

# CURRENT ELECTRICITY



- BEST NCERT NOTES

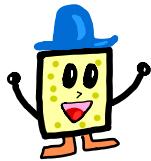
- Guaranteed Full Marks

- All Previous Year Questions Covered

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# CURRENT ELECTRICITY



## Electric current (I)

- Current is defined as the rate of flow of charge | Scalar quantity | SI Unit- ampere (A)
- Direction of current through a cross section is the direction of flow of positive charge.
- If the net charge that flows through a cross-section is negative, it implies a current in the backward direction.

### Instantaneous current

$$I_{\text{inst}} = dq/dt$$

### Average current

$$I_{\text{avg}} = \Delta q/\Delta t$$



## Electric current in conductors

**Conductors:** Materials which allow current to pass through them easily. The charge carriers inside metallic conductors are free electrons. When an electric field is applied, the free electrons experience a force and an electric current is setup inside the conductor.

**Note:** Charge carriers in various conductors-

**Metals-** free electrons | **Electrolytes-** +ve and –ve ions | **semiconductors-** free electrons and holes.

### Inside a conductor-

- In absence of electric field** – In the absence of electric field, the free electrons move due to thermal energy. During this thermal motion the electrons collide with each other and the fixed positive ions. After a collision with a +ve ion, the electron emerges with the same speed as before. However, the direction of its velocity will be completely random. Thus, on average, the number of electrons moving in a particular direction will be equal to the number of electrons moving in the opposite direction. So, there will be no net electric current in the conductor in the absence of an electric field.
- In presence of electric field**- When a constant electric field is applied to the ends of a conductor, the free electrons experience a force in a direction opposite to that of electric field and hence start moving in and therefore a net electric current is setup in the direction of electric field (flow of positive charge). This electric current will remain as long as the field is applied.



## Ohm's Law

Ohm's law states that at constant physical conditions (temp etc), the current through a conductor is directly proportional to the potential difference applied across its ends.

$$V \propto I$$

$$V = IR$$

Where R is a constant of proportionality and is called the Resistance of the conductor | SI Unit- ohm ( $\Omega$ )

R is dependent on both the material and dimensions of the conductor.

Also,

$$\begin{aligned} R &\propto l \\ R &\propto \frac{l}{A} \\ R &= \rho \frac{l}{A} \end{aligned}$$

$$V = i p \frac{l}{A}$$

$$V = \frac{i}{A} pl$$

Where  $\rho$  is called the resistivity of the material



## Current density ( $j$ )

Current density is defined as the current per unit area (taken normal to the current) | SI Unit = A/m<sup>2</sup>

$$j = \frac{i}{A}$$

Consider an electric field  $E$  in a conductor of length  $l$ , then potential difference across it,  $V = E.l$ . Then from ohm's law-

$$V = \frac{i}{A} p l$$

$$E \cdot l = j p l$$

$$\vec{E} = \vec{j} p$$

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

Where  $\sigma$  is called the conductivity of the material and  $\sigma = 1/\rho$  |  $\sigma$  depends on nature of the material and not dimensions.

## Vector form of current density-

According to definition,

$$j = \frac{i}{A \cos \theta}$$

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

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



Where  $\theta$  is the angle between direction of current and normal to the area.

**Note:**  $j$  is directed along  $l$  (current) and is also parallel to  $E$



## Drift velocity ( $v_d$ ) (PYQ 2016, 2012)

It is defined as the average velocity with which the free electrons move towards the +ve end of a conductor under the influence of applied electric field.

Let electric field be  $E$ , the force  $F$  on each electron and hence its acceleration  $a$  will be-

$$F = -eE$$

$$F = ma$$

$$ma = -eE$$

(Where  $m$  is mass of each electron)

$$\vec{a} = -\frac{e\vec{E}}{m}$$

Let initial velocity of electron be  $u$  and velocity after time  $\tau$  be  $v$ . From Newton's first equation of motion-

$$\vec{v} = \vec{u} + \left( \frac{-e\vec{E}}{m} \right) \tau$$

$$\vec{v}_1 = \vec{u}_1 + \left( \frac{-e\vec{E}}{m} \right) \tau_1$$

$$\vec{v}_2 = \vec{u}_2 + \left( \frac{-e\vec{E}}{m} \right) \tau_2$$

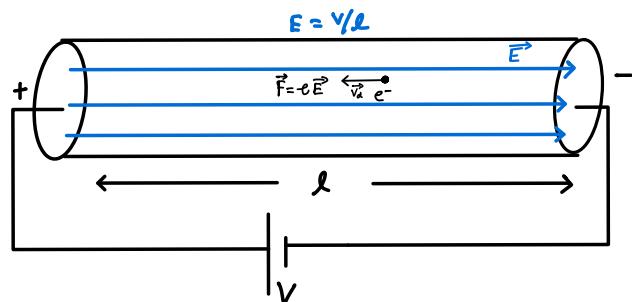
$$\vec{v}_n = \vec{u}_n + \left( \frac{-e\vec{E}}{m} \right) \tau_n$$

$$\vec{v}_d = \frac{\vec{v}_1 + \vec{v}_2 + \vec{v}_3 + \dots + \vec{v}_n}{n}$$

$$\vec{v}_d = \frac{\vec{u}_1 + \vec{u}_2 + \dots + \vec{u}_n}{n} + \left( \frac{-e\vec{E}}{m} \right) \times \frac{\tau_1 + \tau_2 + \dots + \tau_n}{n}$$

$$\vec{v}_d = \frac{-e\vec{E}}{m} \tau_{av}$$

(The -ve sign indicates that Velocity is opp to field)



(The average initial velocity is zero as before electric field is applied, there is no specified direction in which electrons move.)

**Note:** Average relaxation time ( $\tau_{avg}$ ) - It is the average time interval between b/w two successive collisions of a free e<sup>-</sup>



## Relation between drift velocity and current

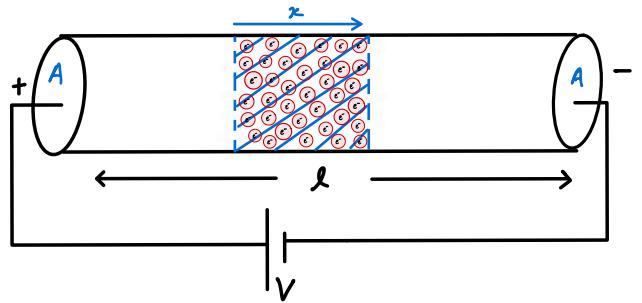
In a conductor of cross-sectional area, A, let number of free Electrons per unit volume be n. Consider a portion of length x. The total number of electrons (N) in it can be written as-

$$N = nAx$$

$$Q = eN = enAx$$

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

$$I = neAV_d$$



Now, we can also relate current density with drift velocity-

$$I = neAV_d$$

$$j = \frac{I}{A} = \frac{neAV_d}{A}$$

$$j = nev_d$$

$$\vec{j} = -ne\vec{v}_d$$

(it is negative because direction of flow Of electrons is opposite to that of current)



## Vector form of ohm's law (PYQ 2016)

We know,

$$\vec{j} = -ne\vec{v}_d$$

$$\vec{j} = -ne \times \left( \frac{-e\vec{E}}{m} \tau_{av} \right)$$

$$\vec{j} = ne^2 \times \frac{\vec{E}}{m} \tau_{av}$$

$$\vec{j} = \left( \frac{ne^2 \tau}{m} \right) \vec{E}$$

Where

$$\frac{ne^2 \tau}{m}$$

is a constant is called conductivity  $\sigma$ . Similarly, we know  $\rho = 1/\sigma$  therefore

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

**Note:** - In Electrodynamic condition (charges are moving) Electric field inside conductor is not zero.

- Thermal speed of electron =  $\sqrt{\frac{3k_B T}{m}}$

(root mean squared speed) (NCERT eg 3.1)  
(K<sub>B</sub> is Boltzmann's constant)



## Mobility ( $\mu$ ) (PYQ 2019, 2014)

Mobility of free electrons in a conductor is defined as the drift velocity per unit electric field | SI unit-  $\text{m}^2/\text{Vs}$

$$\mu = \frac{|\vec{v}_d|}{E}$$

$$V_d = \frac{eE}{m}\tau$$

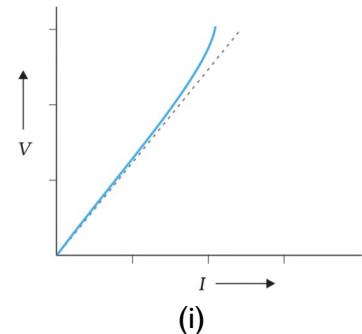
$$\Rightarrow \mu = \frac{e\tau}{m}$$



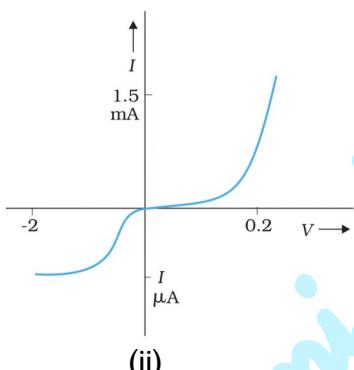
## Limitations of ohm's law

There are certain materials used in electric circuits where the proportionality between V and I does not hold-

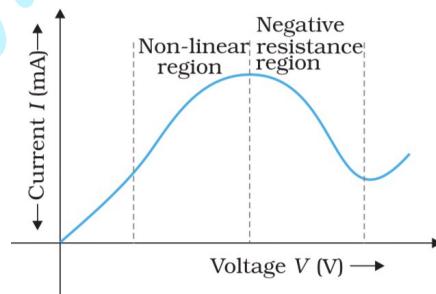
1. V ceases to be proportional to I
2. The relation between V and I depends on the sign of V i.e. If I is the current For a certain V, then reversing the direction of V keeping its magnitude same, does not produce a current of the same magnitude as I in the opposite direction. For e.g. diode
3. The relation between V and I is not unique i.e. there is more than one value of V for the same current I, e.g. GaAs (Gallium Arsenide)



(i)



(ii)

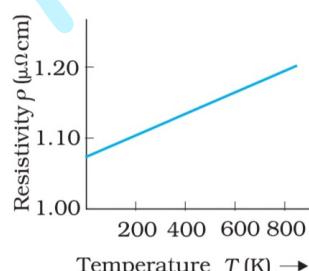


(iii)



## Commercial resistors

1. **Alloys** (PYQ 2017, 2015)- Alloys like constantan, manganin, nichrome etc are used to make wire bound resistors. This is because their resistivities remain almost constant even with change in temperature.



2. **Carbon resistors**- They are compact and inexpensive. Their values are given by a color code which is explained as follows-

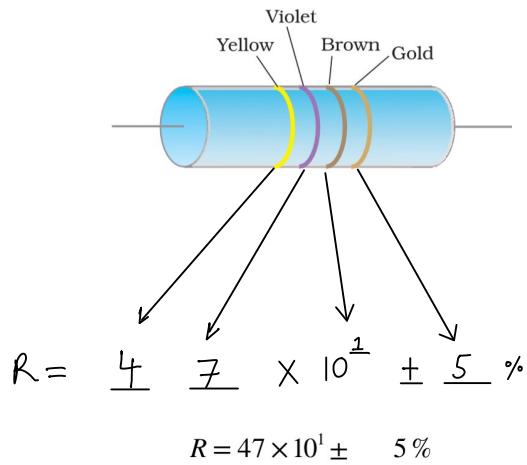
Fun mnemonic to remember the colors:

**BB ROY of Great Britain has Very Good Wife**

Colour	Number	Multiplier	Tolerance (%)
Black	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	$10^7$	
Gray	8	$10^8$	
White	9	$10^9$	
Gold		$10^{-1}$	5
Silver		$10^{-2}$	10
No colour			20

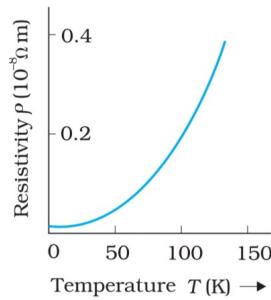
The resistors have a set of co-axial colored rings. The first two bands from the end indicate the first two significant figures of the resistance in ohms. The third band represents the decimal multiplier. Sometimes we even have a fourth band which represents the tolerance/ percentage error in the calculation of resistance.

For e.g.



## Temperature dependence of resistivity

1. **Metals**- For metals, the resistivity increases with increase in temperature. This is because the resistivity  $\rho \propto 1/\tau$  And with the increase in temperature the average relaxation time decreases (as collisions become more frequent)



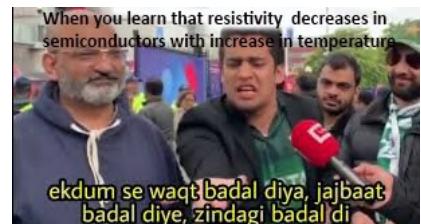
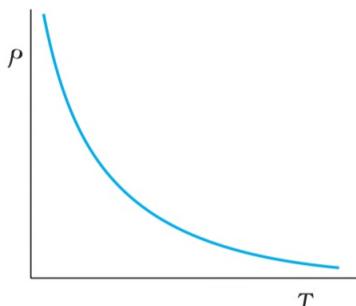
(graph PYQ 2014)

Over a narrow range of temperatures, the resistivity of metallic conductors is approximately given by-

$$P_T = \rho_0 [1 + \alpha (T - T_0)]$$

Where  $P_T$  is the resistivity at temperature  $T$  and  $\rho_0$  is same at a reference temperature  $T_0$ .  $\alpha$  is called as the temperature coefficient of resistivity. For some metals,  $\alpha$  is positive.

- 2. Semiconductors (PYQ 2015)-** For semiconductors, resistivity decreases with increase in temperature this is because  $\rho$  is directly proportional to number of free electrons per unit volume ( $n$ ) and with the increase in temperature, for a semiconductor,  $n$  increases greatly with increase in temperature and more than compensate for the decrease in  $\tau$ . But for metals,  $n$  remains almost constant with the change in temperature therefore the resistivity increases with the decrease in  $\tau$ , when temperature increases.



**Important PYQs**



**Ques:** How does mobility of an electron change when the potential difference across the conductor is doubled keeping the length and the temperature constant (PYQ 2019)

**Ans:** We know,  $E = V/r$

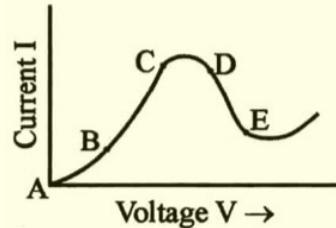
$$\Rightarrow E' = 2V/r; E' = 2E$$

$$\mu = v_d/E$$

$\Rightarrow \mu' = \mu/2$  i.e. the mobility of electrons will be halved.

**Ques:** Graph showing the variation of current versus voltage for a material GaAs is shown in the figure. Identify the region of

- (i) negative resistance
- (ii) where Ohm's law is obeyed. (PYQ 2015)



**Ans:** i) DE  
ii) AB

**Ques:** Why are alloys like constantan and manganin used to make standard resistors? (PYQ 2016)

**Ans:** Alloys like constantan and manganin are used to make standard resistors because their resistivities remain almost constant with increase in temperature.

**Similar PYQ**

**Ques:** When electrons drift in a metal from lower potential to higher potential does it mean that "all" free electrons of the metal are moving in the same direction? (PYQ 2012)

**Ans:** No, all e<sup>-</sup>s don't move in the same direction, but the net movement of charge is towards the +ve end of the conductor.



## Electrical energy, Power (PYQ 2020, 2019, 2017, 2011)

We have seen that when an external field is applied, electrons in the conductor experience a force and move. But according to this, electrons should accelerate but that is not the case as electrons move with a steady drift velocity. This

is because as electrons move, they collide with each other and with the fixed ions and atoms. The energy gained is shared with the fixed atoms and the atoms start vibrating more vigorously i.e. the conductor heats up. So, a part of the energy is dissipated as heat.

Consider a conductor with a potential difference of  $V$  across its ends and current  $I$ . The heat dissipated in time  $t$  can be written as-

$$H = IV \Delta t$$

The energy dissipated per unit time is the power dissipated ( $P$ )

$$P = VI$$

Using Ohm's law-

$$V = IR$$

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

$$P = I^2 R$$

### Important PYQs



**Ques:** Two resistors  $R_1$  and  $R_2$  of  $4\ \Omega$  and  $6\ \Omega$  are connected in parallel across a battery. The ratio of power dissipated in them,  $P_1 : P_2$  will be (PYQ 2020)

- (A)  $4 : 9$
- (B)  $3 : 2$
- (C)  $9 : 4$
- (D)  $2 : 3$

**Ans:**  $P = V^2/R$ ; since they are connected in parallel,  $V$  is same therefore,  $P_1/P_2 = R_2/R_1$

$$\Rightarrow P_1:P_2 = 3:2 \quad \text{— (B)}$$

**Ques:** The potential difference applied across a given resistor is altered such that the heat produced increases by a factor of 9. By what factor did the potential difference change? (PYQ 2017)

**Ans:** ATQ,  $P' = 9P$  and we know,  $P = V^2/R$

$$\begin{aligned} \Rightarrow V &= VRP \\ \Rightarrow V' &= VRP' \\ \Rightarrow V' &= \sqrt{9RP} = 3\sqrt{VRP} \\ \Rightarrow V' &= 3V \end{aligned}$$

**Ques:** Two bulbs are rated  $(P_1, V)$  and  $(P_2, V)$  are connected in i) series and then in ii) parallel. Calculate the power dissipated in both cases in terms of  $P_1$  and  $P_2$  (PYQ 2019, 2011)

**Ans:** we know  $P = V^2/R$ , therefore resistance of each bulb can be written as –  $R_1 = \frac{V^2}{P_1}$ ,  $R_2 = \frac{V^2}{P_2}$

i) In series

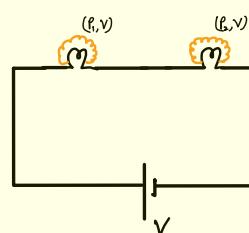
$$R = R_1 + R_2$$

$$R = V^2 \left( \frac{P_1 + P_2}{P_1 P_2} \right)$$

$$I = \frac{V}{R} = \frac{P_1 P_2}{V(P_1 + P_2)}$$

$$P = VI = V \times \frac{P_1 P_2}{V(P_1 + P_2)}$$

$$P = \frac{P_1 P_2}{P_1 + P_2}$$



## II) In parallel

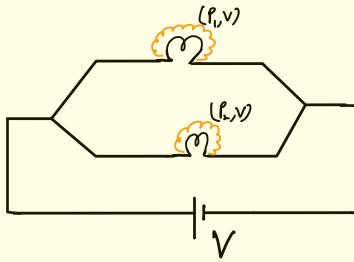
$$R = \frac{R_1 R_2}{R_1 + R_2}$$

$$R = \frac{V^2}{P_1 + P_2}$$

$$I = \frac{V}{R} = \frac{P_1 + P_2}{V}$$

$$P = VI$$

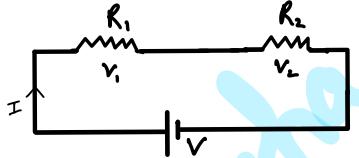
$$P = P_1 + P_2$$



## Combination of resistors ★

### 1. Series combination

Consider two resistors  $R_1$  and  $R_2$ , connected in series. The current through both will be the same. The sum of potential difference across  $R_1$  and that across  $R_2$  will give the total potential drop across the combination.



$$V = V_1 + V_2$$

$$V = IR_1 + IR_2$$

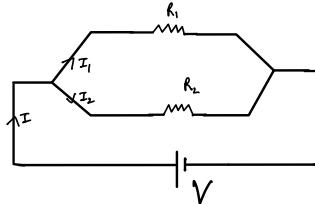
If the two resistors are replaced by a single resistor of resistance equal to that of the combination ( $R_{eq}$ ) then,

$$IR_{eq} = IR_1 + IR_2$$

$$R_{eq} = R_1 + R_2$$

### 2. Parallel combination

Consider two resistors  $R_1$  and  $R_2$  connected in parallel. The sum of the current through both resistors will be equal to the total current through the circuit.



$$I = I_1 + I_2$$

$$I = \frac{V}{R_1} + \frac{V}{R_2}$$

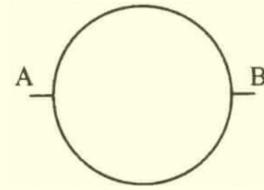
The 2 resistors can be replaced by a single resistor of resistance equal to that of the combination ( $R_{eq}$ )-

$$\frac{V}{R_{eq}} = \frac{V}{R_1} + \frac{V}{R_2}$$

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2}$$

**Ques:** A wire of resistance  $8R$  is bent in the form of a circle as shown. What is the resistance between the ends of diameter AB? (PYQ 2010)

**Ans:** The part of the wire above and below AB can be imagined as two resistors of resistance  $4R$  each connected in parallel. Therefore, the equivalent resistance between AB is –

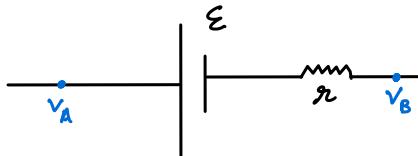


$$R_{eq} = 4R \times 4R / 4R + 4R = 2R$$



## Cells, EMF, and internal resistance (PYQ 2020, 2018, 2016, 2015, 2013, 2012)

An electrolytic cell is a device which maintains a steady current in an electric circuit.



### EMF ( $\epsilon$ )

The potential difference across the electrodes of a cell when no current is drawn from it is called the EMF ( $\epsilon$ ) of the cell  
OR

The work done in complete circulation of a unit positive charge | SI Unit- Volt (V) or  $JC^{-1}$

**Note:** EMF  $\epsilon$  is potential difference and not a force.

### Internal resistance ( $r$ )

The electrolyte through which current flows has a finite resistance which is called the internal resistance of the cell ( $r$ )

### Terminal voltage (V)

The potential difference across the terminals of a cell when current is drawn from it is called the terminal voltage.

\*Now let us calculate the terminal voltage in the following cases

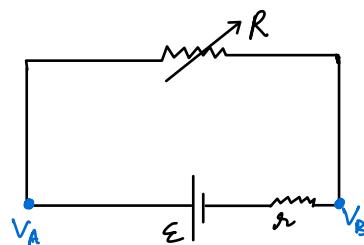
1. **No load condition** (load is any device to which energy is supplied like bulb etc)  
i.e. current ( $I$ ) in circuit is zero

There will be no potential drop across  $r$  since the current in the circuit is 0

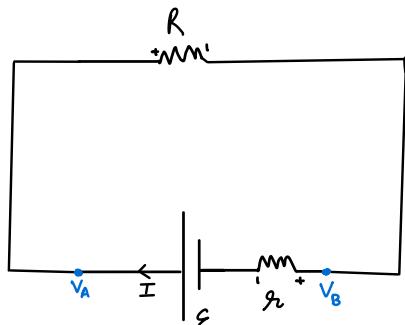
$$I = 0$$

$$V_{BA} = \epsilon$$

Terminal voltage = EMF



2. **Discharging** (providing energy to load)



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

Also,

$$V_{AB} = -Ir + \epsilon$$

$$V_{AB} = \epsilon - Ir$$

$$\Rightarrow V_{AB} < \epsilon$$

(Since r and R are in series)

Also,

$$V_{AB} = IR$$

$$V_{AB} = \left( \frac{\epsilon}{R + r} \right) R$$

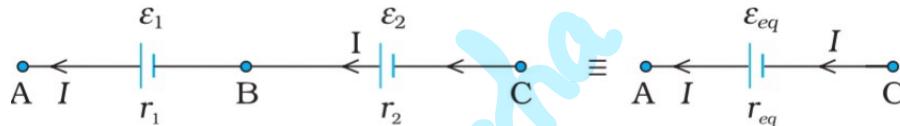
**Note:** For ideal cell, terminal voltage =  $\epsilon$ , always. ( $r=0$ )



## Cells in Series and Parallel

### 1. In Series

Consider two cells of EMF  $\epsilon_1$  and  $\epsilon_2$  and internal resistance  $r_1$  and  $r_2$  connected in series as shown in the fig.



Potential diff across AB-

$$V_{AB} = V_A - V_B = \epsilon_1 - Ir_1$$

Potential diff across BC-

$$V_{BC} = V_B - V_C = \epsilon_2 - Ir_2$$

Potential diff across AC-

$$V_{AC} = (V_A - V_B) + (V_B - V_C)$$

$$= \epsilon_1 - Ir_1 + \epsilon_2 - Ir_2$$

$$V_{AC} = (\epsilon_1 + \epsilon_2) - I(r_1 + r_2) - \textcircled{1}$$

We want-  $V_{eq} = \epsilon_{eq} - Ir_{eq}$  - ②

From 1,2

$$\Rightarrow \epsilon_{eq} = \epsilon_1 + \epsilon_2$$

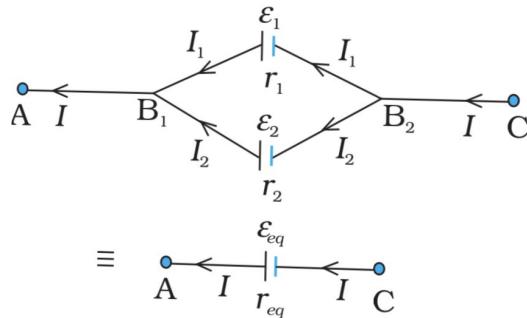
$$\Rightarrow r_{eq} = r_1 + r_2$$

Thus, we can say that

- 1) The equivalent emf of a series combination of n cells is just the sum of their individual emfs
- 2) The equivalent internal resistance of a series combination of n cells is just the sum of their individual internal resistances

### 2. In Parallel (PYQ 2020, 2018, 2016)

Consider two cells of EMF  $\epsilon_1$  and  $\epsilon_2$  and internal resistance  $r_1$  and  $r_2$  connected in parallel as shown in the fig.



For the first cell

$$V_{B_1 B_2} = V_{B_1} - V_{B_2} = \epsilon_1 - Ir_1$$

For the second cell

$$V_{B_2 B_1} = V_{B_2} - V_{B_1} = \epsilon_2 - Ir_2$$

The net current = sum of current through the cells

$$I = I_1 + I_2$$

$$I = \frac{\epsilon_1 - V}{r_1} + \frac{\epsilon_2 - V}{r_2} = \left( \frac{\epsilon_1}{r_1} + \frac{\epsilon_2}{r_2} \right) - V \left( \frac{1}{r_1} + \frac{1}{r_2} \right)$$

On rearranging, we get value of potential  $V$

$$V = \frac{\epsilon_1 r_2 + \epsilon_2 r_1}{r_1 + r_2} - i \left( \frac{r_1 r_2}{r_1 + r_2} \right)$$

Replacing the two cells by a single cell of emf  $\epsilon_{eq}$  and internal resistance  $r_{eq}$ , we get-

$$\epsilon_{eq} = \frac{\epsilon_1 r_2 + \epsilon_2 r_1}{r_1 + r_2}$$

$$r_{eq} = \frac{r_1 r_2}{r_1 + r_2}$$

OR

$$\frac{\epsilon_{eq}}{r_{eq}} = \frac{\epsilon_1}{r_1} + \frac{\epsilon_2}{r_2}$$

$$\frac{1}{r_{eq}} = \frac{1}{r_1} + \frac{1}{r_2}$$

For  $n$  cells,

$$\frac{\epsilon_{eq}}{r_{eq}} = \frac{\epsilon_1}{r_1} + \frac{\epsilon_2}{r_2} + \dots + \frac{\epsilon_n}{r_n}$$

$$\frac{1}{r_{eq}} = \frac{1}{r_1} + \frac{1}{r_2} + \dots + \frac{1}{r_n}$$

### Important PYQs



**Ques:** a cell of emf  $E$  and internal resistance  $r$  is connected across variable load resistor  $R$ . Draw plots of i) terminal voltage  $V$  ii) current  $I$  as a function of  $R$

It is found that when  $R = 4\Omega$ ,  $I = 1\text{ A}$  and when  $R$  is increased to  $9\Omega$  current reduces to  $0.5\text{ A}$ . Find  $E$  and  $r$ . (PYQ 2015)

**Ans:**

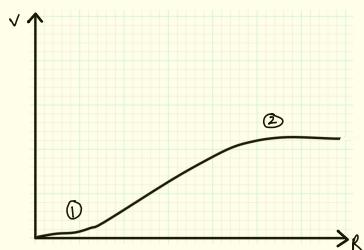
i) We know,

$$V = IR$$

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

From 1,2

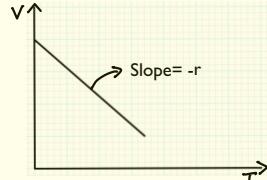
$$V = \left( \frac{E}{R+r} \right) R$$



- There will be two portions of the graph  
 1. When  $R \ll r$ ,  $V$  will be very small  
 2. When  $R \gg r$ ,  $V$  will be almost constant

ii) We know,

$$V = E - Ir \quad (\text{Compare with } y = mx + c)$$



iii) ATQ,

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

$$\text{A. } 1 = \frac{E}{4+r}$$

$$4+r=E$$

$$E-r=4 \quad \text{--- ①}$$

$$\text{B. } 0.5 = \frac{E}{9+r}$$

$$q+r=2E$$

$$2E-r=9 \quad \text{--- ②}$$

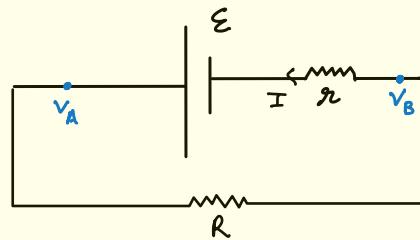
On solving 1,2 we get-

$$E=5$$

$$r=1$$

Ques: The emf of a cell is always greater than its terminal voltage explain why? (PYQ 2013)

Ans: The emf of a cell is always greater than the terminal voltage because the cell has an internal resistance due to which there is a potential drop so the terminal voltage is always less than the emf of the cell. This can be illustrated from the following diagram-



$$V_A - V_B = \epsilon - IR$$

Ques: A cell of emf E and internal resistance r is connected to two external resistances  $R_1$  and  $R_2$  and a perfect ammeter.

The current in the circuit is measured in four different situations:

- (i) Without any external resistance in the circuit
- (ii) With resistance  $R_1$  only
- (iii) With  $R_1$  and  $R_2$  in series combination
- (iv) With  $R_1$  and  $R_2$  in parallel combination

The currents measured in the four cases are 0.42 A, 1.05A, 1.4A, and 4.2A, but not necessarily in that order. Identify the currents corresponding to the four cases mentioned above. (PYQ 2012)

Ans: First let us calculate the net resistances in each condition-

- 1)  $R_{eq} = r$  since there is no other resistance in the circuit
- 2)  $r$  and  $R_1$  are connected in series so,  $R_{eq} = r + R_1$
- 3)  $r$ ,  $R_1$ , and  $R_2$  are all in series so  $R_{eq} = r + R_1 + R_2$
- 4)  $R_1$  and  $R_2$  are connected in parallel so their net resistance will be  $R_1R_2/(R_1+R_2)$  and this net is in series with  $r$  so,  $R_{eq} = r + R_1R_2/(R_1+R_2)$

Now let us calculate the current in each case-

- 1)  $I = E/r$
- 2)  $I = E/r+R_1$
- 3)  $I = E/r+R_1+R_2$
- 4)  $I = E / (r + R_1R_2/(R_1+R_2))$

We know that in a series combination, the net resistance is greater than the net resistance for the same resistors in a parallel combination and that the net resistance in parallel is less than each individual R. So, the order of current will be- 1 > 4 > 2 > 3

So in case 1)  $I = 4.2$  A

2)  $I = 1.4$  A

3)  $I = 1.05$  A

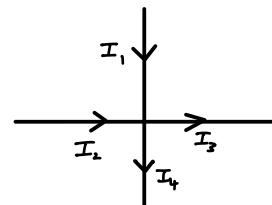
4)  $I = 0.42$  A



## Kirchhoff's laws (PYQ 2019, 2018, 2015, 2014, 2013, 2012, 2011)

### A) Junction law (PYQ 2014)

At any junction, the sum of the currents entering the junction is equal to the sum of the currents leaving the junction. This is based on the law of conservation of charge because when currents are steady, there is no accumulation of charges at any junction or at any point in the wire. Thus, total current flowing in must be equal to the total current flowing out.



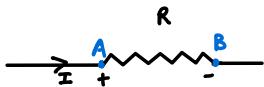
$$I_1 + I_2 = I_3 + I_4$$

## B) Loop law (PYQ 2014)

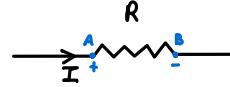
The algebraic sum of changes in potential around any closed loop involving resistors and the cells in the loop is zero. This is based on the law of conservation of energy.

### Some conventions:

1. Potential across a resistor is -ve in the direction of current | Potential across a resistor is +ve in the direction opposite to current

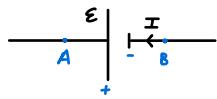


$$V_B - V_A = -IR$$

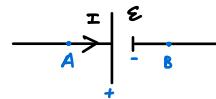


$$V_A - V_B = IR$$

2. Potential is gained on crossing a battery from -ve to +ve terminal | Potential drops on crossing a battery from +ve to -ve terminal



$$V_A - V_B = \epsilon$$

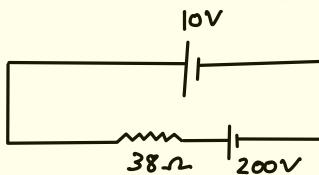


$$V_R - V_A = -\epsilon$$

### Important PYQs



**Ques:** A 10V battery of negligible internal resistance is connected across a 200V battery and resistance of  $38\Omega$  as shown in the figure. Find the value of current in the circuit. (PYQ 2013)



**Ans:** Let current in circuit be  $I$ , using Kirchhoff's loop law in loop ABCD,



$$-10 + 200 - 38I = 0$$

$$38I = 190$$

$$I = 5A$$

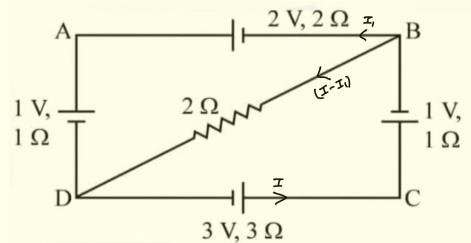
**Ques:** Using Kirchhoff's rules calculate the potential difference between B and D in the circuit diagram as shown in the figure. (PYQ 2018)

**Ans:** In loop DCBD

$$\begin{aligned} -3I + 3 - I - 1 - 2I + 2I_1 &= 0 \\ -6I + 2I_1 + 2 &= 0 \\ 3I - I_1 &= 1 \end{aligned}$$

In loop BADB

$$\begin{aligned} 2 - 2I_1 - 1 - I_1 + 2I - 2I_1 &= 0 \\ 2I - 5I_1 + 1 &= 0 \\ 5I_1 - 2I &= 1 \end{aligned}$$



On solving, we get

$$I = \frac{6}{13}A \quad I_1 = \frac{5}{13}A$$

## Potential difference Between B and D

$$V_B - 2I_1 + 2 - 1 - I_1 = V_D$$

$$V_B - V_D = 3 \times \frac{5}{13} - 1$$

$$V_{BD} = \frac{2}{13}V$$



**Ques:** Using Kirchhoff's rules calculate the current through the  $40\Omega$  and  $20\Omega$  Resistors in the following circuit. (PYQ 2019)

**Ans:** In loop ABCD

$$80 - 20I - 40I_1 = 0$$

$$\Rightarrow I - 2I_1 = 4$$

In loop CFED

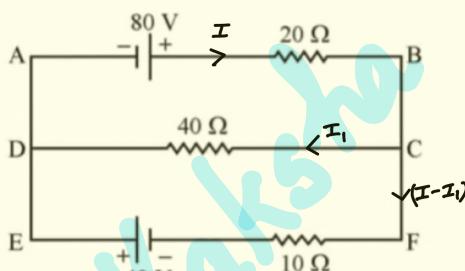
$$-10 \times (I - I_1) + 40 + 40I_1 = 0$$

$$\Rightarrow I - 5I_1 = 4$$

On solving

$$I = 4A$$

$$I_1 = 0A$$



**Ques:** Using Kirchhoff's rules determine the value of the unknown resistance R  
In the circuit such that no current flows through the  $4\Omega$  resistance. Also find the Potential difference between A and D. (PYQ 2011)

**Ans:** Let current in the branch EB be zero and apply Kirchhoff's law in loop CBEDC

$$-3 + 6 + 0 - IR = 0$$

$$IR = 3 \quad \text{--- ①}$$

Now, apply Kirchhoff's law in loop BAFEB

$$9 - I - I + 0 - 6 = 0$$

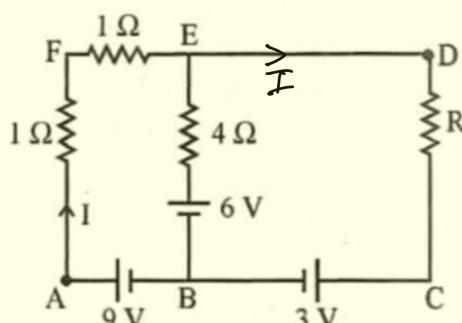
$$2I = 3$$

$$I = 1.5A \quad \text{--- ②}$$

From ①, ②

$$1 \cdot 5 \times R = 3$$

$$R = 2\Omega$$



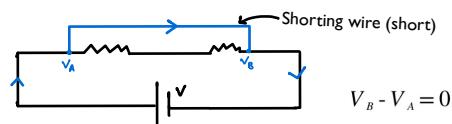
2. Potential difference between A and D-

$$V_A - 9 + 3 + IR = V_D$$

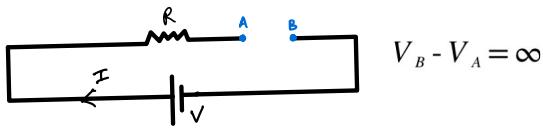
$$V_A - V_D = 9 - 3 - 3$$

$$V_{AD} = 3V$$

**Note:** 1. Potential across a short circuit is zero

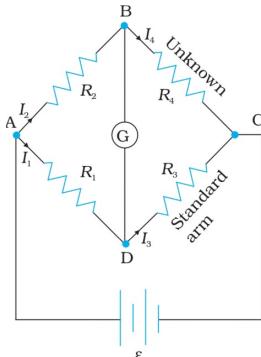


2. Potential across an open circuit is infinite.



## Wheatstone Bridge (PYQ 2015, 2013)

It is an application of Kirchhoff's rules



### Balanced bridge (PYQ 2013, 2015)

When the resistors are such that the current through the galvanometer is zero ( $I_g = 0$ ), it is called a balanced Wheatstone bridge.

Let us derive the relation for this condition using Kirchhoff's rules.

Since  $I_g = 0$ , using junction law,  $I_2 = I_4$  and  $I_1 = I_3$

Using Kirchhoff's law in loop ABDA

$$-I_2 R_2 + 0 + I_1 R_1 = 0 \\ I_1 R_1 = I_2 R_2 \quad \text{--- ①}$$

Using Kirchhoff's law in loop BCDB

$$-I_4 R_4 + 0 + I_3 R_3 = 0 \\ \Rightarrow I_4 R_4 = I_3 R_3 \quad \text{--- ②}$$

From ①, ② we obtain

$$\frac{I_1}{I_2} = \frac{R_2}{R_1} \quad \frac{I_1}{I_2} = \frac{R_4}{R_3}$$

Hence,

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

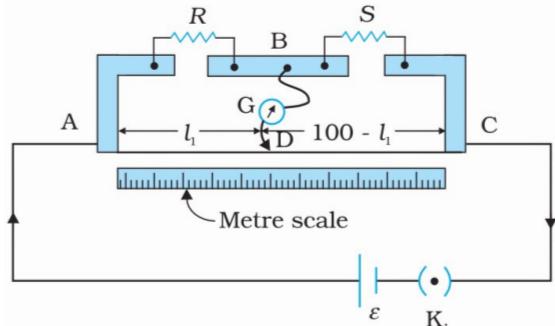
### Application of Wheatstone bridge

It can be used to find the value of an unknown resistance  $R_4$  keeping  $R_1$  and  $R_2$  constant while varying  $R_3$  till galvanometer shows null deflection (also known as **Meter Bridge**)

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



## Meter Bridge (PYQ 2020, 2019, 2017, 2013, 2011, 2010)



## Construction

It consists of a wire of 1m and uniform cross section stretched taught and clamped between two thick metallic strips bent at right angles. The metallic strip has two gaps across which resistors can be connected. The end points where the wire is clamped are connected to the cell through a key. One end of a galvanometer is connected to the metallic strip midway b/w the two gaps. The other end of the galvanometer is connected to a jockey. The jockey is essentially a metallic rod whose one end has a knife edge which can slide over the wire to make electrical connection.

## Working (PYQ 2020, 2017)

In the fig, the arms AB, BC, DA, CD, with resistances R, S,  $\lambda \cdot l$  and  $\lambda(100-l)$  where  $\lambda$  is the resistance per unit cm of the wire, form a Wheatstone bridge. If the jockey is moved along the wire, then there will be one position where the galvanometer will show no current. Let the distance of the jockey from the end A at the balance point be  $l = l_1$ . The four resistances forming the bridge will be R, S,  $\lambda l_1$ ,  $\lambda(100-l_1)$ . The balance condition gives-

$$\frac{R}{S} = \frac{\lambda l_1}{\lambda(100 - l_1)}$$

$$\frac{R}{S} = \frac{l_1}{100 - l_1}$$

$$R = S \cdot \frac{l_1}{100 - l_1}$$

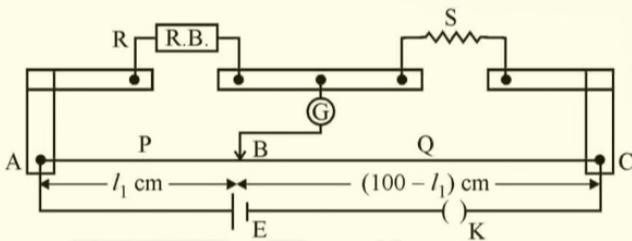
**Note:** The percentage error in R can be minimized by adjusting balance point near the middle of the bridge i.e. when  $l_1$  is close to 50cm

### Important PYQs



**Ques:** What is end error in a metre bridge ? How is it overcome ? The resistances in the two arms of the metre bridge are  $R = 5 \Omega$  and  $S$  respectively.

When the resistance  $S$  is shunted with an equal resistance, the new balance length found to be  $1.5 l_1$ , where  $l_1$  is the initial balancing length. Calculate the value of  $S$ . (PYQ 2019)



**Ans:** As we use thick metallic strips in between the gaps, the resistance of which is unknown some errors arise in the observations. This error is known as end error. It can be overcome by taking multiple observations and then taking the mean.

We know,

$$\frac{R}{S} = \frac{l}{100 - l}$$

$$\frac{5}{S} = \frac{l_1}{100 - l_1} \quad \text{--- ①}$$

Since S is shunted (parallel) with another resistance of the same value

$$\frac{1}{5} = \frac{1}{S} + \frac{1}{S} = \frac{2}{S}$$

$$S' = \frac{S}{2}$$

So new eqn will be

$$\frac{5}{S/2} = \frac{1 \cdot 5l_1}{100 - 1 \cdot 5l_1} \quad \text{--- ②}$$

$$2 = \frac{1 \cdot 5l_1}{100 - 1 \cdot 5l_1} \times \frac{100 - l_1}{l_1}$$

$$200 - 3l_1 = 150 - 15l_1$$

$$l_1 = \frac{100}{3} \text{ cm}$$

Substituting in 1

$$\frac{5}{S} = \frac{\frac{100}{3}}{100 - \frac{100}{3}}$$

$$S = 10 \Omega$$

**Ques:** In the meter bridge experimental setup shown in the figure, the null point D is obtained at distance of 40cm from end A of the meter bridge. If a resistance of  $10\Omega$  is connected in series with  $R_1$ , the null point is obtained at  $AD = 60\text{cm}$ . calculate the value  $R_1$  and  $R_2$ . (PYQ 2013)

**Ans:** We know,

$$\frac{R_1}{R_2} = \frac{l_1}{100 - l_1}$$

$$\frac{R_1}{R_2} = \frac{40}{60}$$

$$R_1 = \frac{2}{3}R_2 \quad \textcircled{1}$$

ATQ,

$$\frac{R_1 + 10}{R_2} = \frac{60}{40}$$

$$R_1 + 10 = \frac{3}{2}R_2 \quad \textcircled{2}$$

Substituting 1 in 2

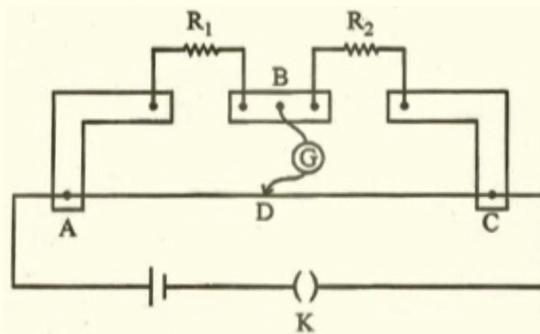
$$\frac{2}{3}R_2 + 10 = \frac{3}{2}R_2$$

$$10 = \frac{5}{6}R_2$$

$$R_2 = 12\Omega$$

$$R_1 = 12 \times \frac{2}{3}$$

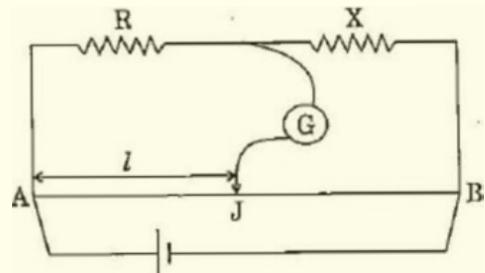
$$R_1 = 8\Omega$$



**Ques:** In the meter bridge experiment, balance point was observed at J with  $AJ = l$ .

- (i) The values of R and X were doubled and then interchanged. What would be the new position of balance point ?
- (ii) If the galvanometer and battery are interchanged at the balance position, how will the balance point get affected ?

(PYQ 2011)



**Ans:** i) We know,

$$\frac{R}{x} = \frac{l}{100 - l} \quad \textcircled{1}$$

ATQ,

$$\frac{2x}{2R} = \frac{l'}{100 - l},$$

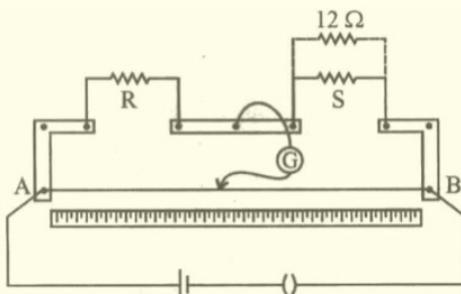
$$\frac{R}{x} = \frac{100 - l'}{l'} \quad \textcircled{2}$$

Comparing numerator and denominator of 1,2

$$l' = 100 - l$$

- ii) If the galvanometer and the battery is exchanged, the balance point will not be affected.

**Ques:** In a meter bridge, the null point is found at a distance of 40 cm from A. If a resistance of  $12\Omega$  is connected in parallel with S, the null point occurs at 50.0 cm. from A. Determine the values of R and S. (PYQ 2010)



**Ans:** We know,

$$\frac{R}{s} = \frac{40}{60}$$

$$R = \frac{2}{3}s$$

ATQ,

$$\frac{1}{5} = \frac{1}{s} + \frac{1}{12}$$

$$s' = \frac{12s}{12+s}$$

Now,

$$\frac{R}{\frac{12s}{s+12}} = \frac{50}{50} = 1$$

$$R = \frac{12s}{s+12} = \frac{2}{3}s$$

$$18 = s + 12$$

$$s = 6\Omega$$

$$R = \frac{2}{3}s$$

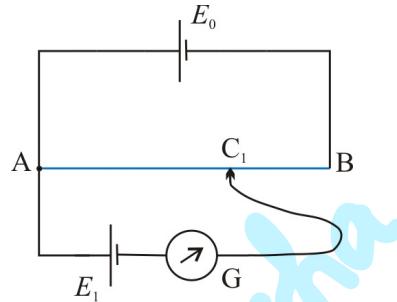
$$R = \frac{2}{3} \times 6$$

$$R = 4\Omega$$



## Potentiometer (PYQ 2020, 2016, 2014, 2013, 2012, 2010)

It is a device which used to measure the potential difference/ EMF without drawing any current from the voltage source.



### Principle

it works on the principle that when steady current flows through a uniform wire, the potential drop across a segment is directly proportional to the length of the segment i.e.

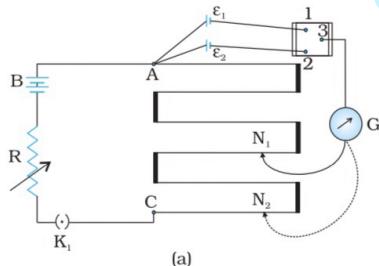
$$\epsilon(l) = \phi l$$

where  $\phi$  is the potential drop per unit length of the wire

### Applications

#### 1. Comparing EMFs of two cells

Consider two cells of emf  $\epsilon_1$  and  $\epsilon_2$ . First, we close the key of  $\epsilon_1$  and then move the jockey along the potentiometer wire. There will be a point( $N_1$ ) on the wire where if the jockey is kept, the current in the galvanometer becomes zero (balance condition). Let the distance of the balance point from A be  $l_1$ . Using Kirchhoff's law in the loop  $AN_1G31A$ ,



$$\phi l_1 + 0 - \epsilon_1 = 0$$

$$\epsilon_1 = \phi l_1$$

Now closing the key for  $\epsilon_2$  we get a balance point  $N_2$  at a distance  $l_2$  from A. using Kirchhoff's rule in loop  $AN_2$

$$\phi l_2 + 0 - \epsilon_2 = 0$$

Dividing both the equations we get,

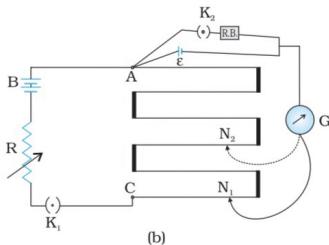
$$\epsilon_2 = \phi l_2$$

$$\frac{\epsilon_1}{\epsilon_2} = \frac{l_1}{l_2}$$

-This way we can compare emf of two cells and even calculate the emf of one cell if emf of the other is known

## 2. Calculating internal resistance of a cell (PYQ 2010)

Consider a cell with emf  $E$  and internal resistance  $r$ , connected across a resistance box through a key  $K_2$ . Keeping  $K_2$  open we obtain the balance point at a length  $l_1$ ; so, we can write



$$\epsilon_1 = \phi l_1$$

Now  $K_2$  is closed then balance point is obtained at a length  $l_2$ ,

$$V = \phi l_2$$

$$\frac{\epsilon}{V} = \frac{l_1}{l_2} - 0$$

We also know that if  $I$  is current,

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

$$\epsilon = I(R+r)$$

$$V = IR$$

$$\frac{\epsilon}{V} = \frac{(R+r)}{R} - ②$$

Dividing 1,2

$$\frac{R+r}{R} = \frac{l_1}{l_2}$$

$$1 + \frac{r}{R} = \frac{l_1}{l_2}$$

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

### Advantage

Advantage of potentiometer is that it gives the actual value of potential as it draws no current from the voltage source that is being measured

### Important PYQs

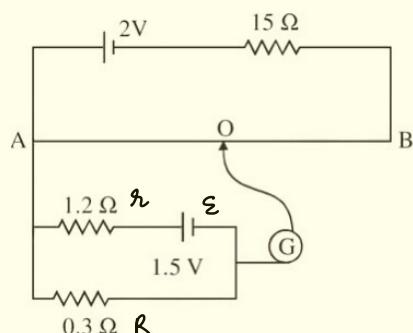


Ques: A potentiometer can measure emf of a cell because

- (A) the sensitivity of potentiometer is large.
- (B) no current is drawn from the cell at balance.
- (C) no current flows in the wire of potentiometer at balance.
- (D) internal resistance of cell is neglected. (PYQ 2020) (Ans- C)



Ques: In the following potentiometer circuit AB is a uniform wire of length 1 m and resistance 10 Ω. Calculate the potential gradient along the wire and balance length AO ( $= l$ ). (PYQ 2016)



**Ans:** To calculate the pot. Drop-

$$R_{eq} = 15\Omega + 10\Omega = 25\Omega$$

$$I = \frac{V}{R} = \frac{2}{25} A$$

$$V_{AB} = 10 \times \frac{2}{25} = \frac{4}{5} V$$

$$\phi = \frac{V_{AB}}{AB} = \frac{4}{5} \times V / m$$

To calculate the balancing length-

$$I = \frac{\epsilon}{R+r} = \frac{1.5}{1.2+0.3} = 1A$$

$$V = IR = 1 \times 0.3 = 0.3V$$

$$V = \phi l$$

$$l = \frac{V}{\phi} = \frac{0.3}{0.8} = \frac{3}{8} m$$

Ques: A potentiometer wire of length 1m has a resistance of  $10\Omega$ . It is connected to a  $6V$  battery in series with a resistance of  $5\Omega$ . Determine the emf of the primary cell which gives a balance point at 40cm. (PYQ 2014)

**Ans:** To calculate emf we have to first calculate the potential gradient

$$R_0 = 10 + 5 = 15\Omega$$

$$I = \frac{V}{R_0} = \frac{6}{15} = \frac{2}{5} A$$

$$V = IR_{AB} = \frac{2}{5} \times 10 = 4V$$

$$\phi = \frac{V_{AB}}{l} = 4 \times \frac{V}{m}$$

$$\epsilon = \phi l$$

$$\epsilon = 4 \times \frac{40}{100}$$

$$\epsilon = 1.6V$$

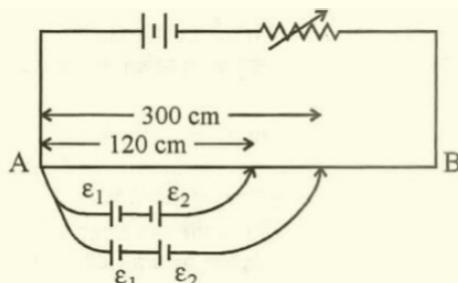
Ques: Write two possible causes for one sided deflection in a potentiometer (PYQ 2013)

**Ans:** 1. The emf of the cell whose emf is to be calculated is greater than the total potential drop across the potentiometer wire

2. The +ve and -ve terminals of the cell (whose emf is to be calculated) and the source battery may not be connected to the same terminal of the potentiometer wire

Ques: In the figure, a long uniform potentiometer wire AB having a constant potential gradient along its length. The null points of two primary cells of emfs  $\epsilon_1$  and  $\epsilon_2$  connected in manner shown are obtained at a distance of 120cm and 300 cm from the end A. Find (i)  $\epsilon_1/\epsilon_2$  and (ii) position of null point for cell  $\epsilon_1$

How is the sensitivity of a potentiometer increased? (PYQ 2010)



**Ans:** We can increase the sensitivity of a potentiometer by increasing the length of the potentiometer wire.

I) we know that,  $V \propto l$

$$\therefore \epsilon_2 + \epsilon_1 = \phi l_2$$

$$\frac{\epsilon_1 - \epsilon_2}{\epsilon_2 + \epsilon_1} = \frac{l_1}{l_2}$$

$$\text{If, } \frac{a}{b} = \frac{c}{d} \quad (\text{Componendo and dividendo})$$

$$\frac{a+b}{a-b} = \frac{c+d}{c-d}$$

$$\text{Let, } a = \epsilon_1 - \epsilon_2 \quad c = l_1$$

$$b = \epsilon_1 + \epsilon_2 \quad d = l_2$$

$$= \frac{\epsilon_1 - \epsilon_2 + \epsilon_1 + \epsilon_2}{\epsilon_1 - \epsilon_2 - \epsilon_1 - \epsilon_2} = \frac{l_1 + l_2}{l_1 - l_2}$$

$$\Rightarrow \frac{2\epsilon_1}{-2\epsilon_2} = \frac{l_1 + l_2}{-(l_2 - l_1)}$$

$$\Rightarrow \frac{\epsilon_1}{\epsilon_2} = \frac{120 + 300}{300 - 120} = \frac{420}{180} = \frac{7}{3}$$

$$\frac{\epsilon_1}{\epsilon_2} = \frac{7}{3}$$

$$\text{(ii)} \quad \frac{\epsilon_1 - \epsilon_2}{\epsilon_1 + \epsilon_2} = \frac{120}{300}$$

$$\epsilon_2 = \frac{3}{7}\epsilon_1$$

$$\frac{4}{10}\epsilon_1 = \frac{120}{300}$$

$$\epsilon_1 = 1V$$

