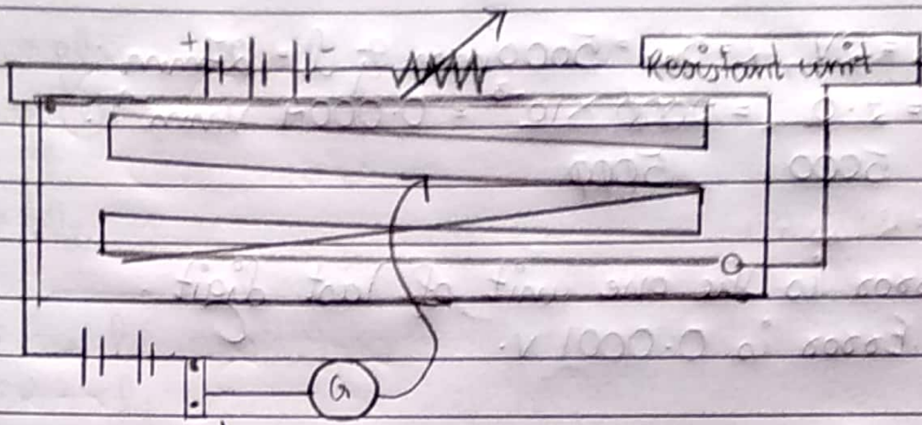
- Introduction -

Device to measure potential difference between two points.

- Principle -

It works on the principle of (i) Potential gradient and (ii) No current at zero potential.

- Description:



If V is potential difference given by source battery then potential drop per mm is $\frac{V}{L}$ where L is the total length of resistance wire.

Potential difference across l mm $\frac{V}{L} \times l$.

$\boxed{V = \rho l}$ where, ρ - potential gradient.

- In a potentiometer, the potential gradient is fallen of potential per unit length of wire.

Q Why potentiometer is a better device than voltmeter?

Ans When voltmeter is fitted in a circuit it draws some current for its own operation, therefore current in main circuit decreases and potential difference gets lesser reading. Whereas in potentiometer the reading is taken when circuit is zero. Hence there is no potential loss. Therefore potential meter gives accurate and precised operation.

Q A battery having 2V potential difference is applied across potentiometer wire of 5 meter. To find -

(1) What is the potential gradient of this instrument?

(2) Across a length of 27mm, how much is the potential difference and what is possible error in it?

Ans $V_s = 2V$, $L = 5m = 5000mm$ & $l = 27mm$

$\rho = \frac{2.0}{5000} = \frac{2000 \times 10^{-3}}{5000} = 0.0004\ Vmm^{-1}$.

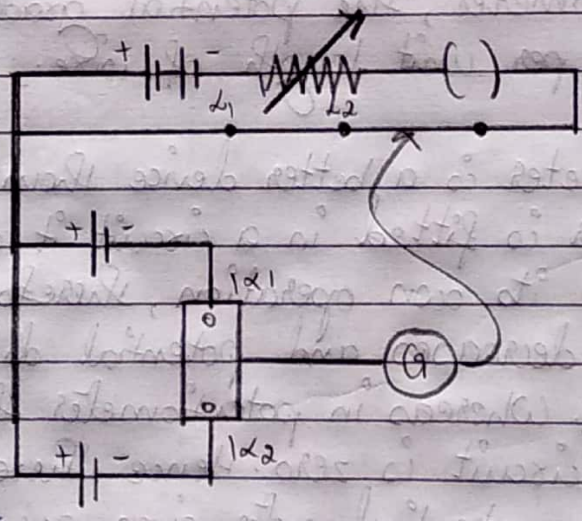
Error is the one unit of last digit.
∴ Error is 0.0001 V.

$V = \rho l$
$V = 0.0004 \times 27 = 0.0108\ Vmm^{-1}$

- Application of potentiometer:

① Comparison of EMF of 2 cells.

Voltmeter cannot measure EMF because there is never no-current situation, but EMF can be measured by potentiometer.



Working-

A small potential difference is created across potentiometer. ~~V~~ By trial point L_1 is searched such ~~that~~ deflection in galvanometer is zero. Then potential difference $V = \rho l$ is balanced by PD by cell 1.
∴ $E_1 = \rho L_1$ —(1) (Because at zero current $V = E$).
K_1 is open K_2 is closed. Repeated experiment and null point located at L_2 with cell.

$\therefore \mathcal{E}_2 = \rho l_2$ — (ii)

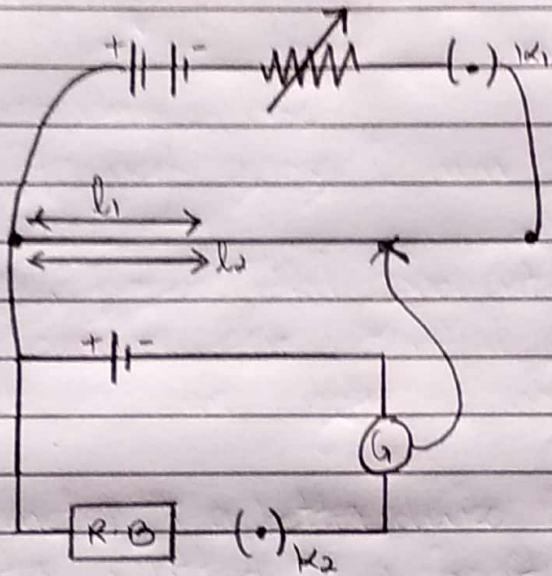
By eq (i) & (ii)

$\mathcal{E}_1 = \rho l_1$

$\mathcal{E}_2 = \rho l_2$

$\therefore \frac{\mathcal{E}_1}{\mathcal{E}_2} = \frac{l_1}{l_2}$

(2) To find out internal resistance of a cell:



Procedure:

(1) K_1 is close, K_2 is open
Null point found at l_1
$\mathcal{E} = \rho l_1$ — (i) (Current zero $\therefore V_1 = \mathcal{E}$).

(2) A resistance R is taken out and K_2 is closed. Again null point is searced found at distance l_2.

$V = \rho l_2$ — (ii)

$\frac{\mathcal{E}}{V} = \frac{\rho l_1}{\rho l_2}$

$\frac{\mathcal{E}}{V} = \frac{l_1}{l_2}$

$$r = R\left(\frac{E}{V} - 1\right)$$

$$r = R\left(\frac{l_1}{l_2} - 1\right)$$