# The Collegedunia NCERT Notes

*The Ultimate NCERT Revision Notes for Class 12 Physics*

# Chapter 3: Current Electricity

## 1 Electric Current and Flow of Charges

### 1.1 Electric Current

Electric current is the flow of electric charge through a conductor. Whenever electric charges move in an ordered manner, current is said to flow.

### 1.2 Definition of Electric Current

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

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

For varying charge:

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

where:

- $Q$ = charge passing
- $t$ = time taken

**SI Unit of Current**

SI unit of current is **Ampere (A)**.

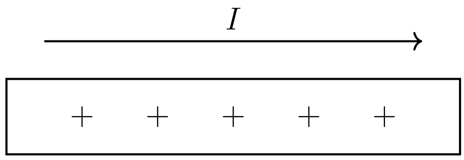
$$1 \text{ Ampere} = 1 \frac{\text{Coulomb}}{\text{second}}$$

**Definition of 1 Ampere**

If 1 Coulomb of charge flows in 1 second through a conductor, current is 1 Ampere.

$$1A = 1C/s$$

**Flow of Charge**




## 1.3 Direction of Current

### Conventional Current

Conventional current is taken as the direction of flow of positive charges.

From positive terminal to negative terminal

### Electron Flow

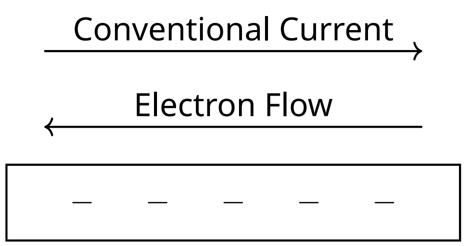
In metallic conductors:

- Free electrons move.
- Electrons flow from negative terminal to positive terminal.

Electron Flow: Negative $\Rightarrow$ Positive

### Why Current Direction is Opposite to Electron Flow

- Current direction was defined before discovery of electrons.
- It was assumed that positive charges move.
- Hence, conventional direction is opposite to electron motion.




## 1.4 Current as a Scalar Quantity

Electric current is treated as a scalar quantity.

Even though charge carriers have drift velocity $\vec{v_d}$ (a vector), current itself is scalar because:

- Current represents rate of charge flow.

- It does not obey vector addition rules.
- At a junction, currents are added algebraically.

Current in terms of drift velocity:

$$I = nqAv_d$$

where:

- $n$ = number of charge carriers per unit volume
- $q$ = charge of each carrier
- $A$ = cross-sectional area
- $v_d$ = drift velocity (magnitude)

Thus:

- Drift velocity has direction.
- Current magnitude is scalar.
- Direction is assigned separately.

**Concept Summary**

- $I = \frac{Q}{t}$
- SI unit = Ampere
- Conventional current flows positive to negative.
- Electron flow is opposite.
- Current is scalar quantity.

# 2 Electric Current in Conductors (Microscopic View)

## 2.1 Free Electrons in Metals

**Conductors vs Insulators**

- Conductors have large number of free charge carriers.
- Insulators have very few or no free charge carriers.

In metals:

- Outer (valence) electrons are loosely bound.
- These electrons become free and move throughout the metal.

### Valence Electrons

Valence electrons are the outermost electrons of an atom.

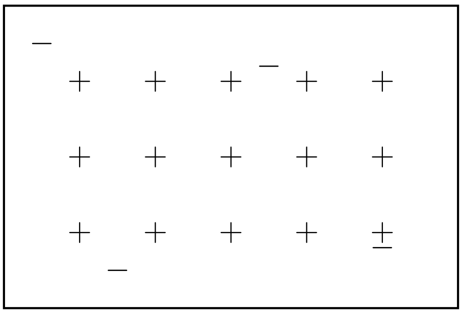
- In metals, valence electrons are weakly attached.
- They can easily leave the atom and move freely.

### Electron Gas Model

According to the electron gas model:

- Free electrons behave like a gas inside the metal.
- Positive ions remain fixed in lattice.
- Electrons move randomly in absence of electric field.

**Electron Gas Model**



## 2.2 Drift Velocity

### Definition

Drift velocity is the average velocity acquired by free electrons in a conductor when an external electric field is applied.

Without electric field:

- Electrons move randomly.
- Net current is zero.

With electric field:

- Electrons drift opposite to field.
- Small net velocity appears.

### Derivation of Drift Velocity

Force on electron:

$$F = -eE$$

Acceleration:

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

If $\tau$ is relaxation time (average time between collisions):

$$v_d = a\tau$$

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

where:

- $e$ = charge of electron
- $E$ = electric field
- $\tau$ = relaxation time
- $m$ = mass of electron

## 2.3 Relation Between Current and Drift Velocity

Consider conductor of cross-sectional area $A$.
In time $dt$:
Distance travelled:

$$dx = v_d dt$$

Volume of charge crossing area:

$$Adx = Av_d dt$$

If $n$ is number density of electrons:

$$\text{Number of electrons} = nAv_d dt$$

Total charge:

$$dQ = neAv_d dt$$

Current:

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

$$\boxed{I = neAv_d}$$

where:

- $n$ = number density
- $e$ = charge
- $A$ = area
- $v_d$ = drift velocity

## 2.4 Mobility

Mobility is defined as drift velocity per unit electric field.

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

Using drift velocity expression:

$$\mu = \frac{e\tau}{m}$$

$$\boxed{\mu = \frac{e\tau}{m}}$$

Higher mobility means electrons respond quickly to applied field.

## 2.5 Ohm's Law (Microscopic Form)

Current density:

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

Using $I = neAv_d$:

$$J = nev_d$$

Substitute $v_d = \mu E$:

$$J = ne\mu E$$

Since $\sigma = ne\mu$:

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

where:

- $J$ = current density
- $\sigma$ = electrical conductivity

Resistivity:

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

**Complete Summary**

- $v_d = \frac{eE\tau}{m}$
- $I = neAv_d$
- $\mu = \frac{v_d}{E} = \frac{e\tau}{m}$
- $J = \sigma E$
- $\rho = 1/\sigma$

# 3 Ohm's Law and Resistance

## 3.1 Ohm's Law (Macroscopic Form)

### Statement

Ohm's Law states that at constant temperature and physical conditions, the current flowing through a conductor is directly proportional to the potential difference applied across its ends.

$$V \propto I$$

Removing proportionality constant:

$$\boxed{V = IR}$$

where:

- $V$ = potential difference
- $I$ = current
- $R$ = resistance

Resistance is defined as:

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

SI unit of resistance:

$$1\ \text{Ohm} = 1\frac{\text{Volt}}{\text{Ampere}}$$

## 3.2 V–I Graph

From Ohm's Law:

$$V = IR$$

### Linear Relationship

If $V$ is plotted on y-axis and $I$ on x-axis:

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

### Observations

- Straight line passing through origin.
- Larger slope $\Rightarrow$ higher resistance.
- Smaller slope $\Rightarrow$ lower resistance.

## 3.3 Ohmic and Non-Ohmic Conductors

### Ohmic Conductors

A conductor that obeys Ohm's Law is called an Ohmic conductor.
Characteristics:

- Linear $V$–$I$ graph.
- Resistance remains constant (at constant temperature).

Example:

- Metallic conductor.

### Non-Ohmic Conductors

A conductor that does not obey Ohm's Law is called a Non-Ohmic conductor.
Characteristics:

- Non-linear $V$–$I$ graph.
- Resistance changes with voltage or temperature.

Examples:
**1. Semiconductor**

- Current increases rapidly after certain voltage.
- Non-linear graph.

**2. Diode**

- Allows current mainly in one direction.
- Sharp rise in forward bias.

**3. Filament Bulb**

- Resistance increases with temperature.
- Curved $V$–$I$ graph.

**Concept Summary**

- $V = IR$
- Straight line graph $\Rightarrow$ Ohmic conductor.
- Slope gives resistance.
- Metals $\Rightarrow$ Ohmic.
- Diode and filament bulb $\Rightarrow$ Non-Ohmic.

# 4 Resistance

## 4.1 Definition of Resistance

Resistance is the property of a conductor by virtue of which it opposes the flow of electric current through it.

When a potential difference $V$ is applied across a conductor and a current $I$ flows through it, resistance is defined as:

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

where:

- $R$ = resistance
- $V$ = potential difference
- $I$ = current

This relation is valid for Ohmic conductors at constant temperature.

Physically, resistance arises because moving electrons collide with lattice ions and other imperfections inside the conductor. These collisions oppose the motion of electrons and reduce current.

More collisions $\Rightarrow$ more opposition $\Rightarrow$ higher resistance.

## 4.2 SI Unit of Resistance

SI unit of resistance is **Ohm** ($\Omega$).

$$1\Omega = 1\frac{\text{Volt}}{\text{Ampere}}$$

Definition:

A conductor has resistance of 1 Ohm if a potential difference of 1 Volt produces a current of 1 Ampere.

$$1\Omega = 1\frac{V}{A}$$

Large resistances are measured in:

- kilo-ohm ($k\Omega = 10^3\Omega$)
- mega-ohm ($M\Omega = 10^6\Omega$)

## 4.3 Factors Affecting Resistance

Resistance of a uniform conductor depends on four main factors:

- Length ($l$)
- Cross-sectional area ($A$)
- Nature of material
- Temperature

Mathematical relation:

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

where:

- $\rho$ = resistivity of material
- $l$ = length
- $A$ = cross-sectional area

### 1. Dependence on Length

$$R \propto l$$

If length of conductor increases:

- Electrons travel longer path.
- Probability of collisions increases.
- Resistance increases.

If length is doubled:

$$R_{\text{new}} = 2R$$

### 2. Dependence on Cross-Sectional Area

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

If area increases:

- More electrons can flow simultaneously.
- Effective opposition decreases.
- Resistance decreases.

If area is doubled:

$$R_{\text{new}} = \frac{R}{2}$$

### 3. Dependence on Material (Resistivity)

Resistivity $\rho$ is a property of material.

$$\rho = \frac{RA}{l}$$

Unit of resistivity:

$$\Omega\,\text{meter}$$

Different materials have different resistivities:

- Copper $\Rightarrow$ very low $\rho$
- Nichrome $\Rightarrow$ higher $\rho$
- Rubber $\Rightarrow$ extremely high $\rho$

Thus, resistance depends strongly on nature of material.

### 4. Dependence on Temperature

For metallic conductors:
When temperature increases:

- Lattice vibrations increase.
- More collisions occur.
- Resistance increases.

Relation:

$$R = R_0(1 + \alpha\Delta T)$$

where:

- $R_0$ = resistance at reference temperature
- $\alpha$ = temperature coefficient of resistance
- $\Delta T$ = change in temperature

For metals:

$$\alpha > 0$$

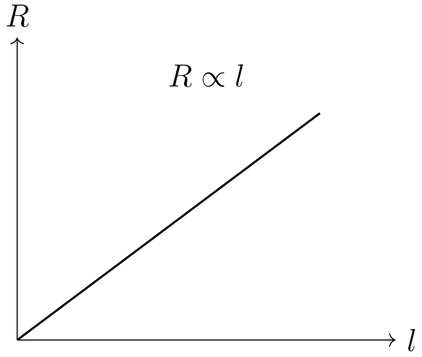
For semiconductors:

$$\alpha < 0$$

That means:

- Metals $\Rightarrow$ resistance increases with temperature.

- Semiconductors $\Rightarrow$ resistance decreases with temperature.




**Complete Concept Summary**

- Resistance opposes current.
- $R = \frac{V}{I}$
- Unit = Ohm ($\Omega$)
- $R = \rho \frac{l}{A}$
- Increases with length
- Decreases with area
- Depends on material (resistivity)
- For metals, resistance increases with temperature

# 5 Resistivity

## 5.1 Definition of Resistivity

Resistivity is a material property that indicates how strongly a material opposes the flow of electric current.

From the relation:

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

Rearranging:

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

where:

- $\rho$ = resistivity
- $R$ = resistance

- $l$ = length of conductor
- $A$ = cross-sectional area

Thus, resistivity is the resistance of a conductor of unit length and unit cross-sectional area.

## 5.2 SI Unit of Resistivity

From:

$$\rho = \frac{RA}{l}$$

Since:

$$R = \Omega, \quad A = m^2, \quad l = m$$

$$\boxed{\text{Unit of } \rho = \Omega\, m}$$

That is, Ohm meter.

## 5.3 Nature of Resistivity

**Property of Material**

Resistivity depends only on the nature of material.
For example:

- Copper $\Rightarrow$ very low resistivity
- Nichrome $\Rightarrow$ moderate resistivity
- Rubber $\Rightarrow$ very high resistivity

**Independent of Dimensions**

Resistivity does not depend on:

- Length of conductor
- Cross-sectional area

Even if length or area changes, resistivity remains constant for a given material (at constant temperature).

## 5.4 Temperature Dependence of Resistivity

Resistivity varies with temperature.
For small temperature change:

$$\boxed{\rho_T = \rho_0(1 + \alpha \Delta T)}$$

where:

- $\rho_T$ = resistivity at temperature $T$
- $\rho_0$ = resistivity at reference temperature
- $\alpha$ = temperature coefficient of resistivity
- $\Delta T$ = change in temperature

### Temperature Coefficient of Resistivity

$$\alpha = \frac{\rho_T - \rho_0}{\rho_0 \Delta T}$$

It represents the fractional change in resistivity per unit temperature change.

### For Metals

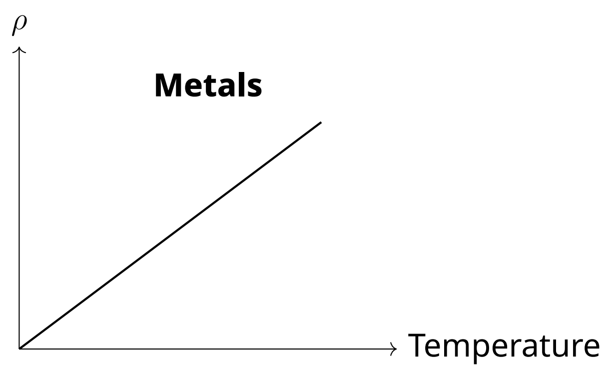
When temperature increases:

- Lattice vibrations increase.
- Electron collisions increase.
- Resistivity increases.

Thus:

$$\alpha > 0$$

Graph: Linear increase of $\rho$ with temperature.



#### For Semiconductors

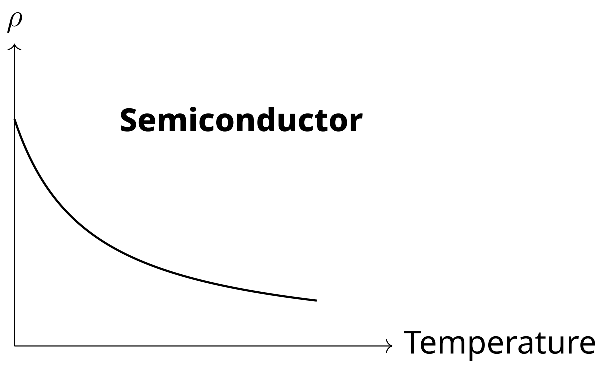
When temperature increases:

- Number of charge carriers increases.
- Resistivity decreases.

Thus:

$$\alpha < 0$$

Graph: Decreasing curve.




**Complete Summary**

- $\rho = \frac{RA}{l}$
- Unit = $\Omega m$
- Property of material
- Independent of dimensions
- $\rho_T = \rho_0(1 + \alpha \Delta T)$
- Metals $\Rightarrow$ resistivity increases with temperature
- Semiconductors $\Rightarrow$ resistivity decreases with temperature

# 6 Electrical Energy and Power

## 6.1 Electrical Energy

When electric current flows through a conductor, electrical work is done. This electrical work is converted into other forms of energy such as heat, light, or mechanical energy.

### Work Done by Electric Current

Consider a conductor connected to a battery of potential difference $V$. If current $I$ flows for time $t$, then total charge passing:

$$Q = It$$

Work done:

$$W = VQ$$

Substituting $Q = It$:

$$\boxed{W = VIt}$$

Thus, electrical energy consumed is equal to potential difference × current × time.
Unit:

$$1 \text{ Joule} = 1 \text{ Volt} \times 1 \text{ Coulomb}$$

## 6.2 Electrical Power

Electrical power is defined as the rate at which electrical work is done.

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

Using $W = VIt$:

$$\boxed{P = VI}$$

Unit of power:

$$1 \text{ Watt} = 1 \frac{\text{Joule}}{\text{second}}$$

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

## 6.3 Alternative Forms of Power

Using Ohm's Law:

$$V = IR$$

### 1. In terms of Current

Substitute $V = IR$ in $P = VI$:

$$P = I(IR)$$

$$\boxed{P = I^2 R}$$

**2. In terms of Voltage**

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

$$P = V\left(\frac{V}{R}\right)$$

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

Thus, power can be written in three forms:

$$P = VI$$

$$P = I^2R$$

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

## 6.4 Commercial Unit of Energy

Electrical energy consumed in homes is measured in kilowatt-hour (kWh).

$$1\ \text{kWh} = 1000\ \text{W} \times 3600\ \text{s}$$

$$\boxed{1\ \text{kWh} = 3.6 \times 10^6\ \text{J}}$$

1 kWh is also called one "unit" of electricity.

## 6.5 Heating Effect of Current

When current flows through a conductor, heat is produced due to resistance.

### Joule's Law of Heating

The heat produced in a conductor is:

$$\boxed{H = I^2Rt}$$

This shows:

- Heat is directly proportional to square of current.
- Directly proportional to resistance.
- Directly proportional to time.

Using $V = IR$:

$$H = VIt$$

## 6.6 Applications of Heating Effect

**1. Electric Heater**

- Uses high resistance wire (nichrome).
- Produces large heat due to $I^2R$ effect.

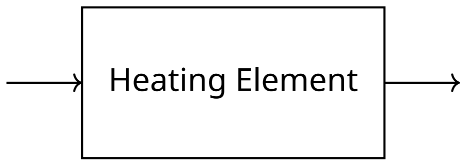
**2. Fuse**

- Made of low melting point material.
- Excess current produces large heat.
- Fuse melts and breaks circuit.

**3. Electric Iron**

- Heating element converts electrical energy into heat.
- Thermostat controls temperature.

**Heating Due to Current Flow**




**Complete Summary**

- $W = VIt$
- $P = VI$
- $P = I^2R$
- $P = \frac{V^2}{R}$
- $1$ kWh $= 3.6 \times 10^6$ J
- $H = I^2Rt$

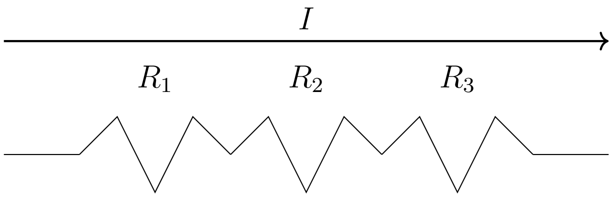
# 7 Combination of Resistors

## 7.1 Resistors in Series

When two or more resistors are connected end to end in such a way that there is only one path for current to flow, they are said to be connected in series.

In a series circuit:

- The same current flows through all resistors.
- The total voltage is divided among the resistors.




### 7.1 Same Current in Series

Since there is only one path:

$$I_1 = I_2 = I_3 = I$$

This is because:

- Charge cannot accumulate at any point.
- Whatever current enters a resistor must leave it.

Thus, current remains the same throughout the series circuit.

### 7.2 Total (Equivalent) Resistance

Let total applied voltage be $V$.
According to Ohm's Law:

$$V = IR_{eq}$$

Voltage across individual resistors:

$$V_1 = IR_1$$

$$V_2 = IR_2$$

$$V_3 = IR_3$$

Total voltage across combination:

$$V = V_1 + V_2 + V_3$$

Substituting:

$$V = IR_1 + IR_2 + IR_3$$

$$V = I(R_1 + R_2 + R_3)$$

Comparing with:

$$V = IR_{eq}$$

We get:

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

Thus, for series combination:

- Equivalent resistance is equal to sum of individual resistances.
- Equivalent resistance is always greater than any single resistor.

### Physical Interpretation

In series:

- Length of conductor effectively increases.
- More opposition to current.
- Hence resistance increases.

### 7.3 Voltage Division Rule

Since current is same in series:

$$V_1 = IR_1$$

$$V_2 = IR_2$$

$$V_3 = IR_3$$

Using:

$$I = \frac{V}{R_{eq}}$$

Substitute:

$$V_1 = \frac{V}{R_{eq}} R_1$$

$$\boxed{V_1 = V \frac{R_1}{R_1 + R_2 + R_3}}$$

Similarly:

$$V_2 = V \frac{R_2}{R_1 + R_2 + R_3}$$

$$V_3 = V \frac{R_3}{R_1 + R_2 + R_3}$$

This is called the Voltage Division Rule.
It states:

- Voltage divides in proportion to resistance.
- Larger resistance gets larger voltage drop.

**Important Observations**

- If one resistor increases, total resistance increases.
- Removing one resistor breaks the entire circuit.
- Used in voltage divider circuits.

**Complete Concept Summary**

- Same current flows in series.
- $R_{eq} = R_1 + R_2 + R_3$
- Voltage divides proportionally.
- Larger resistance $\Rightarrow$ larger voltage drop.
- Series increases total resistance.

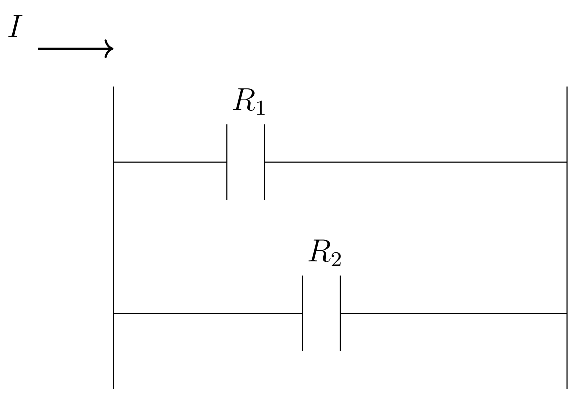
# 8 Resistors in Parallel

## 8.1 Resistors Connected in Parallel

When two or more resistors are connected between the same two points such that each resistor has its own separate path for current, they are said to be connected in parallel.

In parallel combination:

- Voltage across each resistor is same.
- Current divides among the resistors.



### 8.1 Same Voltage in Parallel

Since both ends of each resistor are connected to the same two nodes:

$$V_1 = V_2 = V$$

This means:

- Each resistor experiences the same potential difference.
- Voltage does not divide in parallel.

### 8.2 Equivalent Resistance

Let total current be $I$.
Current through each resistor:

$$I_1 = \frac{V}{R_1}$$

$$I_2 = \frac{V}{R_2}$$

Total current:

$$I = I_1 + I_2$$

$$I = \frac{V}{R_1} + \frac{V}{R_2}$$

$$I = V\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

But:

$$I = \frac{V}{R_{eq}}$$

Comparing:

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

For three resistors:

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

### Important Observation

- Equivalent resistance in parallel is always less than the smallest resistance.
- Adding more parallel branches decreases total resistance.

Physical interpretation:
In parallel, effective cross-sectional area increases, so resistance decreases.

### 8.3 Current Division Rule

In parallel, current divides inversely proportional to resistance.
For two resistors:

$$I_1 = \frac{V}{R_1}$$

$$I_2 = \frac{V}{R_2}$$

Using $I = I_1 + I_2$:

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

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

Similarly:

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

Thus:

- Smaller resistance $\Rightarrow$ larger current.
- Larger resistance $\Rightarrow$ smaller current.

**Complete Concept Summary**

- Same voltage across all resistors in parallel.
- $\frac{1}{R_{eq}} = \sum \frac{1}{R_i}$
- Equivalent resistance decreases.
- Current divides inversely to resistance.
- Smaller resistance gets larger share of current.

# 9 Cells and Circuits

## 9.1 Electric Cell

An electric cell is a device that converts chemical energy into electrical energy.
It maintains a potential difference between its terminals by using chemical reactions inside the cell.

### 9.1 Source of EMF

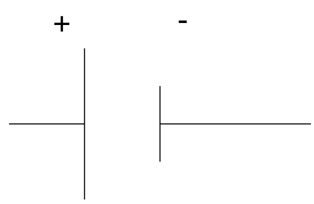
Inside an electric cell:

- Chemical reactions take place.
- These reactions push electrons from one electrode to another.
- One terminal becomes positive and the other negative.

Thus:

$$\text{Chemical Energy} \rightarrow \text{Electrical Energy}$$

The cell continuously supplies energy to move charges through the external circuit.




**Electric Cell**

## 9.2 Electromotive Force (EMF)

### Definition

Electromotive force (EMF) is defined as the work done per unit charge by the source in moving a charge once around the complete circuit.

$$\boxed{\text{EMF} = \frac{W}{Q}}$$

Unit of EMF:

$$\text{Volt}$$

Even though it is called "force", EMF is actually a potential difference.
EMF is usually denoted by:

$$\mathcal{E}$$

### Physical Meaning of EMF

- It is the maximum potential difference of the cell.
- It is measured when no current flows in the circuit.
- It represents energy supplied per unit charge.

## 9.3 Difference Between EMF and Terminal Voltage

- EMF is the total energy supplied per unit charge by the source.
- Terminal voltage is the potential difference across the terminals when current flows.

If internal resistance of cell is $r$ and current is $I$:

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

where:

- $\mathcal{E}$ = EMF
- $V$ = terminal voltage
- $Ir$ = internal voltage drop

**Key Differences**

- EMF is measured in open circuit condition.
- Terminal voltage is measured when circuit is closed.
- EMF is always greater than or equal to terminal voltage.

When no current flows:

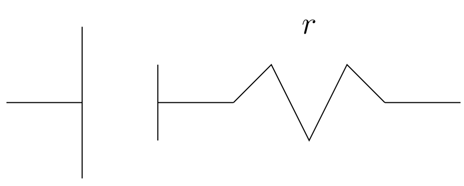
$$I = 0$$

$$V = \mathcal{E}$$

When current flows:

$$V < \mathcal{E}$$

because part of energy is lost inside the cell due to internal resistance.




**Cell with Internal Resistance**

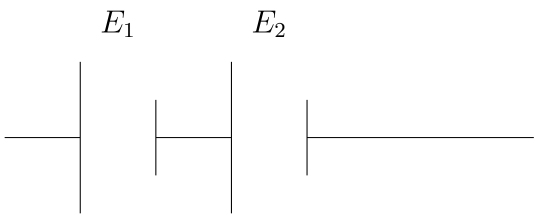
**Complete Concept Summary**

- Electric cell converts chemical energy into electrical energy.
- EMF = work done per unit charge.
- EMF is maximum potential difference.
- Terminal voltage decreases when current flows.
- $V = \mathcal{E} - Ir$

# 10 Combination of Cells

## 10.1 Cells in Series

When two or more cells are connected such that the positive terminal of one cell is connected to the negative terminal of the next, they are said to be connected in series.




**Equivalent EMF**

In series, EMFs add up:

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

For $n$ identical cells:

$$E_{eq} = nE$$

**Equivalent Internal Resistance**

Internal resistances also add:

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

For $n$ identical cells:

$$r_{eq} = nr$$

### Current in Series Combination

If external resistance is $R$:

$$I = \frac{E_{eq}}{R + r_{eq}}$$

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

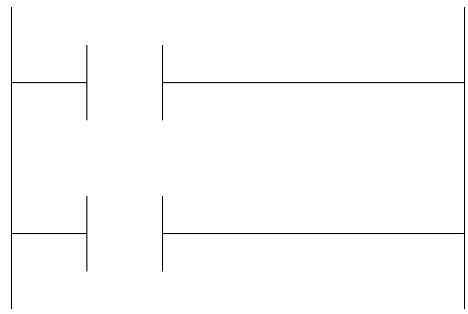
### Important Observation

Series combination is useful when:

- High voltage is required.

## 10.2 Cells in Parallel

When positive terminals of all cells are connected together and negative terminals are connected together, they are said to be connected in parallel.



### Equivalent EMF

For identical cells:

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

EMF remains same as that of one cell.

### Equivalent Internal Resistance

For $n$ identical cells:

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

Internal resistance decreases.

### Current in Parallel Combination

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

### Important Observation

Parallel combination is useful when:

- High current is required.
- External resistance is small.

## 10.3 Condition for Maximum Current

Current supplied by battery:

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

To get maximum current:

- Internal resistance should be small.

For series combination:

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

For parallel combination:

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

### Selection Rule

- If $R \gg r \Rightarrow$ Use cells in series.
- If $R \ll r \Rightarrow$ Use cells in parallel.

### Reason

- When external resistance is large, increasing EMF increases current.
- When external resistance is small, reducing internal resistance increases current.

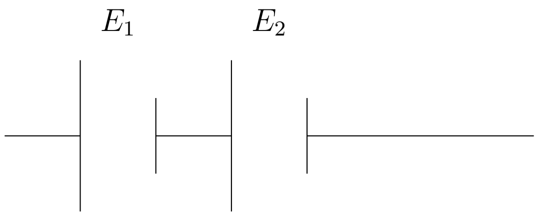
**Complete Summary**

- Series: $E_{eq} = nE$, $r_{eq} = nr$
- Parallel: $E_{eq} = E$, $r_{eq} = \frac{r}{n}$
- For large $R \Rightarrow$ series
- For small $R \Rightarrow$ parallel

# 11 Combination of Cells

## 11.1 Cells in Series

When two or more cells are connected such that the positive terminal of one cell is connected to the negative terminal of the next, they are said to be connected in series.




### Equivalent EMF

In series, EMFs add up:

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

For $n$ identical cells:

$$E_{eq} = nE$$

### Equivalent Internal Resistance

Internal resistances also add:

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

For $n$ identical cells:

$$r_{eq} = nr$$

### Current in Series Combination

If external resistance is $R$:

$$I = \frac{E_{eq}}{R + r_{eq}}$$

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

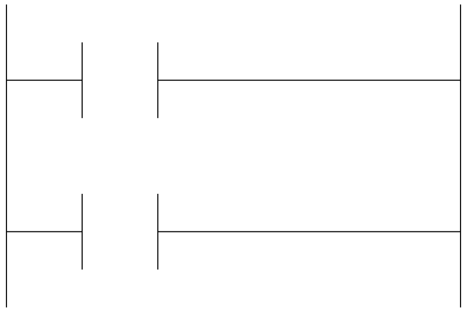
### Important Observation

Series combination is useful when:

- High voltage is required.

## 11.2 Cells in Parallel

When positive terminals of all cells are connected together and negative terminals are connected together, they are said to be connected in parallel.



**Equivalent EMF**

For identical cells:

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

EMF remains same as that of one cell.

**Equivalent Internal Resistance**

For $n$ identical cells:

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

Internal resistance decreases.

**Current in Parallel Combination**

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

**Important Observation**

Parallel combination is useful when:

- High current is required.
- External resistance is small.

### 11.3 Condition for Maximum Current

Current supplied by battery:

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

To get maximum current:

- Internal resistance should be small.

For series combination:

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

For parallel combination:

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

#### Selection Rule

- If $R \gg r \Rightarrow$ Use cells in series.
- If $R \ll r \Rightarrow$ Use cells in parallel.

#### Reason

- When external resistance is large, increasing EMF increases current.
- When external resistance is small, reducing internal resistance increases current.

**Complete Summary**

- Series: $E_{eq} = nE$, $r_{eq} = nr$
- Parallel: $E_{eq} = E$, $r_{eq} = \frac{r}{n}$
- For large $R \Rightarrow$ series
- For small $R \Rightarrow$ parallel

## 12 Kirchhoff's Laws

### 12.1 Kirchhoff's Rules

Kirchhoff's laws are used to analyze complex electrical circuits involving multiple loops and junctions.

They are based on two fundamental conservation principles:

- Conservation of charge
- Conservation of energy

## 12.2 12.1 Junction Rule (Kirchhoff's Current Law – KCL)

### Statement

At any junction (node) in an electrical circuit, the algebraic sum of currents is zero.

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

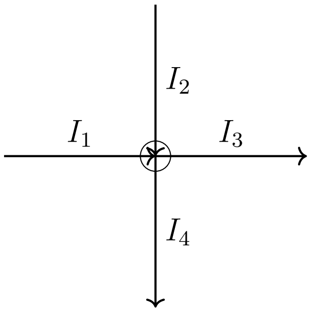
This means:

$$\text{Total current entering} = \text{Total current leaving}$$

### Physical Basis

KCL is based on conservation of charge.

- Charge cannot accumulate at a junction.
- Whatever charge enters must leave.




Example:

$$I_1 + I_2 = I_3 + I_4$$

## 12.3 12.2 Loop Rule (Kirchhoff's Voltage Law – KVL)

### Statement

In any closed loop of a circuit, the algebraic sum of potential differences is zero.

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

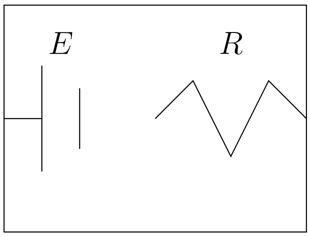
This means:

$$\text{Total EMF} = \text{Total voltage drops}$$

#### Physical Basis

KVL is based on conservation of energy.

- Energy supplied by source equals energy lost in resistors.
- No energy is lost in ideal wires.




For single loop:

$$E - IR = 0$$

$$E = IR$$

## 12.4 12.3 Sign Conventions

Proper sign convention is essential while applying Kirchhoff's laws.

#### For KCL

- Current entering junction $\Rightarrow$ positive
- Current leaving junction $\Rightarrow$ negative

(Or vice versa, but must remain consistent.)

#### For KVL

While traversing a loop:

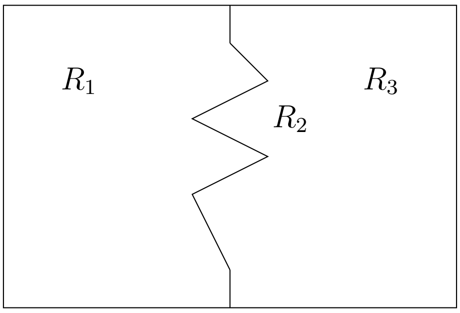
- Going from negative to positive terminal of battery $\Rightarrow$ +E
- Going from positive to negative $\Rightarrow$ -E
- Across resistor in direction of current $\Rightarrow$ -IR (voltage drop)
- Across resistor opposite to current $\Rightarrow$ +IR

Consistency is most important.

## 12.5 12.4 Solving Multi-Loop Circuits

Steps to solve multi-loop circuits:

1. Assign current directions arbitrarily in each branch.
2. Apply KCL at junctions.
3. Apply KVL to independent loops.
4. Write equations using sign conventions.
5. Solve simultaneous equations.




Example equations:

$$\text{Loop 1: } E_1 - I_1R_1 - (I_1 - I_2)R_2 = 0$$

$$\text{Loop 2: } E_2 - I_2R_3 - (I_2 - I_1)R_2 = 0$$

Solve these equations simultaneously to find currents.

**Complete Concept Summary**

- KCL $\Rightarrow$ Based on conservation of charge.
- $\sum I = 0$
- KVL $\Rightarrow$ Based on conservation of energy.
- $\sum V = 0$
- Follow correct sign conventions.
- Use simultaneous equations for multi-loop circuits.

# 13 Wheatstone Bridge and Meters

## 13.1 Wheatstone Bridge

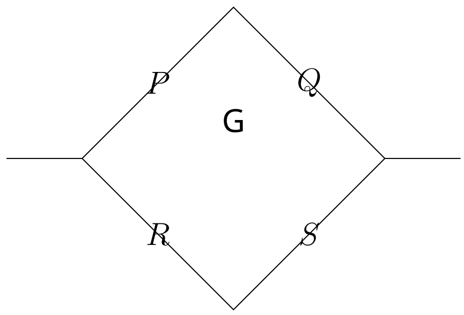
Wheatstone Bridge is an electrical circuit used to measure an unknown resistance accurately by comparison method.

## 13.2 13.1 Principle of Wheatstone Bridge

The Wheatstone bridge works on the principle of null deflection.
It is based on the fact that:

- When no current flows through the galvanometer,
- The potential at both junctions connected to the galvanometer is equal.

At this condition, the bridge is said to be balanced.




## 13.3 13.2 Balanced Condition

Let the four arms of bridge be $P$, $Q$, $R$, and $S$.
When the galvanometer shows zero deflection:

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

This is the balanced condition of Wheatstone bridge.
Derivation concept:
If no current flows through galvanometer:

- Potential at both junction points is equal.
- Ratio of resistances in one branch equals ratio in other branch.

Thus, unknown resistance can be calculated:

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

## 13.4 13.3 Null Deflection Method

In this method:

- Adjust one known resistance.
- Observe galvanometer.
- When galvanometer shows zero deflection, bridge is balanced.

Advantages:

- No current flows through galvanometer at balance.
- Very accurate measurement.
- Independent of galvanometer resistance.

Because measurement is taken at null condition, it reduces errors.

### 13.5 13.4 Applications of Wheatstone Bridge

- Measurement of unknown resistance.
- Used in meter bridge.
- Used in strain gauge measurements.
- Used in temperature sensing circuits.

**Complete Concept Summary**

- Works on null deflection principle.
- Balanced condition: $\frac{P}{Q} = \frac{R}{S}$
- Used to measure unknown resistance accurately.
- High precision because current through galvanometer is zero at balance.

## 14 Meter Bridge

### 14.1 14.1 Construction

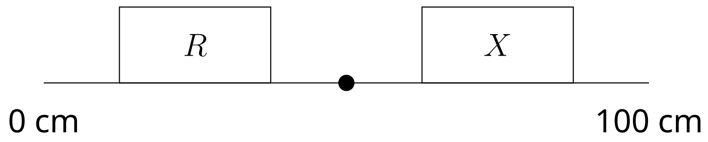
A meter bridge is a practical application of Wheatstone bridge used to measure unknown resistance.

Main parts:

- A uniform resistance wire of length 1 meter (usually manganin wire).
- Two known gaps to place resistances.
- A galvanometer.
- A jockey (sliding contact).
- A cell and key.

The 1-meter wire is stretched on a wooden board and divided into 100 cm.

**Meter Bridge**




## 14.2 14.2 Working Principle

Meter bridge works on the principle of Wheatstone bridge.
When the bridge is balanced:

- No current flows through the galvanometer.
- Potential at the two points connected to galvanometer is equal.

Since the wire is uniform:

$$\text{Resistance} \propto \text{Length}$$

Thus, ratio of resistances equals ratio of lengths.

## 14.3 14.3 Balanced Condition

Let:

- $R$ = known resistance
- $X$ = unknown resistance
- $l$ = balancing length from one end

Remaining length:

$$100 - l$$

Using Wheatstone bridge principle:

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

Thus:

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

This is the balanced condition formula for meter bridge.

### 14.4 14.4 End Correction

In practical situations:

- Ends of wire may not be perfectly uniform.
- Contact resistance at joints may exist.

This causes small error in measurement.
To reduce error:

- Interchange positions of $R$ and $X$.
- Take mean of two calculated values.

This process is called end correction.
It improves accuracy of measurement.

**Complete Concept Summary**

- Meter bridge is practical form of Wheatstone bridge.
- Based on null deflection method.
- Balanced condition: $\frac{R}{X} = \frac{l}{100-l}$
- $X = R\frac{100-l}{l}$
- End correction reduces experimental error.

## 15 Potentiometer

### 15.1 15.1 Principle of Potentiometer

A potentiometer works on the principle that the potential drop along a uniform wire carrying steady current is directly proportional to its length.
If a uniform wire of length $L$ carries a constant current, then:

$$V \propto l$$

or

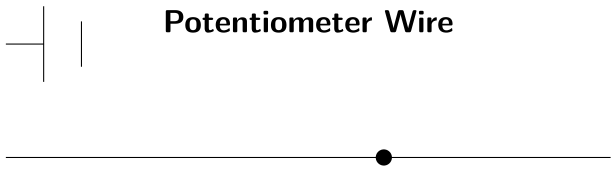
$$\boxed{V = kl}$$

where:

- $V$ = potential difference
- $l$ = balancing length
- $k$ = potential gradient (potential per unit length)

$$k = \frac{V}{L}$$

Thus, potential drop is proportional to length of wire.




## 15.2 15.2 Comparison of EMF

Let two cells have EMFs $E_1$ and $E_2$.

Let balancing lengths be:

$$l_1 \text{ for } E_1$$

$$l_2 \text{ for } E_2$$

Since:

$$E = kl$$

Then:

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

Thus, EMFs can be compared without drawing current from cells.

This is called null method because galvanometer shows zero deflection at balance point.

## 15.3 15.3 Measurement of Internal Resistance

Let:

- $E$ = EMF of cell
- $V$ = terminal voltage when external resistance is connected

Let balancing lengths be:

$$l_1 \text{ for EMF}$$

$$l_2 \text{ for terminal voltage}$$

Since $E = kl_1$ and $V = kl_2$:

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

But:

$$V = E - Ir$$

From circuit:

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

Internal resistance:

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

Thus, internal resistance can be determined accurately.

## 15.4 15.4 Advantages Over Voltmeter

- Works on null deflection method.
- No current drawn from test cell at balance.
- More accurate than voltmeter.
- Measures true EMF.

In contrast:

- Voltmeter draws small current.
- Measured voltage is slightly less than EMF.

## 15.5 15.5 Sensitivity of Potentiometer

Sensitivity refers to the ability to detect small potential differences.
Sensitivity increases when:

- Length of potentiometer wire increases.
- Potential gradient $k$ decreases.

Since:

$$k = \frac{V}{L}$$

If $L$ increases:

$$k \text{ decreases}$$

Thus, small potential differences correspond to larger balancing lengths.
Hence:

- Longer wire $\Rightarrow$ greater sensitivity.

**Complete Concept Summary**

- $V = kl$
- $\frac{E_1}{E_2} = \frac{l_1}{l_2}$
- Measures EMF accurately using null method.
- Internal resistance: $r = R\left(\frac{l_1 - l_2}{l_2}\right)$
- More sensitive and accurate than voltmeter.

# 16 Important Graphs for Current Electricity

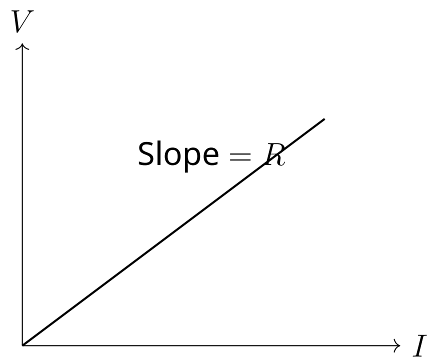
## 16.1 V–I Graph (Ohmic Conductor)

For an Ohmic conductor:

$$V = IR$$

This represents a straight-line relationship between $V$ and $I$.

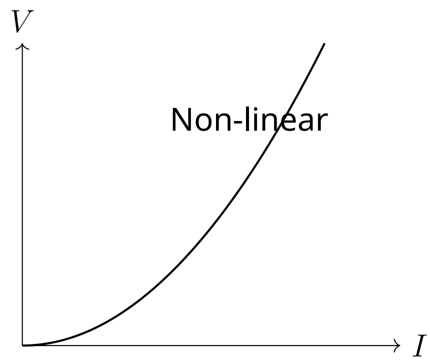
- Straight line passing through origin.
- Slope = Resistance ($R$).




## 16.2 Non-Ohmic Conductor Graph

For non-ohmic conductors (diode, filament bulb):

- Graph is non-linear.
- Resistance changes with voltage.



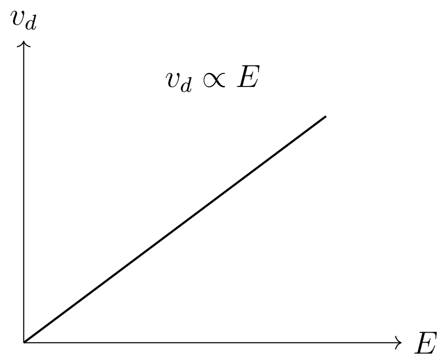

## 16.3 Drift Velocity vs Electric Field

From microscopic theory:

$$v_d = \frac{e\tau}{m}E$$

Thus:

- Drift velocity is directly proportional to electric field.
- Straight-line graph passing through origin.



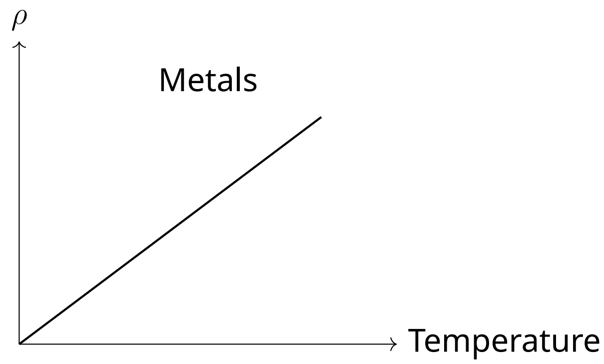

## 16.4 Resistivity vs Temperature

### (a) Metals

For metals:

$$\rho_T = \rho_0(1 + \alpha\Delta T)$$

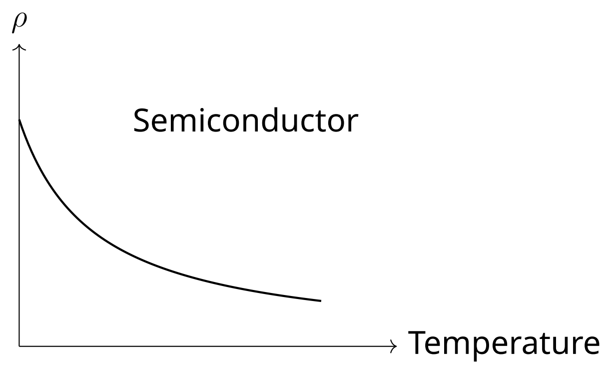
- Linear increase with temperature.




### (b) Semiconductors

For semiconductors:

- Resistivity decreases with temperature.



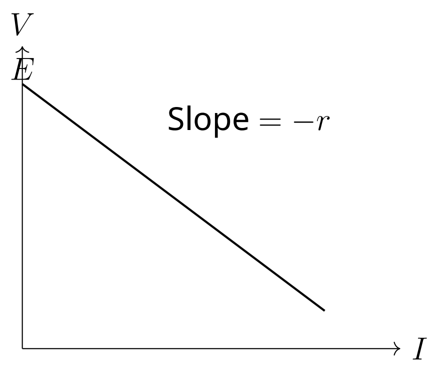

## 16.5 Terminal Voltage vs Current

From:

$$V = E - Ir$$

This is a straight line with:

- Y-intercept = $E$
- Slope = $-r$



**Graph Summary**

- Ohmic conductor $\Rightarrow$ Straight line $V$–$I$ graph.
- Non-ohmic $\Rightarrow$ Curved graph.
- $v_d$ vs $E \Rightarrow$ Linear.
- $\rho$ vs $T \Rightarrow$ Linear (metals), decreasing curve (semiconductors).
- $V$ vs $I$ (cell) $\Rightarrow$ Straight line with negative slope.

# 17 Very Important Conceptual Micro-Topics

## 17.1 Why Current Flows Instantly Though Drift Velocity is Small

Drift velocity of electrons is very small (of the order of $10^{-4}\ m/s$).
Yet, when a switch is turned on, the bulb glows almost instantly.
Reason:

- The electric field is established throughout the conductor almost at the speed of light.
- Electrons are already present everywhere inside the conductor.
- When electric field is applied, all electrons start drifting simultaneously.

Analogy:
Water in a pipe. When you push water at one end, water comes out from the other end immediately because water is already present throughout the pipe.
Thus:

- Signal travels fast (near speed of light).
- Individual electrons move slowly.

## 17.2 Difference Between EMF and Potential Difference

**EMF ($\mathcal{E}$):**

- Work done per unit charge by the source.
- Measured in open circuit.
- Maximum voltage of the cell.

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

**Potential Difference ($V$):**

- Energy used per unit charge between two points.
- Measured in closed circuit.

Relation:

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

Key Difference:

- EMF is total energy supplied.
- Potential difference is usable energy.

## 17.3 Why Fuse Wire Has Low Melting Point

Fuse protects circuit from excessive current.
From Joule's law:

$$H = I^2Rt$$

If current increases:

- Heat produced increases rapidly.

Fuse wire is made of:

- Material with low melting point.
- Relatively high resistivity.

Thus:

- Excess current produces large heat.
- Fuse melts quickly.
- Circuit breaks and appliances are protected.

## 17.4 Why Resistivity Depends on Temperature

For metals:

- Increasing temperature increases lattice vibrations.
- More collisions occur between electrons and ions.
- Resistivity increases.

$$\rho_T = \rho_0(1 + \alpha\Delta T)$$

For semiconductors:

- Increasing temperature increases charge carriers.
- Resistivity decreases.

Thus:

- Metals $\Rightarrow$ resistivity increases with temperature.
- Semiconductors $\Rightarrow$ resistivity decreases with temperature.

## 17.5 Why Cells in Parallel Reduce Internal Resistance

For $n$ identical cells in parallel:

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

Reason:

- Parallel connection increases effective cross-sectional area.
- Opposition to current inside battery decreases.
- More paths for current flow.

Hence:

- Internal resistance decreases.
- Larger current can be supplied.

## 17.6 Why Potentiometer is More Accurate Than Voltmeter

Potentiometer works on null deflection method.

- At balance point, no current is drawn from test cell.
- Hence, no internal voltage drop.

Voltmeter:

- Draws small current.
- Measured voltage slightly less than EMF.

Therefore:

- Potentiometer measures true EMF.
- It is more sensitive and accurate.

**Quick Concept Summary**

- Current flows instantly due to fast electric field propagation.
- EMF is total energy supplied; potential difference is usable energy.
- Fuse has low melting point for protection.
- Resistivity changes due to collisions and carrier concentration.
- Parallel cells reduce internal resistance.
- Potentiometer is more accurate due to null method.

# 18 Important Derivations – Current Electricity

## 18.1 Drift Velocity Derivation

When an electric field $E$ is applied to a conductor:
Force on an electron:

$$F = -eE$$

Acceleration:

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

If $\tau$ is relaxation time (average time between collisions),
Drift velocity:

$$v_d = a\tau$$

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

Thus, drift velocity is directly proportional to electric field.

## 18.2 Current in Terms of Drift Velocity

Let:

- $n$ = number density of electrons
- $A$ = cross-sectional area
- $v_d$ = drift velocity

In time $dt$, electrons move distance:

$$dx = v_d dt$$

Volume crossed:

$$Adx = Av_d dt$$

Number of electrons:

$$nAv_d dt$$

Charge:

$$dQ = neAv_d dt$$

Current:

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

$$\boxed{I = neAv_d}$$

## 18.3 Relation Between Current Density and Electric Field

Current density:

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

Using $I = neAv_d$:

$$J = nev_d$$

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

$$J = ne\left(\frac{eE\tau}{m}\right)$$

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

Since conductivity:

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

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

## 18.4 Resistance Formula

Experimentally:

$$R \propto l$$

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

Combining:

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

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

where $\rho$ is resistivity.

## 18.5 Temperature Dependence of Resistance

Resistance increases linearly with temperature (for metals):

$$R_T = R_0(1 + \alpha\Delta T)$$

Similarly for resistivity:

$$\boxed{\rho_T = \rho_0(1 + \alpha\Delta T)}$$

where $\alpha$ = temperature coefficient.

## 18.6 Series and Parallel Resistors

**Series Combination**

Same current flows:

$$V = V_1 + V_2$$

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

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

**Parallel Combination**

Same voltage across resistors:

$$I = I_1 + I_2$$

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

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

## 18.7 Internal Resistance Formula

From circuit:

$$E = V + Ir$$

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

Also:

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

## 18.8 Wheatstone Bridge Condition

For balanced bridge:

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

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

Unknown resistance:

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

## 18.9 Potentiometer Formula

From principle:

$$V = kl$$

For two EMFs:

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

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

For internal resistance:

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

**Complete Derivation Summary**

- $v_d = \frac{eE\tau}{m}$
- $I = neAv_d$
- $J = \sigma E$
- $R = \rho\frac{l}{A}$
- $\rho_T = \rho_0(1 + \alpha\Delta T)$
- Series: $R_{eq} = R_1 + R_2$
- Parallel: $\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2}$
- $V = E - Ir$
- $\frac{P}{Q} = \frac{R}{S}$
- $\frac{E_1}{E_2} = \frac{l_1}{l_2}$