The flow of charges in a conductor is electric current and the branch of physics that deals with charges in motion is called current electricity.

Electric current [I]: The time rate of flow of charge across any cross section of the conductor is the measure of electric current

$$\therefore I = q/t$$

SI unit → ampere [A]. It is a scalar and the conventional direction of flow of electric current is from +ve to −ve terminal of the cell.

Current carriers (a) In solid conductors the current carriers are the free electrons.

(b) In electrolytes the +vely and −vely charged ions are the current carriers.

(c) In an ionised gas the current carriers are the e^{-s} and the +vely charged ions.

* DRIFT SPEED (i) At room temp:, the free electrons of a conductor are in random motion. The direction of moti[on] are so randomly distributed that the average thermal velocity of the electrons is zero.

$$\therefore \frac{\vec{u}_1 + \vec{u}_2 + \dots + \vec{u}_n}{n} = 0$$

(ii) When an electric field is set up by applying a potential difference then each electron in the conductor experiences a force in the direction opposite to that of the electric field and the electrons are accelerat[ed] towards the +ve end.

(iii) While moving towards the +ve end the electrons suffer frequent collisions with the +ve ions of th[e] conductor and lose energy. The net result is tha[t] the electrons acquire a small velocity towards the +ve end of the conductor.

with which the free electrons get drifted towards the +ve end of the conductor under the influence of an external electric field.

(v) Acceleration of each electron under the influence of 'E' is $\vec{a} = -\frac{e\vec{E}}{m}$.

(vi) At any instant of time the average velocity of all the n electrons is

$$\vec{V_d} = \frac{(\vec{u_1} + \vec{a}\tau_1) + (\vec{u_2} + \vec{a}\tau_2) + \cdots + (\vec{u_n} + \vec{a}\tau_n)}{n}$$

$$\therefore \vec{V_d} = \vec{a}\tau \quad \left[\because \frac{\vec{u_1} + \vec{u_2} + \cdots + \vec{u_n}}{n} = 0 \right.$$
$$\left. \text{and } \frac{\tau_1 + \tau_2 + \cdots + \tau_n}{n} = \tau \right]$$

where τ is the relaxation time and is defined as the average time between successive collisions.

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

※ Relation between current and drift velocity

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

$\therefore$ Volume of the conductor = Al.

If n is the number of electrons per unit volume of the conductor then the total number of free electrons in the conductor = nAl.

If e is the charge on each e^- then the total charge on all the electrons $q = nAle \rightarrow (1)$

Because of the pd applied an electric field is set up and electrons move towards the +ve end with a drift speed V_d.

$\therefore$ Time taken $= l/V_d \longrightarrow (2)$

Also $I = q/t \longrightarrow (3)$

$\therefore$ Substituting (1) & (2) in (3)

$$I = \frac{neAx v_d}{l}$$

$$\therefore \boxed{I = neAv_d}$$

Ohm's law: It states that the current flowing through a conductor is directly proportional to the potential difference across the ends of the conductor provided physical conditions like temperature etc remains constant.

$$I \propto V$$

$$\Rightarrow V \propto I$$

$$\therefore V = IR$$

(a) R is the resistance of the conductor and depends the nature of the material of the conductor and also on the length and shape of the conductor. R also depends on the temperature.

Resistance is defined as the hindrance posed by a conductor to the flow of electric current through it.

SI unit is ohm (Ω)

(b) It is observed that, $R \propto l$

$\propto \frac{1}{A}$

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

The constant of proportionality ρ is the specific resistance of the material of the conductor or the resistivity of the conductor.

Specific resistance is defined as the resistance of unit area of the conductor per unit length.

The unit of specific resistance is ohm metre (Ωm).

Specific resistance does not depend on the dimensions of the conductor but depends on the temperature and material of the conductor.

expression for resistivity in terms of relaxation time.

The relation between current and drift speed is

$$I = neAv_d$$

Since $v_d = \frac{eE\tau}{m}$

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

$$\Rightarrow I = \frac{ne^2 A \tau V}{ml} \quad [\because E = V/l] \longrightarrow ①$$

According to Ohm's law $V = IR \longrightarrow ②$

Comparing (1) and (2)

$$\frac{V}{I} = R = \frac{ml}{ne^2 \tau A} \longrightarrow ③$$

Also $R = \rho \frac{l}{A} \longrightarrow ④$

Comparing (3) and (4)

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

Note: Eqn ③ can be said to be the microscopic picture of Ohm's law $\therefore V = \frac{ml}{ne^2 \tau A}$ ie $V = I($

Thus resistivity of a conductor is inversely proportional to relaxation time. It also indicates that resistivity is independent of the dimensions of the conductor.

Conductance (G): It is the reciprocal of resistance
unit mho or Siemen (S)

Conductivity (σ) It is the reciprocal of resistivity
unit mho m^{-1} or Sm^{-1}

Current density (J) Current density at a point is defined as the amount of current flowing per unit area of the conductor around that point provided the area is held in a direction normal to the current.

$$\therefore J = I/A$$

It is a vector quantity. Its unit is Am^{-2}.
Its direction is the same as that of current.

Mobility (μ). It is defined as the magnitude of drift velocity per unit electric field. $\mu = \frac{|\vec{v_d}|}{E}$
unit: m^2/Vs

Relation between current density and conductivity

We know, $I = neAv_d$

$$J = I/A = nev_d.$$

$$= \frac{ne^2E\tau}{m} \quad \left[\because v_d = \frac{eE\tau}{m}\right]$$

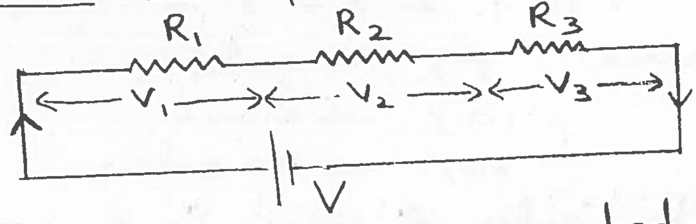
$$\Rightarrow J = \frac{E}{\rho} \quad \left[\because \rho = \frac{m}{ne^2\tau}\right]$$

$\boxed{J = \sigma E}$: > This equation also represent Ohm's law

$\left[\because J = \sigma E \Rightarrow \frac{I}{A} = \frac{1}{\rho}\frac{V}{l} \Rightarrow V = IR \quad [\because R =\right.$

Resistances in series and parallel

(a) Series.



R_1, R_2 and R_3 are the resistances connected in series to a source of potential difference V, then the same current I flows through the resistances.

$$\therefore V = V_1 + V_2 + V_3.$$

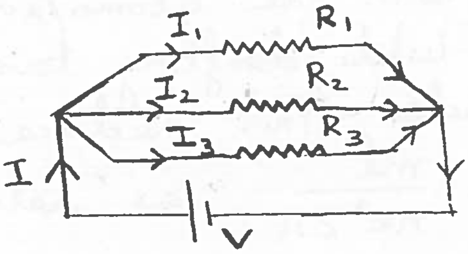
where V_1, V_2 and V_3 are the potential drop across the three resistances

According to Ohm's law, $IR = IR_1 + IR_2 + IR_3$

$$\boxed{R = R_1 + R_2 + R_3}$$

When resistances are connected in series the effective resistance is greater than each of the individual resistances.

(b) Parallel



When resistances are connected in parallel the potential drop V is the same across each of the resistors. If I_1, I_2 and I_3 are the currents flowin through each of the resistances R_1, R_2 and R_3 then,

$I = I_1 + I_2 + I_3$

According to Ohm's law $\frac{V}{R} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$

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

The effective resistance of resistances in parallel is less than each of the individual resistances.

Colour code of resistors.

The resistance of a given resistor can be determined using the following colour code

B	B	R	O	Y	G	B	V	G	W
0	1	2	3	4	5	6	7	8	9

Tolerance
5% → gold
10% → silver
20% → no colour.

If the order of rings in a resistor are yellow, viole[t] orange and silver then

$R = 47 \times 10^3\ \Omega$

tolerance = 10%

- Effect of temperature on resistance

As the temperature increases resistance of the conductor increases.

As the temp. increases, the atoms/ions of the metal vibrate with greater amplitude and frequency about their mean position. The frequency of collisions of the free electrons with the atoms/ions of the conductor increases while drifting towards the +ve end of the conductor. This reduces the relaxation time. Since $R = \frac{ml}{ne^2 \tau A}$, as relaxation time decreases resistance of the conductor increases.

Temperature coefficient of resistance

The variation of temperature with resistance is given by the relation

$$R_2 = R_1(1+\alpha t)$$

where α is the temperature coefficient of resistance

$$\boxed{\alpha = \frac{R_2 - R_1}{R_1 t}}$$

t is the increase in temperature $(t_2 - t_1)$.

R_1 is the resistance corresponding to temperature t_1 and R_2 is the resistance corresponding to temperature t_2

unit of $\alpha = {}^\circ C^{-1}$ [It is defined as the change in resistance per unit resistance per degree rise or fall in temperature

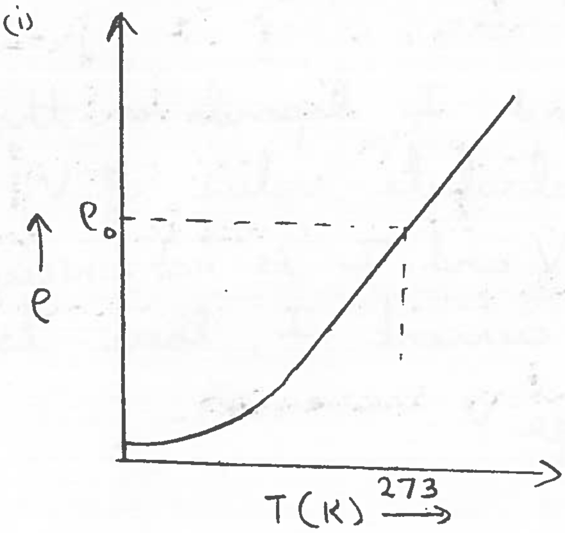
Note (i) For metals like Cu, Ag etc the value of α is positive because resistance increases with increase in temperature.

(ii) For insulators and semiconductors α is -ve because resistance decreases with increase in temperature.

*(iii) For some alloys like manganin, constantan etc α is very small. Due to high resistivity and low temperature coefficient of resistance these alloys are used for making standard resistance coils, potentiometer wire, bridge wire etc.

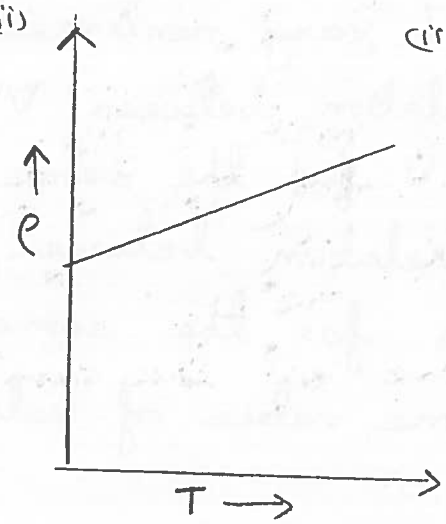
Graphs of variation of resistivity with temperature

(i)



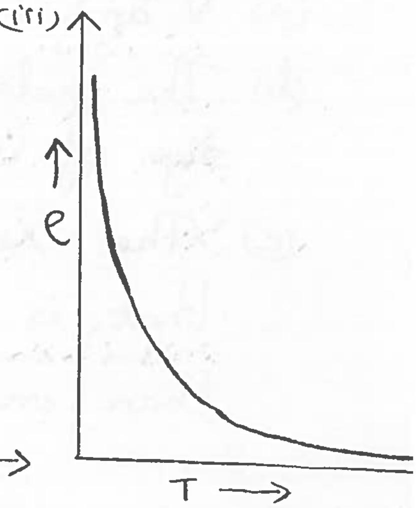
Variation of resistivity of copper as a function of temperature

(ii)



Variation of resistivity of nichrome with temperature

(iii)



Variation of ρ of semiconductors with temperature

Interpretation of the graphs

Graph (i) For conductors such as copper, the temperature dependence of ρ at low temperatures is nonlinear. However the relation between ρ and T is linear over a limited range. ρ_0 indicates resistivity at 273 K.

Graph (ii). Resistivity of nichrome and manganin is independent of temperature [ie weak temperature dependence]. Also, nichrome has residual resistivity even at absolute zero.

Graph (iii) Resistivity of semiconductors decreases rapidly with increasing temperature. Variation of resistivity with temperature is given by $\rho_T = \rho_0 e^{E_g/kT}$, indicating that resistivity increases with decreasing temperature for semiconductors and insulators.

Non ohmic conductors: Ohm's law is not a fundamental law of nature and in many cases the relation between voltage and current is different from that of $V = IR$.

Graphs of some commonly used circuit elements exhibit one or more of the following properties indicating deviation from Ohm's law.

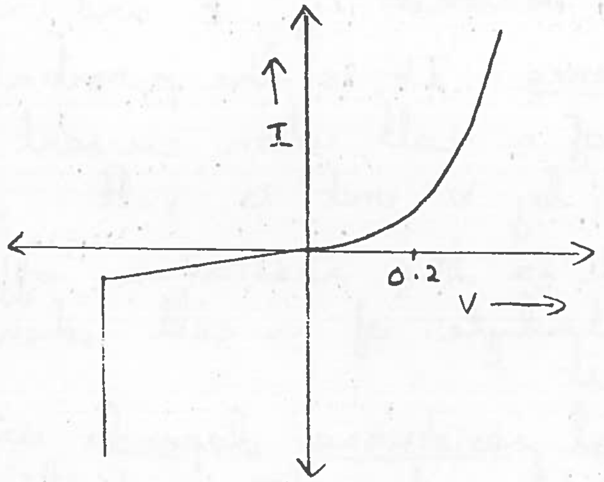
(a) V and I vary nonlinearly

(b) The relation between V and I depends on the sign of V for the same absolute value of V.

(c) The relation between V and I is not unique that is for the same current I, there is more than one value of voltage V.

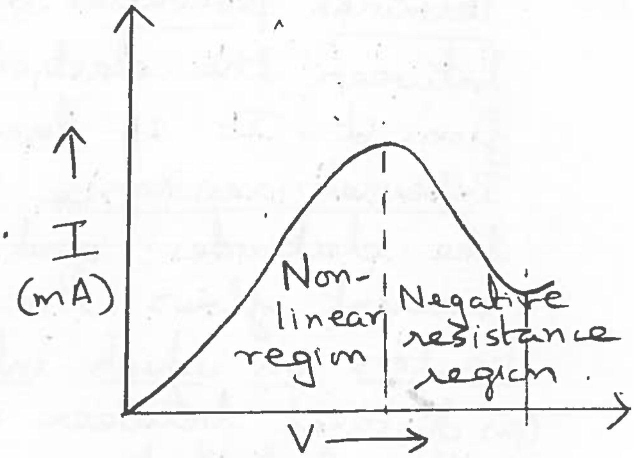
Examples of some conductors that do not obey Ohm's law

(i) semiconductor diode



It is observed that a diode combines properties (a) and (b)

(ii) GaAs



GaAs combines properties (a) and (c)

Thermistor: It is a heat sensitive device in which the resistivity changes rapidly with temperature.

Applications (a) to measure very low temperature.
(b) to protect windings of generator, transformer etc.

Super conductivity: As the temperature of metals and alloys decreases the resistance of the material also decreases considerably and when the temperature reach a point called critical temperature or transition temperat the resistance of the material almost disappears completel and it behaves as a superconductor.

Applications (a) Transmission of electric power without loss energy
(b) magnetically levitated trains
(c) For making strong electromagnets
(d) to produce high speed computers.

The cause of superconductivity is that electrons in a superconductor are mutually coherent. The ionic vibrations which could deflect free electrons in metals are unable to deflect the coherent cloud of electrons in superconductors.

EMF, Terminal potential difference and internal resistance of a cell.

EMF : It is the maximum potential difference between the electrodes of a cell when no current is drawn from the cell. It is denoted by E and unit is volt

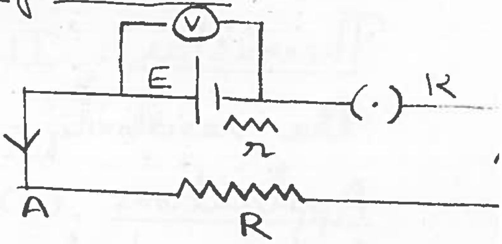
Terminal potential difference : It is the potential difference between the electrodes of a cell when current is drawn from it. It is denoted by V. unit is volt.

Internal resistance : It is the resistance offered by the electrodes and electrolyte of a cell when electric current flows through it.

Factors on which internal resistance depends are
(a) distance between electrodes, (b) nature of electrodes and electrolyte (c) area of electrodes immersed in electrolyte

Expression for internal resistance of a cell

Consider a cell of emf E and internal resistance r connected to an external resistance R through a key K.



(a) When the key is not closed the reading in the voltmeter is equal to E.

(b) When the key is closed the reading in the voltmeter is the terminal potential difference which is less than the EMF by an amount equal to the potential drop across the internal resistance of the cell.

$$\therefore V = E - Ir.$$

Since A is at the same potential as the +ve electrode and B is at the same potential as the -ve electrode the terminal potential difference of the cell is equal to the potential drop across the external resistance R.

$$\therefore V = IR \rightarrow (1)$$

$$\text{Since } I = \frac{E}{R+r} \quad -(2)$$

Substituting (2) in (1)

$$V = \left[\frac{E}{R+r}\right] R$$

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

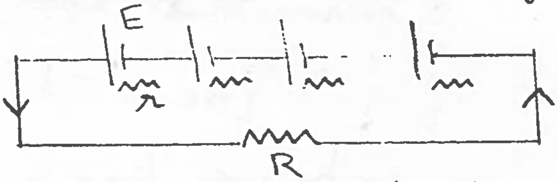
$$\boxed{r = \left[\frac{E-V}{V}\right] R}$$

<u>Note</u>: During charging current flows inside the cell from +ve electrode to −ve electrode

$$\therefore \boxed{V = E + Ir}$$

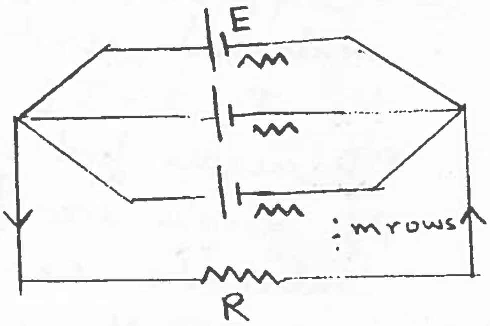
<u>Grouping of cells</u>: [<u>Series</u> <u>and</u> <u>Parallel</u>]

(a) When n identical cells are connected in <u>series</u> each of emf E, internal resistance r and connected through an external resistor R then



$$\boxed{I = \frac{nE}{R + nr}}$$

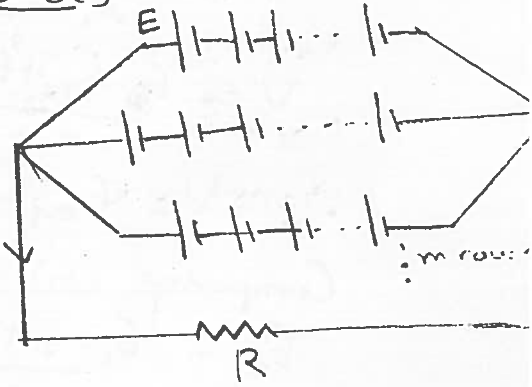
(b) When identical cells of emf E are connected in m rows <u>parallel</u> then,



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

$$\boxed{I = \frac{mE}{mR + r}}$$

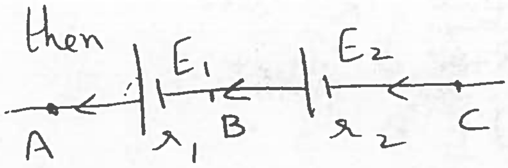
(c) When n identical cells are connected in <u>series</u> <u>and</u> there are m such rows (<u>parallel</u>) then,



$$I = \frac{nE}{R + \frac{nr}{m}}$$

$$\boxed{I = \frac{mnE}{mR + nr}}$$

(d) Suppose two cells of emfs E_1 and E_2 and internal resistances r_1 and r_2 are connected in series then

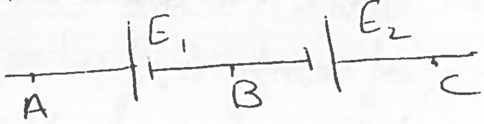


$$V_{AC} = V_{AB} + V_{BC}$$
$$= (E_1 - Ir_1) + (E_2 - Ir_2)$$
$$V_{AC} = E_1 + E_2 - I(r_1 + r_2) \quad \text{— (1)}$$
$$V_{AC} = E_{eq} - I r_{eq} \quad \text{— (2)}$$

Comparing (1) and (2)

$$E_{eq} = E_1 + E_2 \quad \text{and} \quad r_{eq} = r_1 + r_2$$

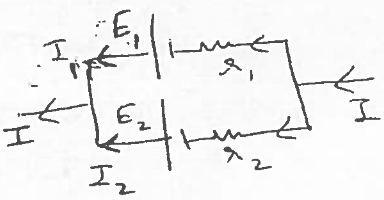
Note: Suppose the two negative electrodes are connected then,



$$V_{BC} = -E_2 - Ir_2$$

hence $E_{eq} = E_1 - E_2$ and $r_{eq} = r_1 + r_2$

(e) Suppose two cells of emfs E_1 and E_2 and internal resistances r_1 and r_2 are connected in parallel



$$I = I_1 + I_2 \quad \text{— (1)}$$

PD across first cell $= E_1 - I_1 r_1 = V$ — (2)

PD across second cell $= E_2 - I_2 r_2 = V$ — (3)

Substitute (2) and (3) in (1)

$$I = \frac{E_1 - V}{r_1} + \frac{E_2 - V}{r_2}$$
$$I = \frac{E_1}{r_1} + \frac{E_2}{r_2} - V\left[\frac{1}{r_1} + \frac{1}{r_2}\right]$$
$$V = \frac{E_1 r_2 + E_2 r_1}{r_1 + r_2} - I\frac{r_1 r_2}{r_1 + r_2} \quad \text{— (4)}$$
$$V = E_{eq} - I r_{eq} \quad \text{— (5)}$$

Comparing (4) and (5)

$$E_{eq} = \frac{E_1 r_2 + E_2 r_1}{r_1 + r_2} \quad \text{and} \quad r_{eq} = \frac{r_1 r_2}{r_1 + r_2}$$