CURRENT ELECTRICITY

2.1 Electric Current

Rate of folow of electric charge, SI Unit is ampare (A).

$I = \frac{q}{t}$, where 'q' is the total charge and 't' is the time period.

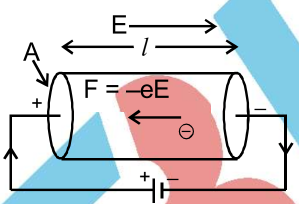
$1 \text{ ampere} = \frac{1\text{coulomb}}{1\text{second}}$

1 **ampare** is defined as the current in a wire if one coulomb of charges flows through it in one second.

2.2 Drift Velocity

In conductors, a large number of free electrons are present, which move in random directions. If $\vec{u}_1, \vec{u}_2, \vec{u}_3, ...\vec{u}_N$ are their random initial velocities, then the average thermal velocity is

$$\frac{\vec{u}_1, \vec{u}_2, \vec{u}_3, ...\vec{u}_N}{N} = 0 \qquad ....(1)$$



When an external electric field $\vec{E}$ is applied across the conductor, the electrons experience a force,

$$\vec{F} = -e\vec{E} \qquad ....(2)$$

If m_e be the mass of electron, then the acceleration of electron will be,

$$\vec{a} = \frac{-e\vec{E}}{m_e} \qquad ....(3)$$

Under the in infuluence of electri field, electron move and subsequently collide with the tions. The time between two successive collisiuons is called **Relaxation time** (τ). he velocity of elecytron just before collision is given by,

$$\vec{v}_1 = \vec{u}_1 + \vec{a}\tau_1 \qquad ....(4)$$

Where $\vec{v}_1$ & $\vec{u}_1$ are the final and initial velocities and τ_1 is the relaxation time of electron I.
The **drift velocity** is defined as the average velocity with which free electrons in a conductor get drifted under the influence of an external field. It is represented by $\vec{v}_d$.

Hence, $$\vec{v}_d = \frac{\vec{v}_1 + \vec{v}_2 + \vec{v}_3 + ... + \vec{v}_N}{N}$$

$$\frac{\vec{u}_1 + \vec{u}_2 + \vec{u}_3 + ... + \vec{u}_N}{N} + \vec{a}\frac{\tau_1 + \tau_2 + ...\tau_N}{N} \qquad ....(5)$$

Where $\frac{\tau_1 + \tau_2 + ...\tau_N}{N} = \tau$, the average relaxation time. Using equation (1), we get,

$$\vec{v}_d = \vec{a}\tau$$

$$\therefore \quad \vec{v}_d = \frac{-e\vec{E}}{m_e}\tau \qquad ....(6)$$

This represents the equation for drift velocity. The drift velocity for metals is of the order of 10^{-3} m/s $\approx 10^{-5}$ m/s

2.3 Relation between Drift Velocity and Electric Current

Let us consider the conductor of cross section area A and length l. Then the volume of the conductor,

$$V = A\,l$$

If n be the no. of free electrons per unit volme, then the total charge on all the free electrons is given by,

$$q = n\,A\,l\,e \qquad ....(1)$$

Under the influence of electric field, the electrons will travel the distance l with drift velocity v_d in

$$t = \frac{\ell}{v_d} \Leftrightarrow I = \frac{q}{t} \qquad ....(2)$$

$$I = neA\,v_d \qquad ....(3)$$

2.4 Mobility

The mobility of free electrons is defined as the drift velocity acquired per unit strength of applied electric field. It is represented by μ. Thus,

$$\mu = \frac{v_d}{E}$$

$\therefore$ $I = n\,A\,\mu\,E\,e$

SI unit of mobility $m^2V^{-1}s^{-1}$

3. OHM'S LAW

The current through a conductor is always directly proportional to the p. d. across its two ends, subject to particular physical conditions (temperature, pressure, etc.) Mathematically.

$I = V$

Or we can say that, $V = I$

$V = RI$, where R is the resistance.

Thus, $R = \frac{V}{I}$

The SI unit of resistance is Ω (ohm).

1 ohm: On applying a p. d. of 1 volt across the conductor, if one ampare current flows through it, the resistance of a wire is said to be 1 ohm.

Failure of Ohm's Law

1. Due to joule's Effect, the increase in current causes an increase in temperature in the conductor. Hence3 the resistance in the wire in the wire increases. Thus, current does not actually vary linearly with potential difference. **Fig. 1.**

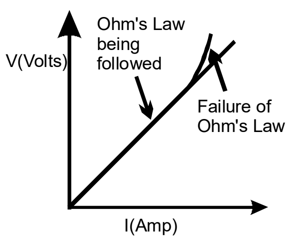


Fig.1

2. When a semiconductor diode is applied with a p. d. across it, the amount of current crossing the diode depends upon the direction in which current flows. In forward biased condition, the current that flows, is given by **Fig. 2** whereas the current that flows during reverse biasing is shown in **Fig. 3.**

3. In electrolytes, the Ohm's Law fails.

4. In semiconductor devices, such as thyristors, the current may increase on decreasing the p. d. **Fig.4.**

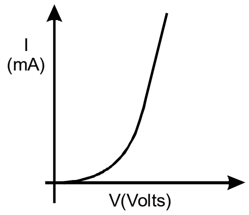


Fig.2

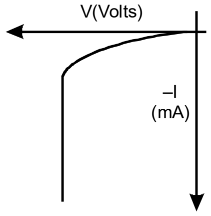


Fig.3

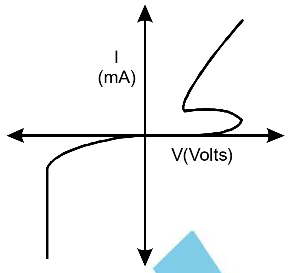
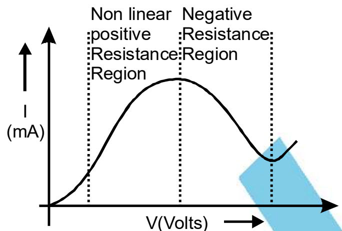


Fig.4



Variation of current versus valtage for GaAs.

3.1 Resistivity (Specific Resistance)

The resistance of a conductor depends upon factors such as length and cross section area of the conductor.

(a) It is directly proportional to the length of the conductor, i.e.,

$R \propto l$

(b) It is inversely proportional to the area of cross section of the conductor

$R \propto \frac{1}{A}$, Hence, $R = \rho\frac{\ell}{A}$

Metal of least :
1. Silver $1.6\times10^{-8}\,\Omega m$
2. Copper $1.7\times10^{-8}\,\Omega m$
Alloy Metal of high :
1. Nichrome $100\times10^{-8}\Omega m$
2. Mercury $98\times10^{-8}\Omega m$

where, ρ is the resistivity of the conductor.
Resistivity is defined as the resistance of a material of a conductor of unit length and unit area of cross section.
SI unit of resistivity is Ω m.

Now, $V = IR = I\rho\frac{\ell}{A}$

$\Rightarrow \quad V = \frac{I}{A}\rho l = j\rho l$ [where $j \rightarrow$ current density]

$\therefore \quad \boxed{E = j\rho} \Rightarrow \boxed{j = \sigma E}$

Material with highest resistivity
Fused quartz $10^{16}\,\Omega m$
Material which is superconducting
$Tl_2Ba_2Ca_2Cu_2O_{10}$

where σ is the conductivity and is reciprocal of ρ.

3.2 Resistivity

The drift velocity of electron $|\vec{v}_d| = \frac{e\vec{E}}{m}\tau$

$\Rightarrow$ $E = \frac{V}{l}$ $\Rightarrow$ $v_d = \frac{eV}{ml}\tau$

$\Rightarrow$ $I = n\,A\,e\,v_d$

$\therefore$ $I = \frac{nAe^2V\tau}{ml}$

But, $R = \frac{V}{I}$

$R = \frac{m}{ne^2\tau}\frac{\ell}{A}$

As we know, $R = \rho\frac{\ell}{A}$

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

$j \to$ Current density

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

$j = \frac{E}{\rho} = \sigma E$ ....(2)

From equations (1) and (2)

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

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

3.3 Temperature Dependence of Resistivity: The relaxation time τ decreases with the increase in temperature. Thus, an increase in the temperature will result in higher resistivity of the material of the conductor. There are two formual, which explain this relation:

$\rho \propto \frac{1}{\tau}; \rho = \rho_0[1+\alpha(T - T_0)]$

$T\uparrow \Leftrightarrow \tau\downarrow \Leftrightarrow \rho\uparrow \Leftrightarrow R\uparrow$

3.4 Dependence on Material : The no. of free electrons per unit volume is 'n' and it varies from material. The resistivity of the conductor also depends upon the material.

$\rho \propto \frac{1}{n}$

3.5 Conductance and Conductivity: Conductance is defined as the reciprocal of resistance of the material. It is represented by G. The SI Unit of conductance is Ohm^{-1} [or Mho or Ω^{-1} or Siemens (S)]

$G = \frac{1}{R}$

Why manganin is used in the construction of standard resistance coil?

Alloys such as manganin have very high resistivity and weak dependence on themperature. Manganin (An alloy of copper, Nickel, Iron and Manganese has 30 to 40 times greater resistivity and temperature coefficient α is 0.00002°C^{-1}. Therefore, the resistance of the coil does not change appreciably due to Joule's Heating Effect.

3.6 Conductivity: Conductivity is defined as the reciprocal of resitivity of the meterial. It is represented by σ. The SI unit of conductance is $Ohm^{-1}m^{-1}$ (or $\Omega^{-1}\,m^{-1}$ or Siemen m^{-1})

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

3.7 Temerature Coefficient of Resistance

Let ρ and ρ_0 be the resistivity of the conducting matrial at θºC and 0º C respectively. Then,

$$\rho = \rho_0(1+\alpha\theta)$$

Material like Nichrome exhibit a very weak dependence of resistivity
Manganin and constantan have similar properties

Since, $R = \rho\frac{\ell}{A}$, we can also write,

$$R = R_0(1 + 1\alpha\theta)$$

$$\therefore \quad \alpha = \frac{R - R_0}{R_0\theta}$$

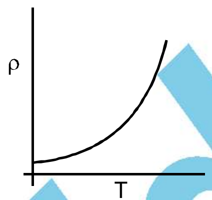
For metals α lies between 10^{-2} to 10^{-4} °C^{-1}

3.8 Conduction in semiconductors : It is due to both electrons and holes.
Hence, $\sigma = ne\mu_e + pe\mu_h$; μ_e and μ_h $\rightarrow$ mobility of electron and hole
n and p $\rightarrow$ electron and hole concentration.

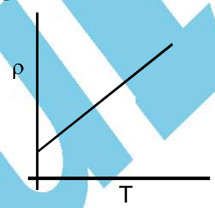
$$v_d = \frac{eE}{m}\tau \text{ and } \mu = \frac{v_d}{E}$$

$$\mu_e = \frac{e\tau_e}{m_e} \text{ and } \mu_h = \frac{e\tau_h}{m_h}$$

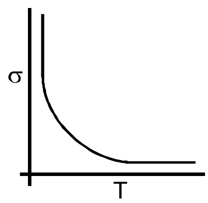
Temperature Vs Resistivity
For conductors, at low temperature, resistivity increases as a higher power of temperature.
Resistivity, $\rho \propto \rho_0[1+\alpha(T-T_0)]$.



Resistivity Vs temperature(Cu)



Resistivity Vs temperature (Nichrome)

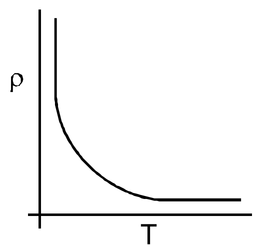


Conductivity Vs Temp (Conductor)

Temperature Vs Resistivity (for Semiconductors and Insulators)
In case of semiconductor and an insulator, the resistivity at an absolute temperature T, is given by, $\rho = \rho_0 e^{\frac{Eg}{kT}}$

where, $E_g \rightarrow$ Band Gap Energy; and k $\rightarrow$ Bolzmann Constant

Superconductivity: The phenomenon, due to which a substance loses its resistance, when cooled below its critical temperature, is known as superconductivity. The substance, which allows current to apss through it without any resistance, is known as superconductor. When Hg is cooled to 4.2 K or below, it loses all its property of resistance. In 1988,

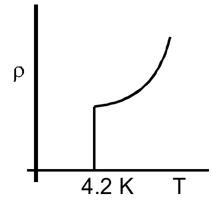


Resistivity Vs Temp. (Semiconductor) (or graphite)

superconductivity was achieved with superconducting oxides at 125K. The cause of superconductivity is that electrons in superconductor are mutually coherent. The ionic vibrations, which can easily.
deflect free electrons in metals, are unable to deflect the coherent cloud of electrons in superconductors.

Applications

1. It can be used to produce super fast computers.
2. It can be used to avoid power loss during transmission
3. It can be used to produce very high magnetic fields without spending electrical power.

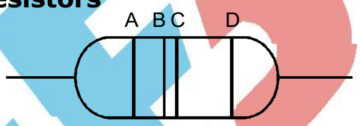


Resistivity Vs Temperature(Hg)

Pneumonic	Colour	Value
B	**B**lack	0
B	**B**rown	1
R	**R**ed	2
O	**O**range	3
Y	**Y**ellow	4
Gets	**G**reen	5
Beautiful &	**B**lue	6
Very	**V**iolet	7
Good	**G**rey	8
Wife	**W**hite	9
Gold	**G**old	10^{-1}
Silver	**S**ilver	10^{-2}

Colour	Tolerance
Gold	± 5%
Silver	± 10%
No Colour	± 20%

Colour Code for Carbon Resistors



Carbon Resistor

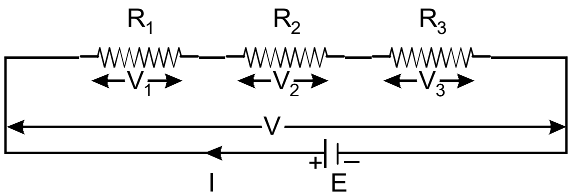
The Formula,
$AB \times 10^{C} \pm D\%$

If A = Red, B = Violet, C= Yellow and D = Gold, then the resistance of the carbon resistor is 27 $\times 10^4\ \Omega \pm 5\%$

D represents '**tolerance**', which means possible variation in % about the specified value

4. Resistors in Series

Consider three resistors R_1, R_2 & R_3 in series, A battary of EMF E is connected across the combination such that a current 'I' passes through the circuit giving rise to p. d. of V_1, v_2 & V_3 across R_1, R_2 & R_3 respectively. Hence



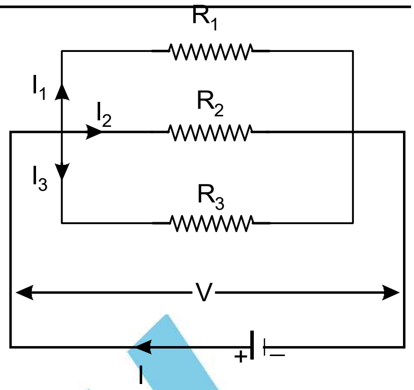
$V_1 = IR_1$; $V_2 = IR_2$; $V_3 = IR_3$

$V = V_1 + V_2 + V_3$

$IR_{eq} = IR_1 + IR_2 + IR_3$

$$\boxed{R_{eq} = R_1 + R_2 + R_3}$$

5. Resistors in Parallel



Consider three resistors R_1, R_2 & R_3 put in parallel combination. A battery of EMF E is connected across the combination. Then the current ' I ' in the circuit can be given by

$$I = I_1 + I_2 + I_3$$

whre I_1, I_2 and I_3 represent the current through R_1, R_2 & R_3 respectively. But, the p. d. across each resistor is V so,

$$I = \frac{V}{R_{eq}} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

$$\boxed{\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

Internal Resistance of Cell: The resistance offered by the electrolyte of the cell to the flow of current. It is repesented by r. It depends upon

(a) Nature of electrolyte (b) Distance between electrodes

(c) Area of electrode (d) Concentration of electrolyte

EMF(Electromotive Force) : The p. d. across the terminals of a cell when no current u being drawn by the circuit. It is denoted by **E. SI** unit is volt.

Relation between EMF (E) & (V)

The EMF is given by , E = I(R + r)

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

where r is the internal resistance of the cell.

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

$\Rightarrow$ V(R + r) = ER

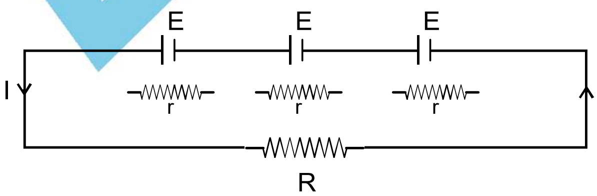
$\Rightarrow$ Vr = (E – V)R

$$\Rightarrow \quad r = \left(\frac{E - V}{V}\right)R$$

1 Volt: The EMF of a cell is one Volt, if one Joule of work is performed by the cell to drive one Coulomb of charge round the circuit.

Grouping of Cells

Cells in Series: Consider **n** cells of EMF **E** and internal resistance **r.**



Cells in Series

For different cells in series,

$$I = \frac{E_1 + E_2 + E_3 + ...}{(r_1 + r_2 + r_3 + ...) + R}$$

For different cells in parallel,

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

Then the total EMF = nE

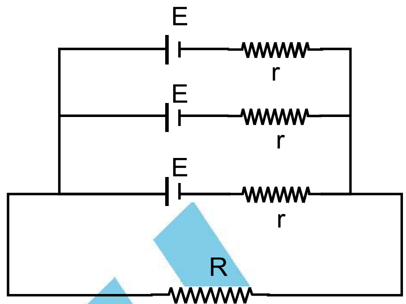
The total resistance = nr + R

Hence, current in the circuit, $I = \dfrac{nE}{R + nr}$

If out of n cells, m cells are grouped in reverse order then, net EMF = nE–(2m)E

Cells in Parallel : Consider **m** rows of cells of EMF **E** and internal resistance **r.**

Then the EMF = E



Cells in Parallel

The total resistance = $\frac{r}{m} + R$

Hence, current in the circuit, $I = \frac{E}{F + \frac{r}{m}}$

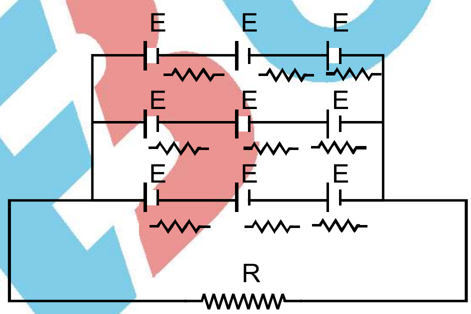
$\therefore$ $I = \frac{mE}{mR + r}$

If r << R, $I = \frac{E}{R}$

In order to increase current, the cells should be connected in parallel.

Mixed Grouping of Cells

Consider **m** rows of cells with **n** cells in each row having an EMF **E** and internal resistance **r** in series in each row. Then,



Net EMF = nE(EMF of one row)

Internal resistance of one row = nr

$\therefore$ Internal resistance of m rows $= \frac{nr}{m}$

$\therefore$ Internal resistance of the circuit $= \frac{nr}{m} + R$

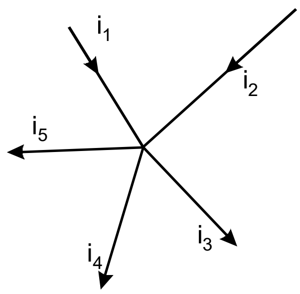
Hence, $I = \frac{nE}{R + \frac{nr}{m}}$

6. ELECTRICAL MEASUREMENTS

Kirchoff's Law : It consists of two laws:

Kirchoff's current Law (Junction Rule):

The aigebraic sum of current meeting at a junction in an electric circuit is zero. It is based on law of conservation of charges.



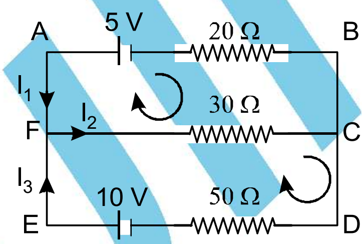
$i_1 + i_2 - i_3 - i_4 - i_5 = 0$

Sign convention: Current entering the junction → + ve
Current leaving the junction → – ve

Kirchoff's Voltage Law [Loop Rule] : The algebraic sum of EMF in any closed loop of circuit is equal to the algebraic sum of all the potential drops. It is based on the law of conser. Vation of energy.

$$\sum E = \sum iR$$

Sign convertion: Consider either a clockwise or anticlockwise loop.
Current in the direction of loop → + ve
While heading the the direction of loop, if the –ve terminal comes first, it is taken + ve.
Example: Find the current in all braches in the given circuit diagram.



Applying Junction Rate,

$$I_1 + I_2 = I_3 \qquad ......(1)$$

Applying loop rule in ABCFA,

$$-5V = -20I_1 - 30I_3 \qquad ......(2)$$

Applying loop rule in FCDEF,

$$+10V = +30I_3 + 50I_2 \qquad ......(3)$$

Using equations (1), (2) & (3), we can find out the value of I_1, I_2 , I_3

Wheatstone Bridge

It is used to determine the resistance of an unknown resistor. When the resistor P, Q, R & S are balanced in such a way that I_g = 0, then

Proof : From the circuit diagram,

$$I = I_1 + I_2 \qquad ......(1)$$

In loop ABDA,

$$I_1P + I_gG - I_2R = 0 \qquad ......(2)$$

Again, in loop BCDB,

$$(I_1 - I_g)Q - (I_2 + I_g)S - I_gG = 0 \qquad ......(3)$$

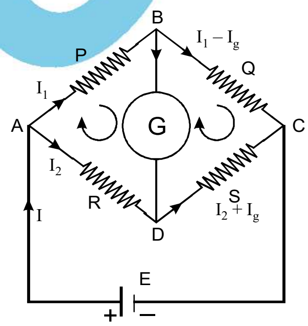
At null point, $I_g = 0$, hence equations (2) & (3) reduce as

$$I_1P = I_2R \qquad ......(4)$$

$$I_1Q = I_2S \qquad ......(5)$$

Dividing equations (4) & (5), we get,

$$\frac{P}{Q} = \frac{R}{S}$$

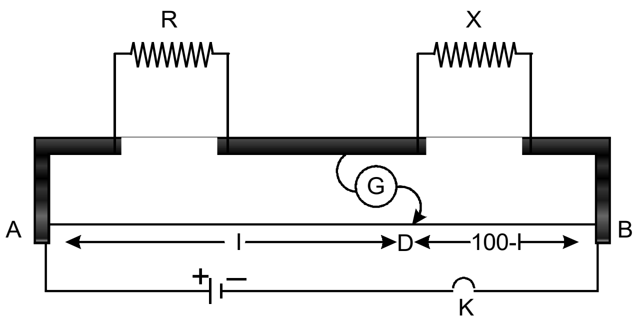


Wheatstone Bridge

Slide Wire Bridge [Metre Bridge] : Metre Bridge is the practical form of Wheatstone bridge. Hence a wire of one metre length is used.

For, $I_g = 0$ $\qquad \frac{P}{Q} = \frac{R}{X}$

But, $\qquad \frac{P}{Q} = \frac{l}{100 - l}$



$\therefore \quad \dfrac{R}{X} = \dfrac{l}{100 - l}$

$\therefore \quad \boxed{X = \dfrac{100 - l}{l} R}$

End Correct: Sometimes at the end points of wire, a part of the wire is under the thick metallic strips, which results in the decrease of effective length (100 – l) or increase. To correct this an additional length of wire is used and additional resistance due to this siere is called 'end resistance'. Due to this the equation

$$\frac{P}{Q} = \frac{l}{100 - l_1} \text{ modifies as } \frac{P}{Q} = \frac{l_1 + \alpha}{100 - l_1 + \beta}$$

On interchanging, we get, $\dfrac{P}{Q} = \dfrac{l_2 + \alpha}{100 - l_2 + \beta}$

Which give, $\alpha = \dfrac{Ql_1 - Pl_2}{P - Q}$ and $\beta = \dfrac{Pl_1 - Ql_2}{P - Q} - 100$

Advantages

1. It is a null method so internal resistance of the cell does not affect the accuracy in determining the resistance of the unknown resistor.
2. Current or Voltage measurement is not required so measurement is not affected due to error in reading .
3. It can be used to measure any range of resistance by altering R and X resistors.

Resistance Thermometer

Wheatstone bridge can be used as a resistance thermometer.

Temperatur e coefficient of resistivity.

$$\alpha = \frac{1}{\rho}\left(\frac{dp}{dt}\right) \text{in} (^\circ C)^{-1}$$

Working Principle: Resistance of a conductor increases with the increase in temperature.

The resistance of a conductor at temperature t is given by ,

$R_t - R_2 (1 + \alpha t)$ ....(1)

where, $R_0 \rightarrow$ Resistance 0ºC

$\alpha \rightarrow$ Temperature coefficient of resistor

$R_t - R_0 = R_0\alpha \times 100$ ....(2)

If R_{100} represents the resistance at 100ºC, then,

$R_{100} - R_0 = R_0\alpha \times 100$ ....(3)

Dividing equation (3) by (2),

$t = \dfrac{R_t - R_0}{R_{100} - R_0} \times 100$ ....(4)

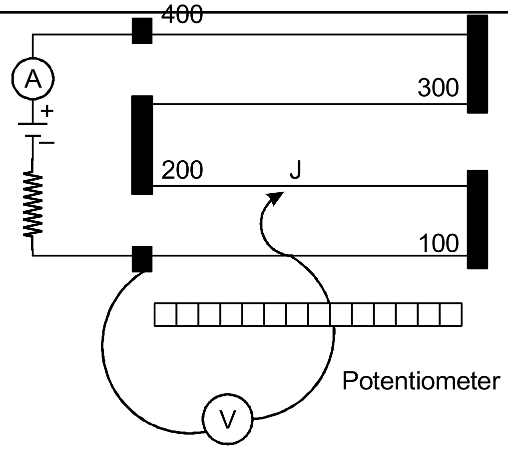
Equation (4) can be used to find the unknown temperature using resistance thermometer.

Potentiometer : It is a device used to compare EMF of two cells or to measure the internal resistance of a cell.

Working Principle : If a constant current is passed through a wire of uniform area of cross section, the potential drop across any portion of the wire is directly proportional to the length of that portion.

Theory : According to Ohm's Law,

$V = IR$



But, $R = \rho \frac{l}{A}$

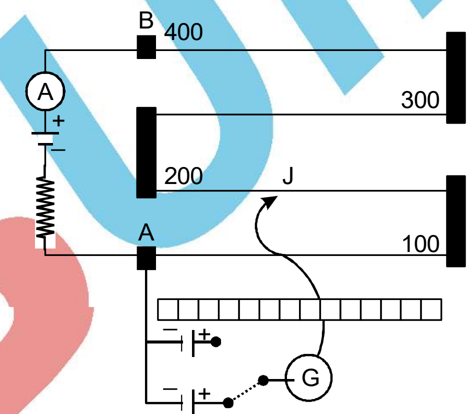
Hence, for a given wire of uniform cross section, 'A' and 'ρ' will be constant, So, we can write,

R ∝ l

$$\boxed{V \propto l}$$

Applications

1. **To compare EMF of Two Cells :** In order to compare EMF of two cells, the circuit is arranged as shown in figure. If x be the resistance per unit length of the potentiometer wire and I, the constant current flowing through it, then,

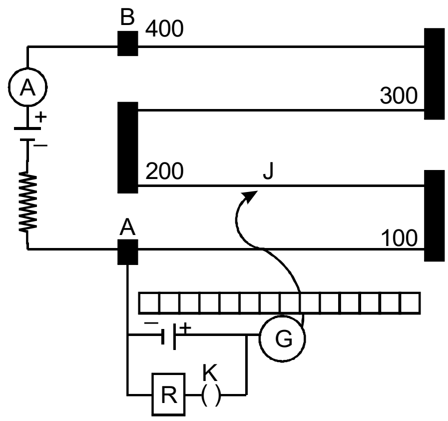


$$E_1 = (xl_1)I$$
$$E_2 = (xl_2)I$$
$$\boxed{\frac{E_1}{E_2} = \frac{l_1}{l_2}}$$

Question: Why potentiometer is considered a better way to measure EMF than voltmeter

Answer : Potentiometer is a better way to measure EMF than voltmeter because at nulpoint no current is drawn form the cell and the true value of EMF is measured.

2. **To Measure Internal Resistance of a Cell :** When an EMF 'E' is applied such that current I flows through the wire of the potentiometyer having uniform area of cross section, a p. d. is developed across the wire. If x be the resistance per unit length of the potentiometer wire and I, and constant current flowing through it, then at balance point.



$$E = (xl_1)I \qquad \text{........(1)}$$

When key is inserted in K, then a current flows inside the cell even at null point, hence a potential drop across at cell, thereby resulting in the shift of null point from l_1 to l_2 Thus,

$$V = (xl_2)I \qquad \text{........(2)}$$

From equations (1) & (2) we get,

$$\frac{E}{V} = \frac{l_1}{l_2} \qquad \text{........(3)}$$

Internal resistance of the cell is given by

$$r = \left[\frac{E}{V} - 1\right] R \qquad \text{........(4)}$$

From equations (3) & (4) ,

$$r = \left[\frac{l_1}{l_2} - 1\right] R$$

Thus, knowing the value of l_1, l_2 and R, the internal resistance 'r' of the cell can be found.

Electrical Energy and Power

The collision of electrons with ions and other electrons in the presence of an electric field gives rise to heat energy.

Electric Power: The rate at which work is done by the source of EMF in maintaining the electric current in a circuit is known as electric power. Consider 'I' current is passed through a conductor for time t. The total charge passed,

$$q = I\,t$$

According to the definition, the work done is moving charge q through a potential defference V is given by

$$W = qV$$

$$\therefore \quad W = V\,I\,t$$

According to definition of electric power,

$$P = \frac{W}{t}$$

$$\therefore \quad P = VI$$

$$\therefore \quad P = I^2 R = \frac{V^2}{R}$$

The SI unit of power is watt.

1 Watt = 1 Volt = 1 Ampere

1 Watt: The electric power is said to be 1 watt if 1 volt of p. d. across a circuit produces 1 ampere of current through it.

Electric Energy: The energy required to maintain the electric current in a circuit. For a given period of time t, we can write,

$$W = P \times t = I^2 R\,t = \frac{V^2}{R} t = V\,I\,t \text{ KWh}$$

SI unit is joule or Watt-Second. The practical unit of Electrical energy is kilowatt hour (k Wh)

$$1 \text{ k Wh} = 3.6 \times 10^6 \text{ J}$$

kWh is also known as Board of Trade Unit (B. O. T.)

(**In case of series combination,** $P = I^2 R \Leftrightarrow P \propto R$

In case of parallel combination, $P = \frac{V^2}{R} \Leftrightarrow P \propto \frac{1}{R}$)

If there is a parallel combination of two resistors, R_1 and R_2, then the current braching through them will have the ratio $\frac{I_1}{I_2} = \frac{R_2}{R_1}$**, where** $I_1 + I_2 = I$

Joule's Law of Heating Effects of Currents

According to Joule's law, the amount of heat produced in a conductor due to flow of current I is directly proportional to

(i) The square of the current, i.e., $Q \propto I^2$

(ii) The resistance of the conductor, i.e., $Q \propto R$

(iii) The time period for which the current is passed, i.e., $Q \propto t$

Combining these we have,

$$Q \propto I^2Rt$$

$$Q = \frac{I^2Rt}{J}$$

where J is a conversion factor, called **Joule's Mechanical Equivalent of Heat.** Its value is 4.18 $JCal^{-1}$.

Note : The value of **I^2Rt** should be divided by **J** only when you need the answer to be in **Calories.**

Applications of Heating Effect

1. It is used in incandescent bulbs. Such bulbs contain filament of tungsten with some inert gas at suitable pressure.
2. Electric Heating Appliances such as electric heater, electric iron, electric immersion rod, electric geyser, electric strove work on Joule's Heating Effect. The heating elements are made of Nichrome (alloy of Ni & Cr), because:
   (a) of high resistivity
   (b) of high melting point
   (c) it does not get oxidized easily, when heated in air
   (d) it can be easily drawn into wires.
3. Arc-lamp: It is made up to two carbon electrodes with a small air gap in between. When voltage is applied, spark jumps across them causing emission of intense light.
4. Electric juse: It is a device used to safeguard the electrical appliances from possible damage due to short-circuit. During short -cricuit; high current passes through the appliances. The fuse is so designed that it melts immediately when current crosses the safety fuse is made up of tim- lead (63% tin, 37 % lead)

SOLVED PROBLEMS

1. ***Two wires of equal length, one of aluminium and the other of copper have the same resistance. Which of the two wires is lighter ? Hence explain why aluminium wires are preferred for overhead power cables (ρAl = 2.63 × 10⁻⁸ Ωm, ρCu = 1.72 × 10⁻⁸ Ωm, Relative density of Al = 2.7; of Copper 8.9)***

Sol. The resistance of wire of legnth l and cross-sectional area A is given by

$$R = \frac{\rho l}{A} \Rightarrow A = \frac{\rho l}{R} \qquad ...(1)$$

mass of wire, m = volume × density = Ald
Substituting the value of A from (1)

$$m = \left(\frac{\rho l}{R}\right) l d \Rightarrow m = \frac{\rho l^2 d}{R}$$

As length and resistane of two wires are same,
so $m \propto \rho d$

$$\frac{m_{Al}}{m_{Cu}} = \frac{\rho_{Al} d_{Al}}{\rho_{Cu} d_{Cu}} = \left(\frac{2.63 \times 10^{-8}}{1.72 \times 10^{-8}} \times \frac{2.7 \times 10^3}{8.9 \times 10^3}\right) = 0.46$$

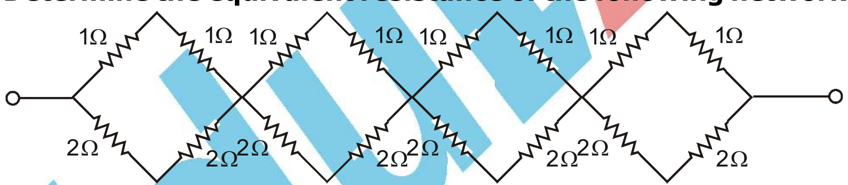
The indicates that aluminium wire is 0.46 times lighter than copper wire. That is why aluminium wires are preferred for overhead power of cables.

2. ***A silver wire has a resistance 2.1 Ω at 27.5° C and a resistance of 2.7 Ω at 100°C. Determine the temperature coefficient of the resistivity of silver.***

Sol. Given, R_1 = 2.1 Ω, t_1 = 27.5° C, R_2 = 2.7 Ω, t_2 = 100°C, α = ?

Temperature coefficient of resistance, $\alpha = \frac{R_2 - R_1}{R_1(t_2 - t_1)} = \frac{2.7 - 2.1}{2.1(100 - 27.5)} = \frac{0.6}{2.1 \times 72.5} = 0.0039 (°C)^{-1}$

3. **Determine the equivalent resistance of the following network.**

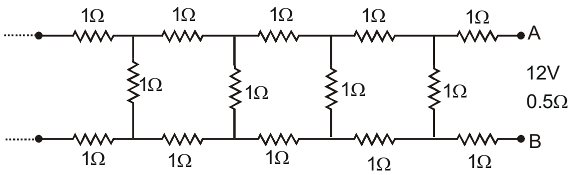


Sol. The given network consists of a series combination of 4 equivalent units.
Resistance of Each Unit : Each unit has 2 rows. The upper row contains two resistance 1 Ω, 1 Ω in series and the lowe row contains two resistance 2Ω, 2Ω in series. These two mutually connected in parallel.
Resistance of upper row, R_1 = 1 + 1 = 2Ω
Resistance of lower row, R_2 = 2 + 2 = 4Ω
∴ Resistance of lower, row, R_2 = 2 + 2 = 4Ω
∴ Resistance of each unit R′ is given by

$$\frac{1}{R'} = \frac{1}{R_1} + \frac{1}{R_2} \Rightarrow R' = \frac{R_1 R_2}{R_1 + R_2} = \frac{2 \times 4}{2 - 4} = \frac{4}{3}\Omega$$

∴ Equivalent resistance between A and B

$$R_{AB} = R' + R' + R' + R' = 4R' = 4 \times \frac{4}{3} = \frac{16}{3}\Omega$$



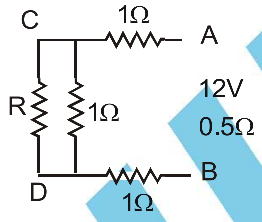
Sol. Let R be equivalent resistance between A and B.
As ∞ ± 1 = ∞, resistance between C and D is the same as between A and B, then equivalent resistance of R and 1 Ω in parallel

$$R_1 = \frac{R \times 1}{R + 1}$$

∴ Net resistance between A and B will be

$$R_{AB} = R_1 + 1 + 1$$

Therefore, by hypothesis $R_1 = 1 + 1 = R$



⇒ $\frac{R}{R+1} + 2 = R$

⇒ R + 2(R + 1) = R (R + 1)

⇒ $3R + 2 = R^2 + R$

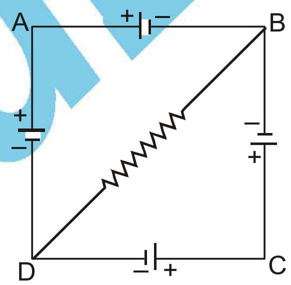
⇒ $R^2 - 2R - 2 = 0$

⇒ $R = \frac{2 \pm \sqrt{4 - 4 \times 1 \times (-2)}}{2}$

$= \frac{2 \pm \sqrt{12}}{2} = (1 + \sqrt{3})\Omega$ = 1 + 1.732 = 2.732 Ω

Current drawn $I = \frac{12}{2.732 + 0.5} = \frac{12}{3.232} = 3.7\,A$

4. ***For the circuit shown here, calculat ethe potential difference between points B and D.*** ***[C B S E 2010]***



Sol. According to Kirchoff's first law the distribution of currents in shown in figure.
Applying Kirchoff's second law to mesh BADB,

$- 2(i - i_1) + 2 - 1 - 1. (i - i_1) + 2i_1 = 0$

⇒ $3i - 5i_1 = 1$

Applying Kirchoff's law to mesh DCBD,

$- 3i + 3 - 1 - 1 \times i - 2i_1 = 0$

⇒ $4i + 2i_1 = 2$

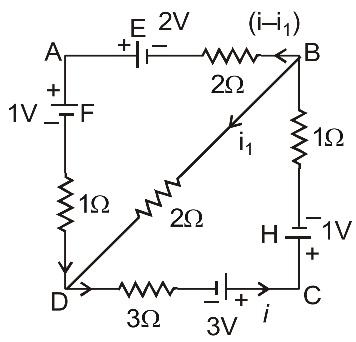
or $2i + i_1 = 1$

Multiplying equation (2) with 5, we get

$10i + 5i_1 = 5$

Adding (1) and (3), we get

$13i = 6 \Rightarrow i = \frac{6}{13} A$



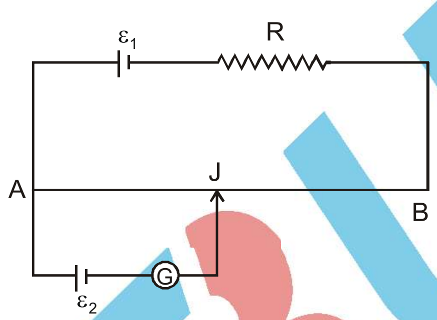
From (2),

$$i_1 = 1 - 2i = 1 - \frac{12}{13} = \frac{1}{13} A$$

Potential difference between B and D is :

$$V_B - V_D = i_1 \times 2 = \frac{2}{13} V$$

5. In the given circuit diagram AB is a uniform wire of resistance 10 Ω ***and length 1m. It is connected to a series arrangement of cell ε_1, of emf 2.0 V and negligible internal resistance and a resistor R terminal A is also connected to an electrochemical cell ε_2 of emf 100 mV and a galvonometer G. In this set-up a balancing point is obtained at 40 cm mark from A. Calculate the value of resistance R. If R_2 were to have an emf of 300 mV, where will you expect the balancing point to be.***



Sol. If k is potential gradient and l_1 the balancing length for cell E_2, then we have

$\varepsilon_2 = kl_1$

$\Rightarrow$ 100 mV = k × 40 cm

$\Rightarrow$ $k = \frac{100}{40} mV/cm$ = 2.5 × 10^{-13} V/cm = 0.25 V/m

Current in primary circuit

$$I = \frac{\varepsilon_1}{R + R_{AB}}$$ where R_{AB} is resistance of wire AB

$$I = \frac{2.0}{R + 10}$$

Potential difference across wire AB, $V_{AB} = I \times R_{AB} = \frac{2.0}{R+10} \times 10 = \frac{20}{R+10}$

$\therefore$ Potential gradient $k = \frac{V_{AB}}{L_{AB}} = \frac{20/(R+10)}{1} = \frac{20}{R+10}$

Comparing (1) and (2), we get

$$\frac{20}{R+10} = 0.25 \quad \Rightarrow \quad R + 10 = \frac{20}{0.25}\Omega = 80\ \Omega$$

$$R = 80 - 10 = 70\ \Omega$$

Balancing length when ε_2 = 300 mV = 300 × 10^{-3} V = 0.3 V is

$$\varepsilon_2' = kl_2 \Rightarrow 0.3 = 0.25 \times l_2 \Rightarrow l_2 = \frac{0.3}{0.25} = 1.2 m$$

6. In a metre bridge, the balance point is found to be 39.5 cm from the end A, when the resistor Y is 12.5 Ω Determine the resistance of X. Why ar the connection between the resistors in metre bridge made of copper strips ? What happens if the galvanometer and cell are interchanged at the balance point of the bridge ? Would be galvanometer shown any current ?

Sol. From Metre Bridge formula

$$\frac{X}{Y} = \frac{l}{100-l} \quad \Rightarrow \quad X = \frac{l}{100-l}Y$$

Give l = 39.5 cm, Y = 12.5 Ω

$$\therefore \quad X = \frac{39.5}{100-39.5} \times 12.5 = \frac{39.5}{60.5} \times 12.5 = 8.16\,\Omega$$

In metre bridge the resistance of connection wires have not been accounted in theory; so the resistance of thick coppe strips are very low and so negligible. Therefore, connections are made of thick copper strips.

If the galvanometer and cell are interchanged, the position of balance point remains unchanged but sensitivity of the bridge changes. Now the galvanometer shows a constant deflection.

7. A fuse wire with a circular cross-section of radius 0.15 mm blows at 15A. What should be the radius of cross-section of a fuse made of the same material, which will blow at 30 A ?
[Given $2^{2/3}$ = 1.59]

Sol. Key idea : For a fuse wire $I^2 \propto r^3 \Rightarrow \frac{I^2}{r^3}$ = constant

$$\therefore \quad \frac{I_1^2}{r_1^3} = \frac{I_2^2}{r_2^3}$$

$$\Rightarrow \quad r_2 = \left(\frac{I_2}{I_1}\right)^{2/3} r_1 = \left(\frac{30}{15}\right)^{2/3} \times 0.15\,\text{mm}$$

$$= (2)^{2/3} \times 0.15 \text{ mm} = 1.59 \times 0.15 \text{ mm} = 0.24 \text{ mm}$$

8. Two heaters are marked 200V, 300W and 200 V, 600 W. If the heaters are connected in series and the combination connected to a 200 V dc supply, which heater will produce more heat ?

Sol. Resistance of heaters $R_1 = \frac{V^2}{P_1} = \frac{(200)^2}{300} = \frac{400}{3}\Omega$

$$R_2 = \frac{V^2}{P_2} = \frac{(200)^2}{600} = \frac{400}{6}\Omega$$

When heaters are connected in series, current in circuit, $I = \frac{V}{R_1 + R_2} = \frac{200}{\frac{400}{3} + \frac{400}{6}} = 1A$

∴ Heat produced in 200 V, 300 W heater per second

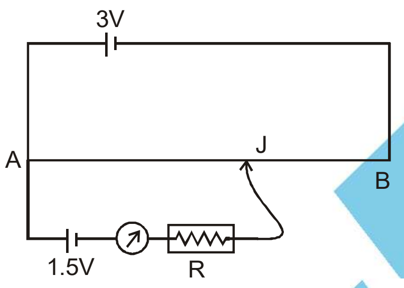
$$Q_1 = I^2R_1 = (1)^2 \times \frac{400}{3} = 133.33 \text{ Js}^{-1}$$

Heat produced in 200 V, 600 W heater per second

$$Q_2 = I^2R_2 = (1)^2 \times \frac{400}{6} = 66.66 \text{ Js}^{-1}$$

Clearly heat produced in 300 W heater is more that produced in 600 W heater.

9. **A potentiometer wire of length 1 is connected to a driver cell of emf 3 V as shown in the figur. When a cell of emf 1.5 V is used in the secondary circuit, the balance point is found to be 60 cm. On repalcing this cell by a cell of unknown emf, the balance point shifts to 80 cm.**
(i) Calcualte unknown emf of the cell



(ii) Explain with reason, whether the circuit works i the driver cell is replaced with a cell of emf 1V.
(iii) Does the high resistance R, used in the secondary circuit affect the balance point ? Justify your answer.

Sol. (i) Unknown emf ε_2 is given by

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

Given ε_1 = 1.5 V, l_1 = 60 cm, l_2 = 80 cm

$$\therefore \quad \varepsilon_2 = \frac{80}{60} \times 1.5 \text{ V} = 2.0 \text{ V}$$

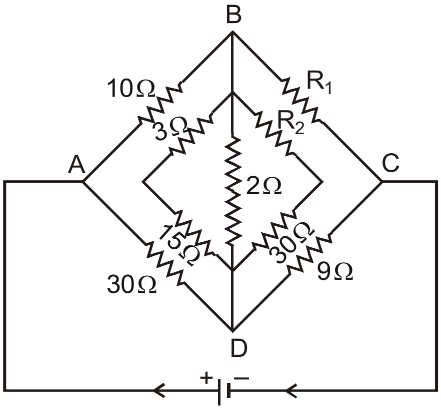
(ii) The circuit will not work if emf of drive cell is 1 V (less than that of cell of secondary circuit), because total voltage across wire AB is 1 V which cannot balance the voltage 1.5 V.

(iii) No, since at balance point no current flows thorugh galvanometer G i.e., cell remains in open circuit.

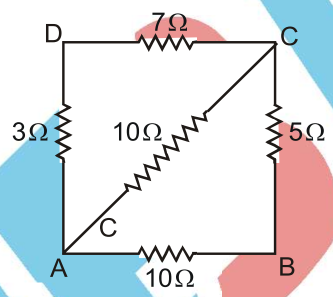
1. In the Wheatstone's Bridge shown below. What should be the value of R_1 and R_2 in order to

EXERCISE - I UNSOLVED PROBLEMS

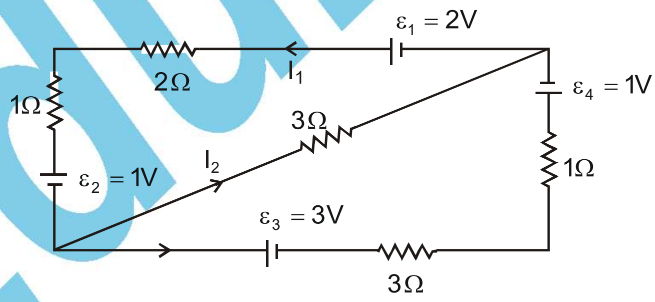
balance the bridge.



2. The resistance connected are shown in figure. adjoint. What is the equivalent resistance between points A and B.



3. In the given network, find the value of current I_1, I_2 and I_3.



4. Why bends in a wire do not affect is resistance ?

5. What is the order of magnitude of number density of free electrons in a metal ?

6. Wht is the order of resistivity of conductors ?

7. What is the ratio of the resistivity of a typical insulator to that of a metal ?

8. Name two paraemters determining the resisitivity of a meterial ?

9. What happens to the drift velocity v_d of electron and to the resistance R, if length of the coductor is doubled (keeping potential difference unchanged) ?

10. Given an example of non-ohmic device which shows up negative resistance.

11. Why can't we use eight ordinary cells connected in series to get a 12V supply instead of battery of e.m.f 12 V ?

12. Why resistance becomes more in series combination ?

13. Why resistace becomes less in parllel combination ?

14. What is a shunt ?

15. Resistance of the humna body is of the order of 10 kΩ. Why does one experience a strong shock when one accidentically touches the live wire of say 240 V supply ?

16. Which gas greater resistance (i) milliameter or ammeter and (ii) millivoltmeter or voltmeter ?

17. Why do we prefer a potentiometer to measure e.m.f of a cell rather than a voltmeter ?

18. Why should the specific resistance of a potentiometer wire be high ?

19. How can we increase the sensitivity of a potentiometer ?

20. How will you make a potentiometer of given wire length more sensitive by using a resistance box ?

21. When is the Wheatstone's bridge most sensitive ?

22. Using metre bridge, it is advised to obtain null point in the middle of the wire. Why ?

23. What do you mean by end error in a metre bridge ?

24. Wheatstone bridge method is considered unsuitable for the measurement of very low resistance. Why ?

25. Why is Wheatstone bridge method considered unsuitable for the measurement of very high resistances ?

26. What happens if the galvanometer and cell are interchanged at the balance point of the bridge ?

27. Why does the terminal potential difference of a cell become zero when it is short circuited ?

28. Under what conditions will the terminal potential difference of a cell be greater than its e.m.f ?

29. Under what conditions will the terminal potential difference of a cell be less than its e.m.f ?

30. Under what condition(s) will ther be a constant potential gradient along the length of a wire carrying current ?

31. Assuming that electrons ar free inside a solid, sketch graphically the distribution n(v) of electrons with speed v.

32. Two wires of equal length, one of copper and the other of maganin, have the same resistance. Which wire is thicker ?

33. Define conductivity of a material. Give its S.I. units.

34. Define conductivity of a mateial. Give its S.I. units.

35. How does conductivity of a semiconductor increase with temperaure ?

36. A simple voltaic cell has an e.m.f equal to 1.0 V. When the circuit is open, is there a net field which would give rise to a force on a test charge.
(i) inside the electrolyte of the cell
(ii) outside the cell ?

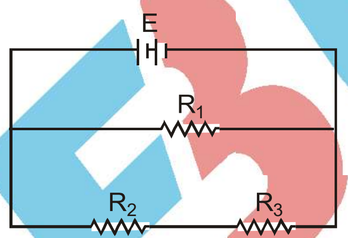
37. Is there a net field inside the cell when the circuit is closed and a steady current amount of current flowing through it ?

38. Does resistance of a wire depend upon amount of current flowing through it ?

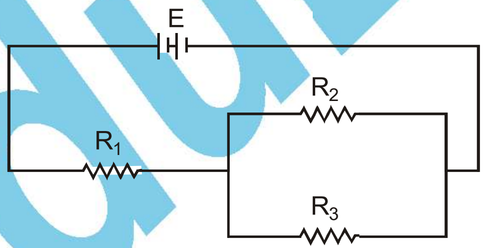
39. Give example of non-ohmic electrolyte.

40. Give example of ohmic electrolyte.

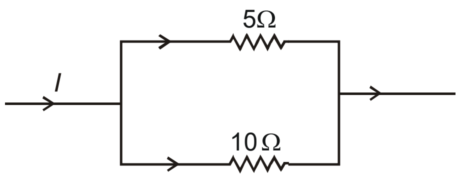
41. Three identical resistors R_1, R_2 and R_3 are connected to a battery as shwon in figure. What will be the ratio of voltages across R_1 and R_3 ?



42. Three identical resistors R_1, R_2 and R_3 are connected to a battery as shown in figure. What will be the ratio of voltaes across R_1 and R_2 ?

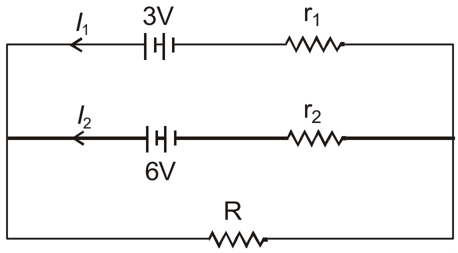


43. In the arrangement of resistors shown here, what fraction of I will pass through 5 Ω resistor ?



44. What is the potential difference between A and B ?

45. Under what condition(s) will the current I_1 and I_2 be in the directions as shown in the diagram here ?



46. Though same current flows through the electric line wires and the bulb filament, yet only the filament glows. Why ?

47. What do you mean by maximum power rating of a resistor ?

48. How much power does a 60 W, 220 V bulb consume when it is operated at 110 V ?

49. A bulb is rated at 110 W, 220 V. Calculate its resistance.

50. Two wires A and B of the same material and having same length, have their cross-sectional areas in the ratio of 1 : 4. What would be the ratio of heat produced in these wires when same voltage is applied across each ?

51. Twenty electric bulb are connected in series with the main of a 220 V supply. After one bulb is fused, the remaining 19 bulbs are again connected in series across the same mains. What will be the effect on illumination ?

52. A 100 W and a 500 W bulbs are joined in series and connected to the mains. Which bulb will glow brighter ?

53. The maximum power rating of a 20 Ω resistor is 2 kilowatt. Can it be connected to a 220 V d.c.supply ?

54. in an electric kettle, water boils in 20 minutes after the kettle is switched on. With the same supply voltage if the water is to boil in 10 minutes, should the length of the heating element be decreased or increased ?

55. Equation $P = I^2R$ seems to suggest that the rate of joule heating in a resistor is reduced if the resistance is made less. However, the equation $P = V^2/R$ seems to suggest the opposite, How do you reconcile this apparent paradox ?

56. A small heating element, connected to a 10 V d.c. supply, draws a current of 5 A. How much electric power is supplied to the heater ?

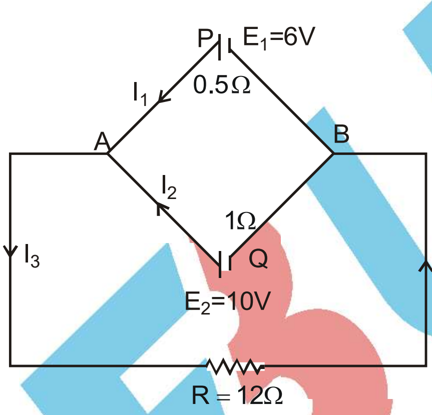
1. Two conducting wires X & Y of same diameter but different materials are joined in series

EXERCISE - II BOARD PROBLEMS

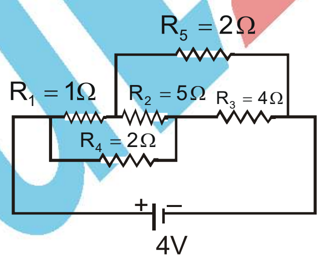
across battery. It the number density of electrons in X is twice that in Y, find the ratio of the drift velocity of electrons in the two wires

2. Write any two factors on which internal resistance of a cell depends. The reading on a high resistance voltmeter, when a cell is connected across it is 2-0 V. When teminals of the cell are also connected to a resistace of 3 Ω as shown in the circuit, the voltmeter reading drops to 1.5 V. Find internal resistance of the cell :

3. State kirchoff's ruler. Apply it to the loop ACBPA and ACBQA, to write the expresssion for the curents I_1, I_2 & I_3 in network

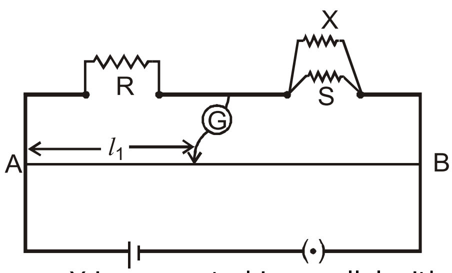


4. Calculate the current drawn from the battery in given network



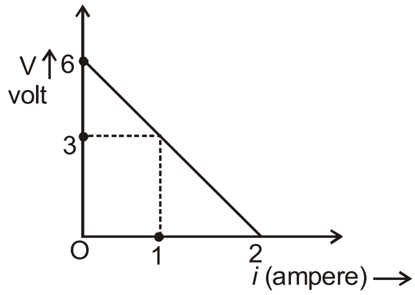
5. A wire of 15 Ω resistance is gradually stretched to double its original length. It is then cut into two equal parts. These parts are then connected in parallel across a 3.0 volt battery. Find the current drawn from battery.

6. **(1)** State the principle of working of a meter Bridge.
(2) In a meter bridge balance point is found at a distance l_1 with resistance R and S as shown.



When an unknown resistance X is connected in parallel with resistance S, balance point shift to distance l_2. Find the expression for X in terms of l_1, l_2 & S

7. The following graph shown the variation of terminal potential difference V, across a combination of three cells in series to a resistor verses current



(1) Calculate emf of each cell

(2) For what current i, will the power dessipation of the circuit bemaximum

8. A potentiometer wire of length 1 m is connected to a driver cell of emf 3V. When a cell of emf 1.5 V is used in the secondary circuit, the balance point is found to be 60 cm, by replacing the cell by cell of unknown emf, balance point shifts to 80 cm.

(i) Calculate unknown emf of the cell

(ii) Explain with reason, whether the circuit works if the driver cell is replaced with a cell of emf 1 V.

(iii) Does the high resistance R, used in the secondary circuit affect the balance point ? Justify your anwer

9. Two wires X, Y have the same resistivity but their cross sectional areas are in the ratio 2 : 3 and length in ratio 1 : 2, They are first connected in series and then in parallel to a d.c source. Find out the ratio of the drift speeds of the electrons in the two wires for the two cases.

10. Explain the variation of conductivity with temperature for

(i) a metallic conductor and

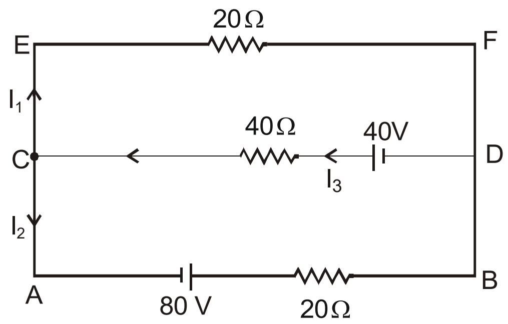
(ii) ionic conductor

11. Prove that current density of a metallic conductor is directly proportional to drift velocity of electron.

12. A cylindrical metallic wire is strectched to increase its length by 10%. Calculate the percentage increase in its resistance

13. A voltage of 30 V is applied acros a carbon resistor with first, second and third rings of blue, black and yellow colour respectively. Calculate the value of current in mA, through the resistor

14. Use Kirchhoff's laws to determine the value of current I_1 in the given circuit



15. How does the resistivity of (1) a conductor and
(ii) a semiconductor vary with temperature. Give reason for each case

16. Establish a relation between electric current and drift velocity.

17. Out of two bulbs marked 25 W and 100W, which has higher resistance

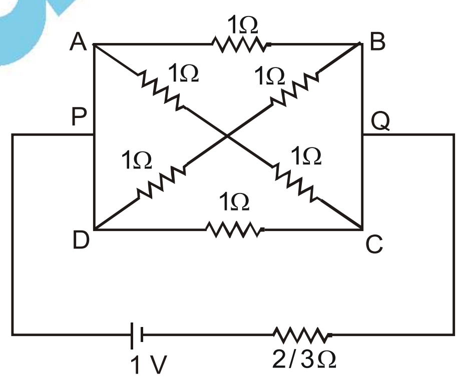
18. Two heated wires of the same dimensions are first connected in series and then in parallel to a source of supply. What will be the ratio of heat produced in the two cases ?

19. A carbon resistor is marked in colour bands of red, black, orange and silver. What is the resistance and tolerance value.

20. A copper wire of resistivity P is stretched to reduce its diameter to half of its original value. What will be its new resistivity ?

21. Give reason why the electrical conductance of electrolyte is less than that of metals.

22. Find the current drawn from a cell of emf 1V and internal resistance $\frac{2}{3}\Omega$ connected to the network given

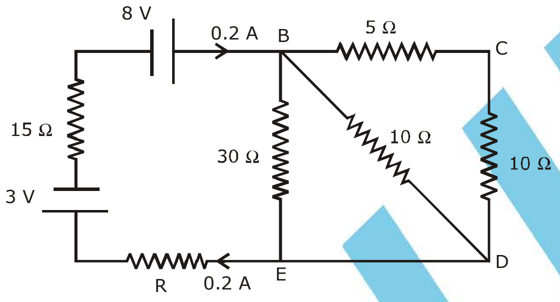


23. What is the effect of heating of a conductor on the drift velocity of free electron.

24. Two wires of equal length, one of copper and the other of manganin have the same resistance. Which wire is thicker ?

Ans. Manganin

25. Calculate the value of the resistance R in the circuit shown in the figure sothat the current in the circuit is 0.2 A. What would be the potential difference between points B and E ?



Ans. R = 5 Ω ,

P.D. between B & E 1 Volt

26. Define relaxation time of the free electrons drigting in a conductyor. How is it related to the drift velocity of free electrons ? Use this relation to deduce the expression for the electrical resistivity of the material.

27. Two identical cells, each of emf E, having negligible interanl resistance, are connected in parallel with each other across an exteranl resistance R. What is the current through this resistance ?

28. Explain the term 'drift velocity' of electrons in a conductor. Hence obtain the expression for the current through a conductor in terms of 'drift velocity.

OR

Describe briefly, with the help of a circuit diagram, how a potentiometer is used to determine the internal resistance of a cell.

ANSWER KEY

EXERCISE - I — UNSOLVED PROBLEMS

1. [$R_1 = 3\ \Omega$; R_2 = any value] **2.** 5 Ω **3.** 2 : 1 **4.** $I_1 = \frac{2I}{3}$

EXERCISE - II — BOARD PROBLEMS

4. $R_{eq} = 2\ \Omega$, I = 2A **5.** $R_p = 15\ \Omega$, I = 0.2 A

6. 1. meter bridge – principle wheatstone bridge

2. (I) $\cos\frac{R}{S} = \frac{l_1}{100 - l_1}$

(II) $$\frac{R}{\left(\frac{XS}{X+S}\right)} = \frac{l^2}{100 - l_2}$$

$$X = S\left[\frac{l_2}{l_1}\left(\frac{100 - l_1}{100 - l_2}\right) - 1\right]^{-1}$$

7. 1. ε = 2V **2.** i = 1.0 A **8. 1.** ε_2 = 2.0 v **2.** will not work **3.** No

9. (a) $\frac{(v_d)_x}{(v_d)_y} = \frac{3}{2}$, (b) $\frac{(v_d)_x}{(v_d)_y} = \frac{2}{1}$ **12.** 21 % **13.** I = 0.05 mA **14.** I_1 = – 1.2 A

16. I = nAevd **17.** $R = \frac{V^2}{P}$ **18.** $Q \propto \frac{1}{R} = \frac{Q_{series}}{Q_{Parallel}} = \frac{R_{parallel}}{R_{Series}} = \frac{1}{4}$ **19.** $20 \times 10^3\ \Omega \pm 20\ \%$

20. no change **22.** I = 1 A **23.** $v_d = \frac{eE\tau}{m}$