Current Electricity

Electric Current

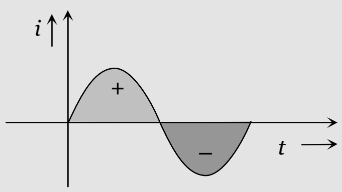
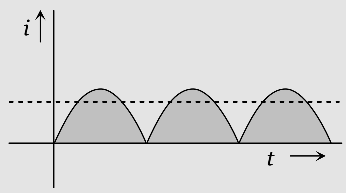
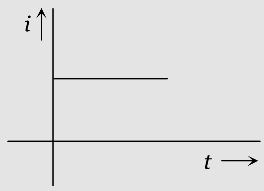
The time rate of flow of electric charge through any cross section is called electric current $i = \frac{dQ}{dt}$. It's S.I. unit is *ampere* (A). It is a scalar quantity but conventionally the direction of electric current is taken along the direction of flow of positive charge and opposite to the direction of negative charge.

(1) For a given conductor current does not change with change in its cross-section.

(2) Conductor remains uncharged when current flows through it.

(3) When 1 A current flows through a conductor, then 6.25×10^{18} electrons flow per second.

(4) Electric current is of two type :

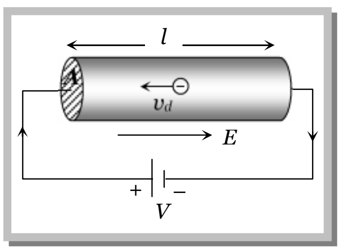
Alternating current (ac)	Direct current (dc)	
(i)  Magnitude and direction both varies with time	(Pulsating dc) 	(Constant dc) 
ac $\rightarrow$ Rectifier $\rightarrow$ dc	dc $\rightarrow$ Inverter $\rightarrow$ ac	
(ii) Shows heating effect only	(ii) Shows heating effect, chemical effect and magnetic effect of current	

(5) **Current density (J) :** The current density (J) at a point is defined as a vector having magnitude equal to current per unit area surrounding that point and normal to the direction of the charge flow, and direction in which current passes through that point. $|\vec{j}| = \frac{di}{dA}$. It's units is *amp/m*^{2}.

Conduction of Electricity Through Metals

Number of free electron per unit volume in a conductor is of the order of 10^{29}. At room temperature these electrons moves randomly with very high speed 10^5 *m/s* in available space between stationary positive ions of lattice. When a potential difference is applied electrons drift opposite to the field resulting in a current. Drift velocity is denoted by symbol v_d and it is of the order of 10^{-4} *m/s*.

(1) **Relation between drift velocity and current :** Consider a conductor of length l and area of cross-section A. Let the number of free electrons per unit volume be n. $\boxed{i = neAv_d}$



$$v_d = \frac{i}{neA} = \frac{J}{ne} = \frac{\sigma E}{ne} = \frac{E}{\rho ne} = \frac{V}{\rho l ne}$$

($J = \sigma E = \frac{E}{\rho}$ and $E = \frac{V}{l}$ *where* σ = conductivity, ρ = Specific resistance)

(2) **Mobility :** Drift velocity per unit field is termed mobility, *i.e.*, $\mu = \frac{v_d}{E}$

(3) With rise in temperature drift velocity decreases.

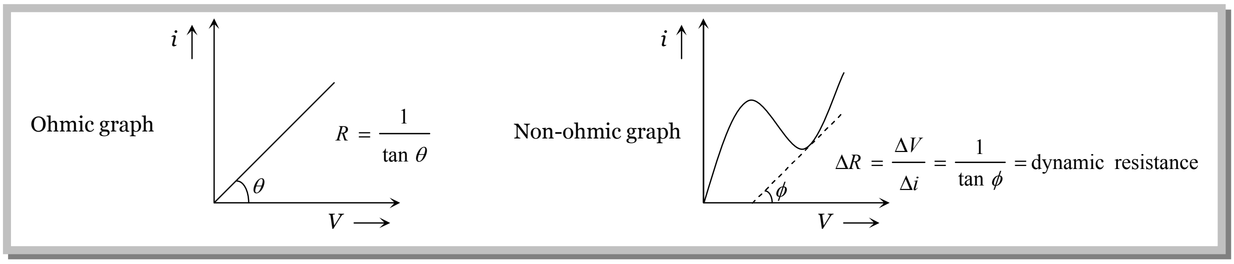
(4) Drift velocity changes with applied potential difference and length of the conductor but it dosen't depends upon the diameter of the conductor.

Ohm's Law

If physical conditions such as length, temperature etc. remains constant the current through a conductor is directly proportional to the potential difference across the conductor. So $\boldsymbol{V = iR}$; where R = resistance.

Since, $\frac{V}{i} = R =$ constant. So graph between V and i is a straight line passing through the origin and reciprocal of slope of this line is called resistance such graph is called ohmic graph.

(1) Ohm's law is not universal as it does not hold good in case of gases, crystal rectifiers, thermionic valves, transistor etc. The devices or substance which do not obeys ohms law are called non ohmic and graph between V and i is called non-ohmic graph (one which is not a straight line).



(2) **Resistance :** The property of substance due to which it opposes the flow of current in it is called resistance $R = \frac{V}{I} = \rho \frac{l}{A}$. where, l = length of conductor, A = area of cross-section of conductor, $\rho \left(= \frac{m}{ne^2 \tau} \right)$ = specific resistance or resistivity of conductor. It's unit = $\frac{Volt}{Amp.}$ or *ohm* (Ω).

Resistance depends upon (i) length as $R \propto l$ (ii) Area of cross-section $R \propto \frac{1}{A} \propto \frac{1}{r^2}$ (iii) Material $R \propto \frac{1}{n}$

(iv) Temperature $R \propto \frac{1}{\tau}$ (as temperature↑, τ ↓ so R↑). If R_0 is the resistance of a conductor at 0^oC and R_t is the resistance at t^oC temperature then $R_t = R_0(1 + \alpha t)$; where α is temperature coefficient of resistance ($\alpha_{conductor} = +ve$, $\alpha_{semiconductor} = -ve$, $\alpha_{insulator} = 0$). Also if R_1 and R_2 are the resistance respectively at temperature t_1 and t_2 then $\boldsymbol{R_2 = R_1 \{1 + \alpha(t_2 - t_1\}}$

Note : ❑ Reciprocal of resistance is called conductance. Conductance $(G) = \frac{1}{\text{Resistance } (R)}$. It's unit is *mho* or *Siemens*.

- Two resistance R_1 and R_2 are made of different materials. The temperature coefficient of material of R_1 is α and that of R_2 is β. The resistance of series combination of R_1 and R_2 will not change with temperature. If $\frac{R_1}{R_2} = \frac{\beta}{\alpha}$
- If a wire stretches, it's length increases, area of cross-section (radius) decreases but volume remains constant. So for the problems of stretching wire remember $\boldsymbol{R \propto l^2}$ and $\boldsymbol{R \propto \frac{1}{A^2} \propto \frac{1}{r^4}}$. Also remember if wire stretches to x%, it's resistance increases by $2x$% (valid only for < 10%).
- If length (l) and mass (m) of the wire is given then resistance of the wire $\boldsymbol{R \propto \frac{l^2}{m}}$.

(3) **Specific resistance or resistivity** – Resistivity is numerically equal to the resistance of a substance having unit area of cross section and unit length. It's unit is *ohm-metre.*

(i) Resistivity is numerically equal to the ratio of magnitude of electric field to current density. ($\rho = \frac{E}{J}$)

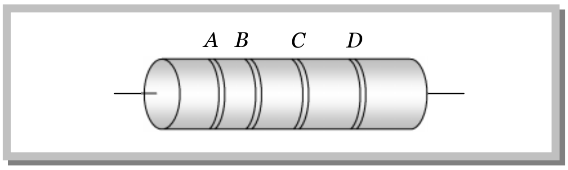
(ii) Reciprocal of resistivity is called conductivity or specific conductance (σ), *i.e,* $\sigma = \frac{1}{\rho}$ with units $\frac{mho}{m}$. $(\sigma_{Ag} > \sigma_{Cu} > \sigma_{Al})$

(iii) With change in shape and size of a body its resistivity ρ (or conductivity σ) will not change while resistance R will change.

(iv) With rise in temperature resistivity increases according to relation $\rho = \rho_0[1 + \alpha\Delta\theta]$ where α is temperature coefficients of resistivity.

Colour Coding of Resistance

In carbon resistance values are represented by four rings as shown in figure. Let us give names A, B, C and D to these to understand better. The colours of the strips are noted from left to right, *i.e.*, just opposite from the tolerance colour.



The first two rings (A, B) represent numbers 0, 1, 2, 3, 4, 5, 6, 7, 8 and 9. The third band C represents 10^0, 10^1, 10^2, 10^3, 10^4, 10^5, 10^6, 10^7, 10^8 and 10^9. The fourth ring may be of two types, if it is golden polished it represents 5% tolerance and if it is of silver polished it represents 10% of tolerance. A chance of absence of this fourth ring is also there, this indicates 20% of tolerance (means indicated value of carbon resistance may vary with this much percentage on both sides, *i.e.* ±).

Colour	Black	Brown	Red	Orange	Yellow	Green	Blue	Violet	Gray	White
Number	0	1	2	3	4	5	6	7	8	9
Multiplier	10^0	10^1	10^2	10^3	10^4	10^5	10^6	10^7	10^8	10^9

To remember keep the sentence in mind – ***B B R O Y Great Britain Very Good Wife.***

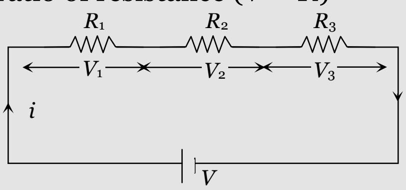
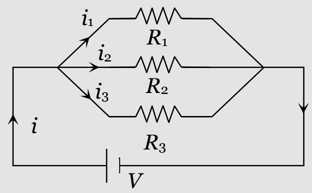
Note : - Suppose colour band sequence is green, brown, yellow and gold. Then, it's resistance will be $R = 51 \times 10^4 \pm 5\% \ \Omega$.

Thermistors

A thermistor is a highly heat sensitive resistor usually made up of semi-conductor materials. Themistors can be of two types – (1) With positive temperature coefficient of resistivity *i.e.* the resistivity of this type of thermistor increases with the rise of temperature. (2) With negative temperature coefficient of resistivity *i.e.*, the resistivity of this type of thermistor decreases with the rise of temperature. Such thermistors have wide applications.

Temperature coefficient of resistivity of a thermistor is very high and resistance of a thermistor changes very rapidly with change in temperature. A thermistor with negative temperature coefficient of resistivity is used in resistance thermometers to measure very low temperatures of the order of 10 *K*. They are also used in the protective circuits of electrical equipment like transformers, motors and generators.

Combination of Resistances

Series combination	Parallel combination
(1) Same current flows through each resistance but p.d distributes in the ratio of resistance ($V \propto R$) $V = V_1 + V_2 + V_3$; $R_{eq} = R_1 + R_2 + R_3$ 	(1) Same p.d. appears across each resistance but current distributes in the reverse ratio of resistance ($i \propto \frac{1}{R}$) $i = i_1 + i_2 + i_3$ $\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$ or $R_{eq} = (R_1^{-1} + R_2^{-1} + R_3^{-1})^{-1}$ 
(2) If n identical resistance, are connected in series, then $R_{eq} = nR$ and potential difference across each resistance, $V' = V/n$	(2) If n identical resistances, are connected in parallel, the equivalent resistance $R_{eq} = R/n$ and current through each resistance = i/n .
(3) Potential difference across any resistance in series $V' = \left(\frac{R'}{R_{eq}}\right).V$ R' = across which p.d is to be determined R_{eq} = equivalent resistance of the series, V = net p.d. across the series	(3) Current through any branch in parallel $i' = i \times \left[\frac{\text{Resistance of opposite branch}}{\text{Total resistance}}\right]$

Cell

Cell is a device which converts chemical energy into electrical energy.

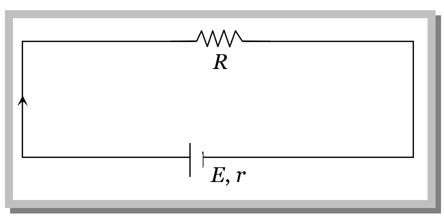
(1) **E.m.f. (E) :** It is the potential difference across the cell when it is not giving any current.

(2) **Potential difference (V) :** It is the difference between the potential of electrodes of the cell.

(3) **Internal resistance (r)** : The opposition offered by the electrolyte of the cell to the flow of current is called internal resistance of the cell. The internal resistance of a cell depends on the distance between electrodes $(r \propto d)$ and immersed area of electrodes $[r \propto (1/S)]$, concentration $(r \propto C)$ and temperature of electrolyte $[r \propto (1/temp.)]$.

(4) **Cell in different position :**

(i) **Close circuit :** Current through the circuit $i = \frac{E}{R + r}$



(a) Potential difference across the resistance $V = iR$

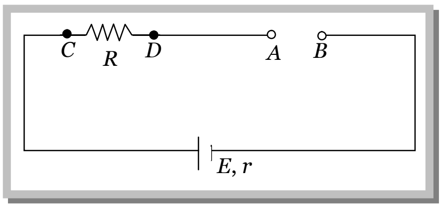
(b) Potential drop in the cell = ir; Equation of cell $\boldsymbol{E = V + ir}$ $(E > V)$

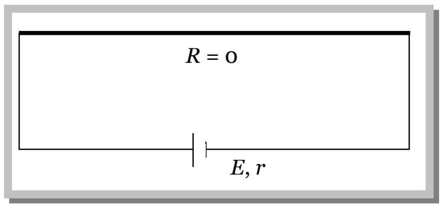
(c) Power dissipated in resistance $P = Vi = i^2R = \frac{V^2}{R}$; Condition for maximum power $\boldsymbol{R = r}$ $\left(P_{max} = \frac{E^2}{4r}\right)$

(d) When cell in charging position then $E = V - ir$ $(E < V)$

Note : ❑ When an external resistance is R_1 connected across the cell (E, r), current through is i_1. When resistance becomes R_2 current through the resistance is i_2 then $\boldsymbol{E = \frac{i_1 i_2}{(i_2 - i_1)}(R_1 - R_2)}$ and $\boldsymbol{r = \frac{(i_2 R_2 - i_1 R_1)}{(i_1 - i_2)} = \frac{(V_2 - V_1)}{(i_1 - i_2)}}$

(ii) **Open circuit and short circuit**





Current through the circuit $i = 0$

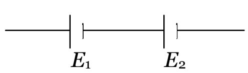
Potential difference between A and B, $V = E$

Potential difference between C and D, $V = 0$

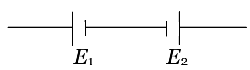
Maximum current (short circuit current) flows momentarily $i_{sc} = \frac{E}{r}$ $(V = 0)$

(5) **Grouping of cell**

(i) **Series grouping :** In series grouping of cell their emf's are additive or subtractive.



$E_{eq} = E_1 + E_2$

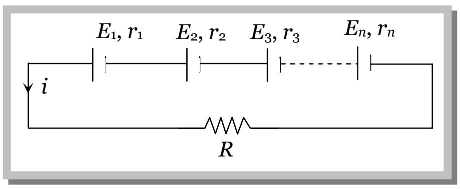


$E_{eq} = E_1 - E_2$ $(E_1 > E_2)$

If polarity of one cell is reversed it cancel out the effects of two cells but equivalent internal resistance will remain same.

If n identical cells each having emf E and internal resistance r are connected in series. If x cell are reversed from this combination then $E_{eq} = nE - 2xE$ and $r_{eq} = nr$, n - number of Total cells, x - number of reversed cells.

If *n* identical cell are connected in series as shown



(a) $E_{eq} = nE$

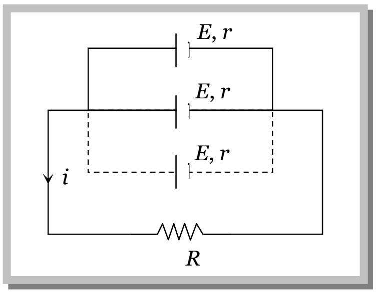
(b) $r_{eq} = nr$

(c) $i = \frac{nE}{R + nr}$ = current from each cell

(d) p.d. across each cell $V' = \frac{V}{n} = \frac{iR}{n}$ (if cells are not identical then $V_1 = (E_1 - ir_1)$ *etc.*)

(e) Condition for maximum power $R = nr \left(P_{max} = n\frac{E^2}{4r} \right)$

(ii) Parallel grouping

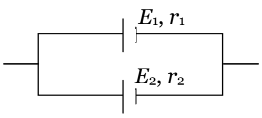


(a) $E_{eq} = E$ (b) $R_{eq} = \frac{r}{n}$ (c) Main current $i = \frac{E}{R + r/n}$

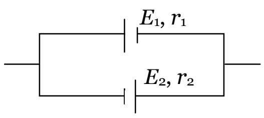
(d) $V = iR$ = potential difference across each cell

(e) Current from each cell $i' = \frac{i}{n}$ (if cells are not identical then $i_1 = (E_1 - iR)/r_1$ etc.)

(f) If two non identical cell are connected in parallel as shown.

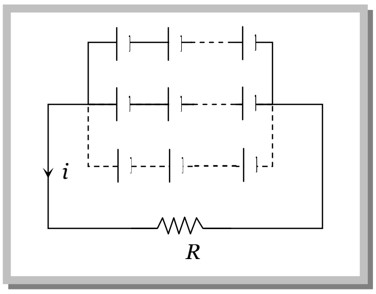


$$E_{eq} = \frac{E_1 r_2 + E_2 r_1}{r_1 + r_2}$$



$$E_{eq} = \frac{E_1 r_2 - E_2 r_1}{r_1 + r_2}$$

(iii) **Mixed grouping** : If suppose n identical cells are connected in a series and such type of m rows are connected in parallel.



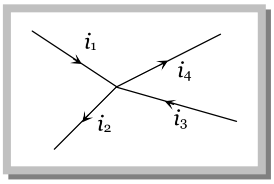
(a) $E_{eq} = nE$ (b) $r_{eq} = \frac{nr}{m}$ (c) $i = \frac{nE}{R + \frac{nr}{m}} = \frac{mnE}{mR + nr}$

(d) Condition for maximum power is $R = \frac{nr}{m}$; $P_{max} = mn\left(\frac{E^2}{4r}\right)$

(e) Total No. of cells in this combination = $m \times n$.

Kirchhoff's Rules

(1) **Kirchoff's current law (KCL)** : In a circuit, at any junction the sum of the currents entering the junction must equal the sum of the currents leaving the junction.

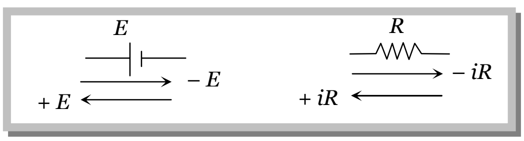


Thus, $i_1 - i_2 + i_3 - i_4 = 0$ or $i_1 + i_3 = i_2 + i_4$

It is based on the ***Law of conservation of charge*** and is commonly known by the point rule.

(2) **Kirchoff's voltage law (KVL) :** It is also called closed loop law, according to it, the algebraic sum of e.m.f.'s present in a closed loop of an electrical circuit is equal to the algebraic sum of product of resistance and their corresponding currents. *i.e.*, $\sum emf = \sum iR$. Following sign conventions should be followed by rounding a trip around the close circuit.

This law is based on ***law of conservation of energy***.

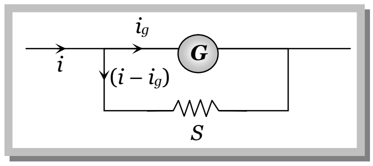


Measuring Instruments

(1) **Galvanometer :** Galvanometer detects the presence of current in the branch where it is connected. It does not measure current.

(2) **Ammeter :** It is an instrument that measures current in the branch where it is connected in series. It's resistance should be small enough (The resistance of an ideal ammeter is zero).

Conversion of galvanometer into ammeter : A galvanometer may be converted into an ammeter by connecting a low resistance (called shunt S) in parallel to the galvanometer G as shown.



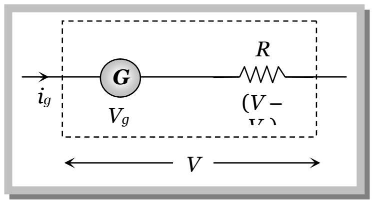
(i) Equivalent resistance of combination = $\frac{GS}{G+S}$

(ii) Necessary shunt $S = \left(\frac{i_g}{i - i_g}\right)G$ where i_g is full scale deflection current of galvanometer, i = current which is to be measured; G = resistance of the galvanometer.

(iii) To pass n^{th} part of main current (*i.e.*, $i_g = i/n$) thorough the galvanometer, required shunt $\boldsymbol{S = G/(n - 1)}$

(3) Voltmeter : It is an instrument that measures voltage across any two points in a circuit. It is always connected in parallel with the branch across which it has to measure the voltage. It's resistance should be large enough (an ideal voltmeter has infinite resistance).

Conversion of galvanometer into voltmeter : A galvanometer may be converted into a voltmeter by connecting a large resistance in series with the galvanometer as shown.

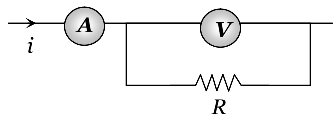


(i) The magnitude of the high resistance is given by $R = \frac{V}{i_g} - G$; where V is the maximum voltage to be measured

(ii) If n^{th} part of applied voltage appeared across galvanometer (*i.e.* $V_g = V/n$) then required series resistance $\boldsymbol{R = (n - 1)G}$

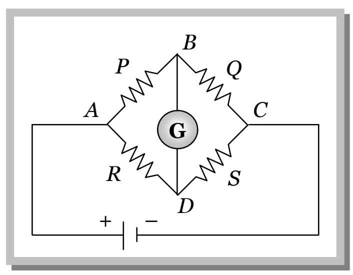
Note : ❑ If an ammeter is connected in parallel to a circuit it is likely to be damaged due to excess current.

❑ Measured value of practical ammeter and voltmeter are not the exact values but some error is observed. e.g. in the shown figure. $R > V/i$



26.10 Wheatstone Bridge

If in a network resistances are arranges as shown in figure, network is called Wheatstone Bridge in which arm AB and BC is called ratio arm. The bridge is said to be balanced if $\frac{P}{Q} = \frac{R}{S}$. In balanced bridge point B and D are at same potential so no current flows galvanometer G. Exchange of position of galvanometer and battery doesn't affect the balance of bridge. That's why the arms AC and BD are called conjugate arms.



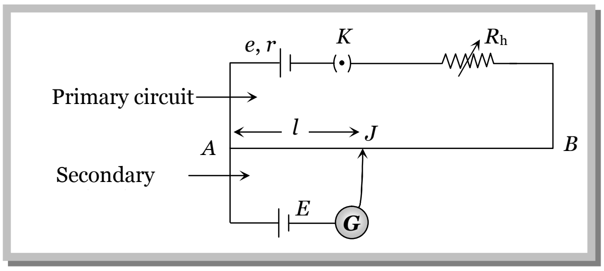
Note : ❑ Meter bridge is an instrument based on the principle of wheatstone bridge. It's used to find the value of unknown resistance $S = \left(\frac{100 - l}{l}\right)R$, where R is the known resistance and l is balancing length on wire of $1m$ length.

❑ In meter bridge or wheatstone bridge for measurement of resistance the known and unknown resistance are interchanged to remove **end correction**.

- The sensitivity of the bridge depends upon the values of resistances. The bridge in most sensitive when all the four resistances are of the same order.

26.11 Potentiometer

It is an instrument for accurate measurement of the potential difference and emf. Based on no deflection method, it does not draw current from cell or circuit, that is, it works as an instrument of infinite resistance.



(1) Primary circuit consist of a battery of emf e, intern at resistance and some other resistance R_h (Rheostat), then current in the primary circuit $i = \frac{e}{(R + R_h + r)}$ where R = resistance of potentiometer wire.

(2) The fall of potential per unit length of potentiometer wire is called potential gradient (x). It's unit is $\frac{V}{m}$ or $\frac{V}{cm}$; $x = \frac{V}{L} = \frac{iR}{L} = \frac{i\rho}{\pi a^2} = \frac{e}{(R + R_h + r)} . \frac{R}{L}$ where V = p.d. across potentiometer wire, L = length of potentiometer wire, ρ = resistivity of potentiometer wire, a = radius of potentiometer wire.

(3) If unknown cell (E) is balanced over the length l of the potentiometer wire, then $E = xl = \frac{V}{L} \times l = \frac{iR}{L} \times l = \frac{e}{(R + R_h + r)} . \frac{R}{L} \times l$

(4) A potentiometer is said to be more sensitive if it measures a small potential difference more accurately.

$$\text{Sensitivity} \propto \frac{1}{\text{Potential gradient}} \propto \text{Length } (L)$$

If any emf E is balanced at l_1 length when the total length of potentiometer wire is L_1. Now if the length of potentiometer wire is changed to L_2 and corresponding balancing length is l_2 then $l_2 = \left(\frac{L_2}{L_1}\right) \times l_1$. Change in balancing length $\Delta l = (l_2 - l_1)$.

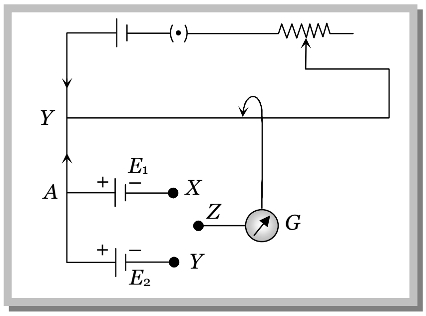
(5) **Dependence of potential gradient**

(i) x directly depends upon : (a) The resistance per unit length of potentiometer wire (R/L) (b) The radius of potentiometer wire (a). (c) The specific resistance of the material of potentiometer wire (ρ) (d) The current flowing through potentiometer wire.

(ii) x indirectly depends on : (a) The emf of battery in the primary circuit (e) (b) The resistance of rheostat in the primary circuit (R_h) (c) The total resistance of potentiometer wire R and its total length L ($\because R = \rho L$) (d) When potential difference V is constant. Then $\frac{x_1}{x_2} = \frac{L_2}{L_1}$ (e) When two wires of length L_1 and L_2 and resistances R_1 and R_2 are joined together to form the potentiometer wire, then $\frac{x_1}{x_2} = \frac{R_1}{R_2}\frac{L_2}{L_1}$ (f) Maximum potential gradient $x_{max} = \frac{eR}{L(R + r)}$, Minimum potential gradient $X_{min} = \frac{eR}{L(R + R_h + r)}$.

(iii) **Standardization of potentiometer :** The process of determining potential gradient experimentally is known as standardization of potentiometer. If suppose the balancing length for emf E_o of a cell is l_o and that for unknown potential V is l, then $E_0 = x_0 l_0$ or $x = \frac{E_0}{l_0}$; $V = xl = \left(\frac{E_0}{l_0}\right) l$

(6) **Application of potentiometer**



To compare the emf's of two cells.

$E_1 = l_1 x$ and $E_2 = l_2 x$ so $\frac{E_1}{E_2} = \frac{l_1}{l_2}$

If two cells support each other, then balancing length is l_1 and when they oppose each other then balancing length is l_2, then

$$\frac{E_1 + E_2}{E_1 - E_2} = \frac{l_1}{l_2} \text{ or } \frac{E_1}{E_2} = \left[\frac{l_1 + l_2}{l_1 - l_2}\right]$$