

Grade 11 physics Unit 6
Electrostatics & Electric
circuit
Competency Based Short Note

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Grade 11 Physics Unit 6

Electrostatics & Electric circuit



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Natural Science
[UEE 2008-2017]

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6. Introduction

- Differentiate between electrostatics and electricity
- Define charge and its type
- List some properties of electric charge

6.1 Coulomb's Law

- State coulomb's law
- Calculate the magnitude and direction of electric force between any two charges.
- Solve problems involving coulomb's law
- Explain coulomb's law using the idea of vectors
- Explain the meaning of a coulomb.

6.2 Electric Fields

- Define the terms, electric field, and electric flux.
- Sketch electric field lines.
- Solve problems involving electric field.
- Calculate the magnitude and direction of electric field due to a point charge and two point charges.

6.3 Electric Potential

- Define the terms electric potential, equipotential surface.
- Solve problems involving electric potential.
- Explain the meaning of a volt, potential difference

6.4 Electric Current, Resistance and ohm's law

- define the terms electric current, current density, resistance, conductivity, resistivity and drift velocity.
- explain the effect on the current (brightness) and potential difference of connecting light bulbs in series.
- explain the effect on the current (brightness) and potential difference of connecting light bulbs in parallel.
- draw electric circuits consisting of three resistors connected in series and parallel.
- determine equivalent resistance of resistors connected in series and parallel. describe the principles of potentiometer and wheatstone bridge.
- describe how to convert galvanometer to a voltmeter and ammeter. explain the meaning of an ohm, resistance.

- explain the SI units of electric current, current density, resistance, resistivity, conductivity.
- state and apply Kirchhoff's laws.
- solve problems involving network of resistors.

6.5 Capacitors and Capacitance

- *Define the terms capacitors, capacitances, dielectric.*
- *Explain the effect of inserting dielectric in the gap between the plates of a capacitor.*
- *Solve problems related to capacitance of parallel plate capacitor.*
- *Calculate the equivalent capacitance of capacitors connected in series and parallel.*

6.6 Electric Circuit in our surrounding

- apply the knowledge about electric circuits to explain household electric installation.

Introduction:

- **Differentiate between electrostatics and electricity**

Electrostatics (static electricity)

- Studies the properties of electric charges at rest.
- With static electricity, the charges are stationary and build on the surface of an insulator

Current (dynamic) electricity

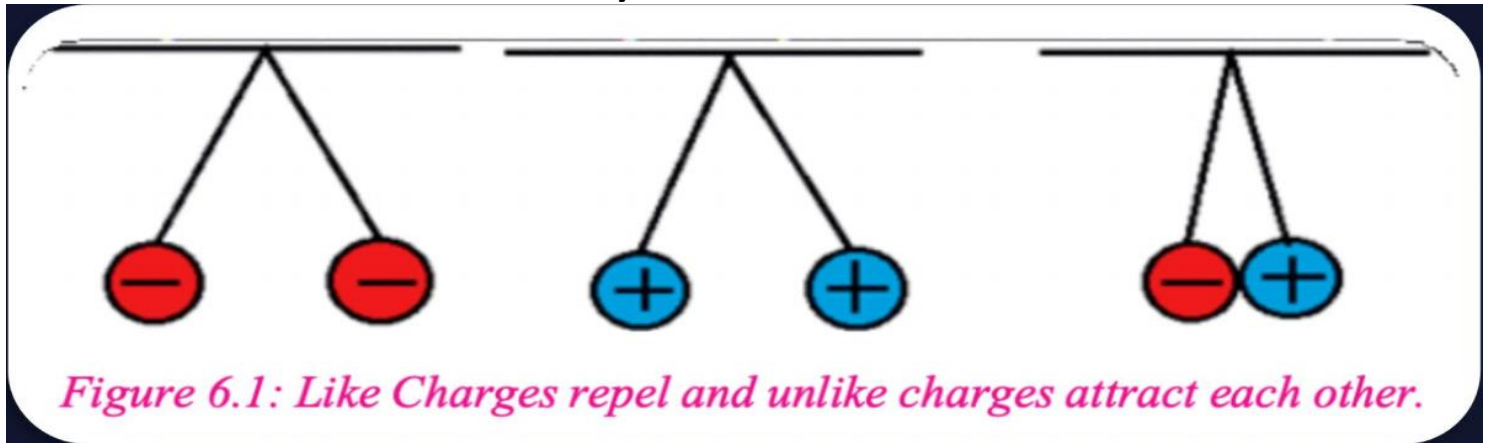
- Studies the Properties of charges in motion.
- in current electricity electron flowing through a conductor form what we call an electric current.

- **Define charge and its type**

- Charge is the fundamental property of matter associated with electrons and protons which are found in any atom.
- There are only two types of charges: negative and positive charges.
- By convention, negative charges are carried by electrons and positive charges are carried by protons.
- **Positively and negatively charged body:**
 - ✓ When the number of electrons and protons in an object are equal that object is said to be electrically neutral.
 - ✓ However, if this electrical balance is disturbed, then the object is said to be electrically charged.
 - ✓ A negatively charged object contains more electrons than protons and positively charged body contains more proton.

➤ List some properties of electric charge

- There are two kinds of electric charges: Positive and Negative.
- Two similarly charged bodies repel each other and two oppositely charged bodies attract each other.
- Electric charge is always conserved, i.e., it cannot be created or destroyed. In any charging process, the number of electrons gained by one object is equal to the number of electrons lost by the other.



- Electric charge is quantized. Charge comes in discrete packets, it means that charge (q) always occurs as some integral multiple of the elementary charge, It can be written as: $q = \pm ne$ (where $n = 1, 2, 3, \dots$)
- The smallest unit of charge that is carried by one electron or proton is called the elementary charge, e . The magnitude of the charge of an electron is:

$$1e = -1.6 \times 10^{-19} \text{ C}$$

$$1p = +1.6 \times 10^{-19} \text{ C}$$

Exercise:

- (a) What number of protons needed to make a charge of $+1.0 \text{ C}$?
- (b) How many electrons are needed to form a charge of -2.0 nC ?
- (c) How many electrons must be removed from a neutral object to leave a net charge of $+0.50 \mu\text{C}$?
- (d) Is there a force of attraction or repulsion between a charged and a neutral body?

Answers:

- a. Number of protons required(n) = 6.25×10^{18} protons
- b. Number of electrons required(n): 1.25×10^{10} electrons
- c. Number of electrons removed: 3.125×10^{12} electrons
- d. Yes, there is a force of attraction between a charged body and a neutral body.

6.1 Coulomb's Law

➤ State coulomb's law

Coulomb's law states that:

"The electrostatic force of attraction or repulsion between two point charges is directly proportional to the product of the magnitudes of the charges and inversely proportional to the square of the distance between them."

Formula:

$$F = k \frac{|q_1 * q_2|}{r^2}$$

Where:

F = electrostatic force

q1 = first charge

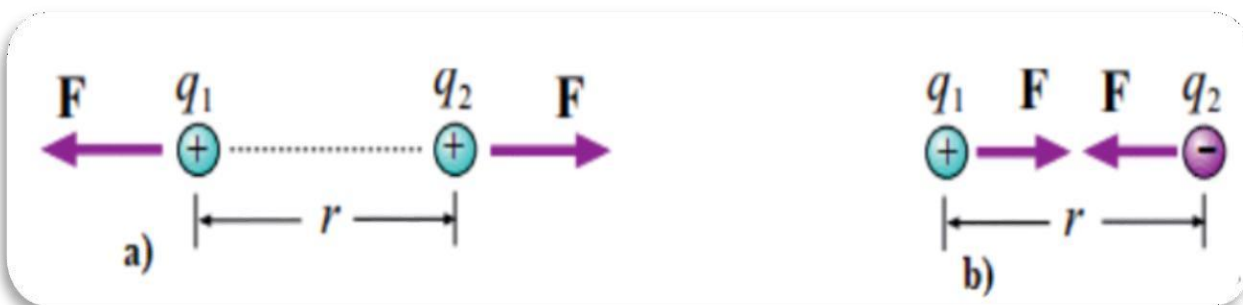
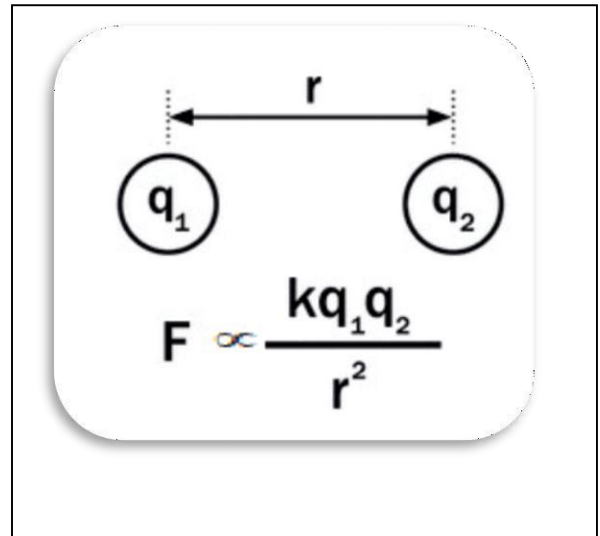
q2 = second charge

r = distance between the charges

k = proportionality constant = $k = 9 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2$

Notes:

- Like charges repel each other.
- Unlike charges attract each other.



➤ Calculate the magnitude and direction of electric force between any two charges.

- To calculate the magnitude of electric force between two charges, use Coulomb's Law.

$$F = k \frac{|q_1 * q_2|}{r^2}$$

- Direction of the Force:
 - Like charges (+,+ or -,-) → Repulsion
 - Unlike charges (+,-) → Attraction
- Steps:
 1. Identify q_1 , q_2 , and r
 2. Substitute into Coulomb's formula
 3. Calculate the magnitude of force
 4. Determine the direction:
 - ✓ Same sign → repel
 - ✓ Opposite sign → attract

➤ **Explain coulomb's law using the idea of vectors**

- Coulomb's law is a vector law because electric force has both magnitude and direction.
- If there are more than one electric forces acting on a charge particle, then the resultant force acting on the particle will be the vector sum of all these forces. This is known as the superposition principle.
- "Consider a system of stationary charges q_1 , q_2 , q_3 ... q_n in vacuum. The force on q_1 due to q_2 , q_3 ... q_n is obtained by taking the vector sum of the individual forces."

$$F_{\text{net}} = F_{12} + F_{13} + F_{14} + \dots + F_{1n}$$

Where:

F_{12} is the force that charge q_2 exerts on q_1

F_{13} is the force that q_3 exerts on q_1

...

F_{1n} is the force that q_n exerts on q_1

➤ **Explain the meaning of a coulomb.**

- A coulomb is the amount of charge transferred by a current of one ampere in one second.

$$1 \text{ C} = 1 \text{ A} \times 1 \text{ s}$$

Where:

C = coulomb,

A = ampere,

s = second

➤ Solve problems involving coulomb's law

Example 1: Two tiny spherical water drops with identical charges of $-1.0 \times 10^{-10} \text{ C}$, have a center-to-center separation of 10 cm. a) What is the electrostatic force acting between them? b) How many excess electrons are on each drop giving it its charge imbalance?

Answer:

- To solve this problem, we apply Coulomb's Law for the force and the quantization of charge to find the number of electrons.

- Given:

$$q_1 = q_2 = -1.0 \times 10^{-10} \text{ C}$$

$$r = 10 \text{ cm} = 0.10 \text{ m}$$

$$k = 9.0 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2$$

- a) Electrostatic Force Between the Drops

$$F = k|q_1q_2| / r^2 = 9.0 \times 10^{-9} \text{ N}$$

- ✓ Since both charges are negative, the force is REPULSIVE.

- b) Number of Excess Electrons on Each Drop

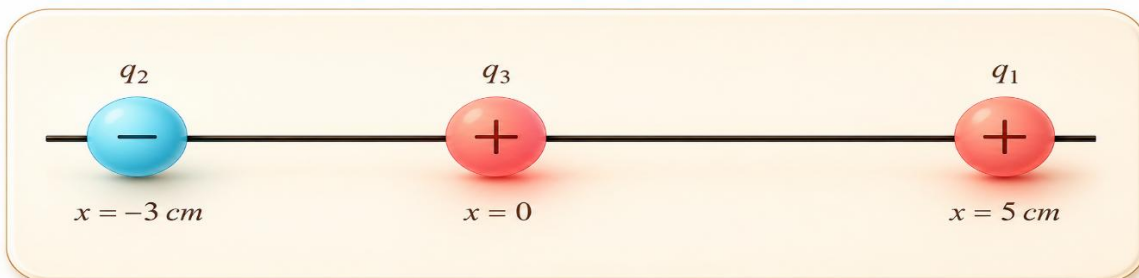
- ✓ Charge of one electron: $e = 1.6 \times 10^{-19} \text{ C}$

- ✓ Formula: $n = q / e$

$$n = (1.0 \times 10^{-10}) / (1.6 \times 10^{-19}) = 6.25 \times 10^8 \text{ electrons}$$

- ✓ Each drop has about 625 million excess electrons.

Example 2: Three point charges are placed on the x-axis: $q_1 = +6\mu\text{C}$ at $x_1 = 5.0\text{cm}$, $q_2 = -5\mu\text{C}$ at $x_2 = -3.0\text{cm}$, and $q_3 = +2\mu\text{C}$ at the origin ($x=0$). What is the magnitude and direction of the total electrostatic force acting on q_3 ?



Given:

$$q_1 = +6 \mu\text{C} = +6 \times 10^{-6} \text{ C}$$

$$q_2 = -5 \mu\text{C} = -5 \times 10^{-6} \text{ C}$$

$$q_3 = +2 \mu\text{C} = +2 \times 10^{-6} \text{ C}$$

$$x_1 = +5.0 \text{ cm} = +0.05 \text{ m}$$

$$x_2 = -3.0 \text{ cm} = -0.03 \text{ m}$$

$$x_3 = 0$$

Find: Total electrostatic force acting on q_3

Step 1: Force on q_3 due to q_1 , [$r_{13} = 0.05 \text{ m}$]

$$F_{13} = k|q_1 q_3| / r^2 = 43.2 \text{ N}$$

Direction:

- ✓ q_1 and q_3 are both positive, so the force is REPULSIVE.
- ✓ See the effect of q_1 , which pushes charge q_3 to the left
- ✓ Therefore, force on q_3 due to q_1 is toward the LEFT.

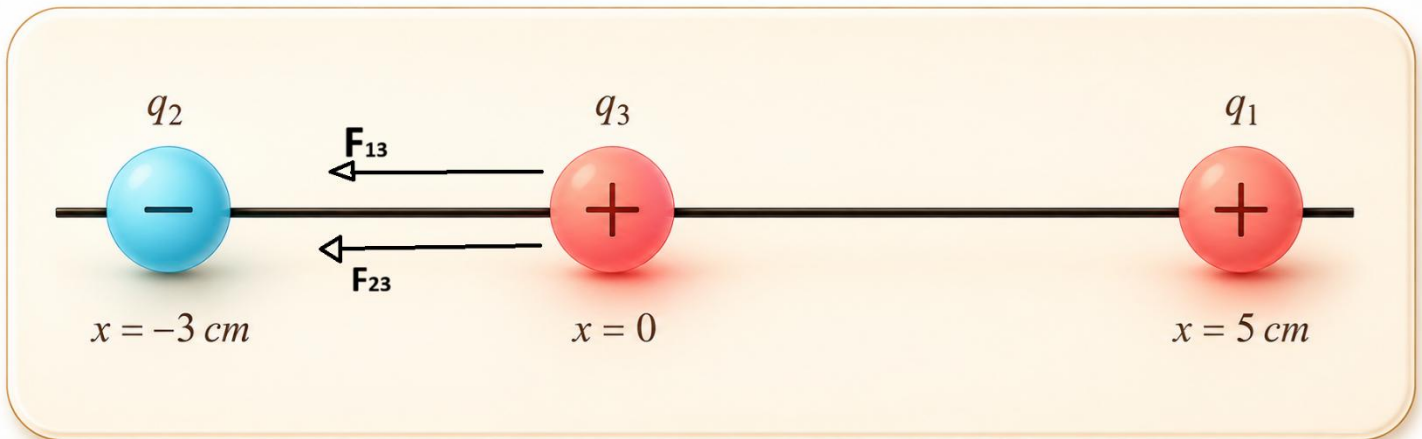
Step 2: Force on q_3 due to q_2 , [$r_{23} = 0.03 \text{ m}$]

$$F_{23} = k|q_2 q_3| / r^2 = 100 \text{ N}$$

Direction:

- ✓ q_2 is negative and q_3 is positive, so the force is ATTRACTIVE.
- ✓ See the effect of q_2 , which attracts charge q_3 to the left
- ✓ Therefore, force on q_3 due to q_2 is toward the LEFT.

Step 3: Total Force on q_3



$$F_{\text{net}} = -F_{13} + (-F_{23})$$

$$F_{\text{net}} = -43.2 - 100$$

$$F_{\text{net}} = -143.2 \text{ N, the negative sign shows direction}$$

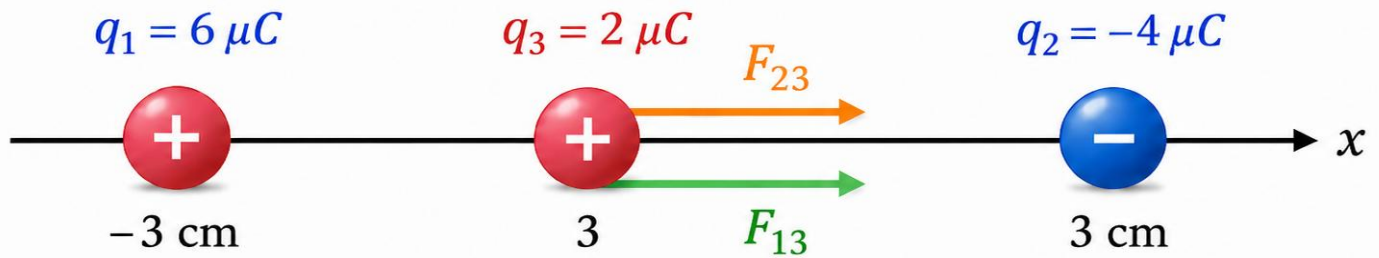
$$F_{\text{net}} = 143.2 \text{ N toward the LEFT or toward the west}$$

Sample UEE Questions:

1. A positive point charge of $2\mu\text{C}$ is placed on the x-axis at the origin and a positive charge of $6\mu\text{C}$ and a negative point charge of $-4\mu\text{C}$ are placed, respectively at $x = -3\text{cm}$ and $x = +3\text{cm}$ on the x-axis. What is the net electric force on the $2\mu\text{C}$ charge?
 - A. 40 N toward the negative x-axis
 - B. 40 N toward the positive x-axis
 - C. 200 N toward the positive x-axis
 - D. 200 N toward the negative x-axis

Hint:

- let the charge at the origin q_3 , q_2 be at $x = +3$ cm and q_1 be at $x = -3$ cm



$$F_{net} = F_{13} + F_{23}$$

F_{13} F_{13} = force of charge 1 on charge 3

F_{23} F_{23} = force of charge 2 on charge 3

2. Suppose that three point charges are placed along a straight line and the electrostatic force exerted on the middle charge is zero. What can we conclude about the charges?
- A. The signs of the three charges should be the same
 - B. The charges at the ends must have the same sign
 - C. The middle charge should be placed at the center between the two charges
 - D. The charge at the middle and at the left end should have the same sign

Hint:

- For the electrostatic force on the middle charge to be ZERO:
 - ✓ The force from the left charge and the force from the right charge must act in opposite directions.
 - ✓ This happens only when the two end charges have the SAME sign.

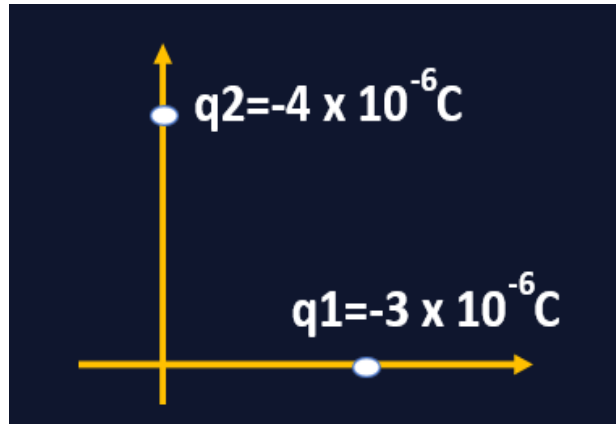
Case 1: If both end charges are positive, the middle charge is repelled by both charges in opposite directions.

Case 2: If both end charges are negative, the middle charge is attracted toward both charges in opposite directions.

Thus, the forces can cancel each other.

Answer: B

3. Charges q_1 and q_2 are located at positions $(3\text{m}, 0)$ on the x axis and $(0, 3\text{m})$ on the y axis respectively as shown in the following figure.



What should be the x and y components of the net electric force on a $1\mu\text{C}$ charge placed at the origin? ($k = 9 \times 10^9 \text{Nm}^2\text{C}^{-2}$)

- A. $F_x = 4 \times 10^{-3} \text{ N}$ and $F_y = 3 \times 10^{-3} \text{ N}$ **B. $F_x = 3 \times 10^{-3} \text{ N}$ and $F_y = 4 \times 10^{-3} \text{ N}$**
 C. $F_x = -4 \times 10^{-3} \text{ N}$ and $F_y = -3 \times 10^{-3} \text{ N}$ D. $F_x = -3 \times 10^{-3} \text{ N}$ and $F_y = -4 \times 10^{-3} \text{ N}$

Hint:

Let say the charge at origin is q_3 , r_1 (along x-axis) = 3m , r_2 (along y axis) = 3m

Step 1: Force due to q_1 ($-3 \times 10^{-6} \text{ C}$) at $(3, 0)$ on $q_3 = 1 \mu\text{C}$

$$F_{13} = k \cdot |q_1 \cdot q_3| / r_1^2$$

$$F_x = F_{13}$$

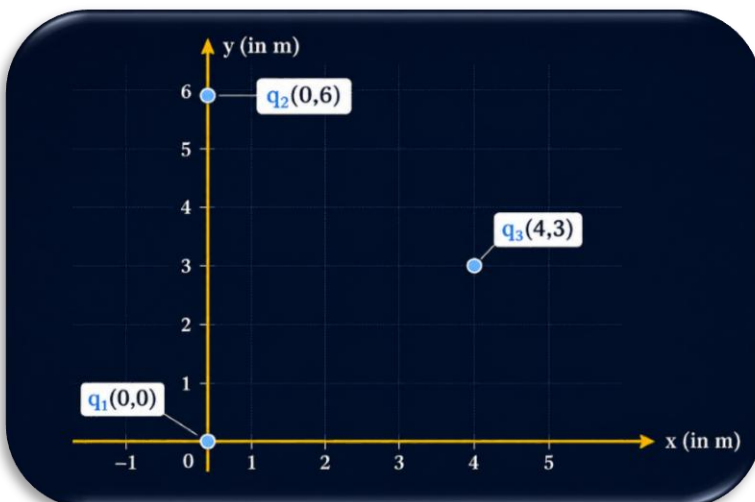
Step 2: Force due to q_2 ($-4 \times 10^{-6} \text{ C}$) at $(0, 3)$ on $q_3 = 1 \mu\text{C}$

$$F_{23} = k \cdot |q_2 \cdot q_3| / r_2^2$$

$$F_y = F_{23}$$

Direction: Both F_x and F_y are on positive axis

4. A charge of $q_1 = -10.0 \times 10^{-9} \text{ C}$, $q_2 = +10.0 \times 10^{-9} \text{ C}$ and $q_3 = -2.5 \times 10^{-8} \text{ C}$ are placed on xy plane as shown in the figure below. What is the electric force on q_3 by q_1 and q_2 ?

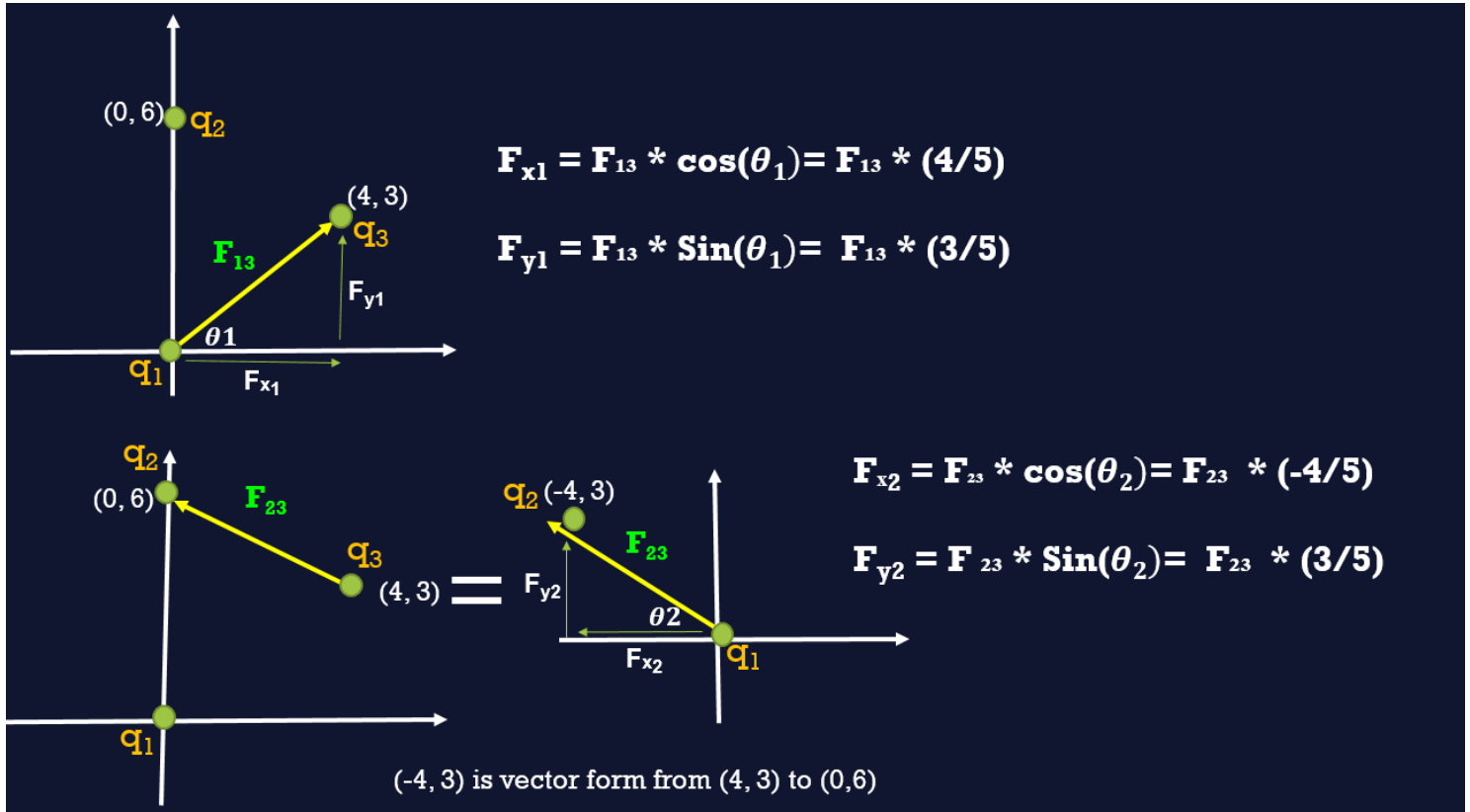


- A. $1.08 \times 10^{-7} \text{ N}$ in the +ve y-direction**
 B. $9.00 \times 10^{-7} \text{ N}$ in -ve y-direction
 C. $1.42 \times 10^{-7} \text{ N}$ in +ve x-direction
 D. $1.42 \times 10^{-7} \text{ N}$ in -ve x-direction

Hint:

Calculate distances from q_3 to q_1 and q_2 :

- r_{13} = distance from q_1 (0,0) to q_3 (4,3)
- $r_{13} = \sqrt{(4-0)^2 + (3-0)^2} = \sqrt{16 + 9} = 5 \text{ m}$
- r_{23} = distance from q_2 (0,6) to q_3 (4,3)
- $r_{23} = \sqrt{(4-0)^2 + (3-6)^2} = \sqrt{16 + 9} = 5 \text{ m}$



Net components:

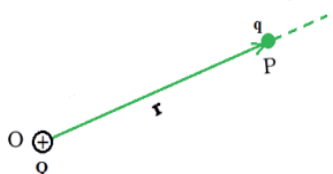
- $F_{\text{net}_x} = F_{x1} + F_{x2}$, $F_{\text{net}_y} = F_{y1} + F_{y2}$

6.2 Electric Fields

➤ Define the terms, electric field and electric flux.

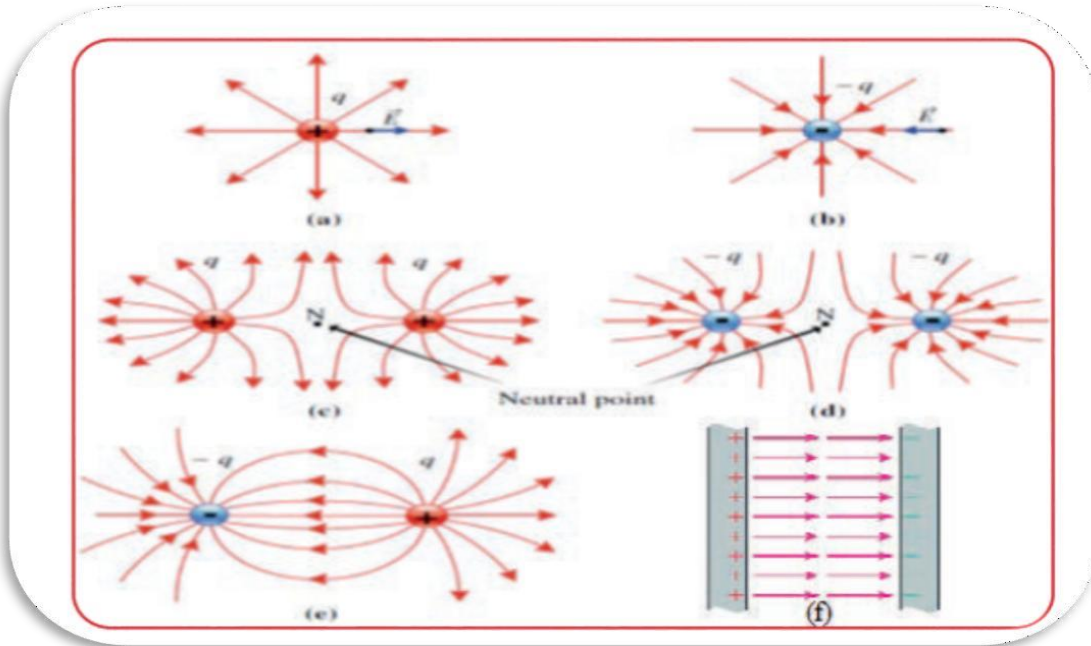
- Electric Field:

- ✓ Electric field is a region around a charged particle within which an electric force would be exerted on other charged particles. Or
- ✓ An *electric field* is a region in space where one charge experiences a force from another charge.
- ✓ The electric field at a point is the electric force per unit positive test charge.



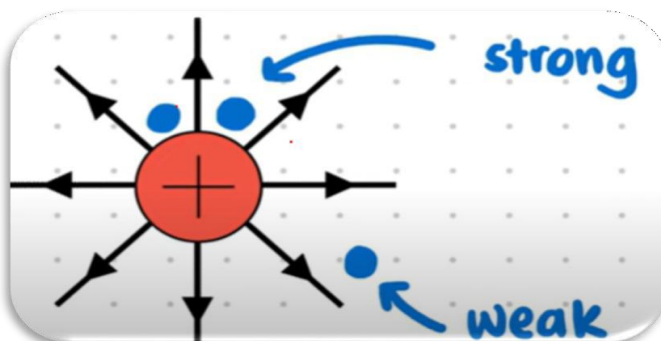
- Electric Field line

- ✓ The electric field produced by a charged particle can be represented by lines of force called electric field lines.
- ✓ Electric field line are the imaginary lines that indicate the *direction of Electric Field*.
- ✓ It is drawn in the direction that a positive charge (positive test charge) would move if placed at a point in the field.
- ✓ Electric field lines are helpful to visualize the vector nature of an electric field.



- Properties of electric Field lines

1. Electric field lines do not cross each other.
2. Electric field lines begin on positive charges and radiate away from them toward negative charges, where they terminate.
3. Electric field lines are always perpendicular to the surface of the charged body.
4. The closer the lines, the stronger the electric field, and the farther apart they are the weaker is the field.
5. Equally spaced electric field lines indicate the field is uniform. The electric field Between two parallel plates.



- Electric field strength

- ✓ Electric field strength (E) is defined as the force experienced by a small positive test charge (q) placed at the point in the field. Or force acting per unit positive charge for a stationary point charge.
- ✓ The magnitude and direction of the electric field is expressed by a quantity called electric field strength or electric field intensity (E)
- ✓ Electric field strength, is the In equation form:

$$\vec{E} = \frac{\vec{F}}{q}$$

- ✓ The SI unit of electric field strength (E) is the newton per coulomb (N/C) or equivalently the volt per meter (V/m).

- Electric field of point charge

- ✓ The electric field of a point charge can be obtained from Coulomb's law. From Coulomb's law, the equation for the force between two electric charges is:

$$F = k \cdot |q \cdot Q| / r^2$$

- ✓ *The electric field strength is then the force per unit of charge.*

$$E = F/q = |Q| / r^2$$

where E is the electric field strength due to a point charge Q, and r is the distance from charge Q to the point of interest.

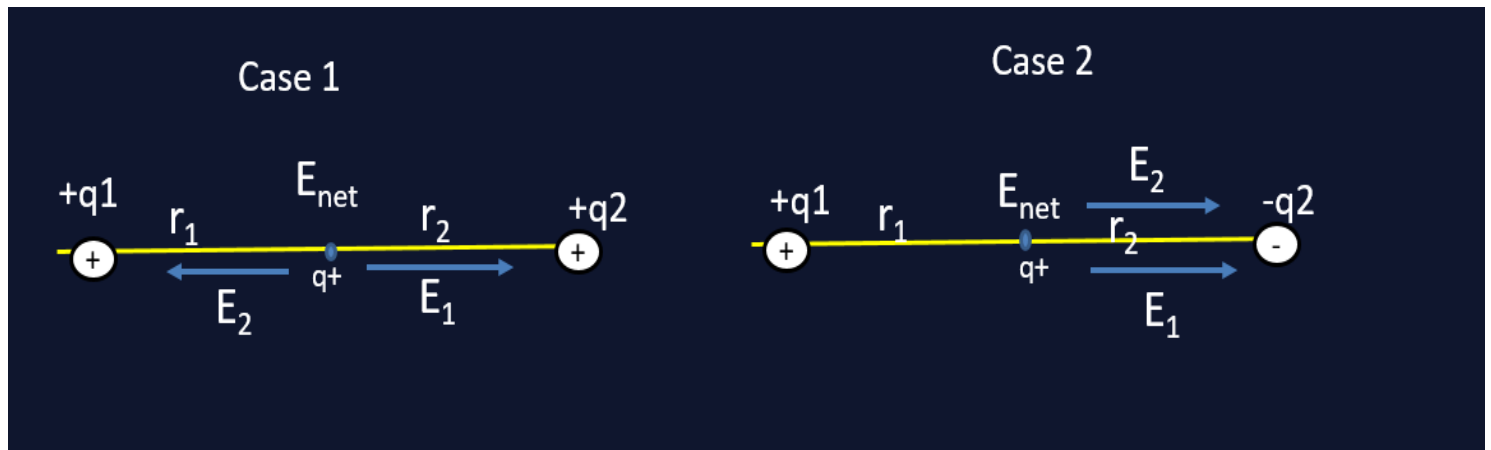
- ✓ Electric field is depend only on the source charge Q and the distance r; it is independent of the test charge q.
- ✓ The direction of the electric field will be in the direction of the force the source charge exerted on a positive test charge.
- ✓ Thus, electric field lines will direct away from a positive source charge and towards a negative source charge.

- Electric field for multiple point charges

- ✓ The electric field from multiple point charges can be obtained by taking the vector sum of the electric fields of the individual charges.

$$\vec{E}_{net} = \vec{E}_1 + \vec{E}_2 + \vec{E}_3 + \dots \vec{E}_n$$

Let's see the two conditions:



Case 1:

$$E_1 = K|q_1|/r_1^2$$

$$E_2 = K|q_2|/r_2^2$$

$$E_{\text{net}} = E_1 + (-E_2)$$

$$= E_1 - E_2$$

Case 2:

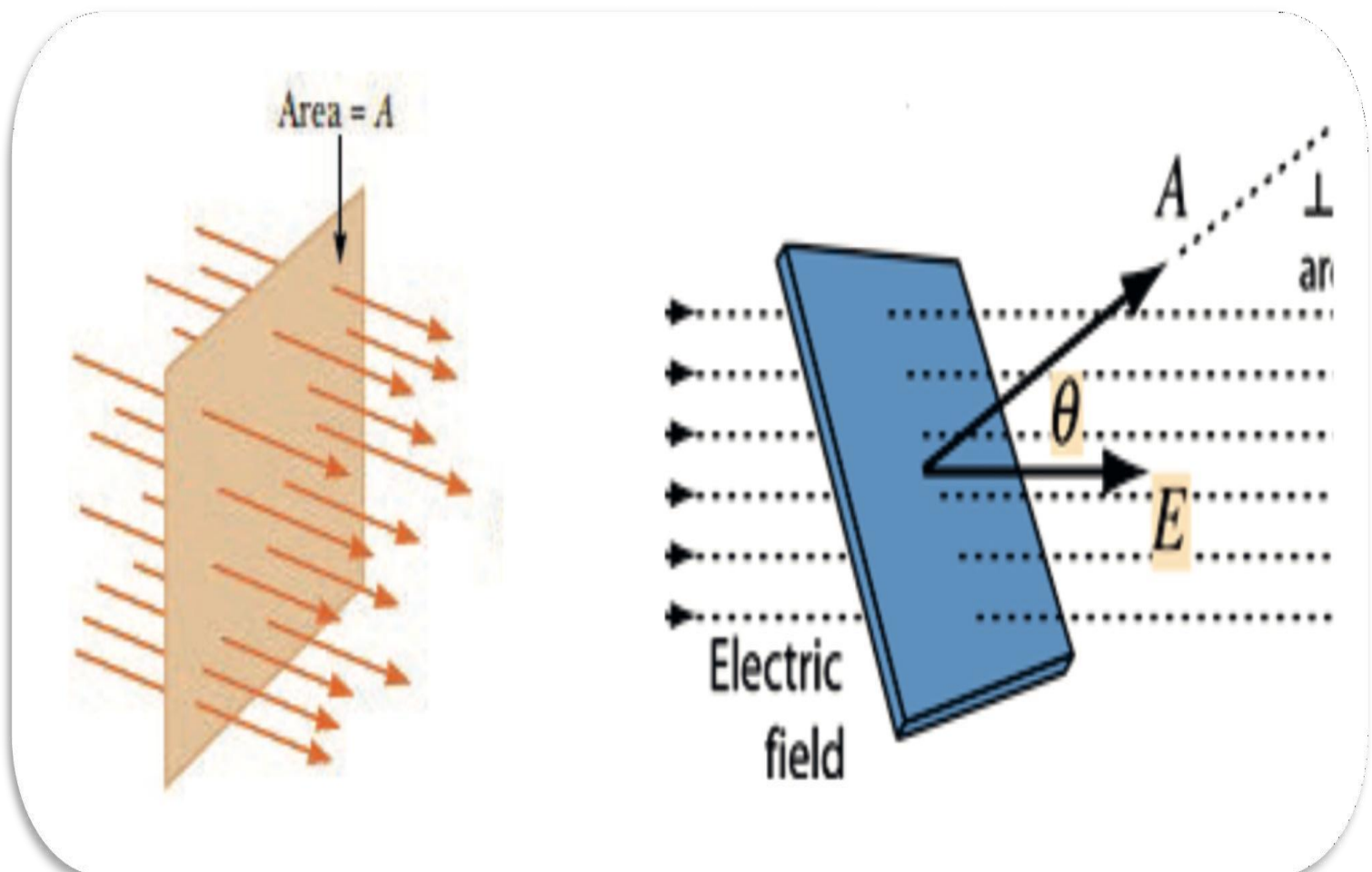
$$E_1 = K|q_1|/r_1^2$$

$$E_2 = K|q_2|/r_2^2$$

$$E_{\text{net}} = E_1 + E_2$$

- Electric flux**

- ✓ **Electric flux** is a measure of the number of electric field lines that crosses a given area.



- For a plane of surface area A placed in a uniform Electric field E , Electric flux is mathematically written as:
 - ✓ $\Phi = E \cdot A = EA \cos \theta \rightarrow$ **use this** If the given angle θ is between Electric Field (E) and areal vector A
 - $\rightarrow$ The Areal Vector (A) is always perpendicular (90°) to the Plane.
 - ✓ $\Phi = E \cdot A = EA \sin \theta \rightarrow$ **use this** If the given angle θ is between Electric Field (E) and the plane
- Electric flux is a scalar quantity; whose SI unit is $N \cdot m^2/C$

Note:

- The area vector of a flat surface of area A has the following magnitude and direction:
 - Magnitude is equal to area of the surface (A)
 - Direction along normal or perpendicular to the surface.
 - The electric field vectors are tangent to the surface at all points and if they don't penetrate the surface, the electric flux through the surface is zero.
- **Calculate the magnitude and direction of electric field due to a point charge and two point charges.**

Example 1: Calculate the strength and direction of the electric field E due to a point charge of 2.0 nC (nano-Coulombs) at a distance of 5.0 mm from the charge.

Given:

$$Q = 2.0 \text{ nC} = 2.0 \times 10^{-9} \text{ C}$$

$$r = 5.0 \text{ mm} = 5.0 \times 10^{-3} \text{ m}$$

$$k = 9.0 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2$$

Formula:

$$E = k|Q|/r^2 = 7.2 \times 10^5 \text{ N/C}$$

Direction:

- Since the charge is POSITIVE, the electric field points AWAY from the charge.

Example 2: Two-point charges $q_1 = 5 \text{ nC}$ and $q_2 = -4 \text{ nC}$ are separated by a distance of 10 cm . What is the magnitude of the electric field at the midpoint?

Given:

- ✓ $q_1 = +5 \text{ nC} = +5 \times 10^{-9} \text{ C}$
- ✓ $q_2 = -4 \text{ nC} = -4 \times 10^{-9} \text{ C}$
- ✓ Distance between charges = $10 \text{ cm} = 0.10 \text{ m}$

Required: Electric field is at the midpoint.

Answer:

Distance from each charge to midpoint: = 0.05 m

$$k = 9.0 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2$$

Step 1: Electric field due to q_1

$$E_1 = k|q_1| / r^2 = 18000 \text{ N/C}$$

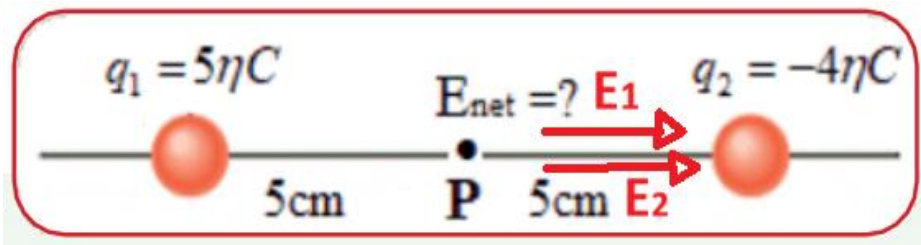
Direction: Away from the positive charge q_1 .

Step 2: Electric field due to q_2

$$E_2 = k|q_2| / r^2 = 14400 \text{ N/C}$$

Direction: Toward the negative charge q_2 .

Step 3: Net Electric Field



$$E_{\text{net}} = E_1 + E_2 = 18000 + 14400$$

$$= 32400 \text{ N/C}$$

$$= 3.24 \times 10^4 \text{ N/C}$$

Example 3: A $2\text{cm} \times 2\text{cm}$ square lies in the xy-plane. Find the electric flux through the square for the electric field vectors, $E = (50\mathbf{k} + 20\mathbf{j}) \text{ N/C}$.

Answer:

- In this case direction of the area vector, which is perpendicular to the surface, is in the z-axis. Because the square lies in the xy-plane.

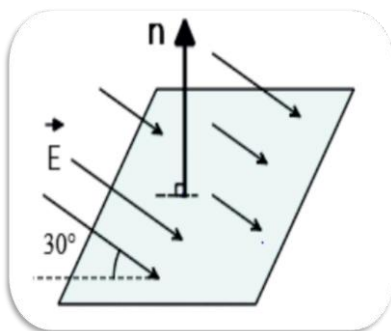
$$A = 4\text{cm}^2\mathbf{k}$$

$$E = (50\mathbf{k} + 20\mathbf{j}) \text{ N/C}.$$

$$\Phi = E \cdot A = (4 \times 10^{-4} \text{m}^2\mathbf{k}) \cdot (50\mathbf{k} + 20\mathbf{j}) \text{ N/C}.$$

$$= 0.02 \text{ N m}^2/\text{C}$$

Example 4: Find the electric flux through the surface with sides of $15\text{cm} \times 15\text{cm}$ positioned in a uniform electric field of $E = 150\text{N/C}$ as shown in the figure below.



Given: $A = 15\text{cm} \times 15\text{cm} = 225\text{cm}^2$ and $E = 150\text{N/C}$

Angle between plane and electric Field is 30°

$$\Phi = E \cdot A = EA \sin \theta = 225 \times 10^{-4} \text{ m}^2 \times 150\text{N/C} \sin 30^\circ$$

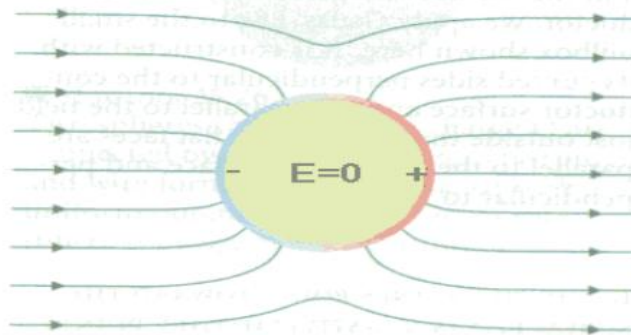
$$= 1.6875 \text{ N m}^2/\text{C}$$

Activity 6. 4:

What would happen when (a) a conductor and (b) an insulator is placed in an electric field?

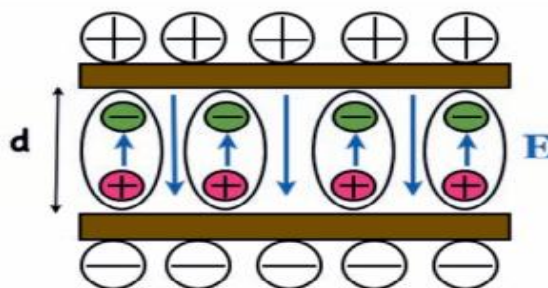
a. When a conductor placed inside an electric field

- In a conductor, electrons are free to move.
- When placed in an external electric field, electrons move opposite to the field direction.
- Electrons accumulate on one side, leaving positive charge on the other side.
- These separated charges create an internal electric field opposite to the external field.
- Eventually, the internal field cancels the external field inside the conductor.
- Therefore, the electric field inside a conductor is zero at electrostatic equilibrium.



b. When an insulator placed inside an electric field

- An electrical insulator does not allow electric current to flow freely.
- Electrons in an insulator are tightly bound and cannot move easily.
- When placed in an electric field, the material becomes polarized.
- Positive charges shift slightly in the direction of the electric field.
- Negative charges shift slightly opposite to the electric field.
- This separation of charge reduces the electric field inside the insulator.
- The net electric field within the insulator is less than the external electric field.
- Electric dipoles are induced within the insulator and produce induced electric field opposite to the external field.
- Unlike a conductor, the electric field inside an insulator is not zero.



Note:

→ It is not possible for electric field lines to go through a conductor. As such, inside a conductor, the electric field is always equal to zero.

Exercise 6. 2

1. What are the similarities and differences between Newton's law of universal gravitation and Coulomb's law?

• **Similarities**

- ✓ Both obey the inverse square law.
→ Both forces decrease as the distance increases
- ✓ Both forces operate in vacuum.
→ meaning they do not need a material medium to exist or to transmit force
- ✓ Both are conservative forces.
→ meaning the work done by the force depends only on the initial and final positions, not on the path taken.
- ✓ Both are central forces.
→ meaning the force acts along the line joining the centers of the two objects.

• **differences**

- ✓ Electrostatic force can be attractive or repulsive, while gravitational force is always attractive.
- ✓ A dielectric medium affects electrostatic force, but it does not affect gravitational force.
- ✓ Electrostatic force is much stronger than gravitational force.

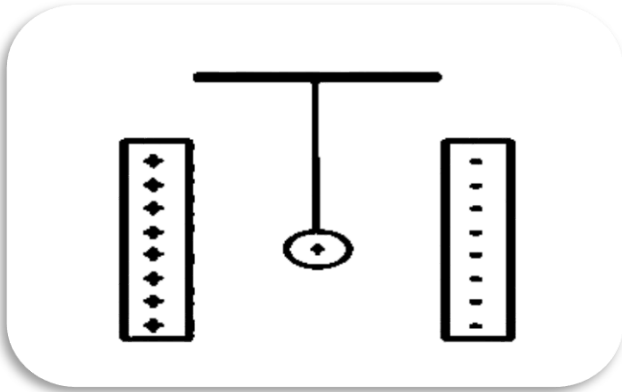
2. Which force is greater between an electron and a proton, the gravitational or the electrostatic? By how much is one larger than the other?

$$\frac{F_e}{F_g} = \frac{kq_1q_2 / r^2}{Gm_1m_2 / r^2} = \frac{kq_1q_2}{Gm_1m_2} = \frac{9 \times 10^9 \times 1.6 \times 10^{-19} \times 1.6 \times 10^{-19}}{6.67 \times 10^{-11} \times 9.1 \times 10^{-31} \times 1.67 \times 10^{-27}} = 2.27 \times 10^{39}$$

- This means the electrostatics force is 2.27×10^{39} larger than the gravitational force between an electron and a proton.
- The electrostatic force between two subatomic particles is far greater than the gravitational force between the same two particles.

Activity 6.3

A positively charged light metal ball is suspended between two oppositely charged metal plates on an insulating thread as shown below. Describe the motion that the ball undergoes.



Answer:

1. Initial Attraction

- The ball is positively charged, it is immediately repelled by the positive plate and attracted to the negative plate. It will swing to the right and strike the negative plate.

2. Charge Exchange at the Negative Plate

Upon contact with the negative plate, electrons flow from the plate onto the metal ball.

1. The ball first becomes neutral and then quickly becomes negatively charged itself.
2. Since the ball and the plate now have the same charge (negative), they repel each other.

3. Motion to the Positive Plate

- The now negatively charged ball is repelled by the negative plate and strongly attracted toward the positive plate.
- It swings across the gap and strikes the positive plate.

4. Charge Exchange at the Positive Plate

When the ball hits the positive plate, it loses its excess electrons to the plate.

- The ball becomes positively charged again.
- Like charges repel, so the ball is pushed away from the positive plate and attracted back toward the negative one.
- This motion continues back and forth between the two plates.
- The movement stops when the plates and the ball become neutral.

Sample UEE Questions:

1. An electric field is defined as a region where [UEE 2017]
 - A. a charged particle loses its charge when it is placed in that region.
 - B. a charged particle experiences no electric force when it is placed in that region.
 - C. a neutral particle experiences electric force when it is placed in that region.
 - D. a charged particle experiences an electric force if it is placed in that region.
2. What is the magnitude of electric field strength at a distance of 2.0 m from a point charge $Q = 4.0 \mu\text{C}$? [UEE 2017]
 - A. $9.0 \times 10^3 \text{ N/C}$
 - B. $22.0 \times 10^3 \text{ N/C}$
 - C. $54.0 \times 10^9 \text{ N/C}$
 - D. $18.0 \times 10^9 \text{ N/C}$
3. When an insulator is placed in an external uniform electric field,
 - a. The net electric field within the insulator is greater than the external electric field.
 - b. The induced electric field within the insulator is perpendicular to the external field.
 - c. Electric dipoles are induced within the insulator and produce induced electric field opposite to the external field.
 - d. The electric field induced within the insulator is greater than the external electric field but has the same direction as the external field.
4. Consider a spherical solid conductor carrying a net positive charge Q . which of the following is NOT true about electrostatic concept?
 - A. The net charge inside the conductor is zero.
 - B. The net charge resides only on the outer surface.
 - C. The electric field is parallel to the surface.
 - D. The electric field inside the conductor is zero.
5. Which one of the following units is NOT a possible unit of electric field strength?
 - A. Volt/meter
 - B. Joule/(Coulomb x meter)
 - C. Newton/Coulomb
 - D. Joule/Coulomb
6. If the surface normal vector $\hat{n}$ makes an angle θ with the electric field E , then the electric flux through a surface of area A is given by
 - A. $E \times A \times \cos(\theta)$
 - B. $E \times A / \cos(\theta)$
 - C. $E \times A \times \sin(\theta)$
 - D. $E^2 \times A \times \cos(\theta)$

7. A uniform electric field of 1000 N/C is directed at an angle of 30° to the rectangular surface with dimensions $2 \text{ m} \times 3 \text{ m}$. What is the electric flux through the surface?

- A) $1.5 \times 10^3 \text{ N}\cdot\text{m}^2/\text{C}$
- B) $2.6 \times 10^3 \text{ N}\cdot\text{m}^2/\text{C}$
- C) $3.0 \times 10^3 \text{ N}\cdot\text{m}^2/\text{C}$
- D) $5.2 \times 10^3 \text{ N}\cdot\text{m}^2/\text{C}$

Answers:

1. D 2. A 3. C 4. C 5. D 6. A 7. C



Review Questions 6.2



- 1 **Define the following terms**, (a) electric field, (b) electric field strength, (c) electric field lines, and (f) electric flux.



- 2 **Map electric field lines** for different arrangement of charges.

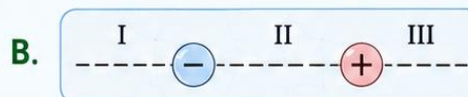


- 3 **Compare and contrast** the following gravitational quantities with their counterpart electrical quantities:

- A. gravitational field and electric field.
- B. Gravitational field strength and electric field strength.



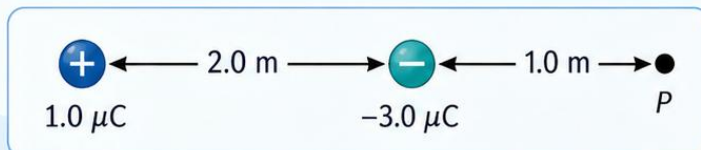
- 4 **For the following figures find the possible region where the electric field could be zero.**



- 5 **How field lines indicate the magnitude of the field they represent?**



- 6 **What is the net electric field strength at point P in the system shown below.**

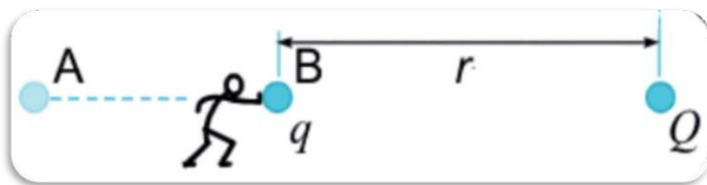


6.3 Electric Potential

➤ Define the terms electric potential Energy, electric potential, equipotential surface.

• Electric Potential Energy

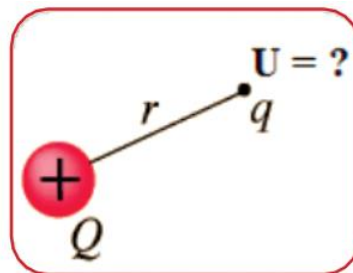
- ✓ The concept of electric potential energy is similar to that of gravitational potential energy.
- ✓ Electric potential energy is the energy possessed by a charge due to its position in an electric field or due to its location relative to other charges.
- ✓ Electric potential energy is the energy that is needed to move a charge against an electric field.
- ✓ It is the work done in bringing a charge from infinity to a point in an electric field.



$$W = q\Delta V = k \frac{qQ}{r}$$

- ✓ The potential energy of a test charge 'q' in the vicinity of a source charge 'Q' will be:

$$U = k \frac{qQ}{r}$$



• Electric Potential

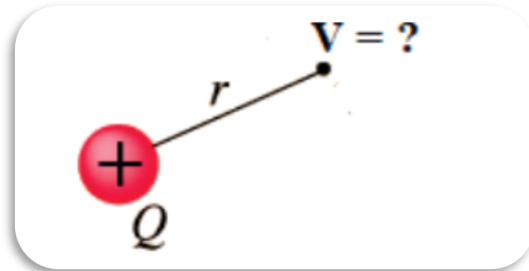
- ✓ **Electric potential** is defined as the amount of work needed to move a unit charge from a reference point to a specific point against an electric field.
- ✓ *Electric potential at a point is the amount of electric potential energy per unit charge at that point.*
- ✓ *Electric potential (denoted by V) is equal to the work done per positive charge in carrying it from infinity to that point in an electric field.*

$$V = \frac{W_{\infty \rightarrow r}}{q} = \frac{\Delta U}{q}$$

- The potential due to a single point charge

- ✓ Electric potential is defined as the work done per unit positive charge to move a positive test charge from infinity to its current position within an electric field.
- ✓ The equation for electric potential at a distance r from a source charge Q is given by:

$$V = \frac{W}{q} = K \frac{Q}{r}$$

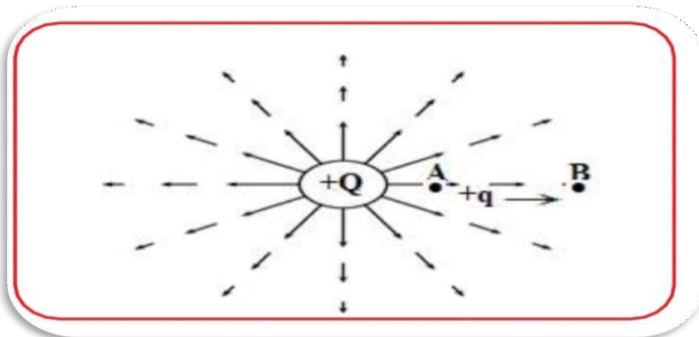


- ✓ Electrical potential is a scalar quantity. Its SI unit is Volt (V) in the honor of Alessandro Volta.

$$1V = \frac{1J}{1C}$$

- Electrical Potential Difference

- ✓ The potential difference between two points (A and B in this case) in an electric field is defined as the work required to move a unit positive test charge from the point of lower potential to that of higher potential.



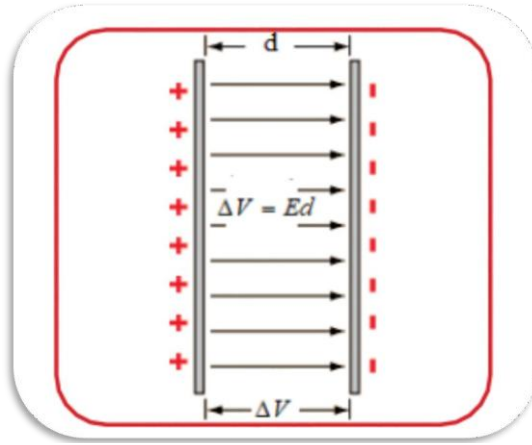
- ✓ If an amount of work W is required to move a charge Q from one point to another, then the potential difference between the two points is given by,

$$\Delta V = \frac{W}{q}$$

- Potential difference in a uniform electric field

- ✓ The electrical potential difference between the two plates is expressed as, the electric field strength times the distance between the plates.

$$\Delta V = Ed$$



- Potential due to a system of point charges

The total potential at P is:



1. Sum of individual potentials

$$V = V_1 + V_2 + \dots + V_n$$



2. Potential due to point charges

$$V = k \frac{Q_1}{r_1} + k \frac{Q_2}{r_2} + \dots + k \frac{Q_n}{r_n}$$



3. At point P

$$V_P = k \left[\frac{q_1}{r_1} + \frac{q_2}{r_2} + \dots + \frac{q_n}{r_n} \right]$$



4. General form (for n point charges)

$$V_P = k \sum_{i=1}^n \frac{q_i}{r_i} \quad (\text{for } n \text{ point charges})$$

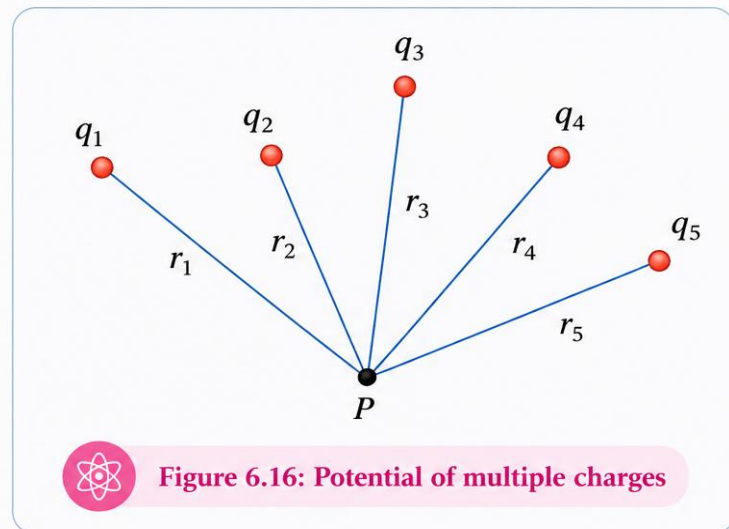


Figure 6.16: Potential of multiple charges

V = Total electric potential at point P

V_i = Potential due to charge Q_i

Q_i or q_i = Magnitude of the i^{th} charge

r_i = Distance from charge i to point P

k = Coulomb's constant = $\frac{1}{4\pi\epsilon_0} \approx 8.99 \times 10^9 \text{ N m}^2/\text{C}^2$

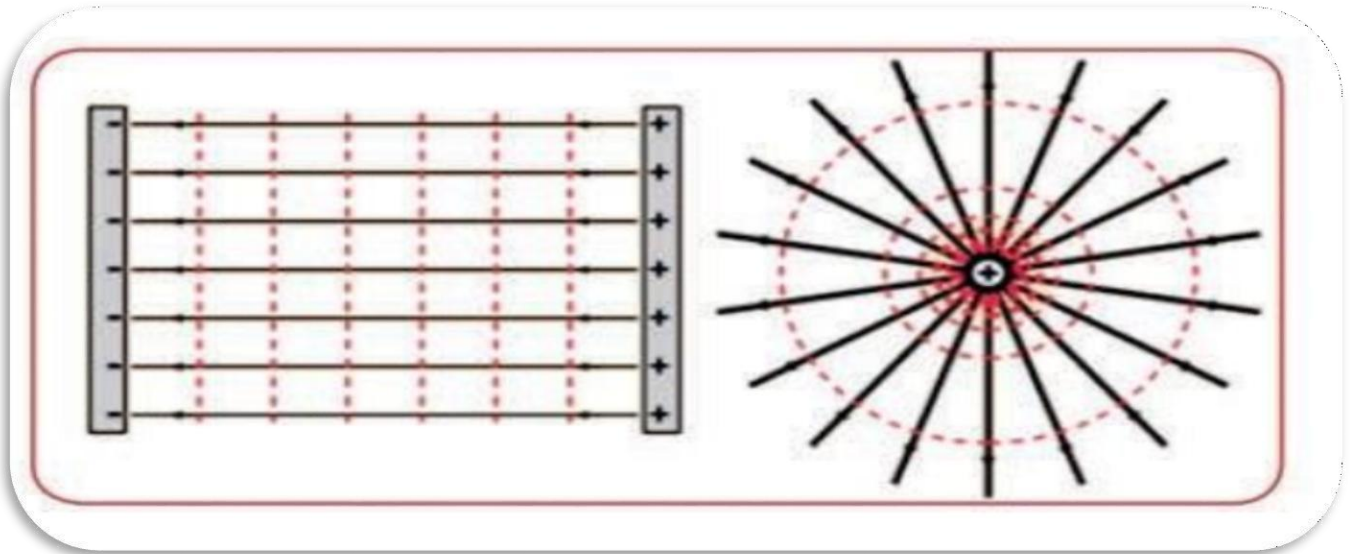


Electric potential is a **scalar** quantity, and potentials due to multiple charges **add algebraically**.

- ✓ Note that the sum in this equation is an algebraic sum. It is not a vector sum.
- ✓ It means the signs of the charges are used in calculating the potential.
- ✓ As a result, the potential of a positive charge is positive and the potential of a negative charge is negative.

• Equipotential lines/surfaces:

- ✓ Equipotential lines are lines connecting points of the same electric potential.
- ✓ When these points lie on a two- or three-dimensional surface, such as the surface of a metallic sphere, they are called equipotential surfaces.
- ✓ If a charge moves along the equipotential line then, there is no change in its potential and hence, no electrical work is done.



• Characteristics of equipotential lines/surfaces:

- ✓ Two equipotential surfaces never intersect each other.
- ✓ The equipotential lines of a uniform field are parallel to each other and the equipotential lines of a point charge are concentric sphere
- ✓ Since the electric field (E) is stronger near the charge, so equipotential surfaces of point charge are crowded near the charge.
- ✓ No work is required to move a charge along an equipotential line because there is no change in potential.
- ✓ Equipotential lines are always perpendicular to the electric field lines

➤ **Solve problems involving electric potential.**

Example 1: Determine the electric potential produced by a charge of $1\mu\text{C}$ at a distance of 1mm from it.

Given:

$$q = 1 \mu\text{C} = 1 \times 10^{-6} \text{ C}$$

$$r = 1 \text{ mm} = 1 \times 10^{-3} \text{ m}$$

$$k = 9.0 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2$$

$$V = kq / r = 9.0 \times 10^6 \text{ V} \\ = 9\text{MV}$$

Example 2: Calculate the change in electrical potential Energy when moving a point charge $q = 1\text{ nC}$ from a distance of 5 cm to 1 cm from the center of a charged sphere that carries a total charge $Q = 1\text{ }\mu\text{C}$.

Given:

- $q = 1\text{ nC} = 1 \times 10^{-9}\text{ C}$
- $Q = 1\text{ }\mu\text{C} = 1 \times 10^{-6}\text{ C}$
- Initial distance: $r_1 = 5\text{ cm} = 0.05\text{ m}$
- Final distance: $r_2 = 1\text{ cm} = 0.01\text{ m}$
- $k = 9.0 \times 10^9\text{ N}\cdot\text{m}^2/\text{C}^2$

Formula:

$$\Delta U = U_f - U_i = kQq \left(\frac{1}{r_2} - \frac{1}{r_1} \right)$$

$$= 7.2 \times 10^{-4}\text{ J}$$

Example 3: Two charged particles are placed on the x-axis of a coordinate system. The first ($q_1 = 2\text{ }\mu\text{C}$) is at the origin. The second ($q_2 = -5\text{ }\mu\text{C}$) is at $x = 1.0\text{ m}$. Determine the potential at $x = 0.2\text{ m}$.

$$V = V_1 + V_2 = k \frac{Q_1}{r_1} + k \frac{Q_2}{r_2}$$

$$V = k \left(\frac{Q_1}{r_1} + \frac{Q_2}{r_2} \right) = 9 \times 10^9 \left(\frac{2 \times 10^{-6}}{0.2} + \frac{-5 \times 10^{-6}}{0.8} \right)$$

$$V = 3.375 \times 10^4\text{ V}$$

Example 4:

Calculate the change in electrical potential energy in moving a from 5 cm to 0.1 cm from a charged sphere with a charge of .

Solution:

$$W = q\Delta V = q(V_B - V_A) = q \left(\frac{kQ}{r_B} - \frac{kQ}{r_A} \right) = kqQ \left(\frac{1}{r_B} - \frac{1}{r_A} \right)$$

$$W = 9 \times 10^9 \times 10^{-6} \times 10^{-9} \left(\frac{1}{0.01} - \frac{1}{0.05} \right)$$

$$W = 7.2 \times 10^{-4}\text{ J} = 72\text{ mJ}$$

➤ **Explain the meaning of a volt, potential difference**

- **Potential difference**

- ✓ Potential difference is the work done per unit charge in moving a positive test charge from one point to another in an electric field.
- ✓ It shows how much electrical potential energy is gained or lost by a charge.

- **Meaning of a Volt**

- ✓ One volt is the potential difference between two points when 1 joule of work is done to move 1 coulomb of charge.

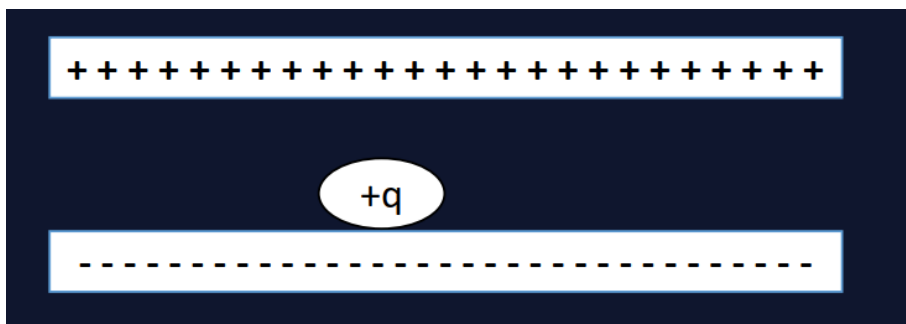
- ✓ Mathematically:

$$1 \text{ volt} = 1 \text{ joule} / 1 \text{ coulomb}$$

$$1 \text{ V} = 1 \text{ J/C}$$

Sample UEE Question:

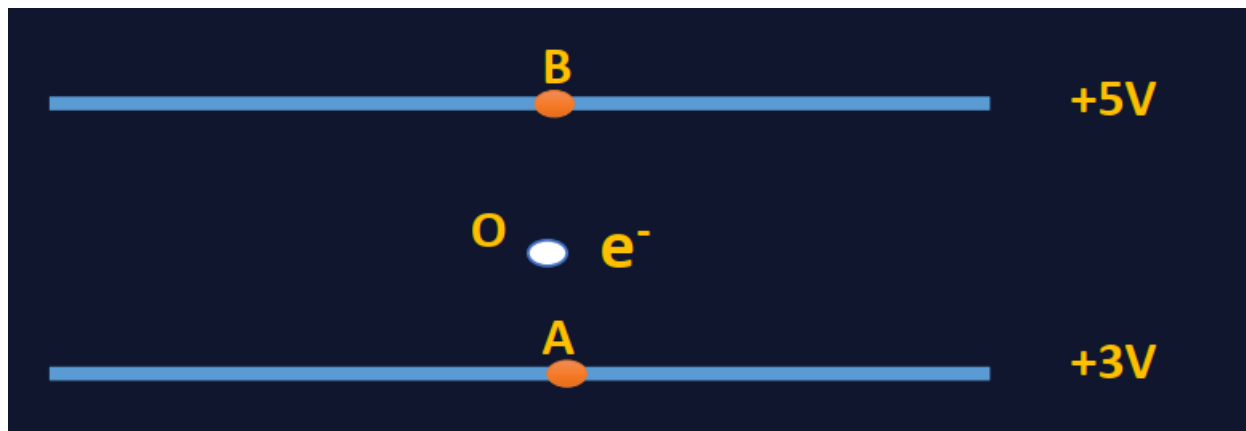
1. What is an electric potential energy? It is the energy a charge possesses because, it is in the
 - A. Region of other charges
 - B. Vacuum
 - C. Region of zero electric field
 - D. Region of other masses
2. What is the potential (V) at a distance of 10m from a charge of +5.0C?
 - A. $-4.5 \times 10^9 \text{V}$
 - B. -0.5V
 - C. $+4.5 \times 10^9 \text{V}$
 - D. $+0.5 \text{V}$
3. The electric potential at a distance of 2cm from $-1.6 \times 10^{-9} \text{C}$ points charge is
 - A. 4.4V
 - B. -720V
 - C. -14.4V
 - D. 720V
4. Many chemical reactions release energy. Suppose that at the beginning of a reaction, an electron and a proton are separated by 0.110 nm, and their final separation is 0.100 nm. The change in the electric potential energy in this reaction (in eV) is
 - A. 13.1 eV
 - B. 1.30 eV
 - C. 27.5 eV
 - D. 14.4 eV
5. A positive charge of $1.0 \times 10^{-4} \text{C}$ is on the negatively charged plate of a parallel plate as shown below.



If the potential (V) on the top plate is +10,000 V and that of the bottom plate is -10,000V, how much work (W) is required to move the charge from the bottom to the top plate?

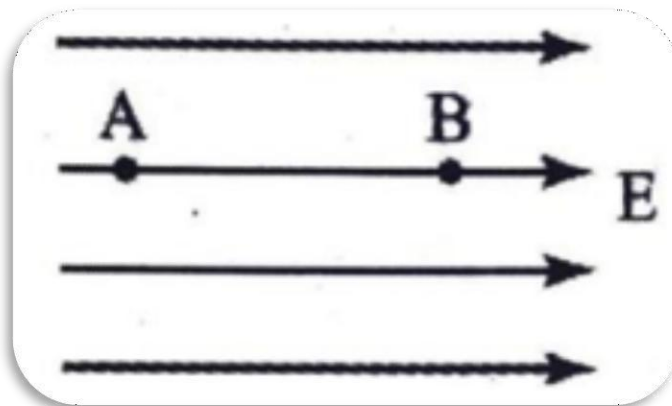
- A. 2.0 J B. 1.0 J C. Zero D. $2.0 \times 10^4 \text{ J}$

6. Two parallel plates are kept at 3 V and 5 V as shown in the diagram below. If an electron is released at O, then which way will the electron move?



- A. Towards B C. Remains at O
B. Towards A D. Parallel to the plates

7. A free electron and a free proton are moved from A to B in a uniform external electric field E shown below



Which of the following is always true about the magnitude of their electrical potential energies?

- A. Increase for both electron and proton
B. Decrease for both electron and proton
C. increase for electron and decrease for proton
D. increase for proton and decrease for electron

8. Two positive charges of magnitude 2.4×10^{-9} and 1.6×10^{-9} are separated in air by a distance of 2.0 cm. How much electrostatic potential is produced by the two charges at midway between them?

- A. 3.6 KV B. 0.72 KV C. 2.16 KV D. 1.44 KV

9. Two equal and opposite charges are located along x-axis at -2.0 cm and $+2.0\text{ cm}$ as shown in the figure below. How much would be the electric potential at the origin?



- A. Zero B. 1.8 MV C. 3.6 MV D. 4.5 MV

10. Consider a point charge Q in an electrostatic field and a point mass m in a gravitational field. Which one of the following statements is correct about the potential energy of the objects?

- A. The gravitational force on mass m is in the same direction of gravitational field while electric force on Q in the same or opposite directions of electric field depending the sign of the charge.
- B. The potential energies at distance r , from the field sources for both Q and m vary inversely with r^2 .
- C. The potential energy of the point charge and that of the point mass changes as they move over equipotential surfaces in their respective fields.
- D. The electric potential decreases as a positive charge moves opposite to the electric field while the gravitational potential of the mass increases when it moves along the gravitational field.

Answers: 1.A 2.C 3. B 4.B 5.A 6.A 7.C 8.A 9.A 10.A

6.4 Electric Current, Resistance and ohm's law

➤ **Define the terms electric current, current density, resistance, conductivity, resistivity and drift velocity and explain the SI units of electric current, current density, resistance, resistivity, conductivity.**

Electric current

- Electric current is a flow of charge.
- In metals, current is due to a flow of electrons.
- When a voltage source is connected to a conductor, it applies a potential difference V that creates an electric field.
- The electric field in turn exerts force on the free or conduction charges of the conductor, causing current.
- For historic reason, what we call electric current is the conventional flow of protons.

- Electric current is defined as the amount of electric charge passing through a specific cross-section of a conductor per unit of time.
- If the net charge that flows through a cross-sectional area A in time (t) , then the current I is given by the equation:

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

- The SI unit of electric current is ampere, denoted by A .
- One ampere is a flow of one coulomb ($1C$) of charge in $1s$.
- Small currents are measured in milliampere (mA), and microampere (μA).
- $1mA = 10^{-3} A$ and $1\mu A = 10^{-6} A$.

Current density

- Current density is a quantity which is used to describe the density of an electric current.
- It is denoted by the symbol J , and defined as the magnitude of the electric current per cross-sectional area.

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

- The SI unit of current density is amperes per square meter.
- Current density is a vector quantity.
- The direction of current density is in the direction of electric field (which is from positive terminal to negative terminal)
- Current density is proportional to the electric field, (E), that produces it, and the conductivity (σ) of the conductor through which it flows.
- The conductivity of a conductor is a measure of its ability to conduct electricity, whereas resistivity is the reverse of conductivity.

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

- Where σ conductivity of the conductor, and ρ resistivity.
- The SI unit of ρ is Ohm- meter ($\Omega.m$), where $1 \Omega.m = 1 V/A$.
- The SI unit of σ is Siemens per meter (S/m), or Ω^{-1} .

Example: A current of $6 mA$, flows through a copper wire of cross-sectional area $12 mm^2$. What is the current density?

$$I = 6 mA = 6 \times 10^{-3} A, \quad A = 12 mm^2 = 12 \times 10^{-6} m^2$$

$$J = \frac{I}{A} = \frac{6 \times 10^{-3} A}{12 \times 10^{-6} m^2} = 500 A / m^2$$

Resistance

- Resistance is the opposition offered by a conductor to the flow of electric current.
- It measures how difficult it is for electric charges to flow through a material.
- Symbol: R
$$R = \rho l / A$$

Where:
R = resistance, ρ = resistivity, A = cross-sectional area L = length of conductor
- Depends on:
 - ✓ Length
 - ✓ cross-sectional area
 - ✓ material
 - ✓ temperature
- Changes when the size or shape of the conductor changes.
- SI Unit: ohm (Ω)

Conductivity

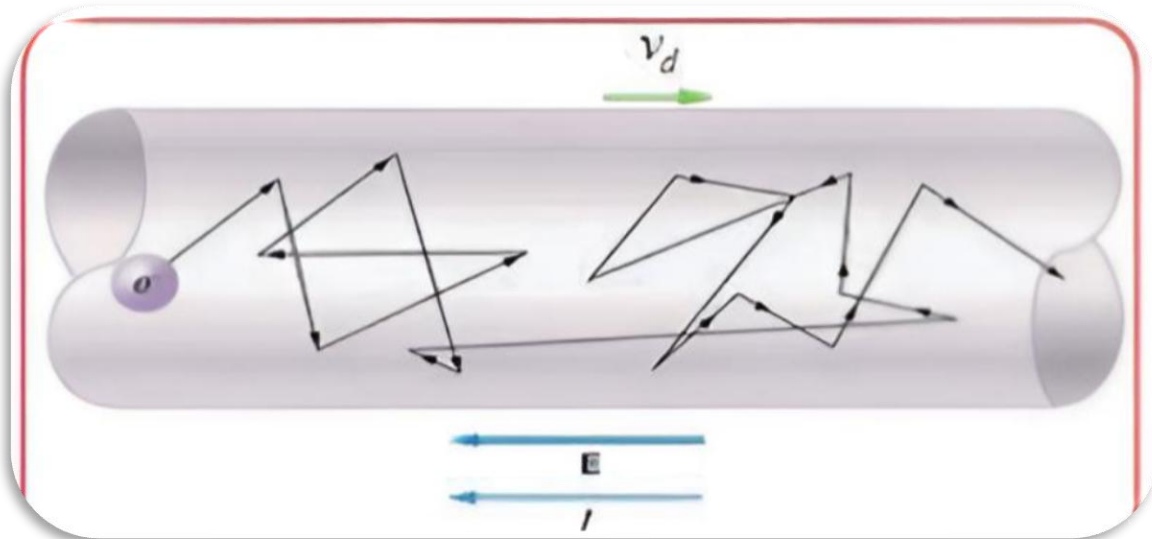
- Conductivity is the ability of a material to allow the flow of electric current through it.
- Materials with high conductivity allow electric charges to move easily through them.
- Key points:
 - ✓ Good conductors have high conductivity.
 - ✓ Insulators have very low conductivity.
 - ✓ Metals such as copper and silver are good conductors.
- SI Unit:
 - ✓ Siemens per meter (S/m)
 - ✓ Symbol: σ (sigma)
- Relationship:
 - ✓ Conductivity is the reciprocal of resistivity.
 - ✓ $\sigma = 1 / \rho$
 - ✓ Where:
 σ = conductivity
 ρ = resistivity

Resistivity

- Resistivity is the **property** of a material that opposes the flow of electric current.
- It is the resistance of a conductor of unit length and unit cross-sectional area.
- Depends only on:
 - nature of the material
 - temperature
- Does not depend on the size or shape of the conductor.
- Symbol: ρ (rho)
- SI Unit: ohm meter ($\Omega \cdot m$)
- Key points:
 - ✓ Good conductors have low resistivity.
 - ✓ Insulators have high resistivity.
 - ✓ Resistivity depends on the nature of the material and temperature.

Drift velocity

- Drift velocity refers to the average speed at which the free electrons in a conductor move through the material.



- The potential difference provided by the source creates an electric field inside the conductor.
- This field exerts a force on each electron in the direction opposite to the field.
- In every collision the electrons lose their kinetic energy and start to drift.
- The average velocity by which the free electrons move through a conductor is called drift velocity.

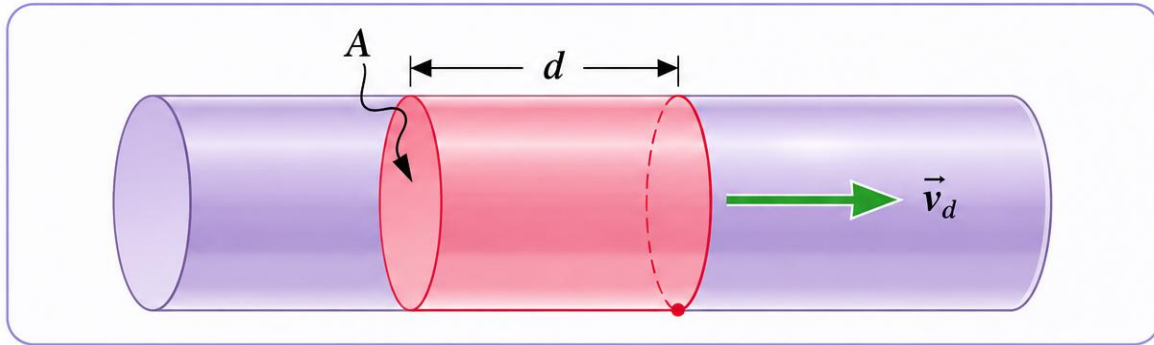
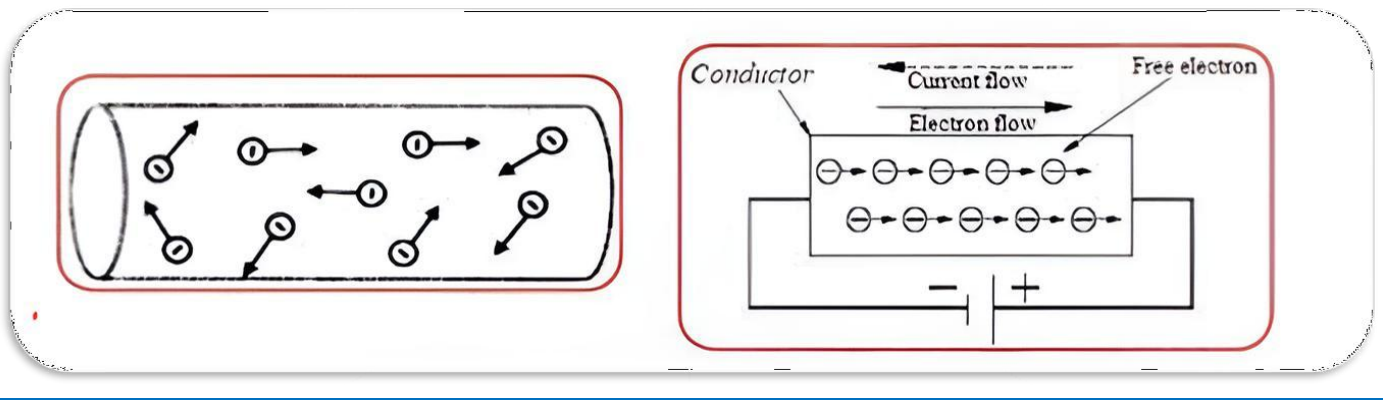


Figure 6.21

✦ The current in the circuit will then be: ✦

1 **Current** = charge passing through area A per unit time

$$I = \frac{Q}{\Delta t} = nAv_d e$$

2 **Current density** ($J = I/A$)

$$\Rightarrow J = \frac{I}{A} = nv_d e$$

Where:

I	: Current (A)
Q	: Charge that passes through area A in time Δt (C)
Δt	: Time interval (s)
n	: Number density of charge carriers (m^{-3})
A	: Cross-sectional area of conductor (m^2)
v_d	: Drift velocity of charge carriers (m/s)
e	: Charge of each carrier ($= 1.602 \times 10^{-19} \text{ C}$)
J	: Current density (A/m^2)



Interpretation: Charge carriers with number density n moving with drift velocity v_d through area A produce current $I = nAv_d e$.

Sample UEE Questions:

1. A wire that has a resistance of 6Ω is drawn out so as to make it into a new wire two times as long as the original and half cross-sectional area of the original. What will be the resistance of the new wire? [UEE 2017]

- A. 12Ω B. 6Ω C. 3Ω D. 24Ω

Hint:

- $R_1 = \rho \times L_1 / A_1$ $R_2 = \rho \times L_2 / A_2$
- New length $L_2 = 2 \times$ original length (L_1)
- New area $A_2 = \frac{1}{2} \times$ original area (A_1)

2. A uniform cylindrical wire of 1cm radius and 10m length has a resistance of $5 \times 10^{-4} \Omega$. What is the resistivity of the wire?
- A. $1.00 \times 10^{-4} \Omega \text{ m}$ B. $1.57 \times 10^{-4} \Omega \text{ m}$
 C. $1.00 \times 10^{-8} \Omega \text{ m}$ D. $1.57 \times 10^{-8} \Omega \text{ m}$

Hint:

- $\rho = R A / L$
- $A = \pi r^2$

3. What will be the direction of the drift velocity of electrons change with respect to the electric field?
- A. Same as that of electric field
 B. Opposite to that of electric field
 C. Perpendicular to that of the electric field in a positive direction
 D. Perpendicular to that of the electric field in negative direction
4. A uniform conductor of length L and cross-sectional area A carries a current I when a potential difference V is applied across its ends. If the number of free electrons per unit volume of the conductor is n , and the electron charge is e , then the drift velocity of the electrons in the conductor
- A. $v = I / neL$ B. $v = I / neLA$ C. $v = I / neA$ D. $v = I / eLA$
5. A copper wire of cross-sectional area 2 mm^2 carrying a current of 1.5 A . If the drift velocity of the electron is 0.00028 m/s , what is the number of charge carriers (free electrons) per unit volume in the copper wire?
- A. $1.5 \times 10^{25} / \text{m}^3$ B. $1.67 \times 10^{28} / \text{m}^3$ C. $1.5 \times 10^{32} / \text{m}^3$ D. $1.67 \times 10^{32} / \text{m}^3$

Hint:

- $I = n A v_d e$
- $v_d = \frac{I}{n A e}$

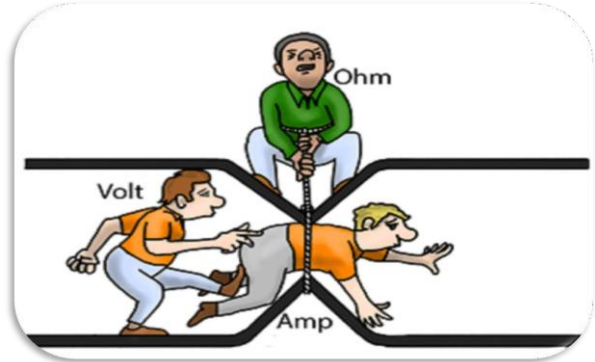
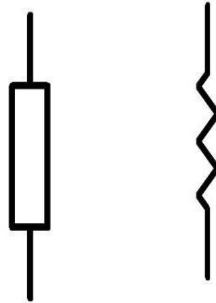
6. A potential difference V is applied across the ends of a uniform conducting wire of length l , cross-sectional area A , and containing n free charge carriers per unit volume. Which one of the following is true?
- A. The electric current in the conductor flows perpendicularly to the drift velocity of the free charges.
 B. The current density in the conductor is directed of the opposite direction of the drift velocity of the free charge carriers.
 C. The free electrons in the conductor flow in the direction of the electric field in the conductor.
 D. The electric current in the conductor flows arbitrarily in all directions.

Answer: 1. D 2. D 3. B 4. C 5. B 6. B

➤ Explain Resistance and ohm's Law

Resistance

- Resistance refers to the opposition to the flow of electric current through a conductor or a circuit.
- Electrical resistance is denoted by R.



Ohm's Law

- Ohm's Law is a fundamental principle in electrical engineering that describes the relationship between three key electrical quantities: voltage (V), current (I), and resistance (R).
- Ohm's Law states that:
“The current (I) flowing through a conductor is directly proportional to the voltage (V) applied across it, and inversely proportional to the resistance (R) of the conductor.”
- This relationship can be expressed mathematically as:

$$I = V/R$$

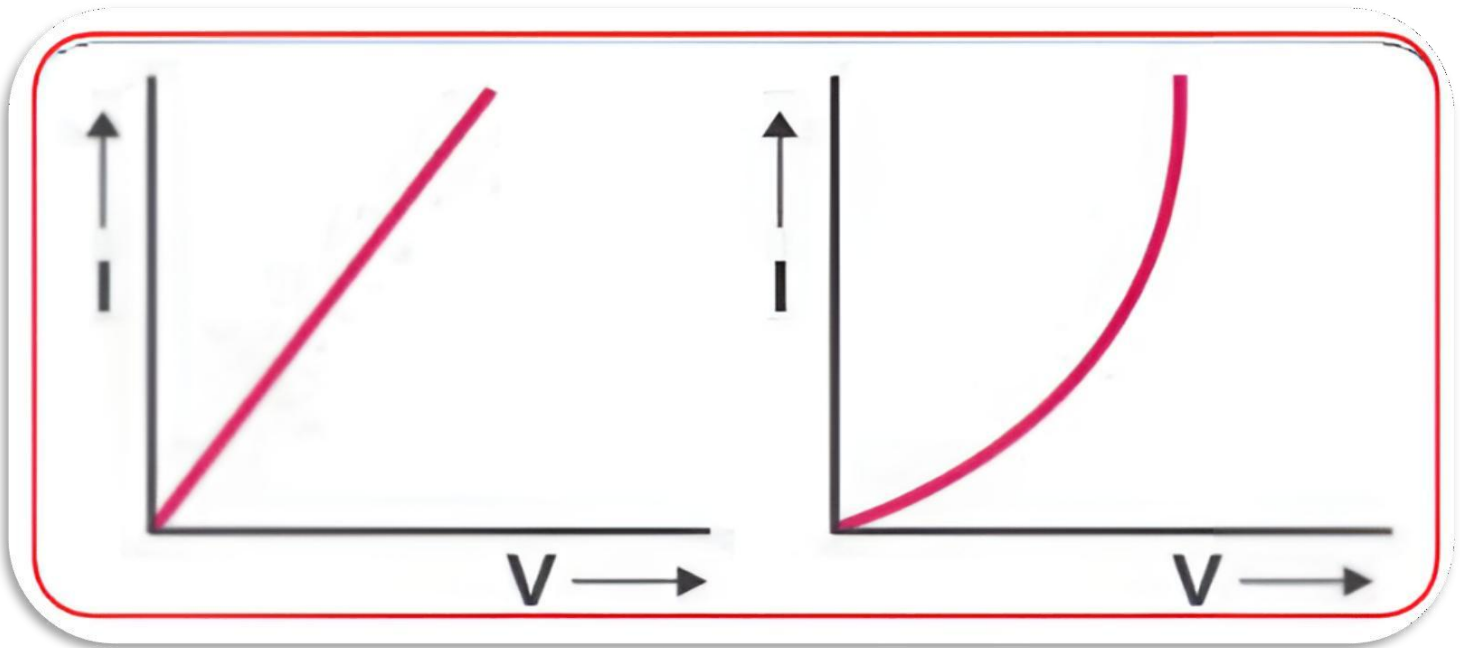
➤ Explain Ohmic and non-ohmic conductors

Conductors that obey Ohm's law.

- The current is directly proportional to the voltage at constant temperature.
- Formula:
 $V \propto I$
- Characteristics:
 - ✓ Resistance remains constant.
 - ✓ V-I graph is a straight line passing through origin.
- Examples:
 - ✓ Metallic wires
 - ✓ Copper wire
 - ✓ Resistors

Non-Ohmic Conductors

- Conductors that do not obey Ohm's law.
- Current is not directly proportional to voltage.
- Characteristics:
 - ✓ Resistance changes with voltage or temperature.
 - ✓ V-I graph is not a straight line.
- Examples:
 - ✓ Diode
 - ✓ Filament lamp
 - ✓ Thermistor



Key Difference

- ✓ Ohmic conductors have constant resistance.
- ✓ Non-ohmic conductors have variable resistance

Property	Ohmic Conductor	Non-Ohmic Conductor
Obeys Ohm's Law?	Yes	No
V-I Relationship	Linear	Non-linear
Resistance	Constant	Variable
V-I Graph	Straight line through origin	Curved line
Examples	Copper wire, resistors	Diode, LED, filament bulb

➤ **Explain the effect on the current (brightness) and potential difference of connecting light bulbs in series.**

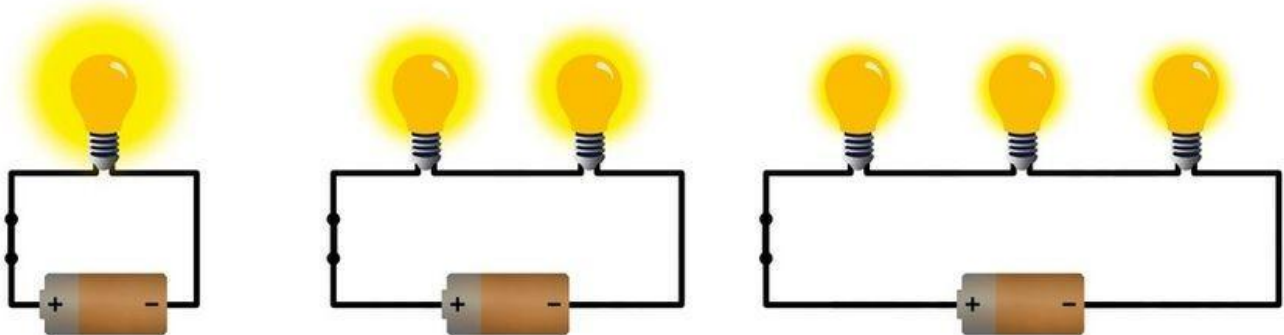
- When light bulbs are connected in series, they are connected one after another in a single path.
- Effect on Current
 - ✓ The same current flows through all bulbs.
 - ✓ Adding more bulbs increases the total resistance.
 - ✓ Increased resistance causes the current in the circuit to decrease.
- Using Ohm's law:
$$I = V/R$$

As total resistance (R_T) increases, current (I_T) decreases.
- Brightness
 - ✓ Since the current becomes smaller, each bulb glows less brightly (dimmer).
 - ✓ More bulbs in series → dimmer bulbs.
- Effect on Potential Difference (Voltage)
 - ✓ The supply voltage is shared among the bulbs.
 - ✓ Each bulb receives only a part of the total voltage.
- For example:
 - ✓ If a 12 V battery is connected to two identical bulbs in series,
 - ✓ each bulb gets about 6 V.

Thus:

- ✓ Potential difference across each bulb is smaller than the source voltage.
- ✓ The sum of the voltages across all bulbs equals the battery voltage.

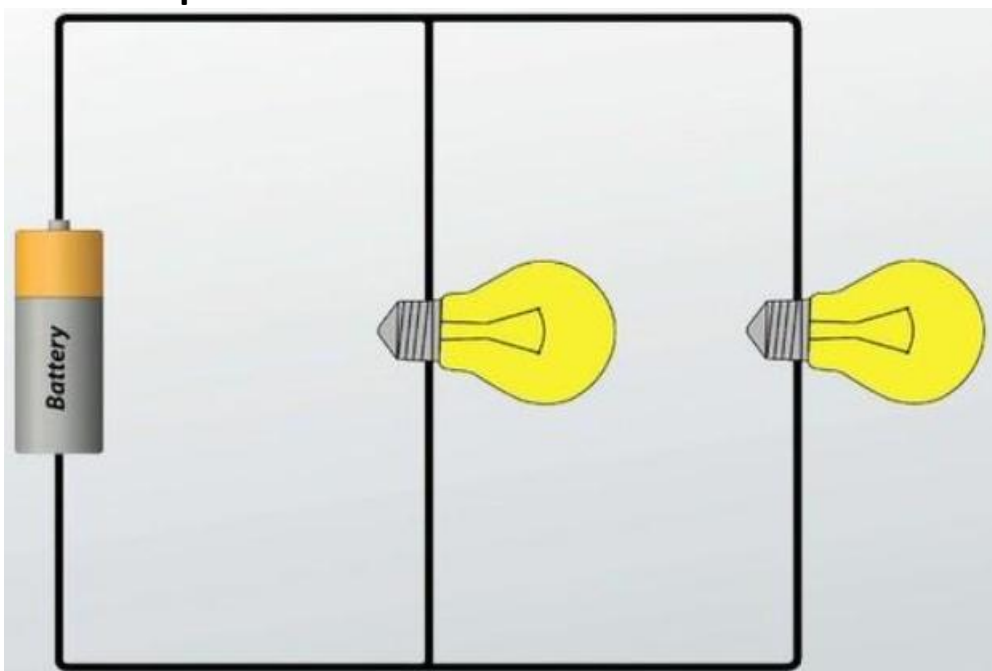
Series Circuit



The light bulbs will be less bright when adding bulbs

➤ **Explain the effect on the current (brightness) and potential difference of connecting light bulbs in parallel.**

- When light bulbs are connected in parallel, each bulb is connected directly across the power supply in separate branches.
- Effect on Current
 - ✓ The current splits into different branches.
 - ✓ Each bulb draws its own current from the source.
 - ✓ Adding more bulbs increases the total current supplied by the battery.
- Brightness
 - ✓ Each bulb receives full supply voltage.
 - ✓ Therefore, each bulb glows with normal brightness.
 - ✓ Adding more bulbs in parallel does not significantly reduce the brightness of the others.
- Effect on Potential Difference (Voltage)
 - ✓ The potential difference across each bulb is the same as the source voltage.
- For example:
 - ✓ If the battery is 12 V,
 - ✓ each bulb gets 12 V.
- Thus:
 - ✓ Voltage across every branch is equal.
 - ✓ Bulbs operate independently.
- Important Feature
 - ✓ If one bulb burns out, the others continue to glow because each branch has its own path for current.

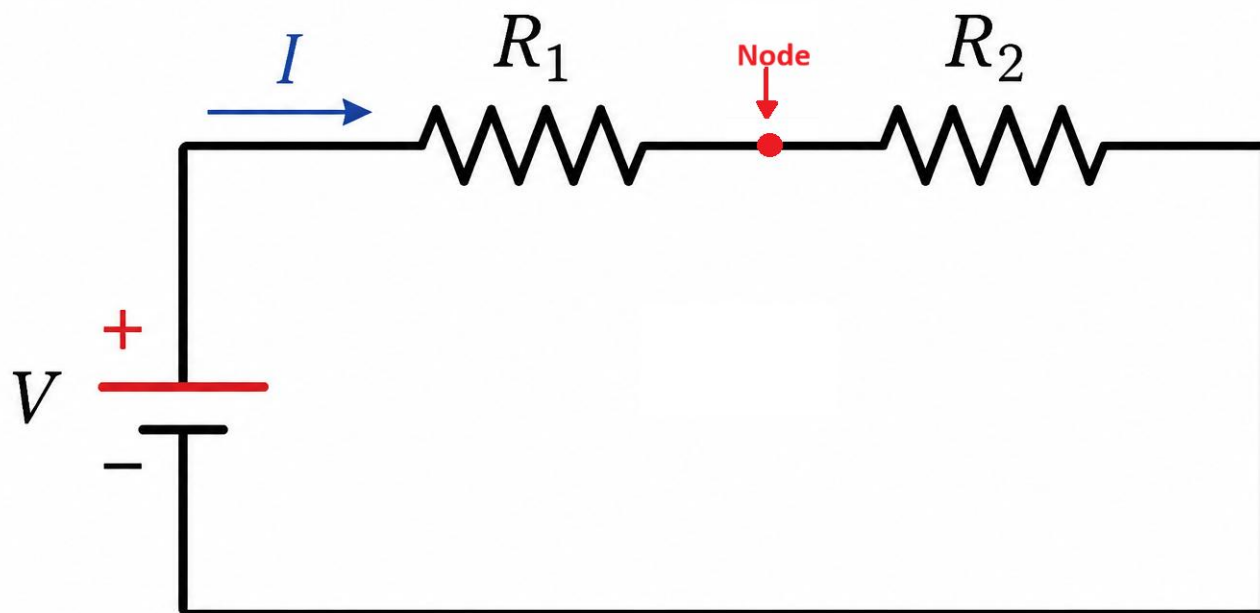


➤ **Determine the equivalent resistance, total current, and voltage drop of resistors connected in series and parallel.**

Let's first see how we can identify series and parallel connections.

1. Two resistors are said to be connected in series if:

- ✓ They are connected end-to-end
- ✓ They have only one common node between them
- ✓ No other branch is connected at that node
- ✓ There is only one path for current



Equivalent resistance

- For resistors connected in series the equivalent resistance is the sum of all resistors.

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

Total Voltage (Source voltage)

- For resistors connected in series the total voltage is equal to the sum of the voltage drops across each resistor.

$$V_T = V = V_1 + V_2$$

Where V_1 and V_2 are voltage drop across resistor 1 and resistor 2 respectively

Total Current [Current comes from the voltage source]

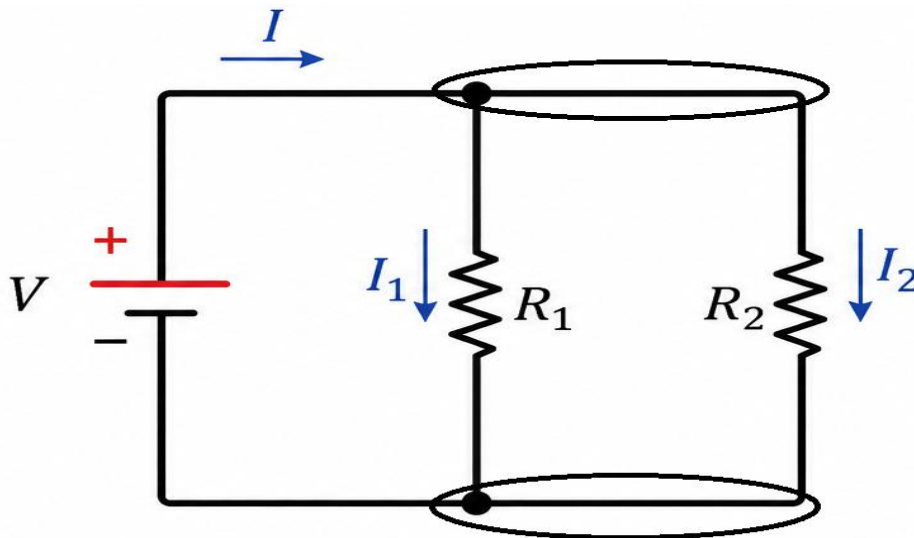
- The same current flows through both resistors.

$$I_T = I = I_1 = I_2$$

Where I_1 and I_2 are current passes through resistor 1 and resistor 2 respectively

2. Two resistors are said to be connected in parallel if:

- ✓ Both resistors are connected across the same two nodes
- ✓ They provide more than one path for current
- ✓ The potential difference across each resistor is the same



Equivalent resistance

- For resistors connected in parallel the reciprocal of the equivalent resistance equals the sum of the reciprocals of individual resistors.

$$1/R_{eq} = 1/R_1 + 1/R_2, \text{ finally solve for } R_{eq}$$

- For only two resistors connected in parallel, the equivalent resistance can be determined by the equation.

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

Total Voltage (Source voltage)

- For a parallel connection the voltage across each branch is the same as the source voltage.

$$V_T = V = V_1 = V_2$$

Where V_1 and V_2 are voltage drop across resistor 1 and resistor 2 respectively

Total Current [Current comes from the voltage source]

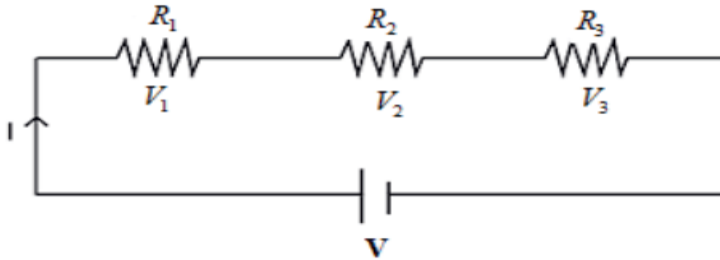
- For a parallel connection the total current is equal to the sum of the branch currents.

$$I_T = I = I_1 + I_2$$

Where I_1 and I_2 are current passes through resistor 1 and resistor 2 respectively

➤ Solve problems involving network of resistors.

Example 1:

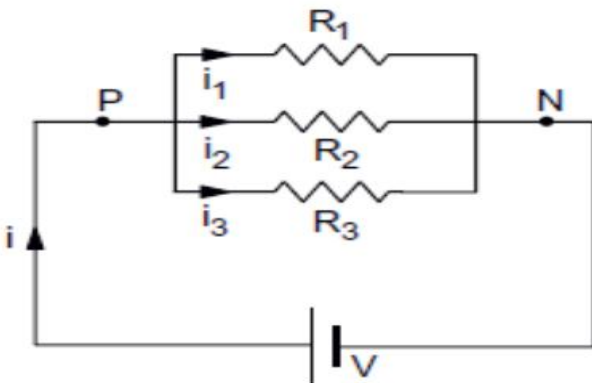


$$R_{eq} = R_1 + R_2 + R_3$$

$$I_T = I = I_1 = I_2 = I_3$$

$$V_T = V = V_1 + V_2 + V_3$$

Example 2:

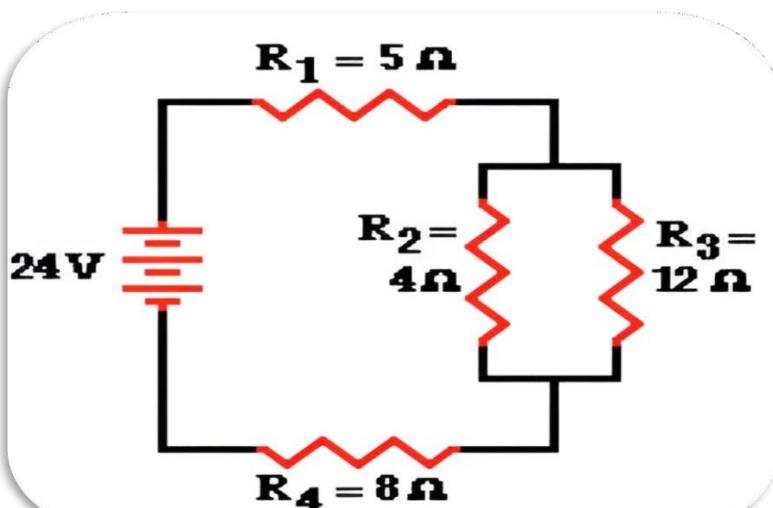


$$1/R_{eq} = 1/R_1 + 1/R_2 + 1/R_3, \text{ finally solve for } R_{eq}$$

$$I_T = I = I_1 + I_2 + I_3$$

$$V_T = V = V_1 = V_2 = V_3$$

Example 3: For the circuit shown in the figure below, determine (a) the equivalent resistance of the circuit, (b), the current through each resistor, and the potential difference across each resistor.



We start by combining resistors R_2 and R_3 in parallel.

$$R_{23} = \frac{R_2 \times R_3}{R_2 + R_3} = \frac{4 \times 12}{4 + 12} = 3 \Omega$$

Then, all the three are connected in series, Therefore,

$$R_{eq} = R_1 + R_{23} + R_4 = 5 \Omega + 3 \Omega + 8 \Omega = 16 \Omega$$

The current from the battery can then be determined by using Ohm's law.

$$I = \frac{V}{R} = \frac{24V}{16 \Omega} = 1.5 A$$

Since R_1 , R_{23} and R_4 are in series with the source, they will have the current of the source. Thus,

$$I_T = I_1 = I_{23} = I_4 = 1.5 A$$

Using Ohm's law:

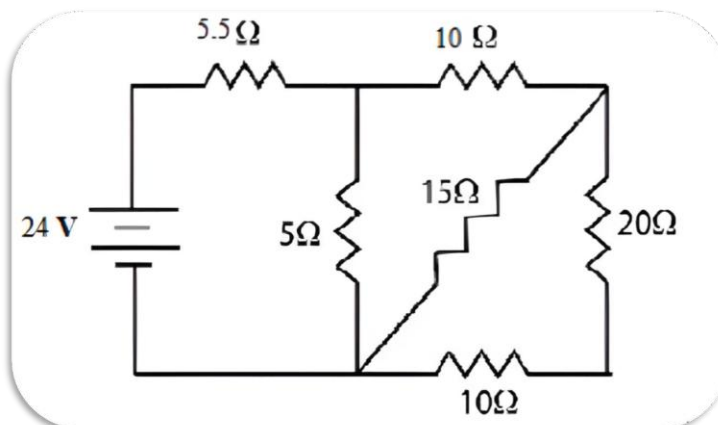
$$V_1 = I_1 R_1 = 1.5 A \times 5 \Omega = 7.5 V$$

$$V_{23} = I_{23} R_{23} = 1.5 A \times 3 \Omega = 4.5 V$$

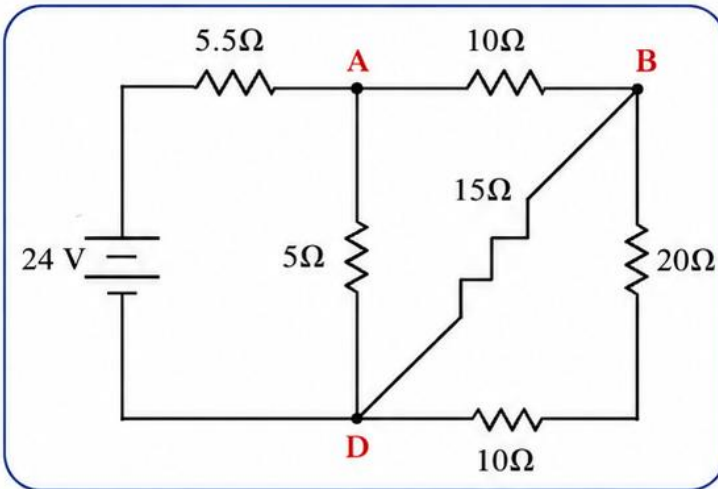
$$\Rightarrow I_2 = \frac{V_{23}}{R_2} = \frac{4.5 V}{4.0 \Omega} = 1.125 A \quad \text{and} \quad \Rightarrow I_3 = \frac{V_{23}}{R_3} = \frac{4.5 V}{12 \Omega} = 0.375 A$$

Example 4:

- What is the equivalent resistance of the circuit shown in the figure?
- What current flows through the 5Ω resistor?



2. (a) What is the equivalent resistance of the circuit shown in the figure?
 (b) What current flows through the 5Ω resistor?



STEP 1: Right side equivalent resistance

- The 20Ω and bottom 10Ω are in series:

$$R_1 = 20\Omega + 10\Omega = 30\Omega$$

- This 30Ω is in parallel with 15Ω :

$$R_2 = \frac{15 \times 30}{15 + 30} = \frac{450}{45} = 10\Omega$$

- Now this 10Ω is in series with the top 10Ω :

$$R_3 = 10\Omega + 10\Omega = 20\Omega$$

- This 20Ω branch is in parallel with 5Ω :

$$R_4 = \frac{5 \times 20}{5 + 20} = \frac{100}{25} = 4\Omega$$

STEP 2: Total equivalent resistance

Finally add the 5.5Ω resistor in series:

$$R_{eq} = 5.5\Omega + 4\Omega = 9.5\Omega$$

(a) Equivalent Resistance

$$R_{eq} = 9.5\Omega$$

STEP 3: Total current from the source

Using Ohm's law,

$$I_T = \frac{V}{R_{eq}} = \frac{24}{9.5} \approx 2.53A$$

$$I_T \approx 2.53A$$

STEP 4: Voltage across the parallel section

The parallel section (between A and D) has equivalent resistance 4Ω .

Voltage across it:

$$\begin{aligned} V_{AD} &= I_T \times 4\Omega \\ &= 2.53 \times 4 \\ &\approx 10.1V \end{aligned}$$

$$V_{AD} \approx 10.1V$$

STEP 5: Current through 5Ω resistor

The 5Ω resistor is across A and D, so the voltage across it is $10.1V$.

Current through 5Ω resistor:

$$I_{5\Omega} = \frac{V_{AD}}{5} = \frac{10.1}{5} \approx 2.02A$$

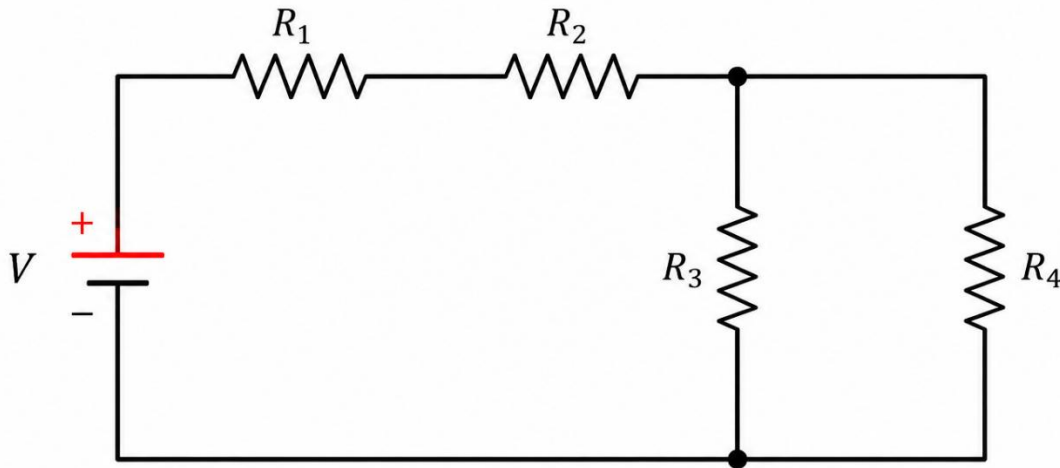
$$I_{5\Omega} \approx 2.02A$$

(b) Current through 5Ω resistor

$$I_{5\Omega} \approx 2.02A$$

Sample UEE Questions:

1. Four resistors are connected to a voltage source as shown in figure below. Which one of the following is correct about the circuit? [UEE 2017]



- A. R_2 is connected in parallel with R_3
- B. R_1 is connected in parallel with R_2
- C. R_1 is connected in series with the effective combination of R_3 and R_4
- D. R_2 is connected in parallel with the effective combination of R_3 and R_4

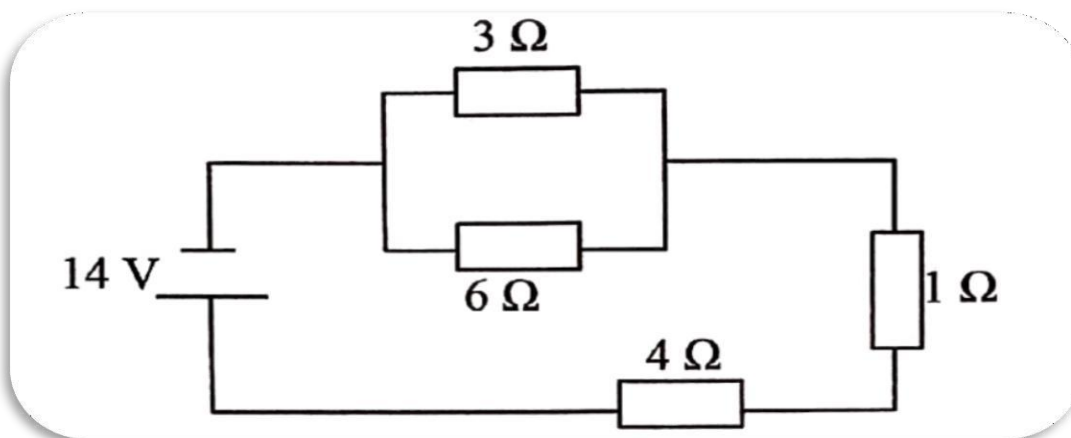
Hint:

- Combine R_3 and R_4 into one effective resistance using the formula for parallel resistors:

$$R_{\text{parallel}} = (R_3 \times R_4) / (R_3 + R_4)$$

- Now the circuit looks like R_1 in series with R_2 and R_{parallel}

2. Four resistors are connected to a voltage source as shown in the circuit photos diagram shown below



What are the current through the 3 Ω resistor and the voltage drop across the 4 Ω resistor, respectively?

- A. $\frac{3}{4}$ A and 8 V B. $\frac{4}{3}$ A and 8 V C. 2 A and $\frac{3}{4}$ V D. $\frac{2}{3}$ A and 4 V

Hint:

1) Identify series and parallel connections:

- The 3 Ω and 6 Ω resistors are in parallel
- The 1 Ω and 4 Ω resistors are in series with the parallel combination

2) Find equivalent resistance of the parallel part:

- $R_{\text{parallel}} = (3 \times 6) / (3 + 6)$

3) Find total circuit resistance:

- $R_{\text{total}} = 2 \Omega + 1 \Omega + 4 \Omega$

4) total current from the source:

- $I_{\text{total}} = V / R$

5) Voltage across the parallel combination:

- $V_{\text{parallel}} = I \times R_{\text{parallel}}$

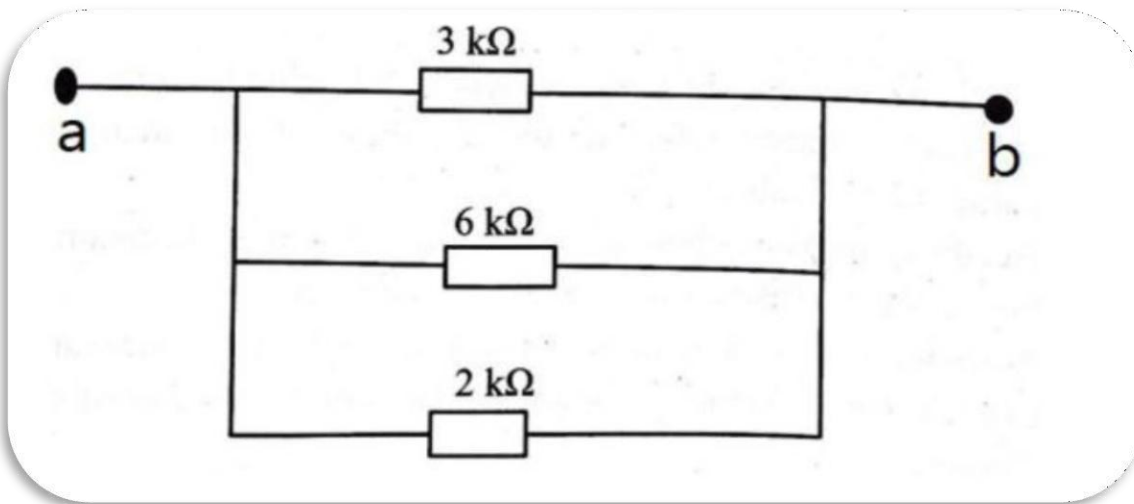
6) Current through the 3 Ω resistor:

- $I_{3\Omega} = V_{\text{parallel}} / R_{3\Omega}$

7) Voltage drop across the 4 Ω resistor:

- $V_{4\Omega} = I_{\text{total}} \times R_{4\Omega}$

3. Three resistors are connected between points a and b as shown figure below.



The effective resistance of the circuit is

A. 1.0 Ω

B. 1 k Ω

C. 11 Ω

D. 11k Ω

Hint:

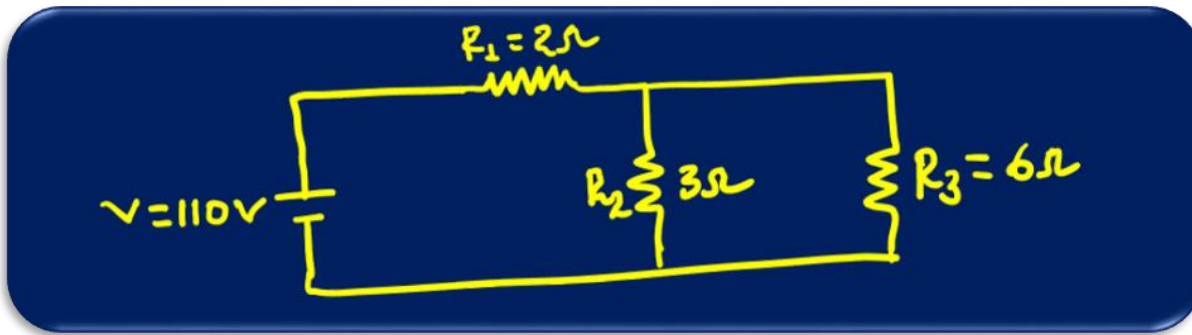
1. Identify the circuit connection

- The 3 k Ω , 6 k Ω , and 2 k Ω resistors are all connected between the same two points or nodes (a and b)
- Therefore, all three resistors are in parallel

2. Write the parallel resistance formula:

- $1 / R_{\text{eq}} = 1 / 3 \text{ k}\Omega + 1 / 6 \text{ k}\Omega + 1 / 2 \text{ k}\Omega$

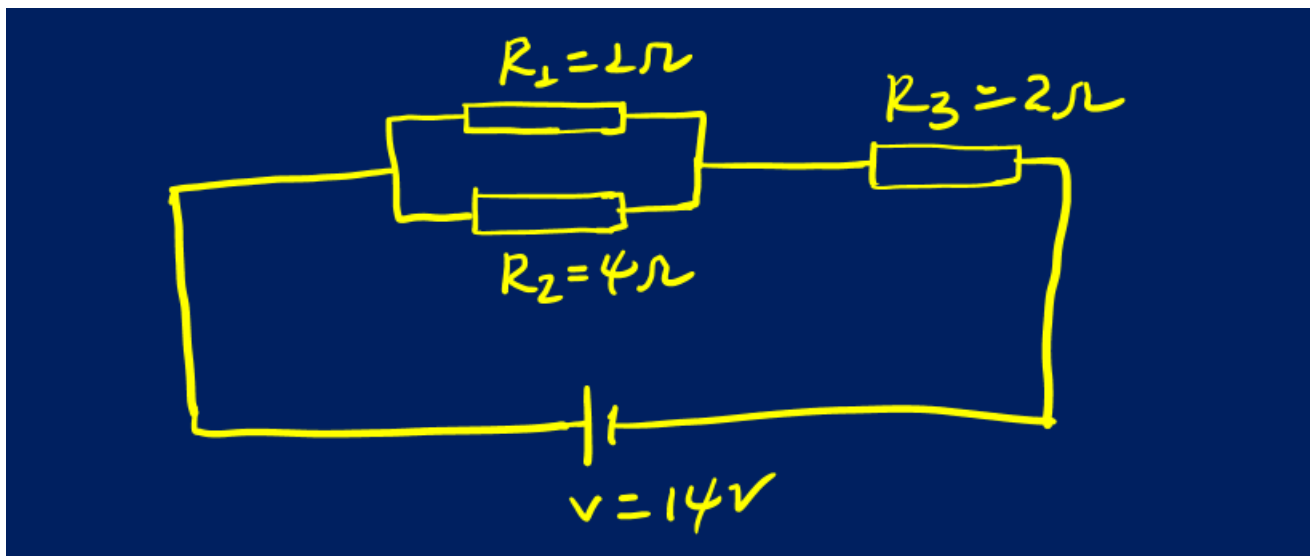
4. Three resistors connected in series have identical voltages labeled ΔV_1 , ΔV_2 , and ΔV_3 respectively. Which of the following expresses the value of the total voltage ΔV_T taken over the three resistors together?
- $\Delta V_T = \Delta V_1 + \Delta V_2 + \Delta V_3$
 - $\Delta V_T = \Delta V_1 = \Delta V_2 = \Delta V_3$
 - $V_T = (1/\Delta V_1 + 1/\Delta V_2 + 1/\Delta V_3)$
 - $V_T = (1/\Delta V_1 + 1/\Delta V_2 + 1/\Delta V_2)$
5. Three resistors are connected across a 110 V battery as shown. The potential difference across resistors R1, R2, and R3 are, respectively:



- 55 V, 55 V, 55 V
- 110 V, 25 V, 30 V
- 50 V, 30 V, 30 V
- 55 V, 82.5 V, 165 V

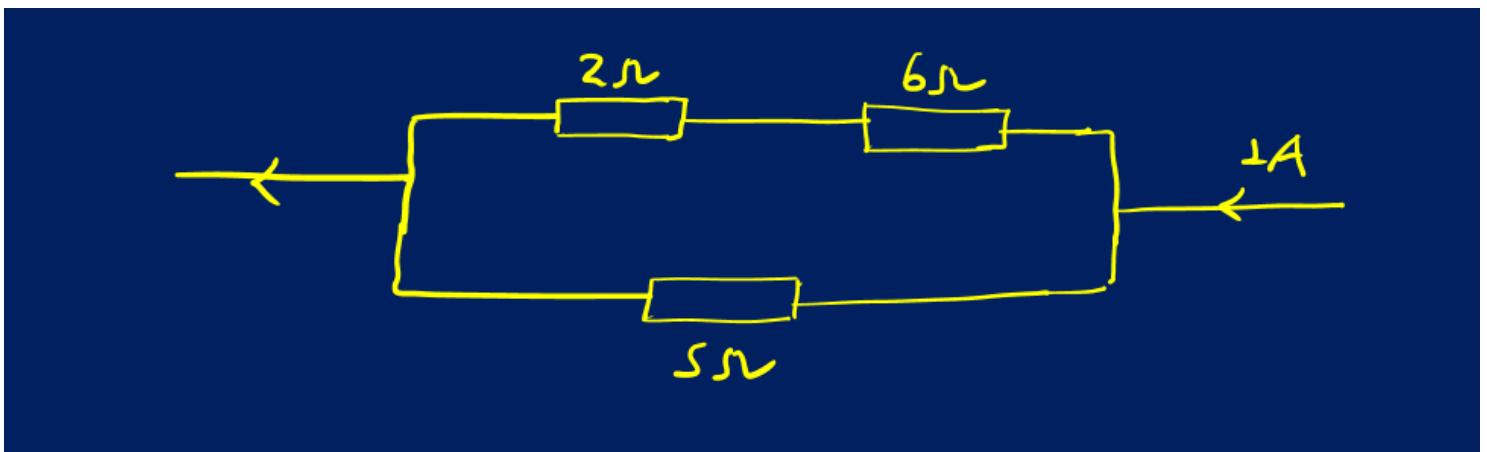
Hint:

- Identify series and parallel parts:
 - R_2 (3 Ω) and R_3 (6 Ω) are connected in parallel
 - This parallel combination is in series with R_1 (2 Ω)
- Find equivalent resistance of R_2 and R_3 (parallel):
 - $1/R_p = 1/3 + 1/6$
- Find total resistance of the circuit:
 - $R_{total} = R_1 + R_p$
- Find total current from the battery:
 - $I_{total} = V / R_{total}$
- Voltage across R_1 :
 - $V_1 = I_{total} \times R_1$
- Voltage across R_2 and R_3 :
 - R_2 and R_3 are in parallel, so voltage is the same across both which is R_2 and R_3 act like 1 resistor.
 - $V_{parallel} = I_{total} \times R_p$
- Two resistors $R_1 = 1\Omega$ and $R_2 = 4\Omega$ are connected in parallel to each other and their combination is connected in series with a third resistor $R_3 = 2\Omega$. The whole combination is connected to a voltage source of 14 V. What is the potential difference across R_1 ?



- A. 5 V B. 4V C. 10V D. 14V

7. A current of 1A flows in the network of resistors shown in the figure below.



The potential drop across a 6Ω resistor is

- A. 0.77V B. 0.38 C. 2.31V D. 3.14V

Answers:

1. C 2. B 3. A 4. A 5. A 6. B 7. C

➤ **Define the terms Galvanometer, Ammeter and voltmeter**

Galvanometer:

- A galvanometer is a sensitive instrument used to detect and measure small electric currents in a circuit.
- Key points:
 - ✓ It shows the presence and direction of current.
 - ✓ It is mainly used in laboratory measurements.
 - ✓ It cannot measure very large currents directly.

Ammeter:

- An ammeter is a device used to measure current flowing in a circuit.
- To measure the current flow in a circuit, the ammeter must be connected in series with the resistor.
- The internal resistance of an ammeter should be as small as possible, so that little energy is dissipated in it.
- Unit of current measured is ampere (A).

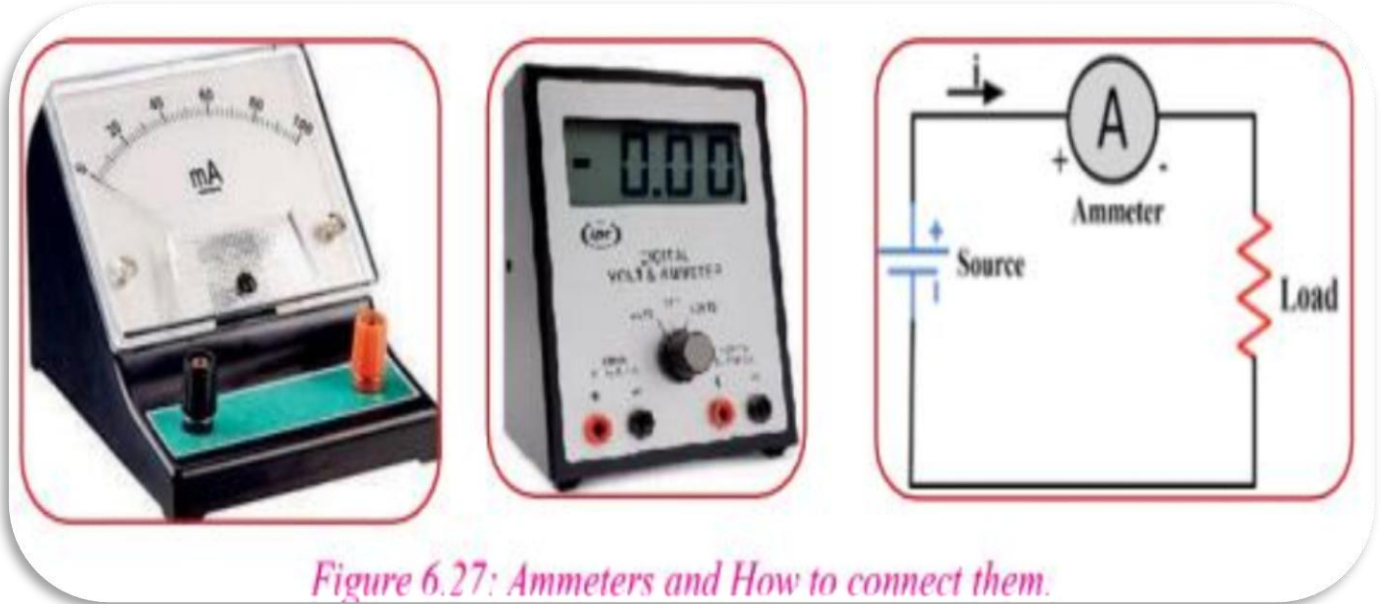
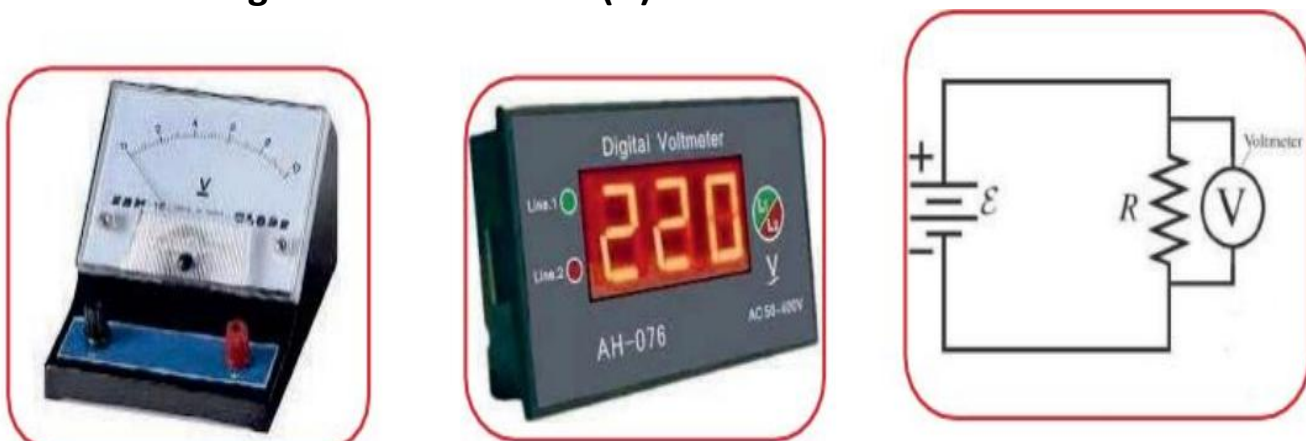


Figure 6.27: Ammeters and How to connect them.

Voltmeter:

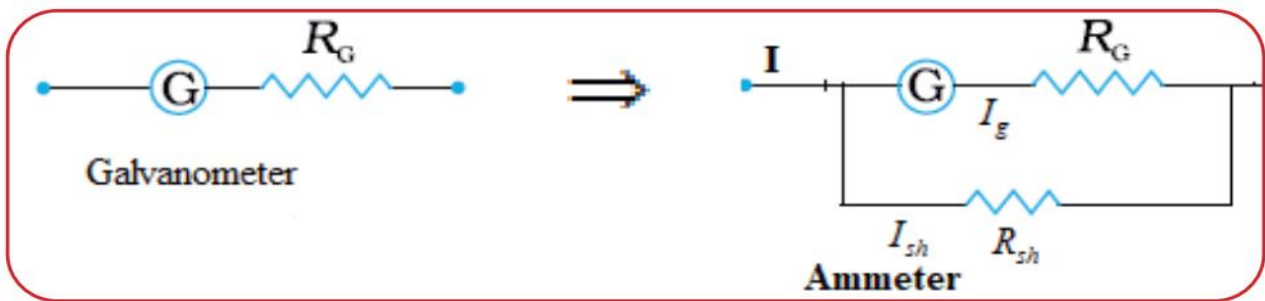
- Voltmeter is a device used to measure the potential difference between two points in the circuit.
- It is connected in parallel across a component.
- Voltmeters should have a very high resistance to take as little current as possible.
- The ideal resistance of a voltmeter would be infinite.
- Unit of voltage measured is volt (V).



➤ **Describe how to convert galvanometer to a voltmeter and ammeter.**

Converting a galvanometer to an ammeter

- A galvanometer can detect only small currents.
- To measure large current, it is converted into an ammeter.
- How?
 - ✓ A very small resistance called a shunt resistor is connected in parallel with the galvanometer. Why?
 - ✓ Most of the current passes through the shunt.
 - ✓ Only a small safe current passes through the galvanometer.
 - ✓ This protects the galvanometer from damage.
- Key Point:
 - ✓ Ammeter must have very low resistance.
 - ✓ Therefore, the parallel shunt reduces total resistance.



Let R_g be the resistance of the galvanometer and I_g be the current for full scale deflection in the galvanometer. The value of the shunt resistance required to convert the galvanometer into an ammeter is,

$$\begin{aligned}V_g &= V_{sh} \\(I - I_g)R_{sh} &= I_g R_g \\R_{sh} &= \left(\frac{I_g}{I - I_g} \right) R_g\end{aligned}$$

Example 6.14

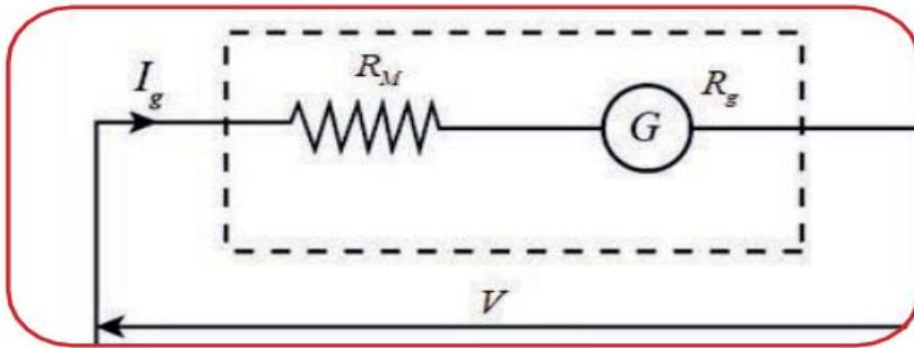
A galvanometer of full-scale deflection 5 mA is to be converted into a 10 A ammeter. If its coil has a resistance of 50 Ω , what value shunt must be fitted?

Solution:

$$\begin{aligned}R_{sh} &= \left(\frac{I_g}{I - I_g} \right) R_g \\R_{sh} &= \left(\frac{5 \times 10^{-3}}{10 - 5 \times 10^{-3}} \right) 50 = \left(\frac{0.005}{10 - 0.005} \right) 50 = \left(\frac{0.005}{9.995} \right) 50 = 0.025 \Omega\end{aligned}$$

Converting a galvanometer to a Voltmeter

- A galvanometer can be converted into voltmeter by connecting with it with a very high resistance called multiplier in series with it.
- Why?
 - ✓ The large resistance limits the current entering the galvanometer.
 - ✓ This allows measurement of high voltages safely.
- Key Point:
 - ✓ Voltmeter must have very high resistance.
 - ✓ Therefore, the series resistor increases total resistance.



$$V = I_g R_M + I_g R_g = I_g (R_M + R_g)$$

$$\therefore R_M + R_g = \frac{V}{I_g}$$

$$R_M = \frac{V}{I_g} - R_g$$

Example 6.14

A galvanometer has a resistance of $40\ \Omega$ and is of $3\ \text{mA}$ full scale deflection. How would you modify it to a $0 - 10\ \text{V}$ voltmeter.

Solution:

$$V = I_g (R_g + R_{sh})$$

$$R_{sh} = \frac{V}{I_g} - R_g = \frac{10}{5 \times 10^{-3}} - 40$$

$$R_{sh} = 1960\ \Omega$$

UEE Sample Questions:

1. Which one of the following statements is NOT correct about galvanometer?
 - A. It is used to measure small amount of current
 - B. It has infinite resistance
 - C. It can be used to measure voltage if shunted with large load in series
 - D. Its working principle is the same as that of the electric motor.
2. Which of the following statement is correct?
 - A. Galvanometer can be converted to voltmeter of different scale by connecting low values resistance in parallel
 - B. Low valued internal resistance increases accuracy of voltmeter
 - C. High valued internal resistance increases the accuracy of ammeter
 - D. Galvanometer can be converted to ammeter of different scale by connecting variety of low valued shunt resistance in parallel
3. Which of the following is true about galvanometer?
 - A. To use a galvanometer as an ammeter that can read large voltages, we connect a small resistance in series with the galvanometer.
 - B. A galvanometer can be converted to an ammeter that can read large currents by connecting a small resistance in parallel with it; and can be converted to a voltmeter by connecting a large resistance in series with galvanometer.
 - C. To use a galvanometer as an ammeter that can measure large currents, we need to increase its resistance by connecting a large resistance in series with the galvanometer.
 - D. A galvanometer can be converted to a voltmeter by connecting a small resistance in parallel with the galvanometer.
4. A galvanometer of full-scale deflection 10mA is to be converted into a 0-10.0A ammeter. If its coil has a resistance of $100\ \Omega$, then what value of shunt resistance must be fitted?
 - A. $0.1\ \Omega$
 - B. $100\ \Omega$
 - C. $9.99\ \Omega$
 - D. $0.999\ \Omega$
5. A galvanometer has an internal resistance of $100\ \Omega$ and deflects full scale for 1mA. The shunt resistance required to use it as an ammeter to read currents up to 1.0 A, and the resistance required to use it as a voltmeter to give a full scale deflection 100 V are, respectively,
 - A. $1.00\ \Omega$ and $10^5\ \Omega$.
 - B. $0.1\ \Omega$ and $100\ \text{k}\Omega$.
 - C. $10\ \text{m}\ \Omega$ and $10^4\ \Omega$.
 - D. $1\ \text{m}^2$ and $9.9 \times 10^4\ \Omega$.

Answers: 1. B 2.D 3.B 4. A 5. B

➤ **describe the principles of potentiometer and Wheatstone bridge.**

- A potentiometer works on the principle that the potential drop along a uniform wire is directly proportional to the length of the wire when a constant current flows through it.
 - ✓ Meaning:
 - Longer wire length → larger voltage drop
 - Shorter wire length → smaller voltage drop
- The potentiometer is used:
 - ✓ to measure the emf of a cell
 - ✓ to compare the emf of different cells
 - ✓ to measure internal resistance as a variable resistor

Potentiometer to measure the emf of a cell

- How it works:
 - ✓ A long uniform wire is connected to a battery called the driver cell.
 - ✓ The cell whose emf is to be measured is connected with a galvanometer and jockey.
 - ✓ The jockey is moved along the wire until the galvanometer shows zero deflection. This point is called the balance point.
- At the balance point:
 - ✓ No current flows through the galvanometer.
 - ✓ The emf of the cell equals the potential drop along the balancing length of the wire.

✓ Formula:

$$E_x = (AY / AB) \times E_0$$

Where:

E_x = unknown emf of the cell

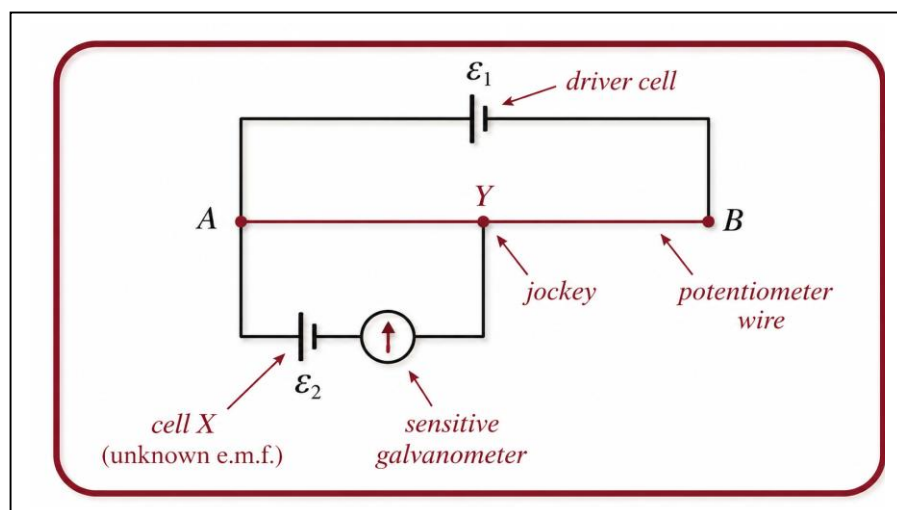
E_0 = emf of the driver cell

AY = balancing length

AB = total length of wire

• Uses:

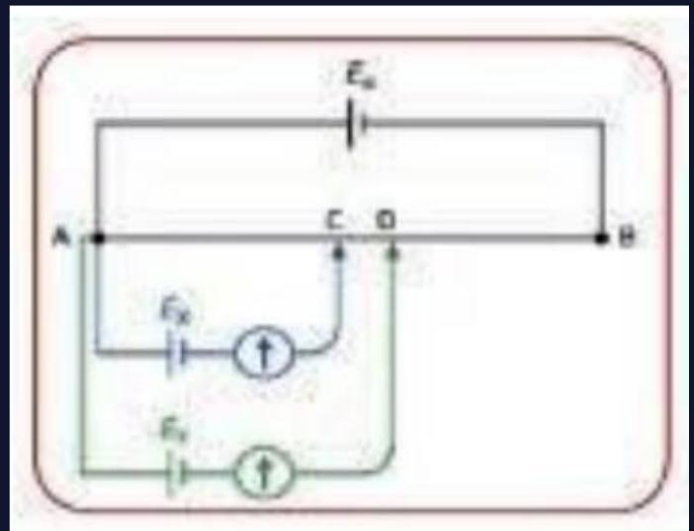
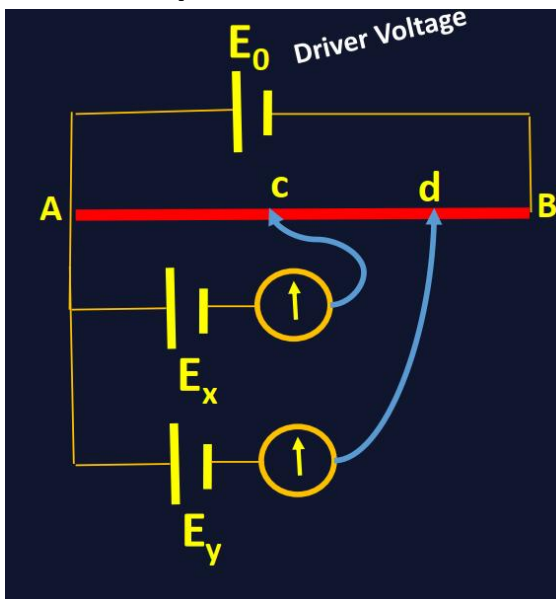
- ✓ To measure emf accurately
- ✓ To compare emf of cells
- ✓ To measure internal resistance of a cell



Potentiometer to compare the emf of two cells

How it works:

- Two cells, EX and EY, are connected one after another to the potentiometer circuit.
- The jockey is moved along the wire to obtain the balance point for each cell.
- Let:
AC = balancing length for EX
AD = balancing length for EY
- Important Idea:
At balance point:
 - No current flows through the galvanometer.
 - The emf of each cell is proportional to its balancing length.
- Therefore:
$$E_X / E_Y = AC / AD$$
- Meaning:
 - ✓ The ratio of the emfs equals the ratio of their balancing lengths.
- Uses:
 - ✓ To compare emf of two cells accurately
 - ✓ To determine unknown emf
 - ✓ To perform accurate electrical measurements



Resistance can be measured directly using an ohmmeter.

Experimentally, resistance is measured using the following two methods:

1. Ammeter–Voltmeter Method
2. Wheatstone Bridge Method

1. Ammeter–Voltmeter Method

- Principle:

This method uses Ohm's law.

Formula: $R = V / I$

Where:

R = resistance

V = voltage across the resistor

I = current through the resistor

- How it works:

- ✓ The resistor is connected in a circuit.
- ✓ An ammeter is connected in series to measure current.
- ✓ A voltmeter is connected in parallel to measure voltage.

- Steps:

1. Measure the current using the ammeter.
2. Measure the voltage using the voltmeter.
3. Use Ohm's law to calculate resistance.
4. The variable resistor is used to adjust the current and voltage as necessary

Advantages:

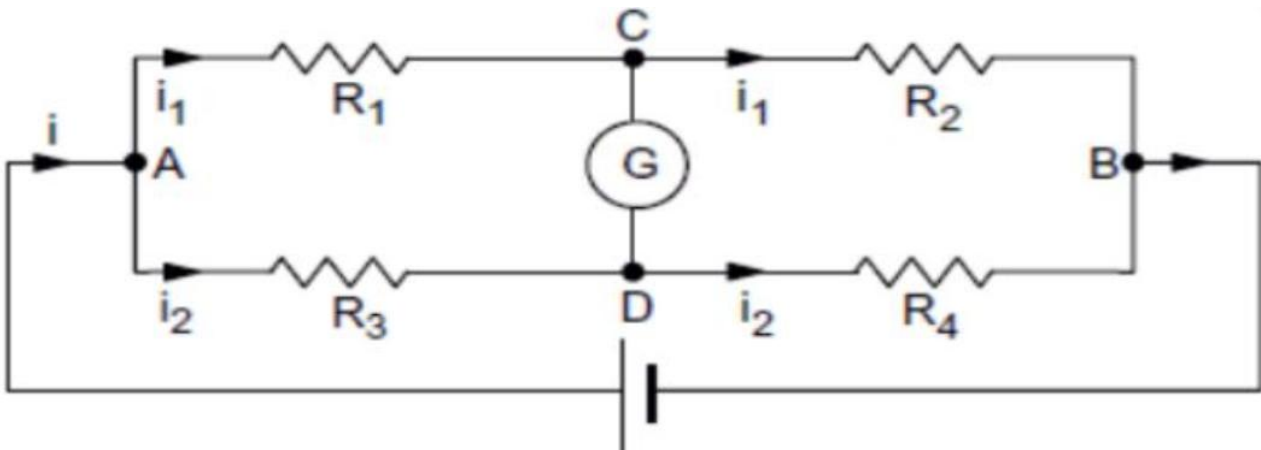
- Simple method
- Easy to perform

Disadvantage:

- Less accurate for very small resistances

2. Wheatstone bridge

- A Wheatstone bridge is an electrical circuit used to measure an unknown resistance accurately.
- It consists of:
 - ✓ Four resistors
 - ✓ A galvanometer
 - ✓ A battery or power source



- **Basic Idea:**
 - ✓ The Wheatstone bridge works by balancing two sides of a circuit.
- **When both sides are balanced:**
 - ✓ No current flows through the galvanometer.
 - ✓ The galvanometer shows zero deflection.
- This condition is called: **BALANCED CONDITION**
- **How it works:**
 - Current flows through the two branches.
 - The galvanometer checks whether both sides are electrically balanced.
 - 1. If: current flows through galvanometer → bridge is NOT balanced
 - 2. If: no current flows through galvanometer → bridge IS balanced
- **Condition for Balance:**

$$R1 / R2 = R3 / R4$$

OR

$$R1 \times R4 = R2 \times R3$$
- **Meaning of the Formula:**
 - ✓ The ratio of resistances on one side must equal the ratio on the other side.
 - ✓ When this happens: potential difference across the galvanometer is zero therefore no current passes through it
- **Finding Unknown Resistance: If R4 is unknown:**

$$R4 = (R2 \times R3) / R1$$
- The Wheatstone bridge is very accurate for measuring small or unknown resistances.

➤ Explain Potential Divider

THE POTENTIAL DIVIDER

A potential divider consists of two or more resistors in series with each other and with a source of fixed potential difference.

The potential difference of the source is divided between the components in the circuit, as they are in series with each other.

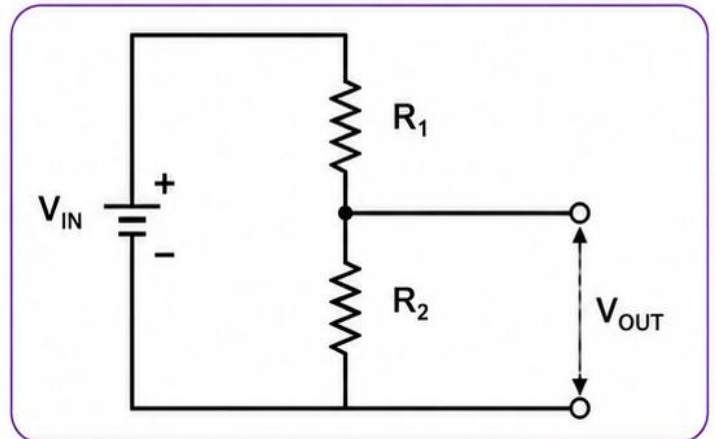


Figure 6.34: Potential divider circuit

FORMULAS FOR THE POTENTIAL DIVIDER CIRCUIT

- 1 Total resistance of the combination:

$$R_T = R_1 + R_2$$

- 2 Current through the resistors:

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

- 3 Potential drop across resistor R_1 :

$$V_1 = IR_1 = \left(\frac{R_1}{R_1 + R_2} \right) V$$

- 4 Potential drop across resistor R_2 :

$$V_2 = IR_2 = \left(\frac{R_2}{R_1 + R_2} \right) V$$

★ KEY TAKEAWAYS

- The input voltage V_{IN} is divided between R_1 and R_2 .
- The same current flows through both resistors.
- The voltage division depends only on the resistor ratio.



PURPOSE

The purpose of a potential divider is to obtain a desired output voltage (V_{OUT}) that is a fraction of the input voltage (V_{IN}).

$$V_{OUT} = V_2 = \left(\frac{R_2}{R_1 + R_2} \right) V_{IN}$$



APPLICATIONS

- ◆ Used to scale down (or set) voltages.
- ◆ Biasing in transistor circuits.
- ◆ Signal conditioning.
- ◆ Measuring unknown voltages.
- ◆ Volume control in audio devices.



NOTES

- ✓ Resistors R_1 and R_2 must be in series.
- ✓ V_{OUT} is taken across R_2 (between the junction of R_1 and R_2 and ground).
- ✓ The output voltage depends on the ratio of the resistors, not their absolute values.

➤ **State and apply Kirchhoff's laws.**

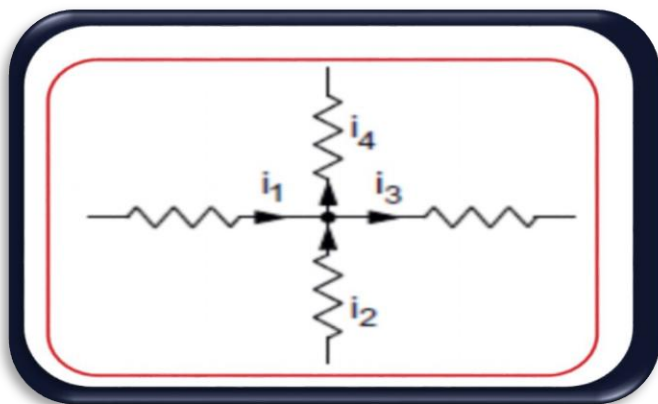
- Kirchhoff's Rules are two fundamental principles that describe the behavior of electric currents in electrical circuits.
 - ✓ Kirchhoff's First Rule (Junction rule)
 - ✓ Kirchhoff's Second Rule (Loop Rule)

Kirchhoff's First Rule (Junction rule)

- Kirchhoff's first rule states that, at any junction in a circuit, the total current entering the junction is equal to the total current leaving the junction.
- The first law of Kirchhoff's is based on the conservation of charge.
- This rule is also called:
 - ✓ Junction Rule
 - ✓ Current Law (KCL)

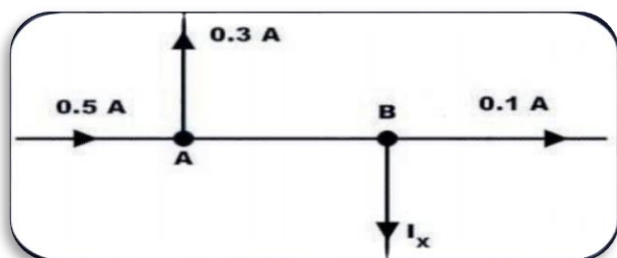
What is a Junction?

- A junction is a point in an electric circuit where three or more wires meet.
- Electric charge cannot accumulate at a junction. Whatever charge enters per second must leave per second. This is based on: Conservation of charge
- Mathematically:
 $\Sigma I_{in} = \Sigma I_{out}$
Meaning: Sum of incoming currents equals sum of outgoing currents.



$$i_1 + i_2 = i_3 + i_4$$

Example: The figure shown below is part of an electric circuit. Determine the value of the unknown current I_x .



$$0.5 = 0.3 + I_{AB}, I_{AB} = 0.2$$

$$I_{AB} = 0.1 + I_x$$

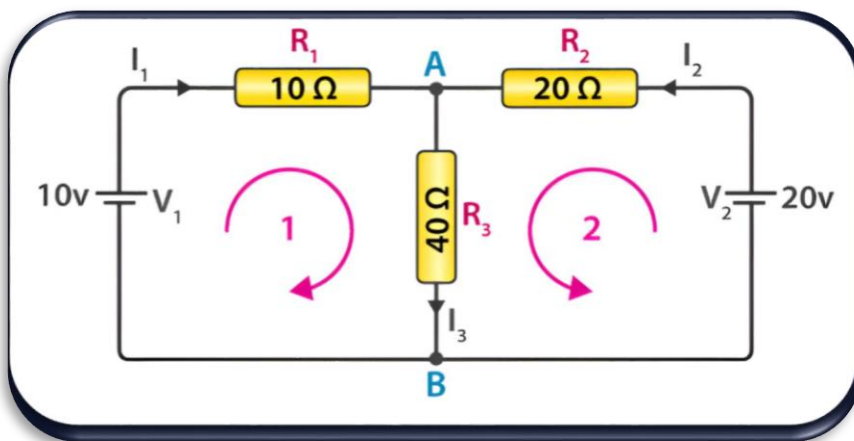
$$0.2 = 0.1 + I_x$$

$$I_x = 0.1$$

Kirchhoff's Second Rule (Loop Rule)

- For any complete loop of a circuit, the sum of the emfs round the loop is equal to the sum of the potential drops around the loop.
- It follows from the law of conservation of energy.
- Meaning:
 - ✓ Energy gained by charges from batteries must equal the energy lost in resistors and other components.
- This rule is also called:
 - ✓ Loop Rule
 - ✓ Voltage Law (KVL)
- Mathematical Form:
 $\Sigma V = 0$ OR
Sum of emfs = Sum of voltage drops
- What is a Closed Loop?
 - ✓ A closed loop is a complete path in a circuit through which current flows and returns to the starting point.
- Voltage Changes in a Loop:
 1. Across a Battery:
 - Moving from negative to positive terminal
→ voltage increases (+ emf)
 2. Across a Resistor:
 - Voltage decreases in the direction of current
→ voltage drop (- IR)

Example 1: find I_1 , I_2 , I_3 and voltage drop across each resistor



CIRCUIT DIAGRAM

GIVEN:
 $R_1 = 10\ \Omega, \quad R_2 = 20\ \Omega, \quad R_3 = 40\ \Omega$
 $V_1 = 10\ \text{V}, \quad V_2 = 20\ \text{V}$

USING KIRCHHOFF'S RULES

At junction A (KCL): $I_3 = I_1 + I_2$

Left loop (KVL):

$$10 - 10I_1 - 40I_3 = 0$$

$$\Rightarrow 10I_1 + 40I_3 = 10$$

$$\Rightarrow I_1 + 4I_3 = 1 \quad \dots(1)$$

From (1):

$$I_1 = 1 - 4I_3$$

$$I_1 = 1 - 4\left(\frac{2}{7}\right)$$

$$I_1 = -\frac{1}{7}\ \text{A}$$

$$I_1 \approx -0.143\ \text{A}$$

Right loop (KVL):

$$20 - 20I_2 - 40I_3 = 0$$

$$\Rightarrow 20I_2 + 40I_3 = 20$$

$$\Rightarrow I_2 + 2I_3 = 1 \quad \dots(2)$$

From (2):

$$I_2 = 1 - 2I_3$$

$$I_2 = 1 - 2\left(\frac{2}{7}\right)$$

$$I_2 = \frac{3}{7}\ \text{A}$$

$$I_2 \approx 0.429\ \text{A}$$

Substitute in $I_3 = I_1 + I_2$:

$$I_3 = (1 - 4I_3) + (1 - 2I_3)$$

$$I_3 = 2 - 6I_3$$

$$7I_3 = 2 \Rightarrow I_3 = \frac{2}{7}\ \text{A}$$

$$I_3 \approx 0.286\ \text{A}$$

FINAL CURRENTS

$\rightarrow I_1 = -0.143\ \text{A}$

$\rightarrow I_2 = 0.429\ \text{A}$

$\downarrow I_3 = 0.286\ \text{A}$

(negative sign means I_1 flows opposite to the assumed direction)

VOLTAGE DROP ACROSS RESISTORS

Across R_1 : $V_{R1} = I_1 R_1 = (-0.143)(10) = -1.43\ \text{V} \rightarrow$ Magnitude = 1.43 V

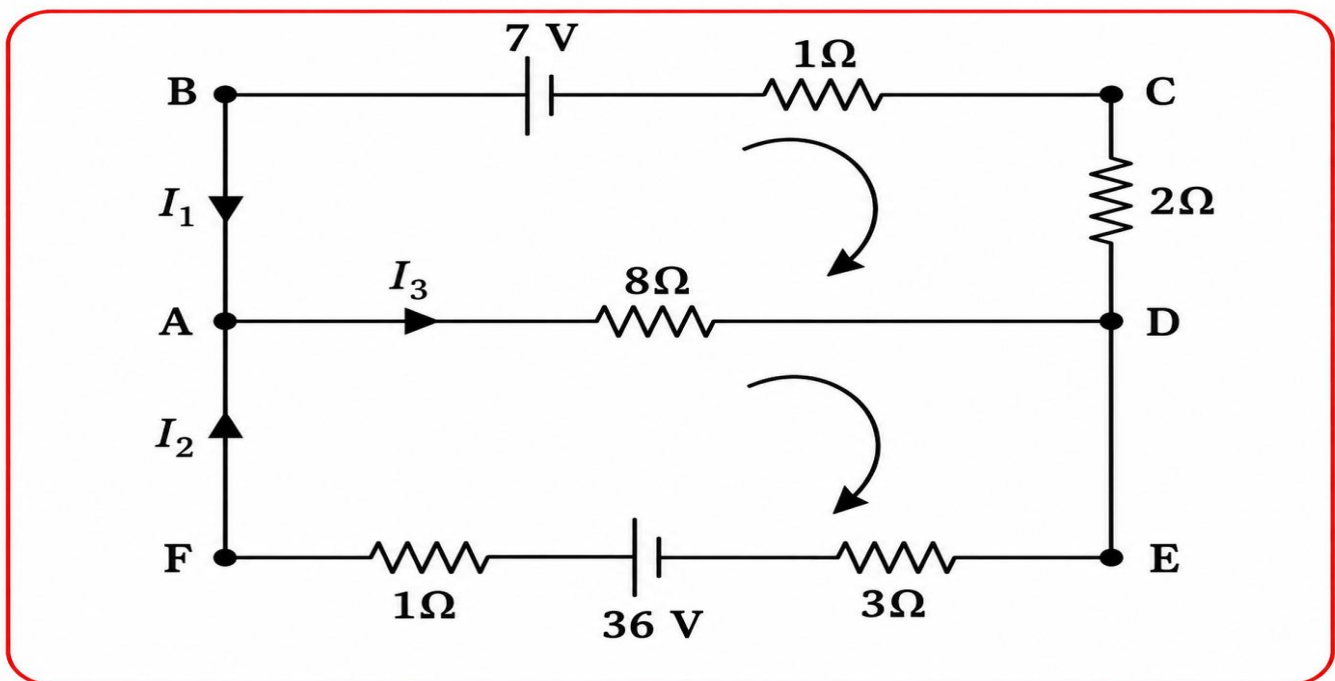
Across R_2 : $V_{R2} = I_2 R_2 = (0.429)(20) =$ 8.58 V

Across R_3 : $V_{R3} = I_3 R_3 = (0.286)(40) =$ 11.44 V

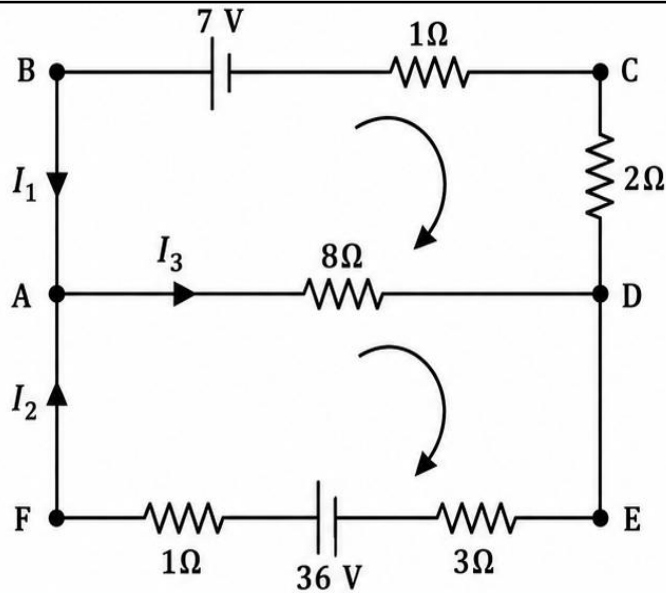
• Voltage drop across $R_1 = 1.43\ \text{V}$
 • Voltage drop across $R_2 = 8.58\ \text{V}$
 • Voltage drop across $R_3 = 11.44\ \text{V}$

Example 2:

Find the currents I_1 , I_2 and I_3 in the circuit shown below.



Answer



1. KIRCHHOFF'S 1ST RULE (KCL)

At junction A:

$$I_3 = I_1 + I_2 \quad \dots (1)$$

2. KIRCHHOFF'S 2ND RULE (KVL)

(a) Upper Loop $A \rightarrow B \rightarrow C \rightarrow D \rightarrow A$ (clockwise)

$$+7 - 1I_1 - 2I_1 - 8I_3 = 0$$

$$7 - 3I_1 - 8I_3 = 0$$

$$3I_1 + 8I_3 = 7 \quad \dots (2)$$

(b) Lower Loop $A \rightarrow F \rightarrow E \rightarrow D \rightarrow A$ (clockwise)

$$+36 - 1I_2 - 3I_2 - 8I_3 = 0$$

$$36 - 4I_2 - 8I_3 = 0$$

$$4I_2 + 8I_3 = 36 \quad \dots (3)$$

3. SOLVE USING KCL AND KVL EQUATIONS

From (1): $I_3 = I_1 + I_2$

Substitute in (2) and (3):

In (2): $3I_1 + 8(I_1 + I_2) = 7$

$$3I_1 + 8I_1 + 8I_2 = 7$$

$$11I_1 + 8I_2 = 7 \quad \dots (4)$$

In (3):

$$4I_2 + 8(I_1 + I_2) = 36$$

$$4I_2 + 8I_1 + 8I_2 = 36$$

$$8I_1 + 12I_2 = 36 \quad \dots (5)$$

Solve equations (4) and (5):

$$11I_1 + 8I_2 = 7 \quad \dots (4)$$

$$8I_1 + 12I_2 = 36 \quad \dots (5)$$

Multiply (4) by 3:

$$33I_1 + 24I_2 = 21$$

Multiply (5) by 2:

$$16I_1 + 24I_2 = 72$$

$$\text{Subtract: } 17I_1 = -51$$

$$I_1 = -3 \text{ A}$$

Substitute $I_1 = -3$ in (4):

$$11(-3) + 8I_2 = 7$$

$$-33 + 8I_2 = 7$$

$$8I_2 = 40$$

$$I_2 = 5 \text{ A}$$

From (1): $I_3 = I_1 + I_2$

$$I_3 = (-3) + 5$$

$$I_3 = 2 \text{ A}$$

4. FINAL ANSWERS

(Directions as shown in the circuit)

$$I_1 = -3 \text{ A}$$

(Opposite to arrow)

$$I_2 = 5 \text{ A}$$

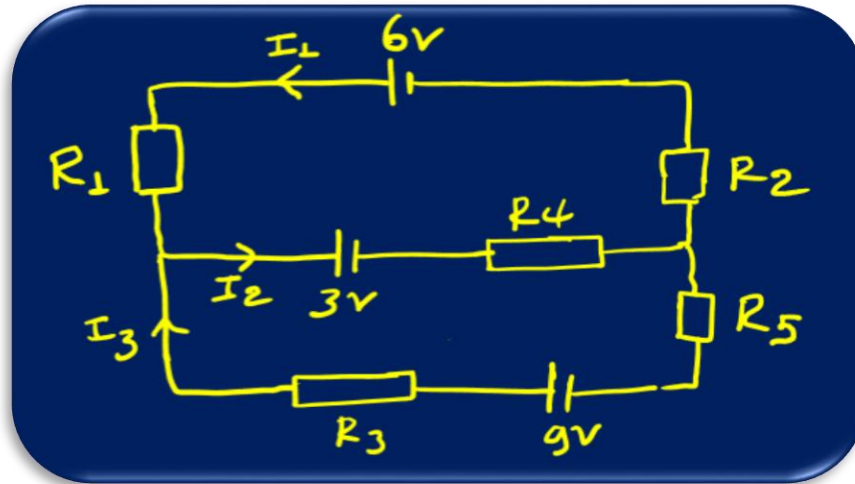
$$I_3 = 2 \text{ A}$$

Sample UEE Questions:

2. According to Kirchhoff's junction rule,

- A. Charges can disappear or appear at the junction.
- B. The amount of electric charge entering a junction is equal to the amount leaving the junction.
- C. The amount of electric charge flowing into a junction is greater than the amount flowing out of the junction.
- D. The amount of electric charge flowing into a junction is less than the amount flowing out of the junction.

3. In the circuit shown below, each resistor has a value of 30Ω . what is the value of the current through R_4 ?



A. 0.75A

B. 1.0A

C. 0.625A

D. 0.125A

Answers: 1. B 2. A

6.6 Capacitors and Capacitance

➤ **Define the terms capacitors, capacitances, dielectric.**

Capacitors:

- A capacitor is an electrical device used to store electric charge, and electric energy.
- It usually consists of:
 - ✓ Two conducting plates
 - ✓ Separated by an insulating material called dielectric
- Key points:
 - ✓ Capacitors store charge temporarily.
 - ✓ They are used in electronic circuits.

Capacitances

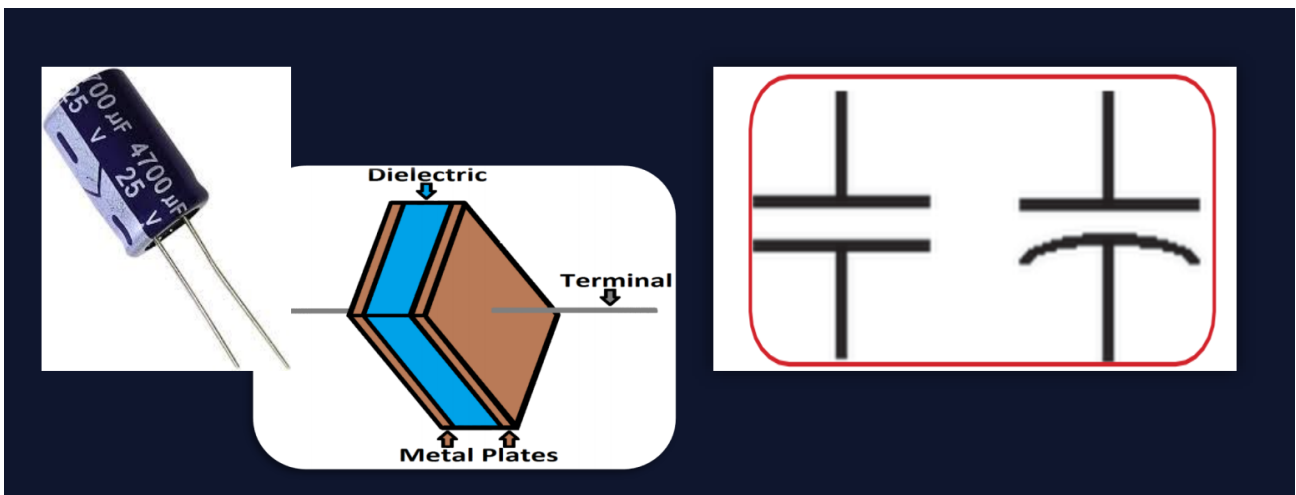
- Capacitance is the ability of a capacitor to store electric charge.
- It is defined as the ratio of charge stored on a conductor to the potential difference across it.
- Formula:

$$C = Q / V$$
 Where: C = capacitance, Q = charge, V = potential difference
- It is independent of Q and V but depends on geometrical factors.
- SI Unit: farad (F)
- Small values of capacitances are measured in micro, Nano and Pico farads.
 $1\mu\text{F} = 10^{-6} \text{ F}$, $1 \text{ nF} = 10^{-9} \text{ F}$, and $1 \text{ pF} = 10^{-12} \text{ F}$

Dielectric.

- A dielectric is an insulating material placed between the plates of a capacitor.
- Examples: Air, Paper, Glass, Plastic, Mica
- Functions of a dielectric:
 - ✓ Prevents the plates from touching
 - ✓ Increases capacitance
 - ✓ Reduces energy loss
- Key point:
 - ✓ A dielectric does not allow current to pass through it.

Device and symbol



➤ Explain the effect of inserting dielectric in the gap between the plates of a capacitor.

Effect of inserting dielectric:

1. Capacitance Increases

- When a dielectric is inserted between the plates, the capacitance of the capacitor increases.
- Reason:
 - ✓ The dielectric reduces the effective electric field between the plates, allowing the capacitor to store more charge.
 - ✓ New capacitance:

$$C = kC_0$$

Where:

C = new capacitance

C₀ = original capacitance

k = dielectric constant

2. More Charge Can Be Stored

- For the same applied voltage:
 - ✓ the capacitor stores more charge.
 - ✓ Since:
 $Q = CV, C = Q/V$
 - ✓ If capacitance increases, charge stored also increases.

3. Electric Field Decreases

- The dielectric weakens the electric field between the plates.
- Reason:
 - ✓ Molecules inside the dielectric become polarized, producing an opposing electric field.

4. Potential Difference Decreases

- If the capacitor is isolated:
 - ✓ Inserting dielectric decreases, the voltage across the plates
 $V = Ed$, electric field decreases means potential difference also decrease

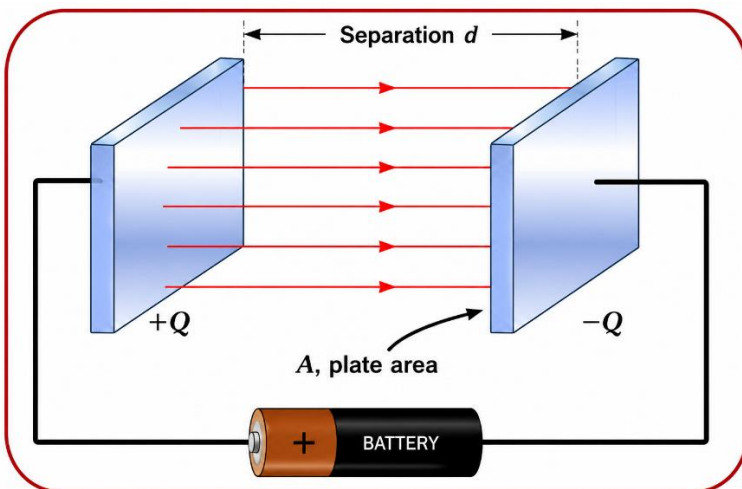
5. Energy Storage Changes

- Because capacitance increases:
 - ✓ the capacitor can store more electrical energy.

Parallel-plate Capacitor

- A parallel-plate capacitor is a capacitor made of two large conducting plates placed parallel to each other and separated by a small distance called the gap.
- The space between the plates may contain:
 - ✓ Air
 - ✓ Vacuum
 - ✓ or a dielectric material

- Structure of a Parallel-Plate Capacitor



- One plate stores positive charge.
- The other plate stores equal negative charge.
- Charges do not pass across the gap.

How It Works

When connected to a battery:

1. Electrons leave one plate
→ making it positively charged.
2. Electrons accumulate on the other plate
→ making it negatively charged.
3. An electric field forms between the plates.
4. Energy becomes stored in the electric field.

Main Purpose

A capacitor is used to:

- ✓ store electric charge
- ✓ store electrical energy temporarily

Capacitance of a Parallel-Plate Capacitor

$$C = \epsilon_0 A / d$$

Where:

C = capacitance

ϵ_0 = permittivity of free space

A = area of one plate

d = distance between the plates

- This equation gives the capacitance of two parallel plates in a vacuum.
- If a dielectric material of dielectric constant k is inserted between the plates, the equation for capacitance became:

$$C = k\epsilon_0 A / d$$

- The capacitance of a parallel plate capacitor depends on the size, distance of separation of the plates, and the medium between them.

Meaning of the Formula

1. Large Plate Area → Large Capacitance

- If plate area increases, more charge can be stored.
- Therefore, capacitance increases.
- Reason: Larger plates can hold more charges.

2. Small Distance → Large Capacitance

- If distance between plates decreases, attraction between opposite charges increases.
- Therefore: more charge is stored easily. So, capacitance increases.

3. Large Distance → Small Capacitance

- If plates are moved farther apart, electric attraction becomes weaker.
- Therefore: capacitance decreases.

4.dielectric constant (k)

- A dielectric constant, k , also called relative permittivity or specific inductive capacity.
- It tells us how much a dielectric material increases the capacitance of a capacitor. Measures the ability of a capacitor to store charge.
- It is the property of the dielectric.
- Larger $k \rightarrow$ Larger capacitance
- Smaller $k \rightarrow$ Smaller capacitance
- This means:
 - ✓ A material with high dielectric constant allows the capacitor to store more charge.
- It is equal to the ratio of the capacitance of a capacitor filled with the given material to the capacitance of an identical capacitor in a vacuum without the dielectric material.

$$K = \frac{\text{Capacitance with dielectric}}{\text{Capacitance without dielectric}} = \frac{C}{C_o}$$

Electric Field Between the Plates

- The electric field between parallel plates is uniform.
- Field lines move from positive plate to negative plate.
- Formula:

$$E = V / d$$

Where:

- ✓ E = electric field strength
- ✓ V = potential difference
- ✓ d = separation between plates

Note:

- The charge density on each of these surfaces has a magnitude.

$$\sigma = Q / A$$

- The electric field between the plates is given by the equation

$$E = \sigma / \epsilon_o = Q / A \epsilon_o$$

- The potential difference between each plate is given by:

$$V = Ed = Qd / A \epsilon_o$$

- Substituting this into our defining equation for capacitance we get:

$$C = Q/V = \epsilon_o A / d$$

- ✓ This equation gives the capacitance of two parallel plates in a vacuum

Dielectric strength

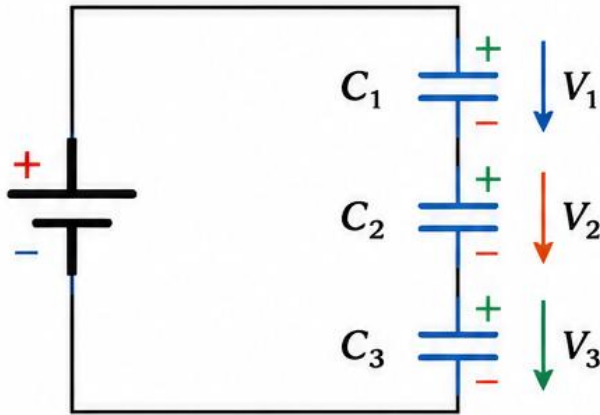
- Dielectric strength is the maximum electric field that a dielectric material can withstand without breaking down.
- Meaning:
 - ✓ If the electric field becomes greater than the dielectric strength, the dielectric loses its insulating property and conducts electricity.
- Unit: volt per meter (V/m)
- Different dielectric materials have different dielectric strengths.

➤ **Calculate the equivalent capacitance of capacitors connected in series and parallel.**

Combination of Capacitors

- Capacitors are manufactured in a certain standard capacitance and working voltages.
- But these values may not be compatible with the ones that we effectively need for a particular application.
- In such cases we obtain the desired values by combining capacitors in different ways.
- Two or more capacitors may be connected either in series or in parallel.

• CAPACITORS IN SERIES •



KEY IDEA

In series, all capacitors carry the same amount of charge. Thus, the magnitude of charge on all plates is the same.

$$Q_{\text{total}} = Q_1 = Q_2 = Q_3$$

1 VOLTAGE ACROSS EACH CAPACITOR

Therefore, if V_1 is the voltage across C_1 , V_2 is the voltage across C_2 , and V_3 is the voltage across C_3 , then

$$V_1 = \frac{Q}{C_1}, \quad V_2 = \frac{Q}{C_2} \quad \text{and} \quad V_3 = \frac{Q}{C_3}$$

$$V = V_1 + V_2 + V_3 \quad \rightarrow \quad V = \frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3} \quad \rightarrow \quad V = Q \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \right)$$

2 RELATION BETWEEN TOTAL VOLTAGE AND CHARGE

From which,

$$\frac{V}{Q} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

3 EQUIVALENT CAPACITANCE

The equivalent capacitance of the capacitors is given by

$$C_{\text{eq}} = \frac{Q}{V} \quad \Rightarrow \quad \frac{1}{C_{\text{eq}}} = \frac{V}{Q}$$

4 COMBINING THE EQUATIONS

Combining these equations, we get

$$\frac{1}{C_{\text{eq}}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

5 GENERAL FORMULA FOR n CAPACITORS IN SERIES

For any number of capacitors in series therefore,

$$\frac{1}{C_{\text{eq}}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \dots + \frac{1}{C_n}$$

LEGEND

C_1, C_2, C_3 : Capacitances

V_1, V_2, V_3 : Voltages across each capacitor

Q : Magnitude of charge on each capacitor

V : Total voltage across the combination

C_{eq} : Equivalent capacitance



IMPORTANT NOTES

✓ Same charge on all capacitors in series.

✓ Total voltage is the sum of the individual voltages.

CAPACITORS CONNECTED IN PARALLEL

1 CIRCUIT DIAGRAM

Consider three capacitors connected in parallel as shown in the figure.

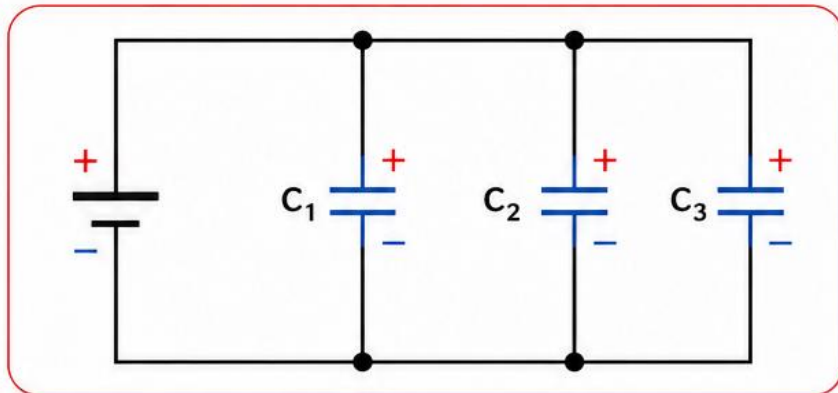


Figure 6.50: Three capacitors C_1 , C_2 and C_3 connected in parallel.

2 POTENTIAL DIFFERENCE

The same potential difference is provided for each capacitor.

$$V = V_1 = V_2 = V_3$$

3 TOTAL CHARGE

Charges Q_1 is stored on capacitor C_1 , and charge Q_2 on capacitor C_2 and so on. The total charge will therefore be:

$$Q = Q_1 + Q_2 + Q_3$$

4 RELATION BETWEEN CHARGE AND VOLTAGE

Since potential difference across the capacitors is the same, V . Then,

$$Q_1 = C_1V, Q_2 = C_2V \text{ and } Q_3 = C_3V$$

$$\Rightarrow Q = Q_1 + Q_2 + Q_3 = (C_1 + C_2 + C_3)V$$

5 EQUIVALENT CAPACITANCE

From which,

$$\frac{Q}{V} = C_1 + C_2 + C_3$$

But we know that $C_{eq} = \frac{Q}{V}$, which yields

$$C_{eq} = C_1 + C_2 + C_3$$

6 GENERAL FORMULA

For any number of capacitors connected in parallel then

$$C_{eq} = C_1 + C_2 + C_3 + \dots + C_n = \sum_{i=1}^n C_i$$



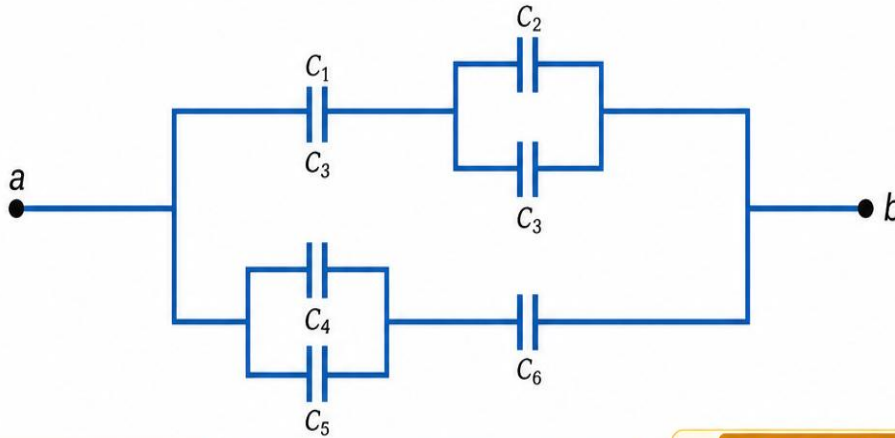
KEY POINTS

- ◆ In parallel connection:
Same **voltage** across all capacitors.
- ◆ Total charge is the **sum of charges** on individual capacitors.
- ◆ Equivalent capacitance is the **sum** of individual capacitances.

➤ **Solve problems related to capacitance of parallel plate capacitor.**

Equivalent capacitance for multiple capacitor circuits

In most electronic circuits, capacitors are connected in series, in parallel or in combinations of series and parallel as well. Consider a capacitor network shown in Figure 6.54.



1. Capacitors in Series

For capacitors $C_1, C_2, \dots, C_n$ in series,

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_n}$$

2. Capacitors in Parallel

For capacitors $C_1, C_2, \dots, C_n$ in parallel,

$$C_{eq} = C_1 + C_2 + \dots + C_n$$



Key Takeaway

Use series formula for capacitors connected end-to-end, parallel formula for side-by-side connections, and reduce complex networks step by step.

3. Given Network – Step by Step Reduction

- 1 Top right: C_2 and C_3 are in parallel

$$C_{23} = C_2 + C_3$$

- 2 Top branch: C_1 in series with $(C_2 + C_3)$

$$C_T = \frac{C_1(C_2 + C_3)}{C_1 + (C_2 + C_3)}$$

- 3 Bottom left: C_4 and C_5 are in parallel

$$C_{45} = C_4 + C_5$$

- 4 Bottom branch: $(C_4 + C_5)$ in series with C_6

$$C_B = \frac{(C_4 + C_5)C_6}{(C_4 + C_5) + C_6}$$

- 5 Final: The two branches are in parallel between a and b

$$C_{ab} = C_T + C_B$$

2.

Consider a parallel plate capacitor with plates of area 200 cm^2 and separated by a sheet of mica thickness 2mm and dielectric constant 6. If the capacitor is connected to 12V source, determine the charge stored on the plates of the capacitor.

Solution:

$$C = k\epsilon_0 \frac{A}{d} = 6 \times 8.85 \times 10^{-12} \text{ C}^2 / \text{N.m}^2 \times \frac{2 \times 10^{-2} \text{ m}^2}{2 \times 10^{-3} \text{ m}}$$

$$= 5.31 \times 10^{-10} \text{ F}$$

$$Q = CV = 5.31 \times 10^{-10} \text{ F} \times 12 \text{ V} = 6.37 \times 10^{-9} \text{ F} = 6.37 \text{ nF}$$

3.

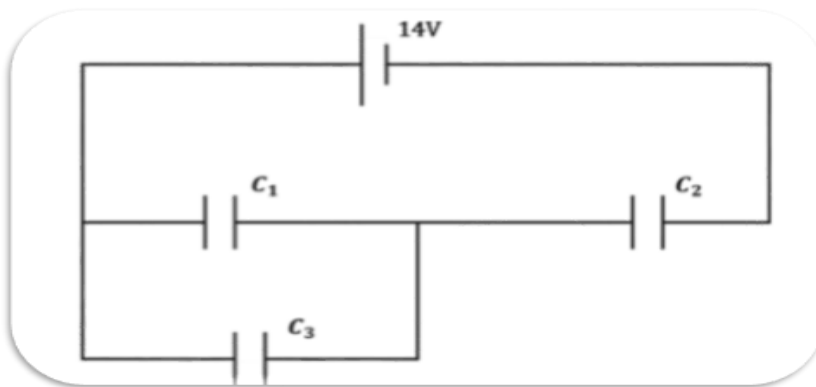
If a dielectric is inserted in the gap between the plates of an isolated capacitor, what are the effects on (a) the capacitance of a capacitor, (b) the potential difference between the plates of a capacitor, (c) amount of the charge stored on the plates, and (d) the electric field in the region between the plates of a capacitor.

Solution:

- When inserting a dielectric in a capacitor its capacitance always increases.
- Due to polarization the potential difference between the plates decreases.
- Since the capacitor is isolated (disconnected from the source) the amount of charge stored on the plates remains the same.
- From the equation $E = \Delta V / d$, the electric field in the region between the plates decreases.

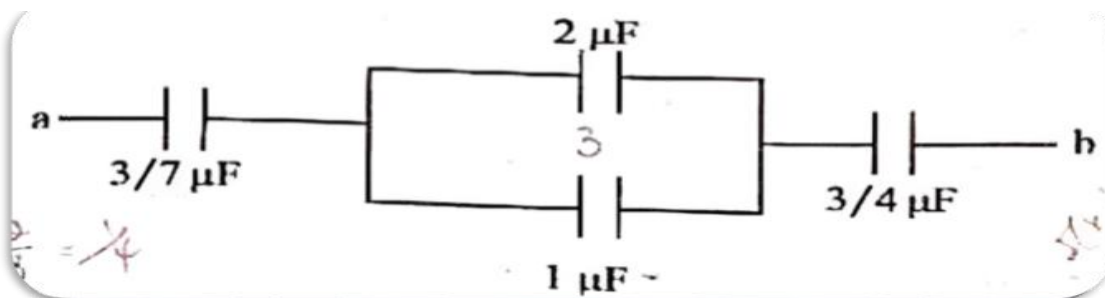
Sample UEE Questions:

1. Three capacitors $C_1 = 1 \mu\text{F}$, $C_2 = 4 \mu\text{F}$ and $C_3 = 2 \mu\text{F}$ are connected to a 14 V battery as shown in the figure. How much total charge will be stored in the capacitors?



- A. $22.1 \mu\text{C}$ **B. $24.00 \mu\text{C}$** C. $1.71 \mu\text{C}$ D. $12.00 \mu\text{C}$

2. Four capacitors are connected in a network as shown in the figure. The equivalent capacitance between terminals a and b (in μF) is:



- A. $3/4$ B. 12 C. 4 **D. $1/4$**

3. The capacitance of a parallel plate capacitor is $10\ \mu\text{F}$. If the distance between the plates is halved, keeping all other quantities constant, what is the new capacitance?

A. $0.2\ \mu\text{F}$

B. $5\ \mu\text{F}$

C. $10\ \mu\text{F}$

D. $20\ \mu\text{F}$

4. A sheet of polythene ($\epsilon_r = 2.3$) and $0.25\ \text{mm}$ thick is to be used in a capacitor by sandwiching it between two sheets of aluminum foil. What area must the sheets have if the capacitor is to have a capacitance of $0.5\ \mu\text{F}$?

A. $12\ \text{m}^2$

B. $6.14\ \text{m}^2$

C. $0.6\ \text{m}^2$

D. $0.12\ \text{m}^2$

5. When dielectric material is placed between two parallel metal plates in the presence of an electric field, they enable the plates to store

A. Much more charge at different potential energy

B. Much more charge at same potential energy

C. The same charge at the same potential difference

D. Much less charge at different potential energy

Assignment:

- apply the knowledge about electric circuits to explain household electric installation.

Thank You!!!!