CURRENT ELECTRICITY

Electric charges in motion constitute an electric current. The rate of flow of electric charges through a given area of a conductor is defined as electric current.

Electric current, $I = q/t$.

* The above expression represents steady current
* when the current is not steady, then

$$I = \frac{dq}{dt}$$

where dq is the net amount of charge flowing through a conductor during the time interval dt.

* By convention, the direction of current flow is positive to negative. Actually, in conductors charge carriers are $\bar{e}$s which flow from negative to positive, hence the flow of $\bar{e}$s is opposite to the direction of conventional current.
* It is a scalar quantity. Though it possess both magnitude & direction, it does not obey vector laws, hence treated as a scalar.

FLOW OF ELECTRIC CHARGES IN A CONDUCTOR IN THE PRESENCE OF AN EXTERNAL FIELD

* when no external field is applied across a conductor, the free $\bar{e}$s present in the conductor are in random motion due to their thermal velocities or energies analogous to random motion of molecules in a gas (of the order of 10^5 m/s).

At a given time, there is no particular direction of the flow of these $\bar{e}$'s, hence there is no net current in the absence of electric field. (as the no. of $\bar{e}$'s travelling in any direction will be equal to no. of $\bar{e}$'s travelling in the opposite direction).

Relation

* This is due to the fact, that as these $\bar{e}$'s move in a conductor, they continuously collide among each other and with positive ions and get scattered in different direction. This accounts for their randomness in their velocities.

* When an electric field is applied (by means of a cell) across the ends of a conductor, the free $\bar{e}$'s get accelerated from negative towards the positive terminal due to electrostatic force of attraction.

* Due to this, there is a flow of electric current in a direction opposite to the direction of electric field so long as the field is maintained b/w the ends.

* The applied electric field ceases the random motion of free $\bar{e}$'s and tends to give it a guided motion (i.e. from negative end to positive end).

DRIFT VELOCITY

The average velocity acquired by the electrons in a conductor with which they drift across the conductor in a direction opposite to that of the applied external field is called <u>drift velocity</u>

Relation b/w drift velocity and electric field ②

In the absence of an electric field, the $\bar{e}$s are in random motion which suffer collisions among each other and with positive ions and hence their average velocity will be zero. If there are 'N' $\bar{e}$s in a conductor, the velocity of the i^{th} $\bar{e}$ is

$$\frac{1}{N}\sum_{i=1}^{N} v_i = 0$$

When an electric field $\vec{E}$ is applied, the $\bar{e}$s get accelerated due to this field. The acceleration is given by

$$a = \frac{-eE}{m}$$

$\left[\because F = ma \quad a = \frac{F}{m}\right.$

$F = qE$

here $q = -e$

where '$-e$' is the charge and 'm' is the mass of the $\bar{e}$. Consider i^{th} electron at any instant t, then if 't_i' is the time elapsed after its last collision, then its velocity will be

$$V_i = v_i + \frac{-eE}{m} t_i$$

$v = u + at$

$\downarrow \quad \downarrow \frac{-e}{m}$

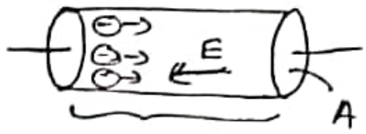
0

$$V_i = 0 - \frac{eE}{m} t_i$$

As the collisions of the $\bar{e}$s do not occur at regular intervals but at random, the average time between subsequent collisions is considered. It is called relaxation time denoted by 'τ' which is the average time two successive collisions.

Thus average velocity gained will be the given by:

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



Relation b/w Drift velocity and current

Consider a metallic conductor of length l and area of cross section A. If e is the charge on an electron 'n' the number density (no. of $\bar{e}$s per unit volume ie $n = \frac{N}{V}$ or $N = nV$), then total charge in the Conductor is,

$$\boxed{Q = nAle}$$

$$\left[\begin{array}{l} N = nV \\ \quad = nAl \\ Q = Ne \\ \quad = nAle \end{array}\right]$$

when a potential difference 'V' is applied b/w the ends of the conductor by means of a cell, a current I flows.

Magnitude of drift velocity V_d in the conductor is

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

∴ time taken by the free $\bar{e}$s to cross the length of the conductor

$$t = \frac{l}{V_d}.$$

The electric current flowing across a conductor in a time duration 't' is

$$I = Q/t = \frac{nAle}{l/V_d} = neAV_d$$

Expression for resistivity

The current flowing in a conductor of length 'l', area of cross section 'A' with N free electrons in it is given by

$$\boxed{I = neAV_d}$$ where n is the number density, $n = \frac{N}{V}$

The current density, j is given by (current flowing per unit area of cross section)

$$\vec{j} = \frac{I}{\vec{A}} = \frac{ne\cancel{A}V_d}{\cancel{A}} = neV_d.$$

The drift velocity is

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

Subs. for V_d

$$j = ne\left(\frac{eE\tau}{m}\right) = \left(\frac{ne^2\tau}{m}\right)E. \quad \text{--- (1)}$$

The vector form of Ohm's law is

$$\vec{J} = \sigma\vec{E} \quad \text{--- (2)}$$ where σ is the conductivity of the material.

Comparing ① and ②

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

Resistivity, $\boxed{\rho = \frac{1}{\sigma} = \frac{m}{ne^2\tau}}$

Mobility : The mobility (μ) is defined as magnitude of drift velocity per unit electric f[ield]

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

$$V_d = \frac{eE\tau}{m}, \text{ ie } \mu = \frac{\frac{e\cancel{E}\tau}{m}}{\cancel{E}} = \frac{e\tau}{m}.$$

[e & m are the charge & mass of the $\bar{e}$ and τ is the relaxation time]

SI unit of mobility is m^2/Vs

Limitations of Ohm's Laws

(i) V ceases to be proportional to I ie V and I is linear for certain range of I. (when large current flows through a conductor, value of R increases due to joule heating effect and hence relation b/w V and I becomes non linear).

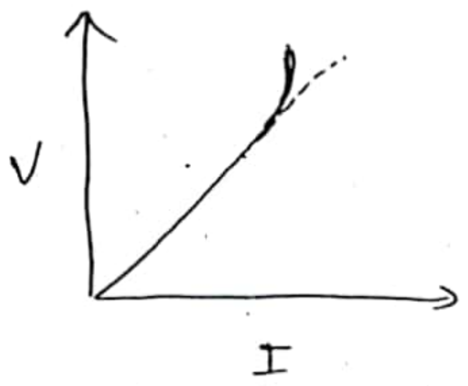


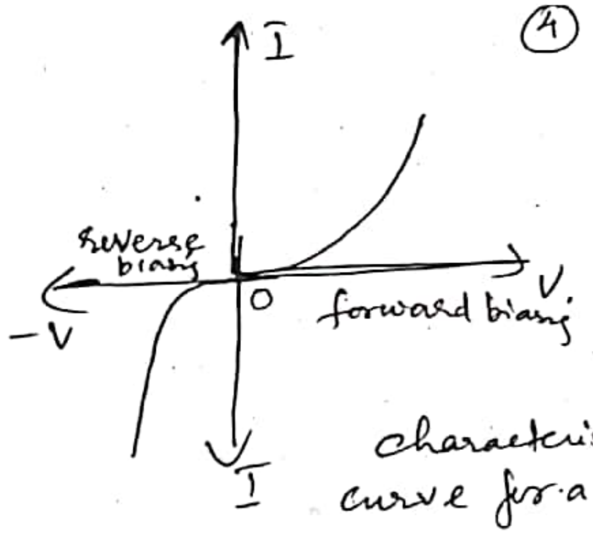
fig (-i)

The dashed line represent linear ohm's law. The solid line represents actual V–I graph for a conductor.

) The relation b/w V and I depends on the sign of V ie if I is the current for a certain V, then reversing the direction of V keeping its magnitude constant, does not give same current as in the previous case. This is exhibited by semi conductor diodes as shown in the graph (ii).

(4)

* The relation b/w V and I is not unique i.e there is more than one value for the same current I. Compound semi conductors like GaAs exhibit such behaviours as shown in fig (iii)



characteristic curve for a diode.

fig (ii)

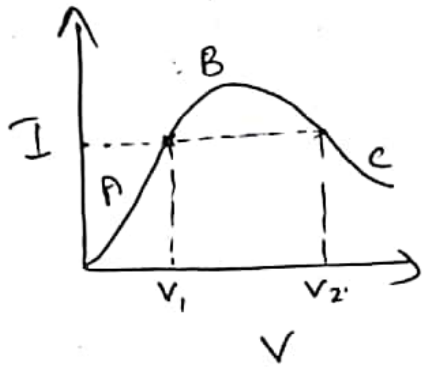


fig (iii).

A → B non linear region with positive slope.

B → C negative resistance region.

Resistivity of Various Materials

Refer the table in text book (Pg. 101) for resistivities of common materials. Materials are classified as conductors, semi conductor and insulators based on their resistivities.

* Resistor are available in two major types
  - → wire bound resistor
  - → Carbon resistors.
* Wire bound resistors are made by winding the wire of an alloy viz Manganin or Nichrome.
* They are made of alloys due to the fact that their

resistivities are relatively independent of tempera temp

* They are available in a range of few ohms to few thousands or hundreds Ω.

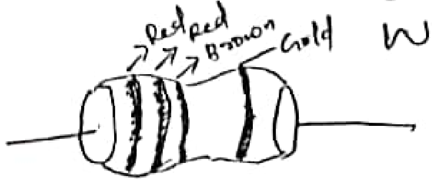
* Resistors of higher range are made mostly from Carbon (ranges from few Ω to Mega Ω.)
* They are compact, cheap and have extensive use in electronic devices.

* There is a colour code system to find the resistance of a given resistor
  * They have a set of coloured rings on them
    - → 1^{st} colour indicates first significant figure.
    - → 2^{nd} colour " 2^{nd} " "
    - → 3^{rd} colour gives the decimal multiplier (power to which 10 is raised).
    - → 4^{th} band is for tolerance or probable variation in percentage about the value of resistance.

Black	Brown	Red	Orange	Yellow	Green	Blue	Violet	Grey	White
B	B	R	O	Y	G	B	V	G	W
0	1	2	3	4	5	6	7	8	9

(Remember it as B B ROY of Great Britain has a Very Good Wife)

Gold	5%
Silver	10%
No colour	20%

Eg: 

$22 \times 10^1 \pm 5\%$

$(220 \pm 5\%)\,\Omega$

Temperature Dependence of Resistivity

* The resistivity of a material depends on the temperature.
* The resistivity of a metallic conductor at a temperature is given by the relation

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

where ρ_T – resistivity at a temp. T

ρ_0 – resistivity at a reference temp T_0 (say at $0°C$ or $273K$)

α – temperature coefficient of resistivity.

* α is defined as the change in resistivity to the initial resistivity $\left(\Delta\rho/\rho_0\right)$ per unit change in temperature.

$$\alpha = \frac{(\rho - \rho_0)}{\rho_0} \times \frac{1}{(T - T_0)} = \frac{\Delta \rho}{\rho_0 \Delta T}$$

S.I unit of α is $/K$ and common unit is $/°C$

* α is positive for metals.

Plot of Resistivity versus Temperature

(i) Conductors: For conductors, resistivity is

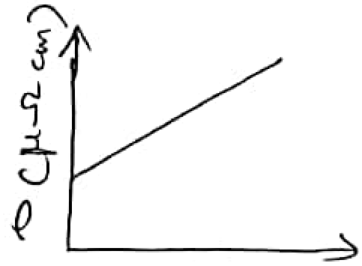
$$\rho = \frac{m}{n e^2 \tau}$$

$m, e \rightarrow$ mass & charge of an e^-

As the temperature increases, the average speed of $\bar{e}$s increases resulting in frequent collisions. Thus average time b/w successive collisions decreases, ie τ decreases. Hence ρ increases as per the above relation. n is almost independent of ρ.

[$n \to$ no. of $\bar{e}$s
$\tau \to$ relaxa. t.

Plot of 'ρ' versus T for pure metal (Cu).

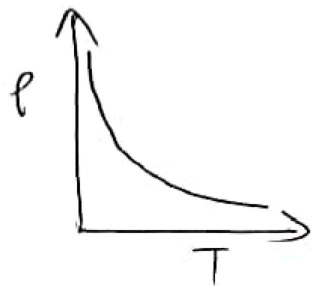


Plot of 'ρ' versus T for alloy like Nichrome.
(ρ is almost independent of Temp).

(ii) Semi Conductors

In case of semiconductors, as the temp. increases, the number density increases ie more $\bar{e}$s become available for conduction and is more dominant on any change in decrease in τ ie according to the eqn, $\rho = \frac{m}{ne^2\tau}$,

as n increases, 'ρ' decreases for a semi conductor.



Plot of ρ versus T for semi conductor.

$$\boxed{R_T = R_0[1 + \alpha(T - T_0)]}$$

$\frac{R_T}{R_0} = 1 + \alpha(T$

Also $$\boxed{\alpha = \frac{R_T - R_0}{R_0(T - T_0)}}$$

$\frac{R_T}{R_0} - 1 = \alpha(T - T$

$\frac{R_T}{R_0} - 1 \Big/ T - T_0 = \alpha.$

[At absolute zero or 0K → an insulator offers resistance to flow of current. For a semicondu it becomes an insulator at 0K. Conversely for conductor, at 0K, the resistivity zero ie no resistance is offered to the flow o current or infinite conductivity. Such a co is called super conductor].

Heating Effect of electric current

* Whenever an electric current is passed a conductor, it becomes hot. This effect is c heating effect of electric current.

* Many electrical appliances like Oven, te Geyser, Bulb etc work on this heating effect.

* Joule studied experimentally and conclud that the amount of heat produced in a conductor when a current I flows throug conductor of resistance R for time 't' is

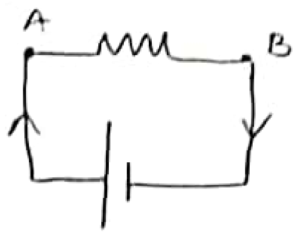
$$\boxed{H = I^2 R t}$$

known as Joule's Law of Heating.

Electrical energy and Power

Consider a conductor of resistance R connected across a cell such that current is flowing from A to B.

As current is flowing from A to B



$V_A > V_B$ and pot. diff. across AB is $V = V_A - V_B > 0$

Suppose in a time interval Δt, ΔQ amount of charge flows, then

$$\Delta Q = I \Delta t$$

The change in potential energy in moving from A to B

$$\Delta U = \text{Final P.E} - \text{Initial P.E}$$

$$= \Delta Q [V_B - V_A]$$

$$\Delta U = -\Delta Q V = -VI\Delta t < 0.$$

If the charges were moving in the conductor without any collisions, their kinetic energy will also change such that total energy remains unchanged.

According to law of conservation of energy,

$$\Delta K + \Delta U = 0$$

or $$\Delta K = -\Delta U = -(-VI\Delta t)$$

$$= VI\Delta t > 0.$$

* So as the charges move under the influence of an external electric field, they accelerate.
* The charges as they eventually collide with the positive ions and atoms, the K.E gained by them is shared among the ions.

As a result, the atoms start vibrating more vigorously which leads to heating of the conductor.

The amount of energy dissipated as heat during the time interval Δt is

$$\Delta H = \Delta W = VI\,\Delta t .$$

* The electrical energy supplied by the cell or total work in maintaining the current for a given time

is $W = VIt$.

* The rate of doing work or energy dissipated per unit time is the power dissipated

$$P = \frac{W}{t} = VI = I^2R = \frac{V^2}{R}.$$

This is the 'ohmic loss' or Power Loss in a conductor of resistance 'R' carrying a current 'I'.

For eg: It is this electrical power which heats up the filament of a bulb to incandescence giving out heat and light.

[SI unit of power is watt (W) or $J s^{-1}$

$$1W = 1V \times 1A = 1AV$$

Higher units are kilowatt (kW) and megawatt (MW)

Commercial unit is horse power (hp)

$$1hp = 746W$$

Commercial unit of electrical energy is kilowatt hour (kWh)

$$1kWh = 1000W \times 3600s$$
$$= 3.6 \times 10^6 J$$]

Application of power Loss :

* Electrical power is transmitted from power Sta, to homes and factories through transmission Cab which may be long distance away.

* Power loss through these cables should be kept minimum. For this, consider an electric device of resistance R to which a power P is to be delivered through transmission cables of resistance R_c. If V is the voltage across R & I is current through it, then $P = VI$ or $I = \frac{P}{V}$

The power dissipated in the transmission cables

$$P_c = I^2 R_c = \frac{P^2}{V^2} R_c .$$

By the above expression, it is seen that to drive an electric device of power P, the wasted power in the cables is inversely proportional to V^2

i.e. $P_c \propto \frac{1}{V^2}$

* Thus these wires carry currents at huge values of V to minimise P_c.

* This is acheived by a device called transformers, which steps up the voltage from the power stations, and steps it down at the other end to a suitable value for use at homes & factories.

Limitations

Static
Variable

Resistivity (or specific resistance : It is defined as the resistance offered by a wire of material of 1 metre length and 1 square metre cross sectional area. Denoted by 'ρ'

* It depends only on the material and is independent of dimensions at a given temperature.
* The SI unit of resistivity is ohm metre (Ωm)

Conductivity : It is defined as the current flowing per unit area per unit electric field. Denoted by 'σ'

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

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

* It depends on the nature of material, relaxation time and number density.
* It is the reciprocal of resistivity

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

* SI unit is $\Omega^{-1} m^{-1}$ (or mho m^{-1}) or $S m^{-1}$

Temperature dependence of resistivity

The resistivity (ρ) of a metallic conductor, over a limited range of temperature (T) is given by the relation $\rho_T = \rho_0 [1 + \alpha (T - T_0)]$

ρ_0 — resistivity of the material at a reference temp T_0

T_0 → reference temp. (usually $0°C$ or $273\,K$)

α – temp. coefficient of resistivity of the material.

$$\therefore \alpha = \frac{\rho_T - \rho_0}{\rho_0 (T - T_0)} = \frac{\Delta \rho}{\rho_0 \Delta T}$$

Super Conductivity

Some substance lose their resistance when cooled below a certain temp. These substances are called super conductors and temp. below which they lose resistance is called transition temp.]

Combination of Powers of Resistors or (devices) in (a) Series (b) parallel. operated at same voltage V.

(a) Series Combination

$$R_{eq} = R_1 + R_2 \quad -(1)$$

As the devices are operated at same voltage, Series = Const. I

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

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

$$\therefore R_1 = \frac{V^2}{P_1} \text{ and } R_2 = \frac{V^2}{P_2}$$

$$\therefore R_{eq} = \frac{V^2}{P_1} + \frac{V^2}{P_2}$$

$$\text{Also } R_{eq} = \frac{V^2}{P_{eq}}$$

$$\therefore \frac{V^2}{P_{eq}} = \frac{V^2}{P_1} + \frac{V^2}{P_2}$$

ie $$\boxed{\frac{1}{P_{eq}} = \frac{1}{P_1} + \frac{1}{P_2}}$$

Combination of Power in series

$P = VI$, $R = V^2/R$

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(ii) Parallel Combination

& Net resistance,

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} \quad -(1)$$

$$R = \frac{V^2}{P} \quad \text{or} \quad \frac{1}{R} = \frac{P}{V^2}$$

Substituting, $\dfrac{P_{eq}}{V^2} = \dfrac{P_1}{V^2} + \dfrac{P_2}{V^2}$

$\therefore \boxed{P_{eq} = P_1 + P_2}$ combination of power in parallel.

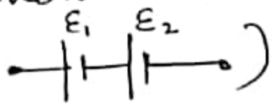
Cells in series and parallel.

[for derivation refer text book].

Series

$$V = \mathcal{E}_{eq} - I r_{eq}.$$

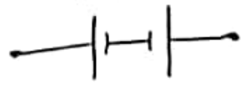
where $\mathcal{E}_{eq} = \mathcal{E}_1 + \mathcal{E}_2$ (when connected



)

$r_{eq} = r_1 + r_2$

[$\mathcal{E}_{eq} = \mathcal{E}_1 - \mathcal{E}_2$ when connected opposing each other ie



].

Parallel

$$V = \mathcal{E}_{eq} - I r_{eq}$$

$$= \left[\frac{\mathcal{E}_1 r_2 + \mathcal{E}_2 r_1}{r_1 + r_2}\right] - I\left[\frac{r_1 r_2}{r_1 + r_2}\right]$$

$$\therefore \mathcal{E}_{eq} = \frac{\mathcal{E}_1 r_2 + \mathcal{E}_2 r_1}{r_1 + r_2} \quad \text{and} \quad r_{eq} = \frac{r_1 r_2}{r_1 + r_2}$$

It can also be written as,

$$\frac{\mathcal{E}_{eq.}}{r_{eq}} = \frac{\mathcal{E}_1}{r_1} + \frac{\mathcal{E}_2}{r_2}$$

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

Relation b/w emf, current, internal resistance and terminal potential difference when a cell is connected across a resistance 'R'

$$\mathcal{E} = IR + Ir$$
$$= I(R+r)$$

or $$\boxed{I = \frac{\mathcal{E}}{R+r}}$$

[$\mathcal{E}$ – emf of cell
I – current in the circui
r – internal resistan
R – device or ext. resistan

$$V = IR$$
$$\mathcal{E} = V + Ir$$
$$\boxed{V = \mathcal{E} - Ir.}$$

Relation b/w E, V, R and r

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

$$r = \frac{\mathcal{E} - V}{I} = \left[\frac{\mathcal{E} - V}{V/R}\right]$$

$$r = \left[\frac{\mathcal{E} - V}{V}\right]R \quad ; \quad r = \left[\frac{\mathcal{E}}{V} - 1\right]R$$

Emf or electro motive force of a cell is defined as the potential difference across the terminal of a cell when it is in the open circuit or when no current is being drawn from the cell. [ie R=0]

Max. current that be drawn from a cell is for R=0

$$\therefore I_{max} = \mathcal{E}/r.$$

$$\text{or } r = \frac{\mathcal{E}}{I_{max}}.$$

The resistance offered by the electrolyte to the flow of current is called internal resistance of a cell.

Meter Bridge and wheatstone bridge (Refer text book for circuit diagram and derivation).

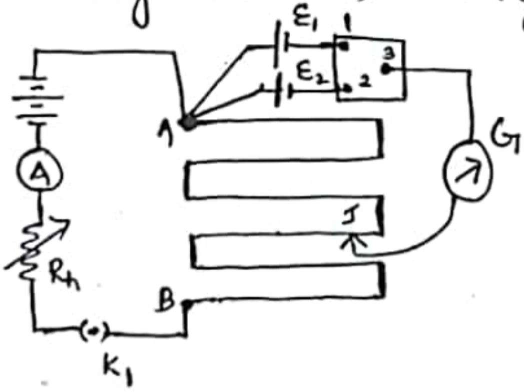
* The bridge is most sensitive when all the four resistances of the bridge are same.
* The meter bridge cannot be used to measure very low or very high resistances. [because the bridge is most sensitive when all the four resistance are of same value which should be either very low or very high. This would require a galvanometer of v. low or v. high resistance which may cause error].
* There is no change or no effect on interchange of positions of battery and galvanometer on the balanced position of meter bridge.

Potentiometer

It is a versatile instrument which can be used to (i) compare/determine the emf of cells and (ii) determine the internal resistance of a cell.

Principle: when a constant current flows through a wire of uniform area of cross section, the potential drop across any length of the wire is directly proportional to the length.

Construction: It consists of a long wire AB of uniform cross section (usually made of an alloy, manganin or constantan). The wire is in the form of segments joined through thick metallic strips fixed on a wooden board. The auxillary circuit has a primary/driver cell, a Rheostat, an ammeter and a key. A steady current flows through the wire by the driver cell. A jockey is provided to make contact at any point on the wire. The cells whose emf has to be determined to be included in the circuit using a two-way key. The galvanometer shows the flow of current in the circuit using which balancing length can be found.



circuit diagram for comparison of emf of two cells.

When the key K_1 is closed, it sends a steady current I through the circuit. The jockey is

slided on the wire to get the null point. The balanci
length is measured.

$$V = IR = \frac{I\rho l}{A}$$

$$V \propto l$$

$$V = \phi l$$

$$\phi = \frac{V}{l}$$; ϕ is known as the potenti
gradient, → potential drop per unit length.

when the cell of emf ε_1 is included in the circuit, let the balancing length be l_1,

then $\varepsilon_1 = \phi l_1$ —(1)

Similarly, for the cell of emf ε_2 is balanced by l_2,

then $\varepsilon_2 = \phi l_2$ —(2)

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{l_1}{l_2}.$$

Thus emfs can be compared.

* The sensitivity of the potentiometer can be increased by keeping 'ϕ' as low as possible. (Smaller value of ϕ, greater is the balancing length which will give accurate measurement. Hence using longer wire increases potentiometer) sensitivity

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Internal Resistance of a cell

Close the key k_1. A const. current flows thru' the potentiometer wire. With key k_2 open, slide the jockey along the wire till it balances the emf $\mathcal{E}$ of the cell. Let l_1 be the balancing length of the wire.

$$\mathcal{E} = \phi l_1$$

With the help of resistance box R.B, include a resistance R and close the key k_2. The balance point for this terminal potential diff. is determined, let it be l_2.

$$V = \phi l_2$$

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

Let r be the internal resistance of the cell. Then from ohm's law, when a current flows thru' a circuit,

$$\mathcal{E} = I(R+r)$$

$$V = IR.$$

$$\frac{\cancel{I}(R+r)}{\cancel{I}R} = \frac{l_1}{l_2}$$

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

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

Potentiometer is preferred over voltmeter to measure the emf of a cell – as it a null method device. At null point, the device does not draw any current from the cell, & hence there is no potential drop due to internal resistance of the cell. It measures p.d. in an open circuit which is the actual emf of the cell.

A voltmeter draws a small current from the cell for its operation. So that it measures the terminal p.d. in a closed circuit which is less than actual

Sensitivity of Potentiometer

— A potentiometer is sensitive if it measures very small potential differences and also shows a significant change in balancing length for a small change in p.d.

The sensitivity can be increased by reducing the potential gradient ϕ. This can be done by

(i) increasing the ~~#~~ length of the potentiometer wire

(ii) For a potentiometer wire of fixed length, ϕ can be decreased by reducing the current in the circuit with the help of a rheostat.

Internal resistance of a cell depends on

a) Nature of the electrolyte.

b) directly prop. to the concentration of the electrolyte

c) directly prop. to the distance b/w the electrodes.

d) varies inversely as the common area of the electrodes immersed in the electrolyte.

e) increases with decrease in temp. of the electrolyte.

Poten
(i)

...ntiometer preferred over voltmeter

(i) At the balancing point giving null deflection, no current flows in the secondary circuit, or no current is drawn from the cell whose emf is to be determined. Hence it gives the accurate value of emf. while a voltmeter draws current from the cell and it gives the terminal p.d. rather than emf of the cell.

(ii) While taking measurements using voltmeter some errors occur in reading the deflection. As potentiometer is based on null deflection, less error occurs.

Internal resistance of a cell (Diagram refer text)

(one of the cell is removed across which a resistance box and a key is connected).

* The emf of the cell whose internal resistance 'r' is to be determined is balanced with length l_1

$$\mathcal{E} = \phi l_1 \quad —(1)$$

ϕ is the potential gradient.

When key K_2 is closed, and insert a resistance 'R' from the resistance box, the cell sends a current I of 'V' is the terminal potential diff. of the cell, then balancing length will be l_2.

$$V = \phi l_2 \quad —(2)$$

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

Also $$r = \left(\frac{\mathcal{E}}{V} - 1\right)R \quad —(3)$$

...view of

EMF, internal resistance and terminal potential difference of a cell

→ EMF of a cell is the maximum potential difference between the terminals of a cell when no current is drawn from it ie when it is in open circuit.

→ Internal resistance of a cell is the resistance offered by the electrolyte of the cell to the flow of current through the cell

→ Terminal potential difference is the potential difference between the terminals of a cell in a closed circuit ie when current is drawn from it.

→ when a cell is in a closed circuit, there is a fall of potential across the internal resistance of the cell as the current passes through it. Thus in a closed circuit, the terminal potential difference is always less than the emf of the cell.

Consider a cell of emf 'ε', internal resistance 'r' connected to an external resistance 'R' as shown in fig (i). when the circuit is open, no current flows through the circuit. The terminal potential difference is equal to the emf of the cell.

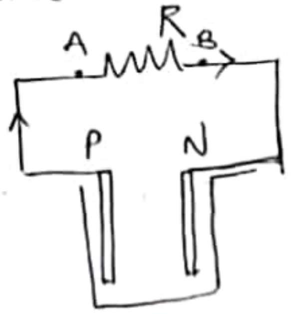


fig (i)

when key is closed, current flows, now total resistance is $R+r$.

$$\therefore \text{Current } I = \frac{\varepsilon}{R+r}$$

$$\text{or } \varepsilon = I(R+r) = IR + Ir$$

Ir is the potential difference across 'r'

and $IR = V$

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

ie terminal potential diff is less than $\mathcal{E}$ by a factor Ir when current is drawn from it.

In the above eqn, if $I = 0$

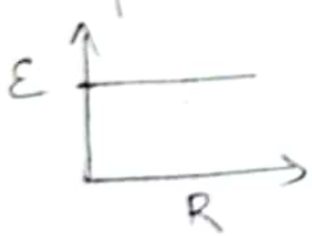
then $V = \mathcal{E}$

[As points A and B ~~hav~~ are at the same potential as that of the terminal P and N of the cell, V is equal to the p.d. across the resistance R]

$$\boxed{r = \frac{\mathcal{E} - V}{I}}$$

subs. for $I = V/R$; $r = \dfrac{\mathcal{E} - V}{V/R} = \left(\dfrac{\mathcal{E}}{V} - 1\right)R$

i) Graph between $\mathcal{E}$ and R



$\mathcal{E}$ is independent of R.

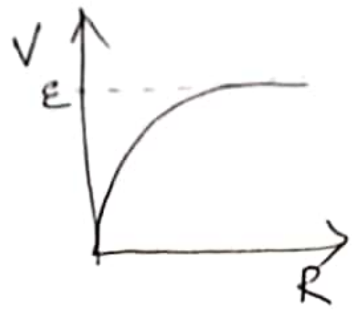
ii) Graph between V and R

$V = \mathcal{E} - Ir \quad = \mathcal{E} - \dfrac{V}{R} r$

or $V = \dfrac{\mathcal{E}}{1 + r/R}$

According to the above eqn, As R increases V also increases.

when $R \rightarrow \infty$, then $V = \mathcal{E}$

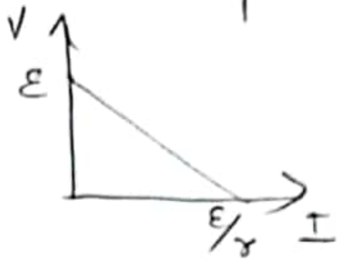


V and I

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

So as I increases, V decreases. $(y = mx + c)$

The graph is a straight line, whose slope is $-r$ and intercept is $\mathcal{E}$



[emf → electromotive force is not a force - it is a mismomer - it is potential difference]

[Current flows from P to N outside the cell & N to P inside the cell]

Internal resistance depends on (i) Distance b/w the electrodes of the cell (directly proportional) (ii) Effective area of electrodes (inversely proportional) (iii) Concentration of solution (directly proportional as it increases the no. of ions/unit volume of solution → hence increases collisions) (iv) Temperature (inversely proportional)

when $R = 0$; $I_{max} = \frac{\mathcal{E}}{r}$

<u>Cells in series</u>

when 2 cells of emf $\mathcal{E}_1$ and $\mathcal{E}_2$ and internal resistance r_1 and r_2 are connected in series as shown in fig.

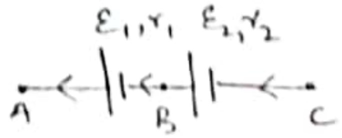


fig (i)

$V_{AB} = V_A - V_B = \mathcal{E}_1 - Ir_1$

$V_{BC} = V_B - V_C = \mathcal{E}_2 - Ir_2$

$\therefore V_{AC} = V_A - V_C = \mathcal{E}_1 - Ir_1 + \mathcal{E}_2 - Ir_2$

$= V_{AB} + V_{BC} = (\mathcal{E}_1 + \mathcal{E}_2) - I(r_1 + r_2)$

④

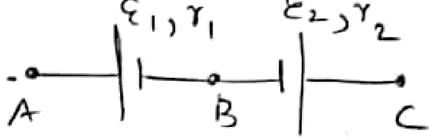
$\therefore \quad V_{AC} = \mathcal{E}_{eq} - I r_{eq}$

ie $\mathcal{E}_{eq} = \mathcal{E}_1 + \mathcal{E}_2$ and $r_{eq} = r_1 + r_2$

for 'n' identical ~~se~~ cells in series

$$\mathcal{E}_{eq} = n\mathcal{E} \quad \text{and} \quad r_{eq} = nr$$

* If the series combination is connected as shown below

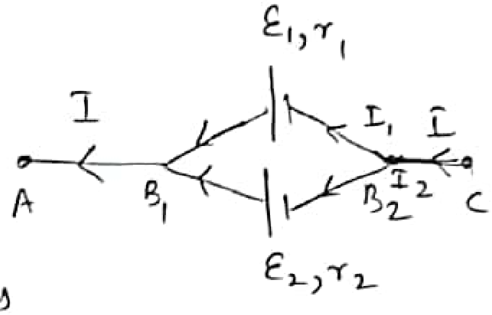


Then $\mathcal{E}_{eq} = \mathcal{E}_1 - \mathcal{E}_2$

fig (ii).

but $r_{eq} = r_1 + r_2$

<u>Cells in parallel</u>



Consider two cells of emf $\mathcal{E}_1$ and $\mathcal{E}_2$ and internal resistances r_1 and r_2 connected in parallel as shown in fig (iii)

$$I = I_1 + I_2 \quad \text{——} (1)$$

Potential at B_1 and B_2 are same (parallel)

$$\therefore \quad V = \mathcal{E}_1 - I_1 r_1$$

$$\text{also} \quad V = \mathcal{E}_2 - I_2 r_2$$

$$I_1 = \frac{\mathcal{E}_1 - V}{r_1} \quad \text{—}(2) \qquad \text{and} \quad I_2 = \frac{\mathcal{E}_2 - V}{r_2} \quad -(3)$$

from (1)

$$I = \frac{\mathcal{E}_1 - V}{r_1} + \frac{\mathcal{E}_2 - V}{r_2}$$

$$I = \left(\frac{\mathcal{E}_1}{r_1} + \frac{\mathcal{E}_2}{r_2}\right) - V\left[\frac{1}{r_1} + \frac{1}{r_2}\right]$$

$$I = \frac{\varepsilon_1 r_2 + \varepsilon_2 r_1}{r_1 r_2} - V\left[\frac{r_1 + r_2}{r_1 r_2}\right]$$

$$\therefore V = \frac{\varepsilon_1 r_2 + \varepsilon_2 r_1}{r_1 + r_2} - I\left(\frac{r_1 r_2}{r_1 + r_2}\right]$$

If this parallel combination of cells is replaced by a single cell between B_1 and B_2 of emf ε_{eq} and r_{eq}

then $V = \varepsilon_{eq} - I r_{eq}$

where $\varepsilon_{eq} = \frac{\varepsilon_1 r_2 + \varepsilon_2 r_1}{r_1 + r_2}$

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

which can be rewritten as

$$\varepsilon_{eq}/r_{eq} = \frac{\varepsilon_1}{r_1} + \frac{\varepsilon_2}{r_2}$$

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

for a parallel combination of 'n' identical cells,

$r_p = \frac{r}{n}$

If R is connected in series with a r_p (of cell)

then total resistance $= R + r/n$

& $I = \frac{\varepsilon}{R + r/n}$

[For series combination of cells, I is max if R >> total int. resistance of cells ie ~~R >> nR~~ R >> nr

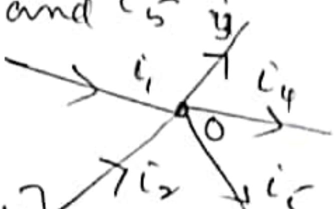
for parallel combination of cells, I is max when $R << r/n$].

Kirchoff's Rules

(Current law)

1. Kirchoff's current/junction rule (Current law): It states that the algebraic sum of various currents meeting at a junction in a closed circuit is zero. ie sum of currents enter a junction is equal to sum of currents leaving the junction. For eg: in fig (i) O is a junction in a circuit carrying currents i_1, i_2, i_3, i_4 and i_5 ∴

$$i_1 + i_2 = i_3 + i_4 + i_5$$



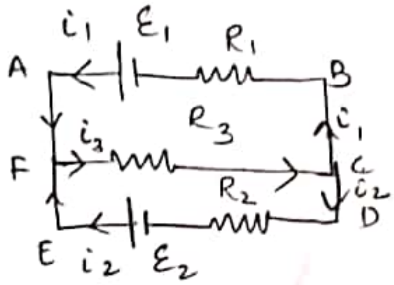
or $i_1 + i_2 - i_3 - i_4 - i_5 = 0$

[sign convention – Current entering +ve
ie $\boxed{\Sigma I = 0}$ Current leaving –ve]

* This law is in accordance with the law of conservation of charges – ie total incoming charges to a junction are equal to total outgoing charges from that junction per unit time or charges do not accumulate at a point of a circuit.

2. Kirchoff's loop/mesh rule (Voltage Law): Around any closed loop of a network, the algebraic sum of changes in potential is zero ie $\Sigma \Delta V = 0$. Or in a closed loop/mesh, algebraic sum of e.m.fs is equal to algebraic sum of the products of various resistances and currents flowing through them

Mathematically, $\Sigma E = \Sigma IR$



Eg: In fig (ii) in loop FCDEF

$$E_2 = i_3 R_3 + i_2 R_2$$

in loop AFCBA

$$E_1 = i_3 R_3 + i_1 R_1$$

[Sign convention - take any direction of traversal in a loop say C.W or a.C.W — if going from P to N of a cell in the loop then on L.H.S $\mathcal{E}$ is +ve if N to P according to the chosen dir'n then L.H.S $\mathcal{E}$ is -ve. Similarly iR becomes +ve when it is in the direction chosen and -ve otherwise].

the refe sen

* Kirchoff's voltage rule - is in accordance with law of conservation of energy. → the workdone by the electrostatic force (which makes the changes circulate) on the changes around a closed loop is zero. Hence net change in the energy of charge in a loop is zero — or no gain or loss in energy in a loop.

Wheatstone's Bridge - It is an arrangement of four resistences in the form of a bridge which is used to find out one unknown resistance in terms of other 3 known resistences.

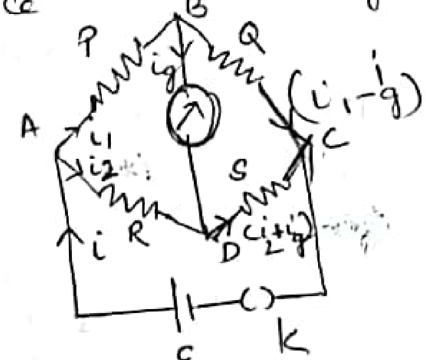


fig (iii)

Fig (iii) shows wheatstone's bridge — used for measuring unknown resistences. Arms AB and BC contain known resistence → Ratio arms. Arm AD contains resistance R which can be varied, Arm DC contains unknown resistence. G is a galvanometer. Under balanced condition, no current flows through Arm BD ie galvanometer shows null deflection (ie by varying R). Then $\frac{P}{Q} = \frac{R}{S}$

known as wheatstone principle.

Proof : consider loop ABDA, apply KVL (Kirchoff's voltage Law).

$$I_1 P + I_g G - (I_2) R = 0$$

where G is the resistance of the galvanometer

for loop BCDB,

$$(I_1 - I_g) Q - (I_2 + I_g) S - I_g G = 0$$

Value of R is adjusted so that $I_g = 0$ ie galvanometer shows zero deflection

$$I_1 P = I_2 R$$

$$I_1 Q = I_2 S$$

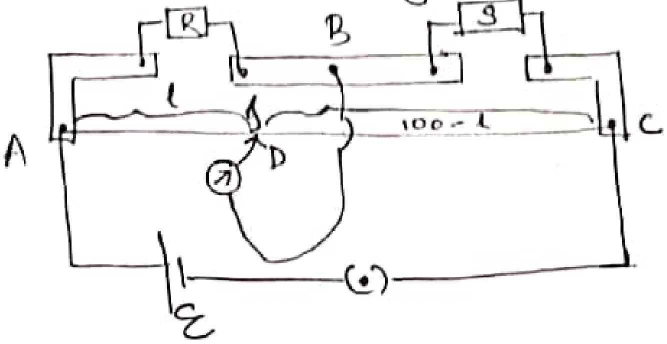
Dividing we get $\frac{P}{Q} = \frac{R}{S}$.

→ It is a null method, hence gives accurate ~~measurement~~ measurement of S

→ It is unaffected by internal resistance of cell and resistance of galvanometer.

→ Bridge is most sensitive when all 4 resistances are nearly same. But it cannot be used to measure very high or very low resistances.

Meter Bridge : It is a practical application of wheatstone bridge used for measuring unknown resistances. The apparatus/arrangement is shown below.



Extra point

Current Electricity

- In a metre bridge, when R - known resistance is equal to X - unknown resistance, balance pt. will be near the middle of slide wire
- Sensitivity is max. when all four resistances are almost same.
- Position of balance pt. shift towards A if X is increased i.e. balancing length decreases.
- Position balance pt. shift towards B if X is decreased i.e. it increases.

Potentiometer

- A potentiometer can be made more sensitive by decreasing the potential gradient ($\phi = V/l$) i.e. by decreasing the potentiometer current or by increasing the length of the wire of potentiometer
- It is a null method, so emf's ~~~~ compared are independent of internal resistances of the cells. when galvanometer gives no deflection, no current is drawn from the cell, Hence terminal pd = emf of the cell & Potentiometer acts as an ideal Voltmeter
- High Resistance is used in series to G to prevent too much current from flowing thru" & prevents damage to it
- Internal resistance, $r = \left(\frac{E}{V} - 1\right) R$.
- Kirchoff's ~~~~ junction ~~rule~~ Law is based on law of Conservation of charges.
- KVL or Loop rule is based on Law of