# Part – 1: Electric Current, Drift of Electrons and Current Density

## Learning Objectives

After studying this part, students will be able to:

- Define electric current.
- Distinguish between conventional current and electron flow.
- Explain the microscopic origin of electric current.
- Derive the expression for electric current.
- Define current density and derive its relation with drift velocity.
- Understand the concept of drift velocity and mobility.

---

## 3.1 Introduction

Electricity plays a vital role in our daily life, from lighting homes to operating electronic devices. In metallic conductors, electric current is produced by the motion of **free electrons** under the influence of an applied electric field.

Unlike electrostatics, where charges are at rest, **Current Electricity** deals with the **motion of electric charges**.

---

## 3.2 Electric Current

### Definition

**Electric current** is the rate of flow of electric charge through any cross-section of a conductor.

Mathematically,

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

- The slope between charge and time graph represents the current.
- The area between current and time graph represents charge flows. It can be given as

$$Q = \int_{t_1}^{t_2} I dt$$

(Here current is also a function of time.)

Where,

- I = Electric current (A)
- Q = Charge (C)
- t = Time (s)

For a constant current,

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

---

**SI Unit:** 1 Ampere (A) =1 Coulomb per second

---

## Nature of Electric Current

Electric current is a scalar physical quantity. Its direction in a circuit is specified by the direction of conventional current, but current itself does not obey vector addition.

---

## 3.3 Conventional Current and Electron Flow

### Conventional Current

In an external circuit, conventional current is taken to flow from the positive terminal to the negative terminal of a source.

### Electron Flow

In metallic conductors, electrons actually move from the **negative terminal** to the **positive terminal**.

Thus,

- **Conventional current** → Positive to Negative
- **Electron flow** → Negative to Positive

---

## 3.4 Microscopic View of Current

A metal contains a large number of free electrons.

- In the absence of an electric field, electrons move randomly.
- Their average velocity is zero.
- Hence, **no net current** flows.

When an electric field is applied,

- Electrons experience an electric force,
- They acquire a small average velocity called **drift velocity**,
- A steady electric current is established.

---

## 3.5 Drift Velocity

### Definition

The **average velocity** acquired by free electrons in a conductor under the influence of an external electric field is called the **drift velocity**.

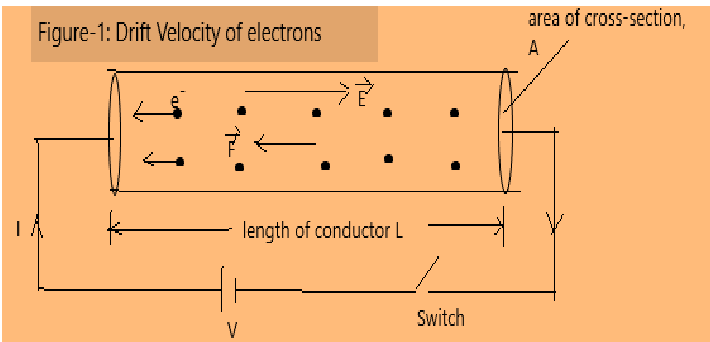
It is denoted by $v_d$

---

## Important Characteristics

- Drift velocity is usually very small and is typically of the order of $10^{-4}\ ms^{-1}$, depending on the conductor and current opposite to the direction of the electric field.
- Responsible for electric current.

---



### 3.6 Expression for Electric Current in Terms of Drift Velocity

Consider a conductor of:

- Cross-sectional area = A
- Free electron number density = n
- Drift velocity = $v_d$

$$\boxed{I = neAv_d}$$

**Derived**

---

### 3.7 Current Density

### Definition

Current density is the **current flowing per unit cross-sectional area** of a conductor.
Mathematically,

$$\boxed{J = \frac{I}{A}}$$

Current density is a vector quantity. The current through a surface is the flux of current density through that surface.

In vector form,

$$I = \vec{J} \cdot \vec{A}$$

Or

$$I = JA\cos\theta$$

The current is a scalar quantity because it does not follow triangle law of vector addition. It is also a scalar because it is the dot product of two vector quantities.

Where,

- J = current density and
- A = area of cross section
- $\theta$ is the angle between current density and area vector

---

Using

$$I = neAv_d$$

We obtain,

$$\boxed{J = nev_d}$$

In vector form,

$$\boxed{\vec{J} = nq\vec{v}_d}$$

---

### SI Unit:

Ampere per square metre ($A\ m^{-2}$)

---

### 3.8 Mobility of Electrons

### Definition

The **mobility** of charge carriers is defined as the drift velocity acquired per unit applied electric field.

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

where,

- μ = Mobility
- $v_d$ = Drift velocity
- E = Electric field

**SI Unit:** $m^2\ V^{-1}\ s^{-1}$

## Solved Example 1

A charge of **24 C** flows through a conductor in **6 s**. Find the current.

**Solution**

Using,

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

Or

$$I = \frac{24}{6} = 4A$$

**Answer:** $\boxed{4A}$

## Solved Example 2

A conductor has n = $8\times10^{28}\ m^{-3}$, A $=2\times10^{-6}\ m^2$, $v_d = 2 \times 10^{-4}$ $m\ s^{-1}$. Find the current.

**Solution**

Using,

$$I = neAv\quad d$$

Where,

e $=1.6\times10^{-19}$C

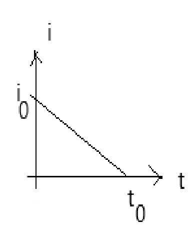
Substituting,

$$I = 8 \times 10^{28} \times 1.6 \times 10^{-19} \times 2 \times 10^{-6} \times 2 \times 10^{-4} = 5.12\ A$$

## Solve Example 3

Find the equation of current and charge flows in the conductor as shown in the figure.

**Solution:**




Here, we see that, charge and current both are a function of time.
From the equation of straight line having two points coordinates $(x_1, y_1)$ and $(x_2, y_2)$, it is given as:

$$y - y_1 = \frac{y_2 - y_1}{x_2 - x_1}(x - x_1)$$

In this way, $(0, i_0)\ and\ (t_0, 0)$ are two points in the above graph between I and t. Hence, the **equation of current** is:

$$i - i_0 = \frac{(0 - i_0)}{t_0 - 0}(t - 0)\ or, i = i_0\left(1 - \frac{t}{t_0}\right) - -this\ is\ the\ required\ equation.$$

For **charge flows** in the conductor,

$$q = \int_{t_1}^{t_2} idt$$

Or

$$q = \int_0^{t_0} i_0\left(1 - \frac{t}{t_0}\right)dt, or, q = i_0 t - \frac{i_0 t}{2}, or, q = i_0 t/2 - -required\ equation$$

For total heat to be dissipated across the conductor,

$$H = \int_0^{t_0} i^2 R\, dt = \int_0^{t_0} {i_0}^2 R\left(1 - \frac{t}{t_0}\right)^2 dt\ or, H = {i_0}^2 R t_0/3 - - - required\ equation.$$

---

## Try Yourself

1) Calculate the current flows in a wire at time t = 2 s if charge flows in the wire as a function of time is given by $q = (2t + 1)\ C$.
2) Calculate the charge flows in the wire between t = 1 s and t = 2 s if the current as a function of time is $I = (t + 2\ )\ A$.
3) A current of 10 A flows uniformly through a conductor having a cross-sectional area of 2 $mm^2$. Find the current density.

---

## Exam Tips

- Remember that **current is a scalar quantity**.
- Conventional current and electron flow are in opposite directions.
- Drift velocity is **very small**, but the electric field propagates rapidly through the conductor.
- Use SI units in all numerical problems.

---

## Common Mistakes

☐ Confusing drift velocity with the random thermal velocity of electrons.
☐ Assuming electrons move from positive to negative terminals.
☐ Forgetting that J = I/A.
☐ Using the wrong unit for current density.

---

## JEE Insight (Beyond NCERT)

### Concept 1: Why is Drift Velocity So Small?

Although electrons drift very slowly, electrical devices start working almost instantly because the **electric field is established throughout the conductor** at a speed determined by the electromagnetic signal propagation in the circuit, causing electrons everywhere in the conductor to begin drifting almost simultaneously.

**Concept 2: Thermal Velocity vs Drift Velocity**

| **Thermal Velocity** | **Drift Velocity** |
|---|---|
| Random in all directions | Directed due to electric field |
| Very large (~$10^5$-$10^6$ m/s) | Very small (~$10^{-4}$ – $10^{-3}$ m/s) |
| Average value is zero | Non-zero average value |

This distinction is a favourite conceptual question in **JEE Main** and **NEET**.

## Try yourself

1) List out factors at which drift speed depend upon.
2) In a conductor, current I flow. If drift speed is doubled, what will be the area of cross-section for the same current flow?
3) A conductor has length L, resistance R and area of cross-section A. When it is connected with a battery of potential difference V, an electric field E is set up. Determine
   (a) Current density
   (b) Resistivity of the conductor
   (c) Drift speed
   (d) Mobility of electron
   (e) If potential difference applied is made triple, what will be the drift speed, keeping other parameters constant?
   (f) If length is reduced to half, what will be new resistance?
   (g) If length is increased double, what will be drift speed?
   (h) Does drift speed change (increase/decrease) if temperature increases? Explain it.
   (i) What will be the conductivity of conductor if temperature increases? Explain it.

# Part – 2: Drift Velocity, Relaxation Time, Ohm's Law, Resistance and Resistivity

## Learning Objectives

After studying this part, students will be able to:

- Explain relaxation time.
- Derive the relation between drift velocity and electric field.
- Derive Ohm's law using the drift theory of electrons.
- Define resistance, resistivity, and conductivity.
- Understand the factors affecting resistance.
- Explain the microscopic interpretation of Ohm's law.
- Derive the relation between current density and conductivity
- Derive the relation between resistivity, electron density and relaxation time.

---

### 3.9 Motion of Electrons in an Electric Field

When an electric field $\vec{E}$ is applied across a conductor, each free electron experiences an electric force

$$\boxed{\vec{F} = -e\vec{E}}$$

Where

- e = magnitude of electronic charge
- Negative sign indicates that the force on an electron is opposite to the electric field.

Using Newton's second law,

$$F = ma$$

Therefore,

$$\boxed{\vec{a} = -\frac{e\vec{E}}{m}}$$

Where, m is the mass of an electron.

---

### 3.10 Relaxation Time (τ)

### Definition

The **average time interval between two successive collisions** of a free electron with the lattice ions of a conductor is called the **relaxation time** (or **mean free time**).

It is denoted by τ.

Typical value: $\tau \approx 10^{-14}$ s

---

### 3.11 Relation Between Drift Velocity and Electric Field

### Derivation-1:

**To obtain the expression of drift velocity**

Between two collisions, an electron accelerates for a time τ.

Using

$$v = u + at$$

Or, in vector form,

$$\vec{v} = \vec{u} + \vec{a}t ----((1)$$

Since the average initial drift velocity is zero, therefore from equation (1) above,

$$\vec{v}_d = \vec{a}\tau --- (2)$$

The force experienced by electrons

$$\vec{F} = -e\vec{E}$$

By Newton's second law,

$$\vec{F} = m\vec{a}$$

Therefore, acceleration of electrons in a conductor,

$$\vec{a} = -\frac{e\vec{E}}{m} --- (3)$$

Substituting, $\vec{a}$ from equation (2) in equation (3), we have

$$\vec{v}_d = -\frac{e\overrightarrow{E\tau}}{m} --- (4)$$

From the equation of motion

$$v = u + at$$

So,

$$\boxed{\vec{v}_d = -\frac{e\vec{E}\tau}{m}}$$

Drift Speed $v_d = |\vec{v}_d|$ is

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

---

## Important Conclusions

- Drift velocity is directly proportional to the electric field.
- Drift velocity increases with increase in relaxation time.
- Drift velocity decreases if collisions become more frequent.
- For a metallic conductor under a fixed electric field, drift velocity generally decreases with increasing temperature because the relaxation time decreases.

---

## 3.12 Relation between Current and Drift Velocity

**Derivation-2:**

**To obtain the relation between current and drift speed**

$$I = \frac{q}{t} = \frac{Ne}{\tau} --- (1)$$

Dividing both sides by volume, we get

$$I = \left(\frac{N}{Vol}\right)(e)\left(\frac{Vol}{\tau}\right) --- (2)$$

Since, electron density or number density or concentration of electrons, $n = N/Vol$, and volume $Area\ A\ \times length\ L$, therefore, from equation (1), we have

$$I = (n)(e)\left(\frac{AL}{\tau}\right) ----(3)$$

The length of conductor divided by relaxation time of electrons is, drift velocity, $v_d$. Hence,

$$I = (n)(e)(A)(v_d) --- (4)$$

Thus, we get

$$\boxed{I = neAv_d}$$

## 3.13 Ohm's Law

### Statement

At constant temperature, the current through a conductor is directly proportional to the potential difference across its ends.

$$V \propto I$$

Or,

$$V = RI$$

Or

$$R = \frac{V}{I} = Constant$$

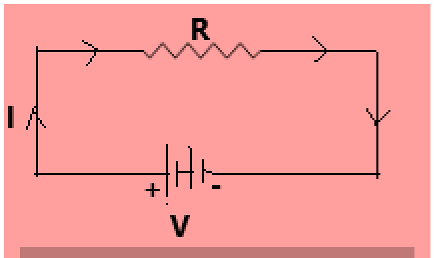



Figure-2: DC resistive Circuit

Where

- V = Potential difference
- I = Current
- R = Resistance

R is proportionality constant, equal to resistance of a conductor. For a given conductor under constant physical conditions, resistance remains constant; changing V changes I proportionally. However, the potential difference and current depend upon resistance.

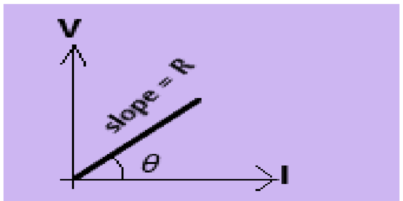



Figure-3: Graph between V and I

### Graphs:

**The slope of a graph between V and I represents Resistance**.
It is a straight line.

- If V on y-axis, and I on x-axis, then higher the slope, the higher will be it resistance.
- If V on x-axis and I on y-axis, then higher the slope, the lower will be its resistance.

**In Figure-4 (a), V vs I**

$$R_A > R_A$$

As

$$Slope_A > Slope_B$$

Whereas, in **Figure-4 (b), I vs V**

$$R_A < R_A$$

As

$$Slope_A > Slope_B$$

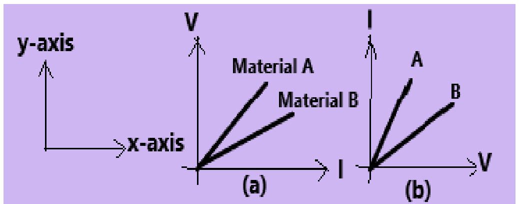



Figure-4: Graphs between V and I with axis changes

## 3.15 Resistance

### Definition

Resistance is the property of a conductor that opposes the flow of electric current.
From Ohm's law,

$$\boxed{R = \frac{V}{I}}$$

**SI Unit:** Ohm (Ω)
1 Ω = 1 $VA^{-1}$

## 3.16 Factors Affecting Resistance

The resistance of a conductor depends upon:

1. Length (L)
2. Cross-sectional area (A)
3. Nature of material
4. Temperature

Mathematically,

$$\boxed{R \propto L}$$

And

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

Combining,

$$\boxed{R = \rho \frac{L}{A}}$$

Where ρ is the resistivity of the material.

## 3.17 Resistivity (ρ)

## Definition

Resistivity is an intrinsic property of a material that measures how strongly it opposes the flow of electric current.

$$\boxed{\rho = \frac{RA}{L}}$$

**SI Unit:** Ω m

## Important Points

- Resistivity depends on the **nature of the material** and **temperature**.
- It does **not** depend on the dimensions of the conductor.

## Graphs:

**Resistivity (Ωm) vs. Temperature (K)**

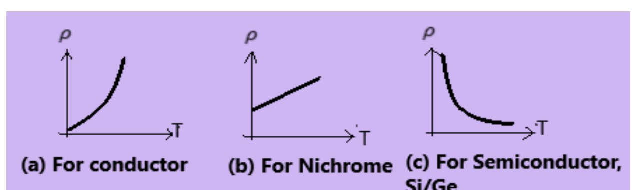



Figure-5: Graphs between Resistivity and Temperature for different materials

## Try Yourself

1) If length of a conductor is increased 100%, what will be it new resistance?
2) What does the negative sign show in the expression $\vec{a} = -\frac{e\vec{E}}{m}$

## 3.18 Conductivity (σ)

Conductivity is the reciprocal of resistivity.

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

---

**SI Unit:** S m$^{-1}$

Where, S stands for **Siemens**.

---

## 3.13 Derivation-3:

## Microscopic Derivation of Ohm's Law

We know

$$I = neAv_d - - - (1)$$

Substitute

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

Then

$$I = neA\left(\frac{eE\tau}{m}\right) - - - (2)$$

Hence,

$$\boxed{I = \frac{nAe^2\tau E}{m}}$$

Since

$$E = \frac{V}{L} - - - (3)$$

Where, L is the length of the conductor,

Substituting E from equation (3) into equation (2), we have

$$I = \frac{nAe^2\tau}{m}\left(\frac{V}{L}\right)$$

Or,

$$V = \left(\frac{mL}{nAe^2\tau}\right)I - - - (4)$$

Rearranging,

$$V = RI$$

Where

$$\boxed{R = \frac{mL}{nAe^2\tau}}$$

Thus,

$$\boxed{V = RI}$$

This is **Ohm's Law**, derived from the microscopic motion of electrons.

---

## Try Yourself

1) If temperature of a conductor is increasing, what will be the effect on its resistance?

## Derivation-4:

**To obtain the relation between current density, conductivity and electric field, Or Derive $\boldsymbol{J = \sigma E}$**

Since current density

$$J = \frac{I}{A} - - - (i)$$

Resistivity $\rho$ is related with conductivity as

$$\rho = \frac{1}{conductivity, \sigma} - - - (ii)$$

And

$$V = EL - - - -(iii)$$

Where

- E = electric field and
- L= length of the conductor

Now, resistance of a conductor is

$$R = \frac{\rho L}{A} - - - -(iv)$$

Also, potential difference across a conductor is

$$V = RI - - - -(v)$$

Therefore, from equation (iii), (iv) and (v), we get

$$EL = \left(\frac{\rho L}{A}\right)(I) - - - (vi)$$

Or

$$E = \left(\frac{I}{A}\right)(\rho) - - - (vii)$$

Or

$$\frac{I}{A} = \frac{E}{\rho} - - - (viii)$$

From equation (i) and (viii), we get finally

$$J = \sigma E - - - -(ix)$$

Or

$$\boxed{J = \sigma E}$$

Also

$$J = \frac{E}{\rho}$$

Where,

- $\rho$ is the resistivity of the conductor

- $E$ is electric field

In vector form,

$$\boxed{\vec{J} = \sigma\vec{E}}$$

**Derivation-5:**

**To obtain the relation between resistivity, relaxation time and electron**

Since,

$$I = neAv_d - - - - - (1)$$

Putting the value of $v_d$ in equation (1), we get

By Ohm's law, I = V/R, therefore,

$$\frac{V}{R} = (neA)\left(\frac{eE\tau}{m}\right) - - - - (2)$$

Since, V=EL, then from equation (2), we have

$$\frac{L}{R} = (neA)\left(\frac{e\tau}{m}\right) - - - - (3)$$

Arranging equation (3) as

$$\frac{RA}{L} = \frac{m}{ne^2\tau} - - - - (4)$$

Since,

$$\rho = \frac{m}{ne^2\tau} - - - - (5)$$

Hence

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

---

## Solved Example 1

A wire has length = 2 m, Area = $2\times10^{-6}$ $m^2$, Resistivity = $1.7\times10^{-8}$ Ωm. Find its resistance.

**Solution**

Using

$$R = \rho L/A$$

Then

$$R = \frac{1.7 \times 10^{-6} \times 2}{2 \times 10^{-6}} = 1.7\ \Omega$$

---

## Solved Example 2

A conductor has resistance 8 Ω. If a potential difference of 24 V is applied, find the current.

**Solution**

Using

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

Then

$$I = \frac{24}{8} = 3A$$

---

## Exam Tips

- Resistance depends on dimensions; resistivity does not.
- Always distinguish between **resistance** and **resistivity**.
- Ohm's law is valid only when **temperature and other physical conditions remain constant**.

---

## Common Mistakes

□ Writing $R = \rho A/L$ instead of $R = \rho L/A$.
□ Confusing conductivity with conductance.
□ Forgetting the SI unit of resistivity.
□ Ignoring the condition of constant temperature in Ohm's law.

---

## JEE Insight (Beyond NCERT)

### 1. Resistance vs Resistivity

| Resistance | Resistivity |
|---|---|
| Depends on dimensions | Independent of dimensions |
| Unit: Ω | Unit: Ω m |
| Property of a conductor | Property of the material |

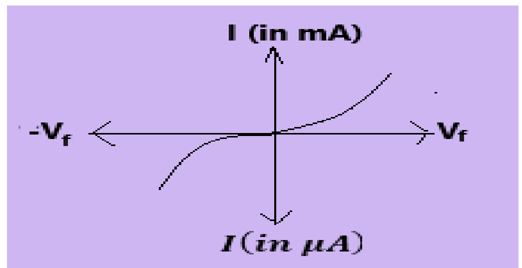



Figure-6: I-V graph

### 2. Conductivity vs Conductance

Students often confuse these terms:

- **Conductivity (σ)** is a material property.
- **Conductance (G)** is the reciprocal of resistance:

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

Its SI unit is **Siemens (S)**.

### 3. Why Does Ohm's Law Fail?

Ohm's law is not obeyed by all materials. Devices such as **diodes, transistors, thermistors, filament lamps (over a wide temperature range), and electrolytes** show a non-linear V-I relationship because their resistance changes with operating conditions.

**Graphs:**

V does not proportional to I.

1. Semiconductor (Si or Germanium)
2. For GaAs material

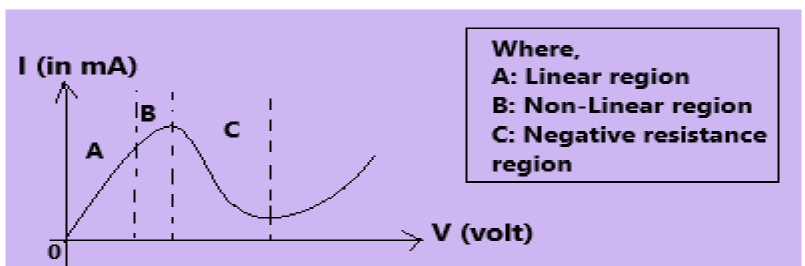



Figure-7: I-V graph, non-linear

# Part – 3: Temperature Dependence of Resistance, Colour Code of Resistors & Combination of Resistors

## Learning Objectives

After studying this part, students will be able to:

- Explain the effect of temperature on resistance.
- Define temperature coefficient of resistance.
- Interpret the colour code of carbon resistors.
- Calculate equivalent resistance in series and parallel combinations.
- Apply resistor combinations in numerical problems.

---

## 3.19 Effect of Temperature on Resistance

The resistance of a conductor changes with temperature.
For **metallic conductors**, resistance **increases** with an increase in temperature because lattice vibrations become more intense, causing more frequent collisions of free electrons.
For **semiconductors**, resistance **decreases** with an increase in temperature because the number of charge carriers increases.

---

## 3.20 Temperature Coefficient of Resistance (α)

## Definition

The **temperature coefficient of resistance** is the fractional change in resistance per unit rise in temperature.
Mathematically,

$$\boxed{\alpha = \frac{R_t - R_0}{R_0 \Delta t}}$$

Where

- $R_0$ = Resistance at initial temperature
- $R_t$ = Resistance at final temperature
- $\Delta T$ = Change in temperature

---

## 3.21 Resistance at Different Temperatures

For moderate temperature changes,

$$\boxed{R_t = R_0(1 + \alpha \Delta t)}$$

Where

- $\alpha$ = Temperature coefficient
- $\Delta T = t - t_0$

---

**Note**: Suppose $R_1$ is the resistance at temperature $t_1$ and $R_2$ is the resistance at temperature $t_2$, if $\alpha$ = temperature coefficient of resistance, then the relation is

$$R_2 = R_1[1 + \alpha(t_2 - t_1)]$$

---

## Important Cases

### Metals

- $\alpha > 0$
- Resistance increases with temperature.

### Semiconductors

- $\alpha < 0$
- Resistance decreases with temperature.

### Alloys (e.g. Manganin, Constantan)

- Very small value of α\alpha
- Resistance remains nearly constant.
- Used in standard resistors and measuring instruments.

---

## 3.22 Superconductivity (Brief Introduction) (JEE/NEET Enrichment)

Some materials, when cooled below a certain **critical temperature (TcT_c)**, exhibit **zero electrical resistance**.

This phenomenon is called **superconductivity**.

### Properties

- Zero resistance
- Perfect diamagnetism (Meissner Effect)
- No power loss

### Applications

- MRI machines
- Maglev trains
- Particle accelerators
- Superconducting magnets

**Note:** For CBSE Class XII, only the basic idea is required.

---

## 3.23 Colour Code of Carbon Resistors (JEE/NEET Enrichment)

Carbon resistors are identified using coloured bands.

### Colour Code Table

| Colour | Digit | Multiplier | Tolerance |
|---|---|---|---|
| Black | 0 | $10^0$ | — |
| Brown | 1 | $10^1$ | ±1% |
| Red | 2 | $10^2$ | ±2% |
| Orange | 3 | $10^3$ | — |
| Yellow | 4 | $10^4$ | — |
| Green | 5 | $10^5$ | ±0.5% |
| Blue | 6 | $10^6$ | ±0.25% |
| Violet | 7 | $10^7$ | ±0.1% |
| Grey | 8 | $10^8$ | ±0.05% |
| White | 9 | $10^9$ | — |
| Gold | — | $10^{-1}$ | ±5% |
| Silver | — | $10^{-2}$ | ±10% |

**Mnemonic (Digit Order)**
**Bl**ack **Br**own **R**ed **O**range **Y**ellow **G**reen **Bl**ue **V**iolet **G**rey **W**hite

---

## 3.24 Combination of Resistors

Resistors are combined mainly in two ways:

1. Series Combination
2. Parallel Combination

---

## A. Resistors in Series

### Circuit Characteristics

- Same current flows through each resistor.
- Potential difference divides among resistors.

---

### Equivalent Resistance

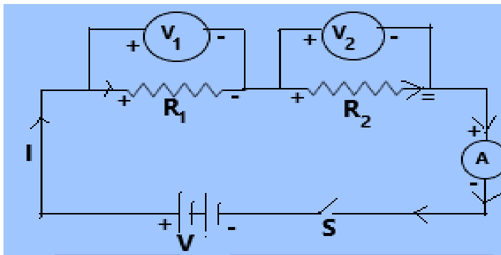


Figure-8: Series Connection of two resistors

When switch S is closed,

$$V = V_1 + V_2$$

(Current is same in both resistors)
Or

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

Or

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

Hence, for n resistors of different values,

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

---

### Potential Difference across each resistor

**In series, voltage is divided across each resistor**.
Since,

$$V = RI \ or \ V \propto R$$

Therefore, potential difference across $R_1$ is

$$V_1 = IR_1 - - - (1)$$

Since,

$$I = \frac{V}{R_{eq}} = \frac{V}{R_1 + R_2} - - - (2)$$

Substituting I from equation (2) in equation (1), we obtain

$$\boxed{V_1 = V\frac{R_1}{R_1 + R_2}}$$

Similarly, potential difference across $R_2$ is

$$V_2 = IR_2 - - - - (3)$$

Hence,

$$\boxed{V_2 = V - V_1 = V\frac{R_2}{R_1 + R_2}}$$

---

### Properties

- Current is the same through all resistors.
- Total resistance increases.
- Voltage divides in proportion to resistance.

---

### Solved Example

Three resistors of 2 Ω, 3 Ω, and 5 Ω are connected in series. Find the equivalent resistance.

**Solution**

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

Or

$$R_{eq} = 2 + 3 + 5 = 10\ \Omega$$

**Answer:** 10 Ω

---

### B. Resistors in Parallel

### Circuit Characteristics

- Same potential difference across each resistor.
- Current divides among different branches.

---

### Equivalent Resistance

When switch S is closed, current is divided inversely Proportional to resistance. As

$$V = RI$$

Since, V is constant, therefore,
Total current,

$$I = I_1 + I_2 - - - (1)$$

Or,

$$\frac{V}{R_{eq}} = \frac{V}{R_1} + \frac{V}{R_2} - - - (2)$$

Or,

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} - - - (3)$$

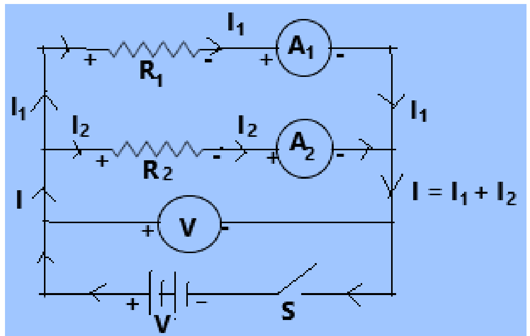



Figure-9: Parallel connection of two resistors

Hence, equivalent resistance is

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

For two resistors,

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

---

### Properties

- Voltage is the same across each resistor.
- Current divides inversely according to resistance.
- Equivalent resistance is always less than the smallest resistor.

## Current across each resistor

**In parallel, current is divided in each resistor**.

Since, V is constant, then

$$V = RI \text{ or } I \propto \frac{1}{R}$$

Therefore, current in $R_1$ is

$$I_1 = V/R_1 --- (1)$$

Since,

$$V = IR_{eq} = I\frac{R_1R_2}{R_1 + R_2} --- (2)$$

Substituting V from equation (2) in equation (1), we obtain

$$\boxed{I_1 = I\frac{R_2}{R_1 + R_2}}$$

Similarly, current in $R_2$ is

$$I_2 = V/R_2 ----(3)$$

Hence,

$$\boxed{I_2 = I - I_1 = I\frac{R_1}{R_1 + R_2}}$$

---

## Solved Example

Two resistors of 6 Ω and 3 Ω are connected in parallel. Find the equivalent resistance.

### Solution

$$R_{eq} = \frac{R_1R_2}{R_1 + R_2}$$

Or

$$R_{eq} = \frac{6 \times 3}{6 + 3} = 2\ \Omega$$

**Answer:** 2 Ω

---

## 3.25 Comparison: Series vs Parallel

| Property | Series | Parallel |
|---|---|---|
| Current | Same | Divides |
| Voltage | Divides | Same |
| Equivalent Resistance | Increases | Decreases |
| Failure of one resistor | Entire circuit stops | Other branches continue |

---

## Exam Tips

- Always identify whether the circuit is **series**, **parallel**, or a **combination** before solving.
- In a parallel circuit, the equivalent resistance is **always less** than the smallest resistor.
- For metals, resistance increases with temperature; for semiconductors, it decreases.

---

## Common Mistakes

- Using the series formula for a parallel circuit.
- Forgetting to take the reciprocal in parallel combinations.
- Confusing resistance with resistivity.
- Reading the resistor colour bands from the wrong end.

---

## JEE Insight (Beyond NCERT)

### 1. Current Division Rule

For two resistors in parallel:

$$\boxed{I_1 = I\frac{R_2}{R_1 + R_2}, I_2 = I\frac{R_1}{R_1 + R_2}}$$

Current divides **inversely proportional to resistance**.

---

### 2. Voltage Division Rule

For two resistors in series:

$$\boxed{V_1 = V\frac{R_1}{R_1 + R_2}, V_2 = V\frac{R_2}{R_1 + R_2}}$$

Voltage divides **directly proportional to resistance**.

---

### 3. Equivalent Resistance Check

A quick check for calculations:

- **Series:** Req must be **greater than the largest resistor**.
- **Parallel:** Req must be **less than the smallest resistor**.

If your answer violates these conditions, recheck your calculations.

# Try yourself

1. If resistance of a wire at $25^0C$ is 2 Ω, then determine the resistance of the same wire at $125^0C$. Given the temperature coefficient of resistance is $1 \times 10^{-4}$ per degree C.
2. In the Figure-(a), find the current in each resistor. Given that R = 6 Ω.

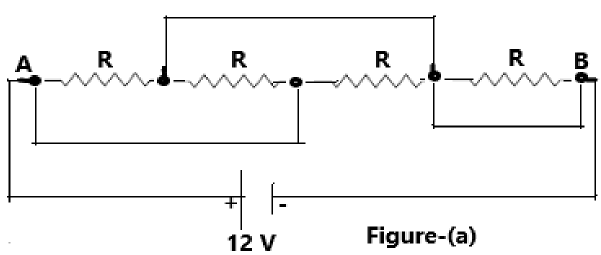



Figure-(a)

# Part – 4: Electromotive Force (EMF), Internal Resistance, Terminal Voltage & Combination of Cells

## Learning Objectives

After studying this part, students will be able to:

- Define electromotive force (EMF).
- Distinguish between EMF and potential difference.
- Explain internal resistance of a cell.
- Derive the relation between EMF and terminal voltage.
- Study cells connected in series and parallel.
- Solve numerical problems based on these concepts.

---

## 3.26 Source of Electrical Energy

A cell or battery converts **chemical energy into electrical energy** and maintains a potential difference between its terminals. This enables continuous flow of current in an external circuit.

---

## 3.27 Electromotive Force (EMF)

## Definition

The emf of a source is the energy supplied by the source per unit charge in driving charge through the source.
EMF is a property of the source and is measured as the terminal potential difference when no current is drawn from the source (open circuit).
It is denoted by **E**.
Mathematically,

$$\boxed{E = \frac{W}{Q}}$$

where

- W = Work done by the cell
- Q = Charge moved

---

**SI Unit:** Volt (V)

---

## Important Note

Despite its name, **EMF is not a force**. It is a **energy** supplied per unit charge by the source.

---

## 3.28 Potential Difference (PD)

The **potential difference** between two points is the work done **per unit charge** in moving a positive test charge between those points.

$$\boxed{V = \frac{W}{Q}}$$

---

### Difference Between EMF and Potential Difference

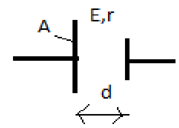
| EMF | Potential Difference |
|---|---|
| Property of the source | Between any two points |
| Measured when no current flows (open circuit) | Measured when current flows |
| Maximum voltage supplied by the cell | Voltage available across a component |
| Symbol: E | Symbol: V |

### 3.29 Internal Resistance of a Cell

### Definition

The opposition offered to the flow of current **inside the cell** is called its **internal resistance**.
It is represented by

$$\boxed{r}$$




### Factors Affecting Internal Resistance

- Distance between electrodes (directly proportional)
- Area of electrodes (inversely proportional)
- Nature and concentration of electrolyte
- Temperature affects internal resistance; the nature and direction of the change depend on the cell chemistry and electrolyte.

### 3.30 Circuit of a Real Cell

A practical cell is represented by:

- EMF = E
- Internal resistance = r
- External resistance = R

When current flows, a part of the EMF is lost inside the cell due to the internal resistance.

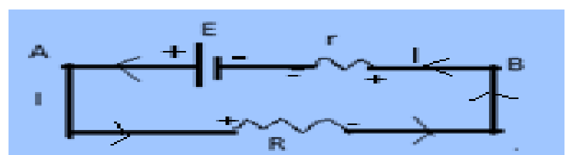



Figure-10: Closed circuit of a cell

### 3.31 Relation Between EMF and Terminal Voltage

Applying Ohm's law to the complete circuit,

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

or

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

Where

- V = Terminal voltage
- I = Current
- r = Internal resistance

### Discharging equation of a cell

From the figure-10,

$$V_B - Ir + E - V_A = 0$$

Or

$$V_A - V_V = E - Ir$$

Or, terminal potential difference,

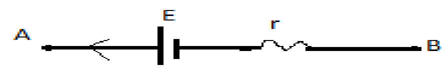
$$\boxed{V = E - Ir}$$

## Special Cases

### Open Circuit

No current flows, I = 0

Hence,

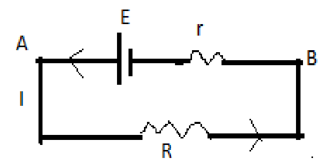



$$\boxed{V = E}$$

Thus, the terminal voltage equals the EMF.

### Closed Circuit

Current flows,




$$V = E - Ir$$

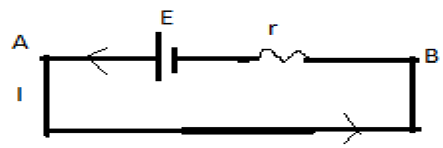
$$\boxed{V < E}$$

because a voltage drop Ir occurs inside the cell.

### Short Circuit

Current flows but V = 0 across the cell.

Therefore,




$$\boxed{I = \frac{E}{r}}$$

## 3.32 Current in the Circuit

For a circuit containing external resistance R and internal resistance r,

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

## Charging equation (initial discharged and now getting charged)

When a cell is connected by an external battery and a series resistor R (to limit the current in cell and to protect it), it takes the current from the external battery.

Charging Equation:

$$+V_A - E - Ir - V_B = 0$$

Or

$$V_A - V_B = E + Ir$$

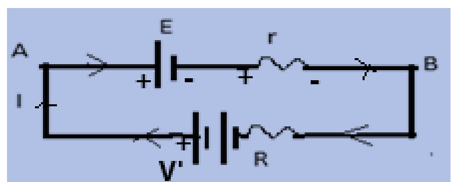



Figure-11: Charging circuit of a cell

Since, $V_A - V_B = V =$ Terminal potential difference across the cell. Therefore

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

Current in the Circuit:

$$V' - E - Ir - IR = 0$$

Or

$$\boxed{I = \frac{V' - E}{r + R}}$$

## Graphs:

**Discharging of a cell: When a cell supplies the current to a load resistance R:**

Since

$$V = E - Ir - - - (1)$$

And

$$V = IR - - - (2)$$

Therefore,

$$I = \frac{E}{r + R} - - - (3)$$

And

$$V = \frac{E}{1 + \frac{r}{R}} - - - (4)$$

**Graph between**

V and I from equation (1)

| V | I |
|---|---|
| **0** | E/r |
| **E** | 0 |

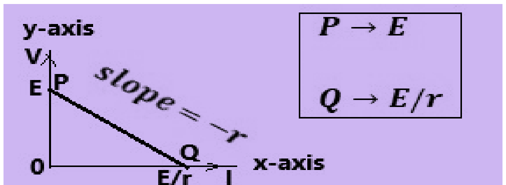


Figure-10-1: Graph between V and I (discharging of a cell)

3. I and R from equation (3)

| I | R |
|---|---|
| **E/r** | 0 |
| **0** | ∞ |

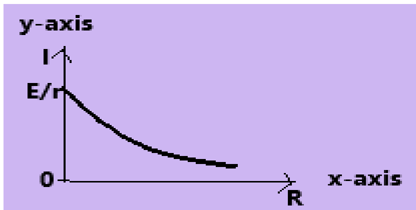


Figure-10-2: Graph between I and R

4. V and R from equation (4)

| V | R |
|---|---|
| **0** | 0 |
| **E** | ∞ |

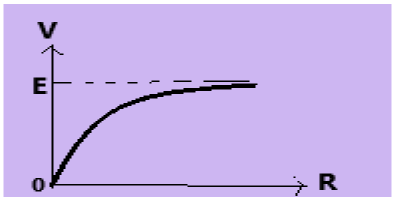


Figure-10-3: Graph between V and R

## Graph

**Charging of a cell:** When the cell takes the current from external battery

Since,

$$V = E + Ir$$

**Graph between V and I**

| V | I |
|---|---|
| **0** | -E/r |
| **E** | 0 |

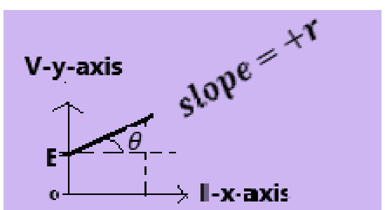


Figure-11-1: Graph between V and I-charging a cell

### Solved Example 1

A cell has EMF = 12 V, Internal resistance = 1 Ω and External resistance = 5 Ω.
Find the current.

**Solution**

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

Or

$$I = \frac{12}{1 + 5} = 2A$$

**Answer:** $\boxed{2A}$

---

### Solved Example 2

A cell has EMF = 6 V, Internal resistance = 0.5 Ω. It supplies a current of 2 A
Find the terminal voltage.

**Solution**

Using

$$V = E - Ir$$

Or

$$V = 6 - 2 \times 0.5 = 6 - 1 = 5V$$

**Answer:** $\boxed{5V}$

---

### 3.33 Cells Connected in Series

**Derivation-6**:

When cells are connected in series:
Using

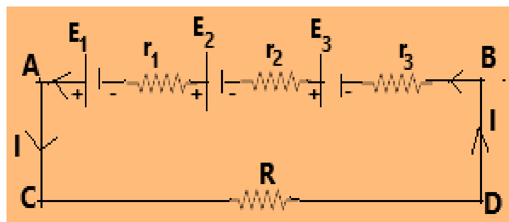



Figure-12: Three Cells connected in series with same polarity

$$V = E - Ir$$

Then

$$V_1 = E_1 - Ir_1$$

$$V_2 = E_2 - Ir_2$$

$$V_2 = E_2 - Ir_2$$

In series connection, current is same, then

$$V = V_1 + V_2 + V_3$$

Substituting above values of V, we get

$$E_{eq} - Ir_{eq} = E_1 - Ir_1 + E_1 - Ir_1 + E_2 - Ir_2$$

Comparing both sides, we obtain equivalent emf as

$$E_{eq} = E_1 + E_2 + E_3$$

And, equivalent internal resistance as

$$r_{eq} = r_1 + r_2 + r_3$$

In general, for n cells of different emfs, we get

**Equivalent EMF**

$$\boxed{E_{eq} = E_1 + E_2 + E_3 + -----}$$

**And,**

**Equivalent Internal Resistance**

$$\boxed{r_{eq} = r_1 + r_2 + r_3 + ----}$$

For n identical cells,

$$\boxed{E_{eq} = nE \text{ and } r_e = nr}$$

**Note:**

If n cells, each capacity E and r are connected in series, and m cells out of n cells have reversed polarities, then Equivalent emf will be

$$\boxed{E_{eq} = (n - 2m)E}$$

And, Equivalent internal resistance will be

$$\boxed{r_{eq} = nr}$$

---

## Terminal Potential Different (V) in parallel combination of cells

If no load resistor is connected across the combination, then

$$I_{total} = 0$$

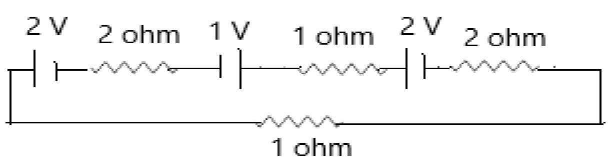
Therefore,

$$\boxed{V = E_{eq}}$$

---

## Solved Example-1: Series Combination

In the circuit shown, find the net emf and current in the circuit.




Solution:
In the given circuit, total number of cells, n = 3
Polarity of cell reversed, m =1
Therefore,
Net emf = 2+2-1= 3 V, and
Net Current

$$I = \frac{Net\ emf}{Net\ Resistance} = \frac{3}{5} = 0.6\ A$$

---

## 3.34 Cells Connected in Parallel

**Derivation-7:**

In parallel connection, potential difference is same.

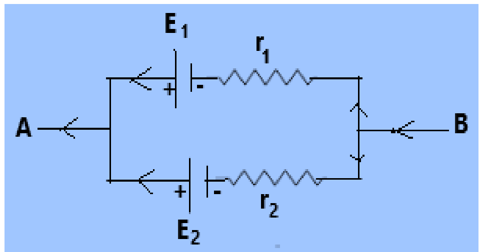



**Figure-13: Circuit diagram of two cells connected in parallel**

Therefore

$$I = I_1 + I_2 ----(1)$$

And

$$I = \frac{E - V}{r} --- (2)$$

Hence,

$$\frac{E_{eqvt}-V}{r_{eqvt}}=\frac{E_1-V}{r_1}+\frac{E_2-V}{r_2}=\left(\frac{E_1}{r_1}+\frac{E_2}{r_2}\right)-V\left(\frac{1}{r_1}+\frac{1}{r_2}\right)$$

Or

$$\frac{E_{eq}}{r_{eq}}-\frac{V}{r_{eq}}=\left(\frac{E_1}{r_1}+\frac{E_2}{r_2}\right)-V\left(\frac{1}{r_1}+\frac{1}{r_2}\right)$$

Comparing both sides, we have

$$\frac{E_{eqvt}}{r_{eqvt}}=\frac{E_1}{r_1}+\frac{E_2}{r_2}\ and\ \frac{1}{r_{eqvt}}=\frac{1}{r_1}+\frac{1}{r_2}$$

Or, equivalent emf of two cells is

$$\boxed{E_{eq}=\frac{E_1r_2+E_2r_1}{r_1+r_2}}$$

And, equivalent internal resistance of two cells is

$$\boxed{r_{eq}=\frac{r_2r_1}{r_1+r_2}}$$

In general,
For n-cells of different emfs, equivalent emf is

$$\boxed{\frac{E_{eq}}{r_{eq}}=\frac{E_1}{r_1}+\frac{E_2}{r_2}+\frac{E_3}{r_3}+\ ------}$$

And, equivalent internal resistance is

$$\boxed{\frac{1}{r_{eq}}=\frac{1}{r_1}+\frac{1}{r_2}+\frac{1}{r_3}+\ ------}$$

For n-identical cells:

**Equivalent EMF**

$$\boxed{E_{eq}=E}$$

**Equivalent Internal Resistance**

$$\boxed{r_{eq}=\frac{r}{n}}$$

Parallel combination is preferred when a larger current is required for a longer time.

---

## Solved Example-1: Parallel combination

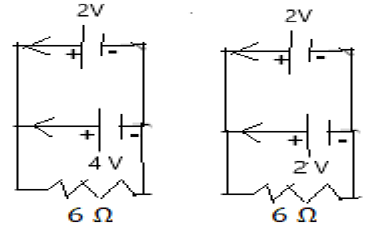


Figure-(a) Figure-(b)

Find the net emf and net current in the circuit shown in Figure-(a) and (b) respectively..

Solution:

In Figure-(a)

Net emf = average of two cells = $\frac{2+4}{2}=3\ V$;

Therefore, net current is $I=\frac{3}{6}=0.5\ A$

In Figure-(b),

Net emf $= \frac{2+2}{2} = 2\ V$

Therefore, net current, $I = \frac{2}{6} = 0.33\ A$

---

## 3.35 Choosing Series or Parallel Combination

### Series Connection

- Increases the effective EMF.
- Suitable for **high external resistance**.

### Parallel Connection

- Reduces internal resistance.
- Suitable for **low external resistance** and higher current demand.

---

## Exam Tips

- EMF is measured under **open-circuit conditions**.
- Terminal voltage decreases when current is drawn from the cell.
- Always include **internal resistance** in complete circuit calculations.
- In series, both EMF and internal resistance add.
- In parallel (identical cells), EMF remains the same while internal resistance decreases.

---

## Common Mistakes

□ Assuming EMF and terminal voltage are always equal.
□ Ignoring internal resistance in numerical problems.
□ Using $I = E/R$ instead of $I = E/(R + r)$ when internal resistance is present.
□ Confusing series and parallel combinations of cells.

---

## JEE Insight (Beyond NCERT)

### 1. Condition for Maximum Current

From

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

Current is maximum when the **external resistance R** is as small as possible.

---

### 2. Why Does a Battery Heat Up?

The power dissipated inside the battery due to its internal resistance is

$$\boxed{P_{internal} = I^2 r}$$

This causes the battery to warm during use.

---

### 3. Choosing the Best Cell Combination

For **identical cells**:

- If R ≫ r, connect cells in **series** to increase EMF.
- If R ≪ r, connect cells in **parallel** to reduce effective internal resistance and deliver a larger current efficiently.

This decision-making concept is frequently tested in **JEE Main**.

# Part – 5: Kirchhoff's Laws and Their Applications

## Learning Objectives

After studying this part, students will be able to:

- State Kirchhoff's Current Law (KCL).
- State Kirchhoff's Voltage Law (KVL).
- Apply the correct sign conventions.
- Solve electrical networks using Kirchhoff's laws.
- Understand the physical basis of these laws.

---

### 3.36 Introduction to Kirchhoff's Laws

Many practical electrical circuits cannot be solved using Ohm's law alone. Gustav Kirchhoff formulated two laws that are based on the conservation principles of physics.

- **Kirchhoff's Current Law (KCL)** → Based on the **conservation of charge**.
- **Kirchhoff's Voltage Law (KVL)** → Based on the **conservation of energy**.

These laws are applicable to both simple and complex electrical circuits.

---

### 3.37 Kirchhoff's Current Law (Junction Rule)

### Statement

At any junction in an electrical circuit, the algebraic sum of currents is zero.
Equivalently,
**The total current entering a junction is equal to the total current leaving the junction.**
Mathematically,

$$\boxed{\sum I = 0}$$

Or

$$\boxed{\sum I_{in} = \sum I_{out}}$$

---

### Physical Basis

KCL is based on the **Law of Conservation of Charge**.
Charge cannot accumulate at an ideal junction.

---

### Example

Suppose,

- $I_1$ and $I_2$ enter a junction.
- $I_3$ and $I_4$ leave the junction.

Then,

$$\boxed{I_1 + I_2 = I_3 + I_4}$$

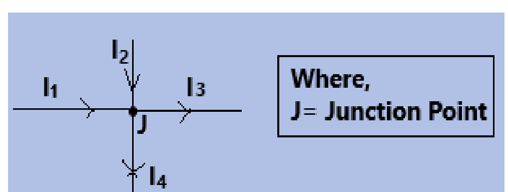


Figure-14: Parts of branches for KCL

---

## 3.38 Kirchhoff's Voltage Law (Loop Rule)

### Statement

In any closed loop of an electrical circuit, the algebraic sum of all potential differences (voltage rises and voltage drops) is zero.

Mathematically,

$$\boxed{\sum V = 0}$$

---

### Physical Basis

KVL is based on the **Law of Conservation of Energy**.

The total energy gained by a charge from sources equals the total energy lost across circuit elements in one complete loop.

---

## 3.39 Sign Convention for Applying KVL

Choose a direction (clockwise or anticlockwise) and follow it consistently.

### Across a Cell

- From **negative to positive terminal** → **+E** (voltage rise)
- From **positive to negative terminal** → **−E** (voltage drop)

### Across a Resistor

- Moving **along the direction of current** → **−IR** (voltage drop)
- Moving **opposite to the direction of current** → **+IR** (voltage rise)

### Example:

- First, check how many loops are given in the circuit.
- Take loop(s) clockwise or anticlockwise or mixed up.
- Fix the branch current by taking current from positive terminal of any one cell/battery.
- Ensure that the taken current, say $(I_1)$ should enter The negative terminal of chosen cell/battery.
- Write the equations as per the direction of loop current chosen, not the branch current.
- **For a cell**, write its value +ve (+E) in the direction of loop current from –ve terminal to +ve terminal of a cell **(voltage rise**) and –ve value (-E) from +ve terminal to –ve terminal of that cell (**voltage drop**).
- **For a resistor**, write -IR if branch current and loop current are in the direction and +IR if branch current and loop current are in opposite direction.
- **Always write the voltage equation in the chosen direction of loop current.**

**The loop equations are:**

In closed loop-1, A-B-C-G-A

$+E_1 - I_1R_1 - (I_1 - I_2)R_3 = 0 - - - (1)$

In closed loop-2, C-D-F-G-C

$-I_2R_2 - E_2 + (I_1 - I_2)R_3 = 0 - - - -(2)$

If $E_1$, $E_2$, $R_1$, $R_2$ and $R_3$ are known, it can easily be Solved values of $I_1$ and $I_2$

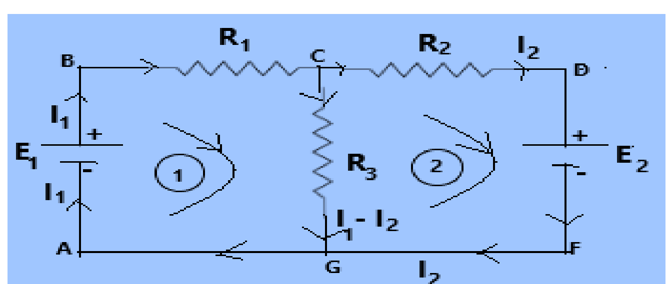



Figure-15: Circuit diagram for solving loop currents (example)

## 3.40 Procedure for Solving Circuit Problems

1. Draw and label the circuit clearly.
2. Assume the direction of current in each branch (if not given).
3. Apply **KCL** at independent junctions.
4. Apply **KVL** to independent loops.
5. Solve the simultaneous equations.
6. If any current comes out negative, its actual direction is opposite to the assumed direction.

---

## Solved Example 1 (KCL)

At a junction,

- $I_1$ =3 A enters.
- $I_2$ = 5 A enters.
- $I_3$ = 4 A leaves.

Find $I_4$.

### Solution

Using KCL,

$$I_1 + I_2 = I_3 + I_4$$

Or

$$I_4 = 3 + 5 - 4 = 4\ A$$

**Answer:** $\boxed{4A}$

---

## Solved Example 2 (KVL)

A circuit contains:

- Cell: 12 V
- Resistor $R_1$=2 Ω
- Resistor $R_2$=4 Ω

connected in series.
Find the current.

### Solution

Applying KVL,

$$\boldsymbol{+E - IR_1 - IR_2 = 0}$$

**Or**

$$\boldsymbol{I = \frac{12}{2+4} = 2A}$$

**Answer:** $\boxed{2A}$

---

## 3.41 Applications of Kirchhoff's Laws

Kirchhoff's laws are used in:

- Multi-loop circuits
- Bridge circuits
- Measurement instruments
- Electronic circuit analysis
- Electrical power distribution systems

---

### 3.42 Limitations

Kirchhoff's laws assume:

- Steady-state currents.
- Negligible electromagnetic radiation.
- Lumped circuit elements (ideal wires and components).

These assumptions are valid for Class XII-level circuit analysis.

---

## Exam Tips

- Always mark the assumed current directions before writing equations.
- Follow one loop direction consistently while applying KVL.
- A negative current in the answer simply means the actual current flows opposite to the assumed direction.

---

## Common Mistakes

□ Mixing the sign convention for voltage rises and drops.
□ Forgetting to include all resistors in the loop equation.
□ Applying KCL incorrectly by adding currents with the wrong sign.
□ Changing the loop direction midway through the calculation.

---

## Comparison of KCL and KVL

| Feature | KCL | KVL |
|---|---|---|
| Based on | Conservation of Charge | Conservation of Energy |
| Applied at | Junction | Closed Loop |
| Mathematical Form | $\sum I = 0$ | $\sum V = 0$ |
| Used for | Current equations | Voltage equations |

---

## JEE Insight (Beyond NCERT)

### 1. Choosing Current Directions

In Kirchhoff problems, the assumed direction of current is **arbitrary**. If the calculated value is negative, it only indicates that the actual current flows in the opposite direction.

---

### 2. Number of Independent Equations

For a circuit with multiple loops:

- Use **KCL** to write equations at independent junctions.
- Use **KVL** for independent loops.
- The total number of independent equations should equal the number of unknown currents.

---

### 3. Common Strategy in JEE Problems

- Simplify any obvious **series** or **parallel** resistor combinations first.
- Apply **KCL** to determine current relationships.
- Then apply **KVL** to solve for the unknown currents.

This approach reduces calculation time and minimizes algebraic errors.

# Part – 6: Wheatstone Bridge, Meter Bridge and Potentiometer

## Learning Objectives

After studying this part, students will be able to:

- Explain the principle of the Wheatstone bridge.
- Derive the balance condition of the Wheatstone bridge.
- Understand the construction and working of the Meter Bridge.
- Explain the principle and operation of a Potentiometer.
- Compare the EMFs of two cells.
- Determine the internal resistance of a cell using a potentiometer.

---

## 3.43 Wheatstone Bridge

### Definition

A **Wheatstone Bridge** is an arrangement of four resistors used to measure an unknown resistance accurately by balancing the bridge.

---

### Construction

The bridge consists of four resistances:

- P
- Q
- R
- S (unknown resistance)

A galvanometer is connected between the middle junctions, and a battery is connected across the opposite corners.

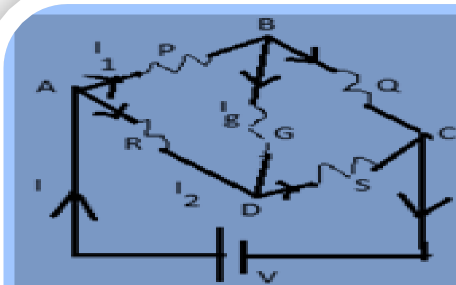



Figure-16: Wheatstone Bridge Circuit

---

### Principle

The Wheatstone bridge works on the **null deflection principle**.

At balance:

- No current flows through the galvanometer.
- The potential difference across the galvanometer is zero.

---

### Balance Condition

$$\boxed{P/Q = R/S}$$

or

$$\boxed{PS = QR}$$

If three resistances are known, the fourth can be calculated.

---

**Important Note (as shown in the figure-16)**

- In the balanced condition, $I_g = 0$; $V_B = V_D$; $PS = QR$
- In the unbalanced condition, when $PS > QR$; the current in the galvanometer branch flows from point D to B and $V_D > V_B$.
- In the unbalanced condition, when $PS < QR$, the current in the galvanometer will flow from point B to point D in the galvanometer branch and then $V_B > V_D$.
- When interchanging galvanometer with battery, there is no effect on balancing of Wheat Stone Bridge Circuit
- The bridge circuit will be most sensitive when all four resistances (P, Q, R and S) are of the same order.

## Other Forms of Wheat Stone bridge Circuit:

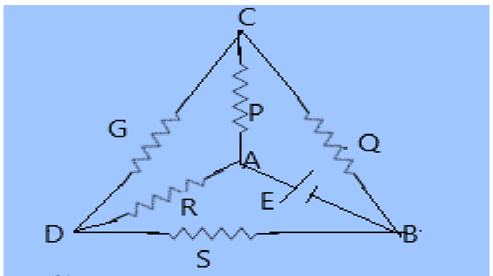


Figure-16-1: Form of Wheatstone bridge circuit

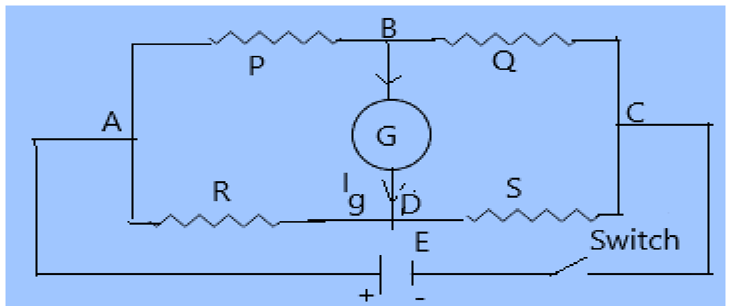


Figure-16-2: Wheat stone bridge circuit

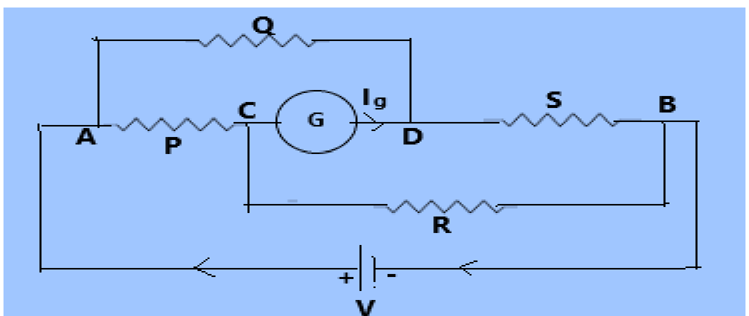


Figure-16-3: Wheatstone bridge circuit

## Solved Example

Given:

- P =2 Ω
- Q = 4 Ω
- R = 6 Ω

Find the unknown resistance S.

## Solution

Using

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

Then

$$S = \frac{QR}{P} = \frac{4 \times 6}{2} = 12\ \Omega$$

**Answer:** $\boxed{12\Omega}$

---

## 3.44 Meter Bridge (Practical / Enrichment Section — Meter Bridge and Potentiometer)

### Definition

A **Meter Bridge** is a practical application of the Wheatstone bridge used for measuring an unknown resistance.

---

### Construction

It consists of:

- A uniform wire of length **1 metre**.
- A jockey.
- A galvanometer.
- A known resistance.
- An unknown resistance.
- A battery.

---

### Principle

It also works on the **null deflection principle**.
At balance,

$$\frac{R}{X} = \frac{l}{100 - l}$$

Where

- R = Known resistance
- X = Unknown resistance
- l = Balance length (cm)

---

### Advantages of Meter Bridge

- Simple construction
- Good accuracy
- Easy to use in laboratories
- Based on Wheatstone bridge principle

---

## 3.45 Potentiometer (Practical / Enrichment Section — Meter Bridge and Potentiometer)

### Definition

A **Potentiometer** is an instrument used to compare EMFs and measure potential differences accurately **without drawing current from the source**.

---

### Principle

The potential drop along a uniform wire carrying a constant current is directly proportional to its length.

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

or

$$\boxed{V = kl}$$

Where

- k = Potential gradient
- l = Length of the wire

## Potential Gradient

The potential drop per unit length of the potentiometer wire is called the **potential gradient**.

$$\boxed{k = \frac{V}{l}}$$

## Comparison of EMFs

Suppose two cells have EMFs: $E_1$ and $E_2$. If their balancing lengths are $l_1$ and $l_2$, then

$$\frac{E_1}{E_2} = \frac{l_1}{l_2}$$

## Determination of Internal Resistance

If

- $l_1$ = Balance length without load
- $l_2$ = Balance length with external resistance connected

Then,

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

Where

- R = External resistance
- r = Internal resistance of the cell

## Why is a Potentiometer More Accurate than a Voltmeter?

A voltmeter draws a small current from the circuit, whereas a potentiometer works on the **null method**, drawing **no current** from the cell being measured. Hence, it provides a more accurate value of EMF.

## Solved Example

Two cells balance at lengths: $l_1$ = 80 cm, $l_2$ = 100 cm. Find the ratio of their EMFs.

### Solution

$$\frac{E_1}{E_2} = \frac{l_1}{l_2}$$

Or

$$\frac{E_1}{E_2} = \frac{80}{100} = \frac{4}{5}$$

**Answer:** $\boxed{4:5}$

## Applications

### Wheatstone Bridge

- Measuring unknown resistance
- Precision electrical measurements

### Meter Bridge

- Laboratory determination of resistance
- Verification of bridge principle

### Potentiometer

- Comparing EMFs
- Measuring internal resistance
- Measuring small potential differences
- Calibration of voltmeters
- Calibration of ammeters

---

## Exam Tips

- Remember that both the Wheatstone bridge and the meter bridge operate on the **null deflection principle**.
- The potentiometer measures **EMF more accurately than a voltmeter** because it does not draw current from the source.
- Learn the balance conditions and know when to apply each formula.

---

## Common Mistakes

 Confusing the Wheatstone bridge with the meter bridge.
 Using balance-length formulas before ensuring the bridge is balanced.
 Forgetting that the potentiometer wire must have **uniform cross-section** and carry **constant current**.
 Confusing **potential difference** with **EMF** in potentiometer questions.

---

## JEE Insight (Beyond NCERT)

### 1. Sensitivity of a Potentiometer

The sensitivity increases when the **potential gradient kk** is reduced. This is achieved by using a **longer potentiometer wire** or reducing the current through it. A smaller potential gradient allows detection of very small differences in EMF.

### 2. Balanced Wheatstone Bridge

When the bridge is balanced:

- No current flows through the galvanometer.
- The galvanometer branch can be ignored while solving the circuit.

This greatly simplifies many JEE Main numerical problems.

### 3. Choosing the Right Instrument

| Instrument | Best Use |
|---|---|
| Wheatstone Bridge | Accurate measurement of an unknown resistance |
| Meter Bridge | Practical laboratory measurement of resistance |
| Potentiometer | Accurate comparison of EMFs and measurement of internal resistance |

# Appendix – A: Concept Enrichment, Higher-Order Thinking & JEE/NEET Insights

## B.1 Current is Not "Used Up"

One of the most common misconceptions is that current gets consumed as it passes through a resistor.

### Correct Concept

Current remains the same throughout a series circuit. What is actually converted is **electrical energy** into other forms such as heat, light, or mechanical energy.

**Remember:**

- Charge is conserved. Therefore, in a steady-state series circuit, the same current flows through every component.
- Energy is transformed.

---

## B.2 Why Do Electrons Move So Slowly but the Bulb Glows Instantly?

The **drift velocity** of electrons is extremely small (typically $10^{-4}$ to 10−3 m $s^{-3}$) m/s, yet an electric bulb lights almost immediately when the switch is turned on.

### Explanation

The electric field is established throughout the conducting wire nearly at the speed of the electromagnetic signal. Electrons already present everywhere in the wire begin drifting almost simultaneously.

**Key Point:** Energy is transmitted rapidly by the electric field, not by individual electrons traveling from the battery to the bulb.

---

## B.3 Drift Velocity vs Thermal Velocity

| Drift Velocity | Thermal Velocity |
|---|---|
| Due to electric field | Due to thermal motion |
| Directed | Random |
| Very small | Very large |
| Produces current | Average effect is zero |

**JEE Favourite:** Thermal velocity is much greater than drift velocity, yet it does not produce a net current because the random motions cancel out.

---

## B.4 Why Does Resistance Increase in Metals?

As temperature increases:

- Lattice ions vibrate more strongly.
- Electron-ion collisions become more frequent.
- Relaxation time (τ) decreases.
- Drift velocity decreases.
- Resistance increases.

Thus,

$$R \uparrow \text{ when } T \uparrow$$

## B.5 Why Does Resistance Decrease in Semiconductors?

In semiconductors:

- Heating creates more free charge carriers.
- The increase in carrier concentration outweighs the increase in collisions.
- Hence, resistance decreases with temperature.

---

## B.6 Why is Copper Used for Electrical Wiring?

Copper is preferred because it has:

- Low resistivity
- High conductivity
- Good ductility
- Excellent mechanical strength
- Reasonable cost
- Good corrosion resistance

Silver has even lower resistivity but is much more expensive.

---

## B.7 Why are Heating Elements Made of Nichrome?

Nichrome is used because it has:

- High resistivity
- High melting point
- Low temperature coefficient of resistance
- Excellent oxidation resistance

Hence, it can produce large amounts of heat without melting quickly.

---

## B.8 Internal Resistance of a Cell

Internal resistance depends on:

- Nature of the electrolyte
- Concentration of the electrolyte
- Temperature
- Distance between electrodes
- Effective surface area of the electrodes

Fresh cells generally have lower internal resistance than old cells.

---

## B.9 EMF vs Terminal Voltage

Students often confuse these quantities.

| EMF | Terminal Voltage |
|---|---|
| Maximum voltage of a cell | Actual voltage across the terminals |
| Measured under open-circuit conditions | Measured while current flows |
| Independent of load | Depends on current and internal resistance |

---

## B.10 Why is a Potentiometer More Accurate than a Voltmeter?

A potentiometer works on the **null method**.

At balance:

- No current is drawn from the test cell.

- There is no loading effect.
- The measured EMF equals the true EMF.

A voltmeter, however, always draws a small current, which can slightly affect the reading.

---

## B.11 Wheatstone Bridge Balance

At balance:

- No current flows through the galvanometer.
- The galvanometer branch can be ignored for calculations.
- This simplifies circuit analysis and improves measurement accuracy.

---

## B.12 Practical Applications

| Device/Concept | Application |
|---|---|
| Copper wire | House wiring |
| Nichrome | Electric heaters, irons, toasters |
| Manganin | Standard resistors |
| Potentiometer | Calibration of voltmeters and ammeters |
| Wheatstone Bridge | Precision resistance measurement |
| Meter Bridge | Laboratory experiments |

---

## B.13 Frequently Confused Terms

| Quantity | Meaning |
|---|---|
| Current | Rate of flow of charge |
| Drift Velocity | Average velocity of electrons due to electric field |
| Resistance | Opposition offered by a conductor |
| Resistivity | Intrinsic property of a material |
| Conductance | Reciprocal of resistance |
| Conductivity | Reciprocal of resistivity |
| EMF | Energy supplied per unit charge by a source |
| Potential Difference | Energy transferred per unit charge between two points |

---

## B.14 High-Probability Conceptual Questions

1. Why is current the same in a series circuit?
2. Why is equivalent resistance in parallel less than the smallest resistor?
3. Why does a potentiometer use a long, uniform wire?
4. Why does a galvanometer show zero deflection in a balanced Wheatstone bridge?
5. Why is a voltmeter connected in parallel while an ammeter is connected in series?
6. Why is copper preferred over iron for electrical wiring?
7. Why is nichrome used in heating appliances?

---

## B.15 Top 10 Exam Mistakes

☐ Confusing **EMF** with **terminal voltage**.
☐ Writing $R = \rho A/L$ instead of $R = \rho L/A$
☐ Forgetting to include **internal resistance** in circuit calculations.
☐ Applying Ohm's law without checking the condition of constant temperature.

 Mixing up **current division** and **voltage division** rules.
 Reading resistor colour bands from the wrong end.
 Ignoring sign conventions in Kirchhoff's laws.
 Assuming current is "used up" in a resistor.
 Confusing **conductance** with **conductivity**.
 Using the Wheatstone bridge balance condition before ensuring the bridge is actually balanced.

# Appendix – B: Assertion–Reason, Case-Based, HOTS & Viva-Voce Questions

## Section A : Assertion–Reason Questions

### Directions

Choose the correct option.
**(A)** Both Assertion and Reason are true, and Reason is the correct explanation of Assertion.
**(B)** Both Assertion and Reason are true, but Reason is not the correct explanation.
**(C)** Assertion is true, but Reason is false.
**(D)** Assertion is false, but Reason is true.

---

### Q1

**Assertion (A):**
Drift velocity of electrons is directly proportional to the applied electric field.
**Reason (R):**
The relaxation time of electrons remains constant for a given conductor at constant temperature.
**Answer: (A)**

---

### Q2

**Assertion (A):**
Current is the same through all resistors connected in series.
**Reason (R):**
Charge cannot accumulate at any point of an ideal series circuit.
**Answer: (A)**

---

### Q3

**Assertion (A):**
Equivalent resistance of parallel resistors is always less than the smallest resistor.
**Reason (R):**
Current has multiple paths to flow in a parallel combination.
**Answer: (A)**

---

### Q4

**Assertion (A):**
A potentiometer measures EMF more accurately than a voltmeter.
**Reason (R):**
A potentiometer works on the null-deflection principle and draws negligible current from the test cell.
**Answer: (A)**

---

### Q5

**Assertion (A):**
The terminal voltage of a cell decreases when it supplies current.
**Reason (R):**
A voltage drop occurs across the internal resistance of the cell.

**Answer: (A)**

---

## Section B : Competency-Based Case Study

# Case Study–1 : Domestic Wiring

A student connects three identical electric heaters in parallel across a 220 V supply. Each heater works independently.
Answer the following:

### Q1

Why are the heaters connected in parallel instead of series?
**Answer:**
Each heater receives the full supply voltage and operates independently.

---

### Q2

If one heater becomes defective, what happens to the others?
**Answer:**
The remaining heaters continue to work normally.

---

### Q3

Which combination draws more total current—series or parallel?
**Answer:**
Parallel combination.

---

### Q4

Which combination has lower equivalent resistance?
**Answer:**
Parallel combination.

---

### Q5

State one practical advantage of parallel wiring in homes.
**Answer:**
Each appliance can be operated independently without affecting the others.

---

## Case Study–2 : Potentiometer Experiment

A student compares the EMFs of two cells using a potentiometer. The balancing lengths are:

- Cell A = 80 cm
- Cell B = 100 cm

### Q1

Find the ratio of EMFs.
**Answer**
$E_A / E_B = 80/100 = 0.8$

---

### Q2

Which cell has the greater EMF?

**Answer:**
Cell B.

---

**Q3**
Why does a potentiometer provide a more accurate measurement than a voltmeter?
**Answer:**
Because it works by the null method and does not draw current from the test cell.

---

## Section C: HOTS (Higher Order Thinking Skills)

**Q1**
A bird can safely sit on a high-voltage transmission wire but receives an electric shock if it simultaneously touches the wire and an earthed object. Explain.
**Answer:**
When the bird sits on only one wire, both feet are at nearly the same potential, so practically no current flows through its body. Touching another conductor at a different potential creates a potential difference, causing current to flow.

---

**Q2**
Why is thick copper wire preferred for domestic wiring instead of a thin wire?
**Answer:**
- Lower resistance
- Lower heating
- Greater current-carrying capacity
- Better safety

---

**Q3**
Why does a filament lamp not obey Ohm's law perfectly?
**Answer:**
As current increases, the filament temperature rises, changing its resistance. Therefore, the V-I graph is not perfectly linear.

---

**Q4**
A battery is left connected to a resistor for a long time. Why does the terminal voltage gradually decrease?
**Answer:**
Due to chemical changes inside the battery, the internal resistance increases and the EMF may decrease slightly, reducing the terminal voltage.

---

## Section D : Viva-Voce Questions

### Q1
Define drift velocity.
**Answer:**
The average velocity acquired by free electrons under an applied electric field.

---

**Q2**
What is relaxation time?
**Answer:**
The average time between two successive collisions of a free electron with lattice ions.

---

**Q3**
State Ohm's law.
**Answer:**
At constant temperature, current through a conductor is directly proportional to the potential difference across it.

---

**Q4**
Why is copper used for electrical wiring?
**Answer:**
Because it has low resistivity, high conductivity, good ductility, and good mechanical strength.

---

**Q5**
What is the SI unit of resistivity?
**Answer:**
Ohm metre (Ω m\Omega\,\text{m}).

---

**Q6**
State Kirchhoff's Current Law.
**Answer:**
The total current entering a junction equals the total current leaving it.

---

**Q7**
State Kirchhoff's Voltage Law.
**Answer:**
The algebraic sum of all potential differences in a closed loop is zero.

---

**Q8**
What is the principle of a potentiometer?
**Answer:**
The potential drop along a uniform wire carrying a constant current is directly proportional to its length.

---

**Q9**
Why is a Wheatstone bridge called a null-method instrument?
**Answer:**
Because at balance, the galvanometer shows zero deflection.

---

**Q10**
Name one instrument based on the Wheatstone bridge principle.

**Answer:**
Meter bridge.

---

## Section E : Board Examination Value-Based Questions

### Q1

A student notices that the insulation of a household wire has melted due to overloading. What safety measures should be followed?
**Answer:**

- Avoid overloading electrical circuits.
- Use wires of proper current rating.
- Install correctly rated fuses or MCBs.
- Replace damaged wiring immediately.

---

### Q2

Why should electrical repairs never be carried out with wet hands?
**Answer:**
Water lowers the body's resistance, increasing the risk of electric shock.

## Important Definitions (One-Line Revision)

- **Electric Current:** Rate of flow of electric charge.
- **Drift Velocity:** Average velocity of free electrons under an electric field.
- **Current Density:** Current flowing per unit cross-sectional area.
- **Resistance:** Opposition offered by a conductor to the flow of current.
- **Resistivity:** Intrinsic property of a material that determines its resistance.
- **EMF:** Energy supplied per unit charge by a source.
- **Internal Resistance:** Resistance offered inside a cell.
- **Potential Gradient:** Potential drop per unit length of a potentiometer wire.