CHP. 13
CURRENT ELECTRICITY.

Def —— "The branch of Physics which deals with the charges in motion is called current electricity or electrodynamics."

#13.1 ELECTRIC CURRENT :

Def —— "The rate of flow of electric charge through a conductor of any cross section in a unit time is called electric current."

If a charge of ΔQ is passing through any section of a wire in time Δt, then ;

Electric current $= I = \dfrac{\Delta Q}{\Delta t}$ ———— ①

UNIT. The SI unit of electric current is **ampere (A)**.

Def— " Electric current is equal to one ampere if a charge of one coulomb is passing through any section of a conductor in one second." i.e;

$$1 A = \dfrac{1 C}{1 S}$$

The motion of electric charge which causes an electric current is due to the flow of charge carriers. In **metallic conductor** e.g; Cu, gold, Al etc, the charge carriers are **free electrons or valence electrons**. In **liquids or electrolyte**, the charge carriers are **positive and negative ions** e.g; In $CuSO_4$ solution, the charge carriers are Cu^{++} and SO_4^{-} ions. In **gases**, the charge carriers are electrons and ions.

In **Semiconductor**, the charge carriers are holes and electrons.

Intrusting Information : When eel senses danger, it turns itself into a <u>living battery</u>. Any one who attacks this fish is likely to get a shock. The potential difference between the head and tail of an electric eel can be up to 600 V.

● CURRENT DIRECTION :
(a) Conventional current.

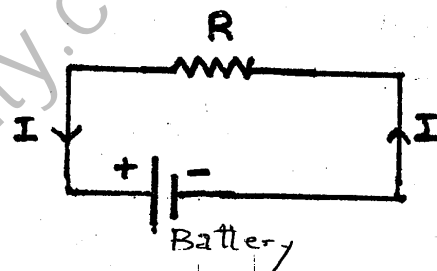The current due to the flow of **Positive charges** is called conventional current.

Def— "The current which passes from a point at higher potential to a point at a lower potential through the external circuit is called conventional current."

R
I   I
+ -
Battery
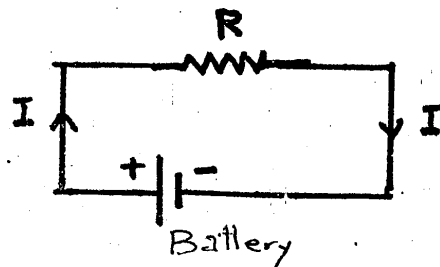
(b) Electronic current.

The current due to the flow of **electrons** is called electronic current.

Def— "The current which passes from a point at lower potential to a point at a higher potential through the external circuit is called electronic current."

R
I   I
+ -
Battery

EXPLANATION.

Early Scientists thought that an electric current is due to flow of positive charges. Later on, it was found that a current in metallic conductors is actually due to flow of electrons. But it is a convention to take the direction of current in which positive charges flow. The reason is that positive charge moving in one direction has same **external effect** (like heat effect, magnetic effect, chemical effect, deflection in metre etc) as a negative charge moving in the opposite direction. The nature of charges does not make any difference in magnitude of the effects e.g; working of devices like fan, motor,

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grinder etc depends upon magnetic fields and magnetic fields are independent of the conventional or electronic current.

USE. In case of circuit analysis we use the direction of the conventional current.

● CURRENT THROUGH A METALLIC CONDUCTOR.

The charge carriers are _free electrons_ in case of metallic conductors.

EXPLANATION.

The valence electrons are not attached to individual atoms in metals. They are free to move about within the body. These electrons are known as free electrons. They are in random motion. They act as charge carriers in metals. The speed of randomly moving electrons depends upon temperature.

CURRENT WITHOUT BATTERY.

If we observe the motion of free electrons through any section of metallic wire, the number of free electrons passing through it from right to left is equal to the number of free electrons passing through it from left to right. As a result the current through the wire is zero.
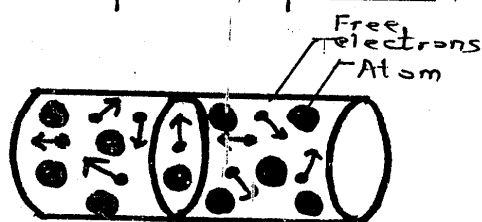
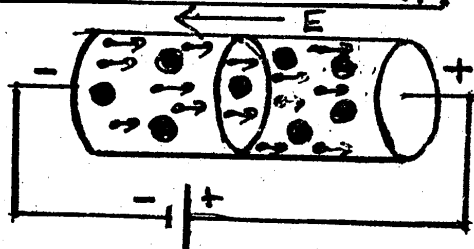fig (a)
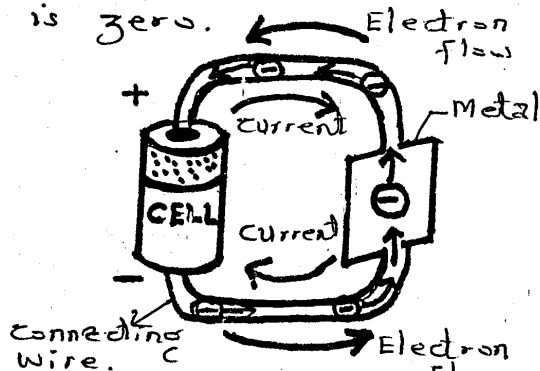
CURRENT WITH BATTERY.

fig. (c)

fig (b)

If the ends of the wire are connected to a battery,

an electric field $\overrightarrow{E}$ will be set up at every point within the wire. The free electrons will now experience a force in the direction opposite to $\overrightarrow{E}$. As a result of this force, the free electrons acquire a motion in the direction of $-\overrightarrow{E}$.

DRIFT VELOCITY.

Def — "A uniform velocity that the electrons acquire in the presence of electric field of the battery is called the drift velocity (i.e; in the direction of $-\overrightarrow{E}$)."

The drift velocity is of the order of $10^{-3}\ m\ s^{-1}$, whereas the velocity of free electrons at room temp. due to their Thermal motion is several hundred kilometers per second.

The force experienced by the free electrons does not produce a net acceleration because the electrons keep on colliding with the atoms of the conductor. The overall effect of these collisions is the transfer the energy of accelerating electrons to the lattice (atom) with the result that the electrons acquire a uniform velocity, called the drift velocity.

STEADY CURRENT.

A steady current is established in a wire when a constant potential difference maintain across it which generate the necessary electric field $\overrightarrow{E}$ along the wire. When an electric field is established in a conductor, the free electrons obtain constant drift velocity due to which a net directed motion of charges takes place along the wire and a current begins to flow through it.

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EXAMPLE 13.1 :

1×10^7 electrons pass through a conductor in 1.0 μS. Find the current in ampere flowing through the conductor. Electronic charge is 1.6×10^{-19} C.

DATA: Number of electrons $= n = 1 \times 10^7$

charge on an electron $= e = 1.6 \times 10^{-19}$ C

Time $= t = 1.0 \mu S$

$I = ?$

Sol. Current 'I' through the conductor is given by

$$I = \frac{\Delta Q}{\Delta t} = \frac{n \times e}{\Delta t}$$

$$I = \frac{1.0 \times 10^7 \times 1.6 \times 10^{-19} C}{1.0 \times 10^{-6} s} = \boxed{1.6 \times 10^{-6} A}$$

13.2 SOURCE OF CURRENT.

Def___ "A source which provides a constant P.d across the conductor or the ends of the wire is called source of current."

or "A device which converts other forms of energy into electrical energy is called a source of current (electromotive force)."

EXPLANATION.

When two conductors at different potentials are joined by a metallic wire, current will flow through the wire. The current continues to flow from higher potential to the lower potential until both are at the same potential. [Fig (a)]. After this the current stops to flow. Thus the current through the wire decreases from a max. value to zero.

fig (a) Conventional current flows from higher to lower potential through a wire.

In order to get a constant current the potential difference across the ends of the wire should

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be maintained constant. This is achieved by connecting the ends of the wire to the terminals of a device called a source of current. [fig (b)].
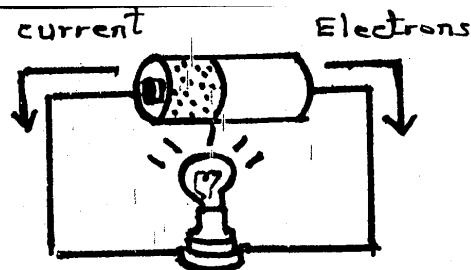

fig (b) A source of current such as battery maintains a nearly constant P.d between ends of a conductor.

TYPES OF SOURCES OF CURRENT.

1— **Cells** (Primary and secondary) which convert chemical energy into electrical energy.

2— **Electric generator** which convert mechanical energy into electrical energy.

3— **Thermo couples** which convert heat energy into electrical energy.

4— **Solar cells** which convert sunlight directly into electrical energy.

#13.3 EFFECTS OF CURRENT.

The presence of electric current can be detected by the various external effects which it produces. The same effects of the current are:

1— Heating effect
2— Magnetic effect
3— Chemical effect.

① Heating effect.

Current flows through a metallic wire due to motion of free electrons. During the course of their motion, they collide frequently with the atoms of the metal. At each collision, they lose some of their K.E and give it to atoms

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with which they collide. Thus as the current flows through the wire, increases the K.E. of the vibrations of the metal atoms i.e., it generates heat in the wire. It is found that the heat "H" produced by a current "I" in the wire of resistance "R" during a time interval "t" is given by

$$H = I^2 R \times t \qquad \text{①}$$

APPLICATION.

The heating effect of current is used in electric heater, kettles, toaster and electric iron etc.

② MAGNETIC EFFECT :

When the current flows through wire, magnetic field is produced around it. The strength of the field depends upon the value of current and the distance from the
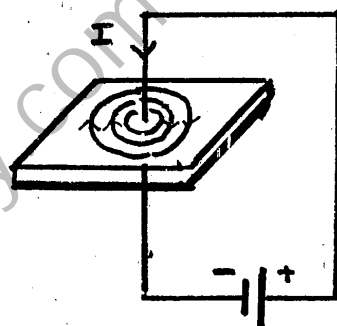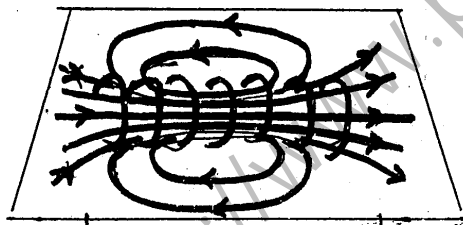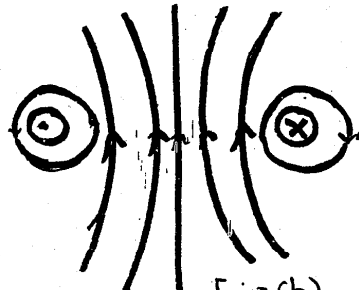

fig (a)

Solenoid
fig (c)

fig (b)

wire. The pattern of the field produced by a current carrying straight wire, a coil and a solenoid is shown in fig (a, b, c) respectively.

APPLICATION.

Magnetic effect is utilized in the detection and measurement of current. All the machines involving electric motors, also use the magnetic effect of current e.g; fan, motor, grinder, drill machine etc.

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③ CHEMICAL EFFECT.

(a) Electrolyte.
The liquid which conducts electric current and is decomposed is called electrolyte.

(b) Electrolysis.
Certain liquids conduct electricity due to some chemical reactions that take place within them. The study of this process is known as electrolysis e.g; dilute sulphuric acid and copper sulphate solution.

CHEMICAL CHANGES

The chemical changes produced during the electrolysis of a liquid are due to chemical effects of the current. It depends upon the nature of the liquid and the quantity of electricity passed through the liquid.

Following are the **main parts of electrolysis.**

(i) Electrode
   1— Anode
   2— cathode

(ii) voltameter.

(i) ELECTRODE.
The material in the form of wire or rod or plate which leads the current into or out of the electrolyte is known as electrode.

They are of two types i.e;

1—Anode. The electrode which is connected with the positive terminal of the battery is called Anode. Negative ions are moving towards it.

2—Cathode. The electrode which is connected with negative terminal of the battery is called cathode. Positive ions are moving towards it.

(ii) VOLTAMETRE.
The apparatus consisting of a vessel containing an electrolyte and two electrodes

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in which electrolysis taken place is called voltametre. (It is not the voltmeter which measures P.d)

EXPLANATION.

We consider the electrolysis of copper sulphate solution ($CuSO_4$) in voltametre whose both electrodes are made of copper. When copper sulphate is dissolved in water, it dissociates into Cu^{++} and SO_4^{--} ions. When current is passing through the voltametre Cu^{++} moves towards the cathode and the following reaction takes place.

$$Cu^{++} + 2e^- \longrightarrow Cu$$

fig:
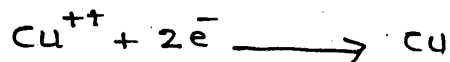
The copper atoms are deposited at cathode plate. While Cu^{++} is being deposited at the cathode, the SO_4^{--} ions move towards the anode. copper atoms from the anode go into the solution as copper ions which combine with sulphate ions to form copper sulphate.

$$Cu^{++} + SO_4^{--} \longrightarrow CuSO_4$$
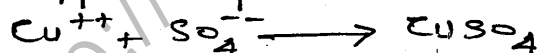
During the electrolysis, copper is continuously deposited on the cathode while an equal amount of copper is dissolved into the solution. The density of copper sulphate solution remains unchanged.

ELECTROPLATING.

Working principle of electroplating is based on electrolysis.

Def —— " A process of coating a thin layer of some expensive metal (gold , silver etc) on an article of some cheaper metal (iron) is called electroplating."
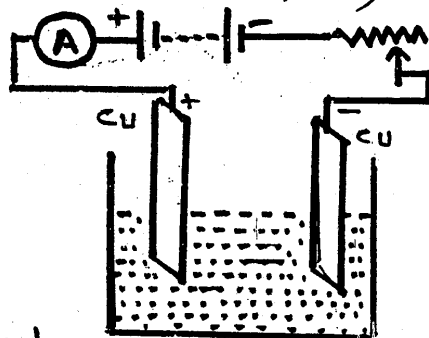
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#13.4 OHM's LAW:

German physicist <u>George Simon Ohm</u> states that:

<u>Statement</u> ——— "The current flowing through a conductor is directly proportional to the potential difference across its ends provided the physical state such as temp. , density etc of the conductor remains constant."

<u>Mathematically</u> ,

$$I \propto V$$

$$\text{or} \quad V = R I \underline{\qquad\qquad} ①$$

Where "R", the constant of proportionality is called the **resistance**.

Def —— "The opposition to the motion of electrons due to their continuous bumping with the atoms of the lattice."

The value of the resistance depends upon the <u>nature, dimensions and the physical state of the conductor</u>.

UNIT . The unit of resistance is **Ohm** (SI) with symbol of "Ω" (omega).

OHM.

Def —— "A conductor has a resistance of 1 ohm if a current of 1 ampere flows through it when a P.d of 1 volt is applied across its ends."

$$R \ (ohms) = \frac{V \ (volts)}{I \ (amperes)} \underline{\qquad} ②$$

GRAPH.

A conductor is said to obey Ohm's law if its resistance "R" remains constant and the graph "I" versus "V" is a <u>straight line</u> .[fig (a)].

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(a) OHMIC.

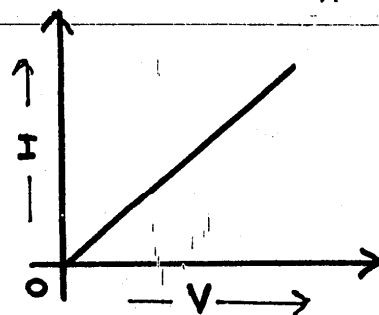Def —" A conductor which strictly obeys ohm's law is called ohmic." [Fig (a)].

fig(a): current voltage graph of an ohmic material.

(b) NON OHMIC.

Def —" A conductor which does not obey ohm's law is called non ohmic." [fig (b)]

e.g. filament of bulbs and semiconductor diodes.

fig (b)

EXPLANATION.

Apply a certain p.d across the terminals of a filament lamp. Measure the current passing through it. If we repeat the measurement for different values of p.d and draw a graph of 'I' and 'V'. The graph is not a straight line [fig(b)] It means that a filament is a non ohmic device. This deviation of I-V graph from straight line is due to the increase in the resistance of the filament with temperature. When the current passing through the filament is increased from zero, the graph is a straight line in the initial stage. As the current is small, the increase in temp. is very small and the change in resistance is negligible. When the current is further increased, the resistance of the filament continues to increase due to rise in its temperature.
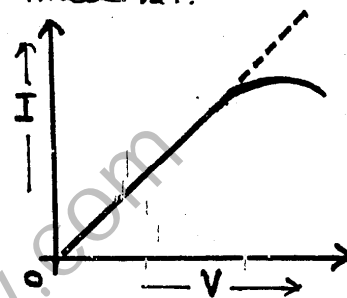
SEMICONDUCTOR DIODE.

Another example of non ohmic device is a semiconductor diode. The 'I' versus 'V' graph of a diode is shown in fig 'c'. The graph is not a straight line so Semiconductor diode is also a non ohmic device.
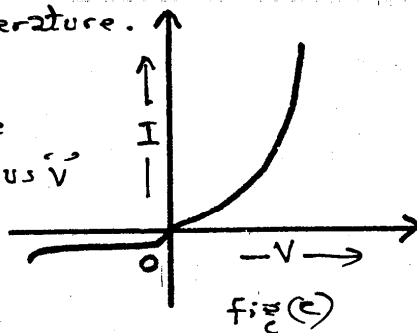

fig (c)

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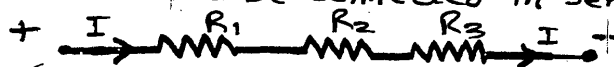
COMBINATIONS OF RESISTORS:

In electrical circuit two or more resistors are connected together by two arrangement:

(a) Series

(b) parallel

(a) SERIES COMBINATION.

Def —— " If the resistors are connected end to end such that, the same current passes through all of them, they are said to be connected in series. "

The equivalent resistance 'R$_e$' is given by;   fig(a)

$$R_e = R_1 + R_2 + R_3 + \ldots \quad ——①$$

N.B In this case current 'I' remains same through all the resistors but P.d 'V' across all the resistors divides according to their values.
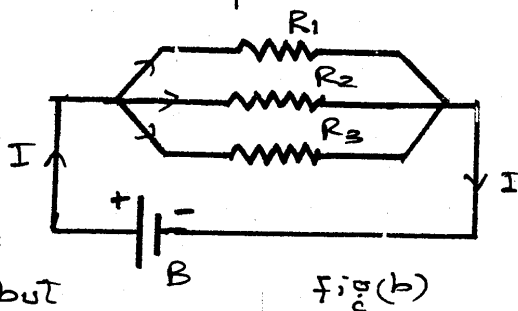
(b) PARALLEL COMBINATION.

Def —— " If the resistors are connected side by side with their ends joined together at common points, they are said to be connected in parallel."

The equivalent resistance 'R$_e$' is given by;

$$\frac{1}{R_e} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots \quad ——②$$

N.B In this case P.d 'V' across all the resistors remains same but current 'I' divide according to the values of the resistors.

#13.5 RESISTIVITY AND ITS DEPENDENCE UPON TEMPERATURE.

● It has been experimentally seen that the resistance 'R' of a wire is directly proportional to its length 'L' and inversely proportional to its cross sectional area 'A'.

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Mathematically,

$$R \propto L$$

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

or $R \propto L/A$

$$\therefore \quad R = \varsigma \frac{L}{A} \quad \text{——} ①$$

Where 'ς' is a constant of proportionality known as **resistivity** or **Specific resistance** of the material of the wire.

If   L = 1m , A = 1 m^2 , then ;

$$R = \varsigma \quad \text{——} ②$$

RESISTIVITY.

Def — "The resistance of a metre cube of a material is called resistivity."

UNIT.   Ohm-metre (Ω m)

DIFFERENCE B/W RESISTANCE AND RESISTIVITY.

Resistance is the characteristic of a particular wire where as the resistivity is the property of the material of which the wire is made.

RESISTIVITY DEPENDS UPON TEMPERATURE.

The resistivity of a substance depends upon the temp. As the resistance offered by a conductor to the flow of electric current is due to collisions, which the free electrons encounter with atoms of the lattice. As the temp. of the conductor rises, the amplitude of vibration of the atoms in the lattice increases and hence, the probability of their collision with free electrons also increases. Therefore resistance of the conductor increases.

Experimentally the change in resistance of a metallic conductor with temp. is found to be nearly linear over a considerable range of temp. above and below 0°c [fig (2)].

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Over such a range the fractional change in resistance per Kelvin is known as the temp. co-efficient of resistance.
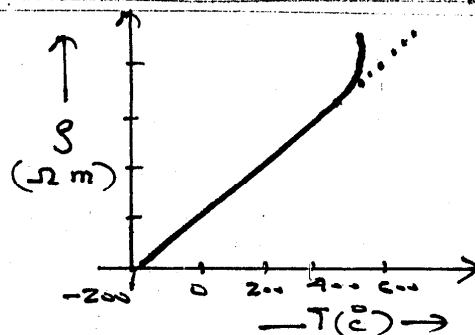
$$\alpha = \frac{R_t - R_o}{R_o \times t} \qquad ③$$

Where R_o is the resistance of the conductor at $0°c$ and R_t is the resistance at a temp $t°c$.

We know that resistivity is directly proportional to the resistance. Therefore, we can express eq.③ in terms of resistivity as;

$$\alpha = \frac{\rho_t - \rho_o}{\rho_o \times t} \qquad ④$$

Where ρ_o is the resistivity at $0°c$ and ρ_t is the resistivity at $t°c$. The α is temp. co-efficient of resistivity of a substance.

N.B There are some substances like germanium, silicon etc; whose resistance decrease with increase in temp. i.e; these substances have negative temp. co-efficient.

Fig(a) Variation of resistivity of Cu with temp.

● CONDUCTANCE.

Def —— "The reciprocal of resistance is called conductance."
i.e; Conductance = $\frac{1}{Resistance}$

or $\quad e = \frac{1}{R} \qquad ⑤$

It is another quantity used to describe the electrical properties of materials.

UNIT. The SI unit of conductance is **mho** or **Siemen**.

CONDUCTIVITY.

Def —— "The reciprocal of resistivity is called conductivity."
i.e; conductivity = $\frac{1}{Resistivity}$

or $\quad \sigma = \frac{1}{\rho} \qquad ⑥$

UNIT. The SI unit of conductivity is **Ohm^{-1} m^{-1}** or **Mho m^{-1}**.

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N.B. Gold, Silver and copper are good conductors. That is the reason that most electric wires are made of copper and connection in IC's are made by gold.

EXAMPLE 13.2 0.75A current flows through an iron wire when a battery of 1.5 V is connected across its ends. The length of the wire is 5.0 m and its cross sectional area is $2.5 \times 10^{-7} m^2$. Compute resistivity of iron.

Sol. As $R = \dfrac{V}{I} = \dfrac{1.5 V}{0.75 A} = 2\Omega$ ——①

The resistivity 'ρ' of iron is;

$$\rho = \dfrac{RA}{L} = \dfrac{2 \times 2.5 \times 10^{-7}}{5} = \boxed{1.0 \times 10^{-7} \Omega m}$$

EXAMPLE 13.3 A platinum wire has resistance of 10Ω at $0°c$ and 20Ω at $273°c$. Find the value of temp. co-efficient of resistance of platinum.

Sol. $R_0 = 10\Omega$, $R_t = 20\Omega$, $t = 546 K - 273K = 273 K$

Temp. co-efficient of resistance can be found by;

$$\alpha = \dfrac{R_t - R_0}{R_0 \times t} = \dfrac{20 - 10}{10 \times 273} = \dfrac{1}{273K} = \boxed{3.66 \times 10^{-3} K^{-1}}$$

#13.6 COLOUR CODE FOR CARBON RESISTANCES:

Carbon resistors are most common in electronic equipment. They consist of a high grade ceramic rod or cone (called the substrate) on which a thin resistive film of carbon is deposited. The numerical value of their resistance is indicated by a **colour code** which consists of bands of different colours printed on the body of the resistor. The colour used in this code and the digits represented by them are given in table.

THE COLOUR CODE	
COLOUR	**VALUE.**
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9

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Remember It is easy to remember colours and their respective numbers with the help of this sentence.

B	B	R	O	Y	Great	Briton	very	good	Wife
0	1	2	3.4		5	6	7	8	9

or

B	B	R	O	Y	Goes	Briton	Via	Germany	West
0	1	2	3	4	5	6	7	8	9

COLOUR BAND

Usually the code consists of <u>four bands</u>. Starting from <u>left to right</u>, the colour bands are interpreted as follows:

1— First band. The first band indicates the first digit in the numerical value of the resistance e.g; red = 2

2— Second band. The second band gives the second digit e.g; violet = 7

3— Third band. The third band is decimal multiplier i.e; it gives the number of zeros after the first two digits e.g; orange = 3, we put three zero (000) after second digit.

rst digit
2nd digit ←
No. of 0s ←

Tolerance
Gold ±5%
Silver ±10%

fig (a)

Red   Violet   orange   Silver
2   7   000   ±10%

$R = 27000\Omega\ (\pm 10\%)$

fig (b)

4— Fourth band. The fourth band gives <u>resistance tolerance</u>.

Def— "The possible variation from the marked value is called tolerance."

Its colour is either silver or gold. Silver band indicates a tolerance of ±10%, a gold band shows a tolerance of ±5%.

If there is **no fourth band**, tolerance is understood to be ±20%.

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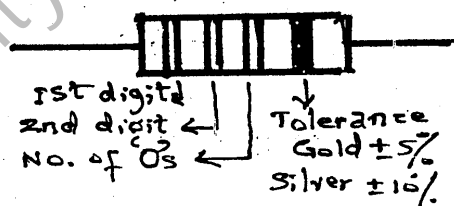13-17

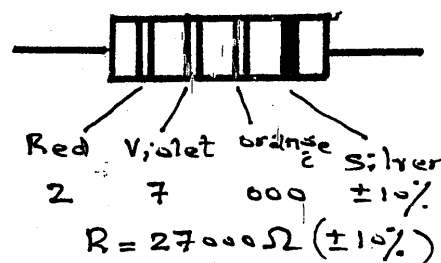## EXAMPLE. A 1000 Ω resistor with a tolerance of ±10% will have an actual resistance anywhere between 900 Ω and 1100 Ω.

N.B A zero-ohm resistor is indicated by a single colour band around the body of the resistor.

● RHEOSTAT:

Def—"The wire wound variable resistance is called Rheostat."

CONSTRUCTION. It consists of a bare manganin wire wound over an insulating cylinder. The ends of the wire are connected to two fixed terminals 'A' and 'B' [fig (a)]. A third terminal 'C' is attached to a sliding contact which can be moved over the wire.
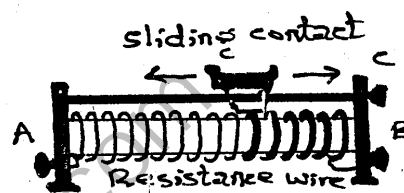

fig(a) A Rheostat.

fig(b) Its use as variable resistor.

USES. A rheostat can be used as

1— a variable resistor

2— a potential divider

1— VARIABLE RESISTOR.

A rheostat acts as a variable resistor when terminal 'A' and the sliding terminal 'C' are connected in a circuit [fig(b)]. In this way the resistance of the wire between 'A' and 'C' is used. If sliding contact is shifted from the terminal 'A', the length and hence the resistance included in the circuit increases and if the sliding contact is moved towards 'A', the resistance decreases.

2— POTENTIAL DIVIDER.

A P.d 'V' is applied across the ends 'A' and 'B' of the rheostat with the help of a battery. If 'R' is

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the resistance of wire AB, the current 'I' passing through it is given by

$$I = \frac{V}{R} \qquad \text{①}$$

The P.d between the portion BC of the wire AB is given by ;

$$V_{BC} = \text{current} \times \text{resistance}$$
$$= \frac{V}{R} \times r$$
$$V_{BC} = \frac{r}{R} \times V \qquad \text{②}$$

fig (c) Use of rheostat as potential divider.

Where 'r' is the resistance of BC of the wire. Eq.② shows that this circuit can provide at its output terminals a P.d varying from zero to the full P.d of the battery depending on the position of the sliding contact. As the 'c' is moved towards the end 'B', the length and hence the resistance 'r' decreases which decrease V_{BC}. On the other hand if 'c' is moved towards the end 'A', the output voltage V_{BC} increases.
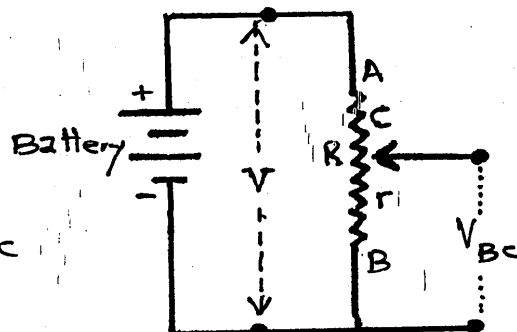
● THERMISTORS

Def — "A heat sensitive resistor is called a thermistor."

Most of the thermistors have negative temperature co-efficient (ntc) of resistance i.e; <u>the resistance of such thermistors decrease when their temperature is increased</u>. Thermistors with positive temperature co-efficient are also available.

FABRICATION.

Thermistors are made by heating under high pressure. <u>Semiconductor ceramic made from mixtures of metallic oxides of manganese, nickel, cobalt, copper, iron etc.</u>
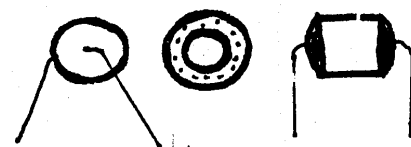
fig (a) Thermistors of different shapes.

(P.T.o)

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These are pressed into desired shapes and then baked at high temperature. Different types of thermistors are shown in fig. They may be in the form of beads, rods or washers.

Thermistors with high negative temp. co-efficient are very accurate for measuring low temp. especially near 10 K. The higher resistance at low temp. enables more accurate measurement possible.

APPLICATIONS.

Thermistors have wide application as **temperature Sensors** i.e; they convert changes of temp. into electrical voltage or signals. It is also used in the devices where high temp. rise is not required like an overloaded electric motor.

#13.7 ELECTRICAL POWER AND POWER DISSIPATION IN RESISTORS:

● ELECTRICAL POWER.

Def—— "The rate at which the battery is supplying electrical energy is the power output or electrical power of the battery."

EXPLANATION· Consider a circuit consisting of a battery 'E' connected in series with a resistance 'R' as shown. A steady current 'I' flows through the circuit and a steady potential difference 'V' exists between the terminals 'A' and 'B' of the resistor 'R'. Terminal 'A' is at a higher potential than the terminal 'B'.

P.d is the work done in moving a charge 'ΔQ' up through the P.d 'V' is given by;

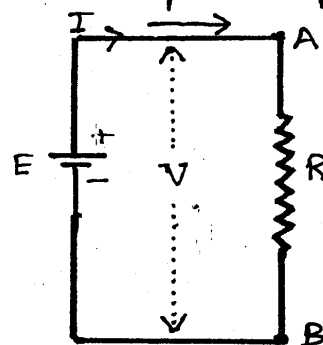$$Work done = \Delta W = V \times \Delta Q \quad ——①$$

fig. The power of a battery appears as the power dissipated in the resistor 'R'.

(P.T.O)

<u>By definition ;</u>

$$\text{Electrical power} = \frac{\text{Energy Supplied}}{\text{Time Taken}} = \frac{V \times \Delta Q}{\Delta t}$$

$$\because I = \frac{\Delta Q}{\Delta t}$$

$$\therefore \text{Electrical power} = V \times I \quad \underline{\qquad \text{②}}$$

Eq ② is a general relation for power delivered from a source. The power supplied by the battery is used in the resistor 'R'. The principle of conservation of energy tells us that power dissipated in the resistor is also given by eq ②. So

$$\boxed{\text{Power dissipated } (P) = V \times I} \quad \underline{\qquad \text{③}}$$

<u>UNIT</u> . 1 watt = 1 volt × 1 amp (SI)

As $V = IR$ or $I = V/R$;
Putting in eq. ③, we have

$$\boxed{P = I^2 R = \frac{V^2}{R}} \quad \underline{\qquad \text{④}}$$

#13.8 ELECTROMOTIVE FORCE (EMF) AND POTENTIAL DIFFERENCE.

● ELECTROMOTIVE FORCE(EMF).

Def — "The P.d between the terminals of battery when no current is flowing through an external circuit (or, when the circuit is open) is called emf."

EXPLANATION.

When a source of electrical energy (e.g ; a cell or battery) is connected across a resistance 'R', it maintains a steady current through it [fig(a)].

E $\begin{array}{c}+\\-\end{array}$ R

fig (a) emf of a cell .

The cell continuously supplies energy which is dissipated in the resistance of the circuit. Suppose when a steady current has been established in the circuit, a charge ΔQ passes through any cross section of the circuit in time Δt. During the course of motion, this charge enters the cell at its low potential end and
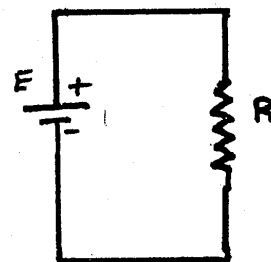
(P.T.o)

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leaves at its high potential end. The source supply energy ΔW to the positive charge to force it to go to the point of high potential. The emf "E" of the source **is defined** as the energy supplied to unit charge by the cell.

i.e;

$$E = \frac{\Delta W}{\Delta q} \quad \text{———①}$$

__UNIT.__ 1 volt = $1J/1C$ (SI)

__N.B__ The energy supplied by the cell to the charge carriers is derived from the conversion of chemical energy into electrical energy inside the cell.

● **POTENTIAL DIFFERENCE (P.d.).**

Def —"The voltage or P.d between the terminals of battery when current is flowing through an external circuit is called terminal P.d."

It is a local phenomenon. We always speak of emf of a battery but P.d across a circuit or part of the circuit

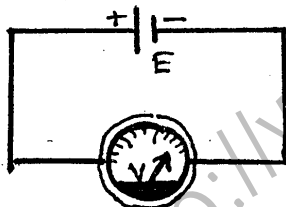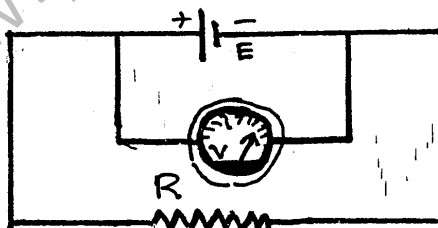## DIFFERENCE B/w emf AND P.d.

fig (b)   fig (c)

A voltmeter connected across the terminals of a cell measures (b) the emf of the cell on open circuit, (c) the terminal P.d on a closed circuit.

● **INTERNAL RESISTANCE.**

A cell offers some resistance. This resistance is due to the electrolyte present between the two electrodes of the cell. It is called internal resistance "r" of the cell. Thus a cell of emf E having internal resistance "r" is equivalent to a source of Pure emf E with a resistance "r" in series as shown in fig (d).
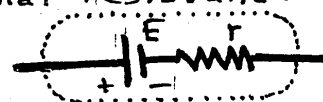

fig(d) An equivalent circuit of a cell of emf E and internal resistance "r".

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A voltmetre measures the P.d across the external resistance 'R'. The current flowing through the circuit is given by;

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

$$E = I(R+r)$$

$$\text{or} \quad E = IR + I \times r \quad \text{——②}$$

fig (e) The terminal P.d V of a cell is $EI - R$

Where 'IR' is the terminal P.d of the cell in the Presence of current 'I'.

$$E = V_t + I \times r$$

$$\text{or} \quad V_t = E - I \times r \quad \text{——③}$$

When the switch 'S' is open, no current passes through the resistance. In this case the voltmeter reads the emf 'E' as terminal voltage. This terminal voltage in the presence of the current (Switch on) would be less than the emf 'E' by 'I×r'.

   The left side of eq.② is the emf 'E' of the cell which is equal to energy gained by unit charge as it passes through the cell from its negative to positive terminal. The right side states that 'I×r' is dissipated into the cell (called lost voltage). The rest of the energy is dissipated into the external resistance 'R'.

The emf is the 'cause' and P.d is its 'effect'. The emf is always present even when no current is drawn through the battery or the cell, but the P.d across the conductor is zero when no current flows through it.

MAX. POWER OUTPUT.

   In the circuit of fig (e), as the current 'I' flows through the resistance 'R', the charges flow from a
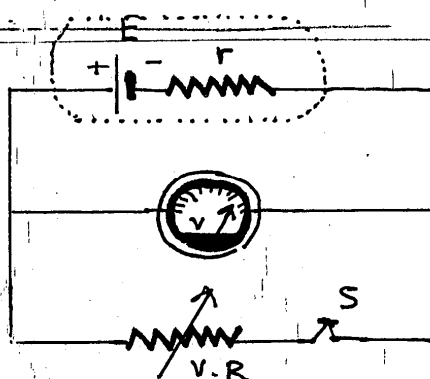
(P.T.o)

point of higher potential to a point of lower potential and as such, they loose P.E. If V is the P.d across 'R', the loss of P.E per second is $V \times I$. This loss of energy per second appears in other forms of energy and is known as __power delivered to 'R'__ by current I.

Power delivered to $R = P_{out} = VI$

$$= I^2 R \qquad (\because V = IR)$$

As $\qquad I = \dfrac{E}{R+r}$

So $\qquad P_{out} = \dfrac{E^2 R}{(R+r)^2} = \dfrac{E^2 R}{(R-r)^2 + 4R \times r} \qquad —— ④$

When $R = r$, the denominator of the expression of P_{out} is least and so P_{out} is then a maximum. Thus we see that maximum power is delivered to a resistance (load), when the internal resistance of the source equal the load resistance. The value of this maximum output power as given by eq ④ is

As $\qquad r = R$

Max. output power $= \dfrac{E^2 \times r}{4r \times r} = \dfrac{E^2}{4r} \qquad —— ⑤$

EXAMPLE 13.4 The P.d between the terminals of a battery in open circuit is 2.2 V. When it is connected across a resistance of 5Ω, the potential falls to 1.8 V. calculate the current and the internal resistance of the battery.

DATA: P.d $= E = 2.2$ V , Resistance $= R = 5\,\Omega$
Fall in potential $= V = 1.8$ V , current $= I = ?$
Internal resistance $= r = ?$

Sol: (i) As $V = IR \Rightarrow I = \dfrac{V}{R} = \dfrac{1.8}{5} = \boxed{0.36\ A}$

(ii) As $E = V + I \times r \Rightarrow I \times r = E - V$

and $r = \dfrac{E-V}{I} = \dfrac{2.2 - 1.8}{0.36} = \boxed{1.11\ \Omega}$

(P.T.o)

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#13.9 KIRCHHOFF'S RULES :

Quite often we find circuits in which the resistors are not simply in series or parallel, or their combination, and a number of voltage sources. In order to solve the more complicated circuit problems, two rules established by the German Physicist Gustar Robert Kirchhoff (1824-1887) are used.

(a) KIRCHHOFF'S FIRST RULE OR KIRCHHOFF'S POINT RULE.

Statement ____ "The sum of the currents meeting at a point in the circuit is zero" or "sum of all the currents flowing towards a point (node) is equal to the sum of all the currents flowing away from the point(node)."

Mathematically ,

$$\sum I = 0 \quad \underline{\quad\quad} \quad ①$$

EXPALANATION.

Consider a circuit where four wires meet at a point 'A' [Fig(a)]. The currents 'I₁' and 'I₂' are flowing towards the point 'A' and currents 'I₃' and 'I₄' are flowing away from the point 'A'.
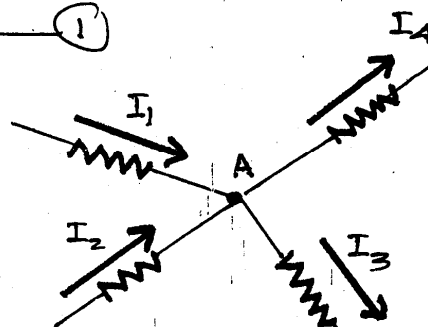
fig. According to
(a) Kirchhoff's 1st rule
$I_1 + I_2 = I_3 + I_4$

According to convention current flowing towards a point is taken as positive and that flowing away from a point is taken as negative. Applying Kirchhoff's point rule, we have;

$$I_1 + I_2 + (-I_3) + (-I_4) = 0$$

or, $$I_1 + I_2 = I_3 + I_4 \quad \underline{\quad} ②$$

The above eq. verifies the law of conservation of charge.

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If there is no sink or source of charge at the point, the total charge flowing towards a point must be equal to the total charge flowing away from the point.

(b) KIRCHHOFF'S SECOND RULE.

Statement — "The algebraic sum of Potential changes for a complete circuit is zero."

Mathematically,

$$\Delta V_{closed\ loop} = 0 \qquad \text{——①}$$

EXPLANATION.

Consider a closed circuit as shown in [Fig(b)]. The direction of the current 'I' flowing through the circuit depend on the cell having the greater emf. Suppose E₁ is greater than E₂, so the current flows in counter
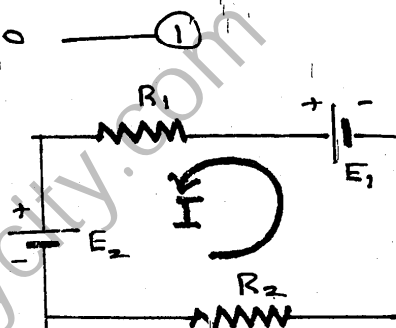
E_1 is greater than E_2, so the current flows in counter clockwise direction. We know that a steady current is equivalent to a continous flow of **positive charges** through the circuit. We also know that a voltage change or P.d is equal to the workdone on a unit positive charge or _energy gained or lost_ by it in moving from one point to the other. Thus when a positive charge ΔQ due to the current 'I' in the closed circuit passes through the cell E_1 from low (−ve) to high potential (+ve), it gains energy because work is done on it.

● Therefore,

Energy gained by the charge $= E_1 \times \Delta Q$ ——②

Fig(b) According to Kirchhoff's 2nd rule

$$E_1 - I R_1 - E_2 - I R_2 = 0$$

Energy $= V \times Q$

● Similarly, when the current passes through the cell E_2

it loses energy equal to $-E_2\Delta Q$ because here the charge passes from high to low potential.
Therefore,

$$\text{Energy lost by the charge} = -E_2\Delta Q \quad \text{——③}$$

● When the charge ΔQ passes through the **resistance R_1,** then;

$$\text{Energy lost by the charge} = -IR_1\Delta Q \quad \text{——④}$$

where according to Ohm's law IR_1 is P.d across R_1. The minus sign indicates that the charge is passing from high to low potential.

● **Similarly,** the loss of energy while passing through the **resistor R_2** is :

$$\text{Loss of energy} = -IR_2\Delta Q \quad \text{——⑤}$$

Finally the charge reaches the negative terminal of the cell E_1 from where we started. Kirchhoff's second rule is really another statement of the law of conservation of energy. According to the law of conservation of energy the total change in energy of our system is zero. Therefore we can write;

$$E_1\Delta Q - IR_1\Delta Q - E_2\Delta Q - IR_2\Delta Q = 0$$

$$\text{or} \quad E_1 - IR_1 - E_2 - IR_2 = 0 \quad \text{——⑥}$$

which is Kirchhoff's second rule. This rule verify the law of conservation of energy in electrical problems.

RULES FOR FINDING THE POTENTIAL CHANGES.

1— If a source of emf. is traversed from negative to positive terminal, the potential change is positive, it is negative in the opposite direction.

2— If a resistor is traversed in the direction of current, the change in potential is negative, it is positive in the opposite direction.

(P.T.o)

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PROCEDURE OF SOLUTION OF CIRCUIT PROBLEMS:

1.__ Draw the circuit diagram.

2.__ The choice of loops should be such that each resistance is included at least once in the selected loops.

3.__ Assume a loop current in each loop, all the loop currents should be in the same sense. It may be either clockwise or anticlockwise

4.__ Write the loop equations for all the loops. The voltage change across any component is positive if traversed from low to high potential and it is negative if traversed from high to low potential.

5.__ Find unknown quantities by solving these eqs.

EXAMPLE 13.6 Calculate the currents in the three resistances of the circuit.

DATA: $R_1 = 10\,\Omega$, $R_2 = 30\,\Omega$, $R_3 = 15\,\Omega$

$E_1 = 40V$, $E_2 = 60V$, $E_3 = 50V$
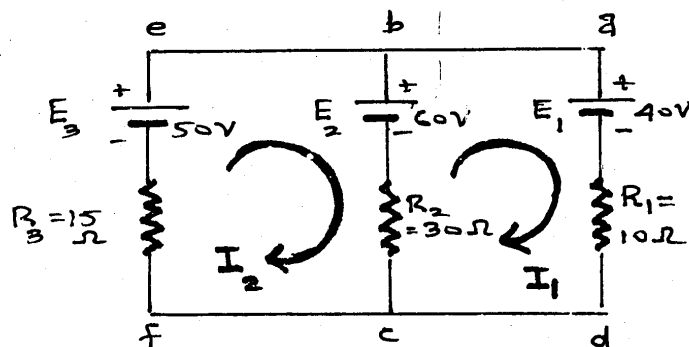
Current through R_1, R_2 and R_3 = ?

Sol.

(i) Choice of loop is arbitrary, but each resistance must be included at least once

(ii) Sence of all loops currents (or their direction) should be same e.g; clockwise

(iii) When two currents flow through one resistor, then the current of loop under consideration is taken as positive otherwise as negative.

(iv) Applying Kirchhoff's 2nd rule

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Loop "abcda"   Starting from pt. 'a'

$$-E_1 - IR_1 - (I_1 - I_2)R_2 + E_2 = 0 \quad\quad ①$$

Putting the values;

$$-40 - I_1 \times 10 - (I_1 - I_2) \times 30 + 60 = 0$$

$$-40 - 10 I_1 - 30 I_1 + 30 I_2 + 60 = 0$$

$$-40 I_1 + 30 I_2 = -20$$

$$4 I_1 - 3 I_2 = 2 \quad\quad ②$$

Loop "bcfeb"

$$-E_2 - (I_2 - I_1)R_2 - I_2 R_3 + E_3 = 0 \quad\quad ③$$

Putting the values;

$$-60 - (I_2 - I_1) \times 30 - I_2 \times 15 + 50 = 0$$

$$-60 - 30 I_2 + 30 I_1 - 15 I_2 + 50 = 0$$

$$30 I_1 - 45 I_2 = 10$$

$$6 I_1 - 9 I_2 = 2 \quad\quad ④$$

Multiplying eq. ② by '3' and subtracting eq. ④ from eq. ②, we have

$$12 I_1 - 9 I_2 = 6$$
$$6 I_1 - 9 I_2 = 2$$
$$\underline{\quad - \quad + \quad - \quad}$$
$$6 I_1 = 4$$

$$I_1 = \frac{4}{6} = \frac{2}{3} = \boxed{0.66 A} \quad\quad ⑤$$

Putting this value of 'I_1' in eq. ②, we have

$$4\left(\frac{2}{3}\right) - 3 I_2 = 2$$

$$\frac{8}{3} - 3 I_2 = 2$$

$$3 I_2 = \frac{8}{3} - 2$$

$$9 I_2 = 8 - 6 = 2$$

$$I_2 = \frac{2}{9} = \boxed{0.22 A} \quad\quad ⑥$$

Current through $R_1 = I_1 = \boxed{0.66 A}$
(Directed from a → d)

Current through $R_2 = I_1 - I_2 = 0.66 - 0.22 = \boxed{0.44 A}$
(Directed from c → b)

Current through $R_3 = I_2 = \boxed{0.22 A}$
(Directed from f → e)

13.9 WHEATSTONE BRIDGE:

Def.— " It is an electric circuit that is used to measure the value of an unknown resistance accurately."

It was first suggested by C.F. Wheatstone.

CONSTRUCTION.

The Wheatstone bridge circuit consists of four resistances R_1, R_2, R_3 and R_4 connected in such a way so as to form a mesh ABCDA as shown. A battery of emf is connected between points 'A' and 'C'. A sensitive galvanometer of resistance 'R_g' is connected between points 'B' and 'D'.
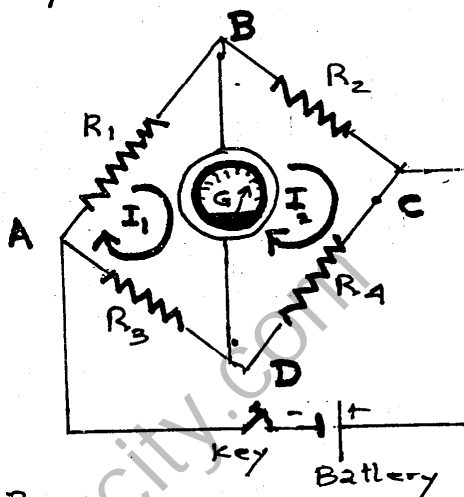

fig: Wheatstone bridge circuit.

WORKING.

If the key 'K' is closed, a current will flow through the galvanometer. We are to determine the condition under which <u>no current</u> will flow through the galvanometer even after the key is closed. This can be done by using Kirchhoff's second rule. Now we consider two loops 'ABDA' and 'BCDB' and assume <u>clockwise</u> loop currents 'I_1' and 'I_2' through the loops respectively.

Applying Kirchhoff's second rule on loop 'ABDA', we have

$$-I_1 R_1 - (I_1 - I_2)R_g - I_1 R_3 = 0 \qquad —①$$

Similarly, applying Kirchhoff's second rule to loop 'BCBA', we have

$$-I_2 R_2 - I_2 R_4 - (I_2 - I_1)R_g = 0 \qquad —②$$

The current flowing through the galvanometer will be zero if $\quad I_1 - I_2 = 0 \quad$ or $\quad I_1 = I_2$

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Therefore eq. ① and ② respectively reduces to;

$$-I_1R_1 - I_1R_3 = 0$$

or $\quad -I_1R_1 = I_1R_3 \quad$ ——— ③

and $\quad -I_1R_2 - I_1R_4 = 0$

or $\quad -I_1R_2 = I_1R_4 \quad$ ——— ④

Dividing eq. ③ by ④, we have

$$\frac{-I_1R_1}{-I_1R_2} = \frac{I_1R_3}{I_1R_4}$$

or $\quad \boxed{\dfrac{R_1}{R_2} = \dfrac{R_3}{R_4}} \quad$ ——— ⑤

This is the condition for the bridge to be balanced and is called the principle of the Wheatstone. Whenever this condition is satisfied, no current flows through the galvanometer and it shows no deflection.

APPLICATIONS OF THE WHEATSTONE BRIDGE.

If we connect three resistances R_1, R_2 and R_3 of known adjustable values and a fourth resistance R_4 of unknown value and the resistances R_1, R_2 and R_3 are so adjusted that the galvanometer shows no deflection then, the unknown resistance R_4 can be determined. A number of resistance measuring instruments (e.g post office box, slide wire bridge etc) based upon this principle have been constructed.

POTENTIOMETER:

13.10 Def.— "It is an electrical instrument which is used to measure the P.d between two points without drawing any current from the original circuit."

Potentiometre is one of the most accurate methods from measuring Potential.

(P-T-o)

EXPALANATION.

A voltmeter measures P.d across a resistor. It can not measure voltage accurately because it draws some current from the circuit. An ideal voltmeter has an infinite resistance so that it could not draw current.

The digital voltmeter and cathode ray oscilloscope (CRO) can measure accurate P.d because they do not draw any current from the circuit because of their large resistance. But these instruments are very expensive and are difficult to use. A very simple instrument which can measure and compare P.d accurately is potentiometer.

CONSTRUCTION AND WORKING

A potentiometer consists of a resistor 'R' in the form of a wire on which a terminal 'c' can slide as shown in fig (a). The resistance between 'A' and 'c' can be varied from 0 to R as the sliding contact 'c' is moved from 'A' to 'B'. If a battery of emf 'E' is connected across 'R' as shown in fig (b), the current flowing through it is;

$$I = \frac{E}{R} \quad\quad ①$$

If we represent the resistance between 'A' and 'c' by 'r', the potential drop between these points will be

$$V = rI = \frac{rE}{R} \quad\quad ②$$

Thus as 'c' slides from 'A' to 'B', 'r' varies from 0 to R, and the potential drop between 'A' and 'c' changes from zero to 'E'. Such an arrangement also known as **Potential divider**. It can be used to measure the unknown emf of a source by using the circuit shown in
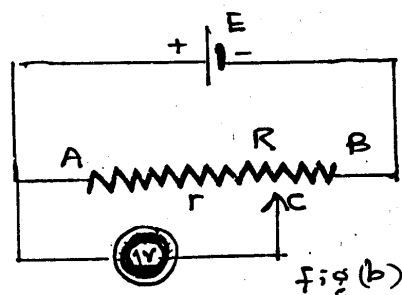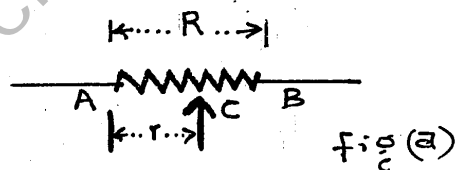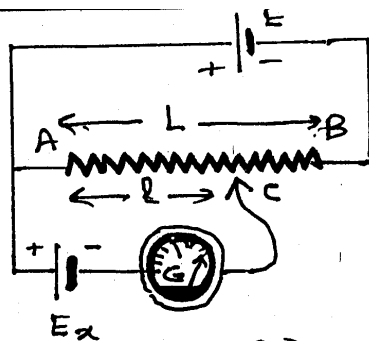
fig (c). Here R is in the form of a straight wire of uniform area of cross section. A Source of potential whose emf E_x is to be measured is connected between 'A' and the sliding contact 'C' through a galvanometer. The positive terminal of E_x and positive terminal of the potential divider are connected to the same point 'A'. If, in the loop AGCA, the point 'C' and the negative terminal of E_x are at the same potential, then the two terminals of the galvanometer will be at the same potential and no current will flow through the galvanometer. Therefore, to measure the potential E_x the position of 'C' is so adjusted that the galvanometer shows no deflection. At this stage, the emf E_x of the cell is equal to the P.d. between 'A' and 'C' whose value $\frac{E \times r}{R}$ is known. In case of a wire of uniform cross section, the resistance is proportional to the length of the wire. Therefore, the unknown emf is also given by

$$E_x = E \times \frac{r}{R} = E \times \frac{\ell}{L} \quad \text{——} \quad ③$$

Where 'L' is the total length of the wire 'AB' and 'ℓ' its length from 'A' to 'C'. The unknown emf E_x should not exceed 'E' value, otherwise the null condition will not be obtained.

COMPARE THE emf's E_1 AND E_2 OF TWO CELLS.

The method for measuring the emf of cell can be used to compare the emf's E_1 and E_2 of two cells. The balancing lengths 'ℓ_1' and 'ℓ_2' are found separately for the two cells, Then ,

$$E_1 = E \times \frac{\ell_1}{L} \quad \text{——} \quad ④$$

$$\text{and} \quad E_2 = E \times \frac{\ell_2}{L} \quad \text{——} \quad ⑤$$

Dividing eq.① and ②, we have

$$\boxed{\frac{E_1}{E_2} = \frac{\ell_1}{\ell_2}}$$

So the ratio of the emf's is equal to the ratio of the balancing length.