
Theory: Electrostatics Explained

What is Electrostatics?

Electrostatics is the branch of physics that studies stationary electric charges and how they interact with each other. Common real-life examples include the shock from touching a metal doorknob after walking on carpet, and the way a balloon sticks to your hair after being rubbed.

1. Electric Charge

- A property of matter that causes it to experience a force when near another electrically charged object.
- Types: Positive and negative.
- SI Unit: Coulomb (C).
- Charges can be transferred by friction, conduction, or induction.
- Fundamental principles:
    - Like charges repel.
    - Unlike charges attract.

2. Properties of Electric Charge

- Quantization: The smallest unit of charge is that of an electron ($e = 1.6 \times 10^{-19}$ C).
- Conservation: Charge is neither created nor destroyed.
- Additivity: Total charge is the algebraic sum of individual charges.
- Invariance: Total charge remains the same in all reference frames.

3. Coulomb's Law

- Describes the force between two stationary point charges:
    - Formula: $F = \frac{1}{4\pi\varepsilon_0}\frac{|q_1 q_2|}{r^2}$
    - F: Force, q_1, q_2: Charges, r: Distance.
- Direction: Along the line joining the two charges.
- The force is much stronger than gravity on a subatomic scale.

4. Electrostatic Force vs. Gravitational Force

- Both are inverse square laws.
- Electrostatic force can be attractive or repulsive, while gravitation is always attractive.

5. Superposition Principle

- The total force on a charge is the vector sum of the forces due to all other charges individually.

6. Electric Field (E)

- Defined as force per unit charge: $E = \frac{F}{q}$.
- Field due to point charge: $E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$
- Direction: Away from positive, toward negative charge.

7. Electric Field Lines

- Visual representation of field strength and direction.
- Point away from positive and toward negative charges.
- Never intersect.

8. Electric Dipole

- Two equal and opposite charges separated by a fixed distance.
- Dipole Moment: $\vec{p} = q \times 2a$(direction from – to +).
- Important in understanding molecule behavior.

9. Dipole in Electric Field

- Experiences a force and torque.
- Torque: $\tau = pE\sin\ \theta$
- Potential energy: $U = -pE\cos\ \theta$

10. Gauss's Law

- The total electric flux through a closed surface is equal to the net charge inside divided by ε_0:

$$\oint \vec{E} \cdot d\vec{A} = \frac{q_{enclosed}}{\varepsilon_0}$$

- Useful for calculating fields of symmetric charge distributions (sphere, cylinder, plane).

11. Electric Potential (V)

- Work done per unit charge in bringing a charge from infinity to a point.
- $V = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}$for point charge.
- SI unit: Volt (V).

12. Potential Difference

- Difference in electric potential between two points: $V = W/q$
- Related to electric field: $E = -\frac{dV}{dr}$

13. Equipotential Surfaces

- Surfaces with the same potential at every point.
- No work done moving a charge along these surfaces.

14. Capacitance and Capacitors

- Capacitance (C): Ability of a system to store charge per unit voltage; $C = Q/V$.
- SI unit: Farad (F).
- Capacitors are practical devices for storing energy in electric fields.

15. Energy Stored in a Capacitor

- $U = \frac{1}{2}CV^2$
- Applies to any capacitor.

Everyday Applications

- Static cling, lightning, paint sprayers, inkjet printers, photocopiers, sensors.

Examples

Example 1: Rubbing a Balloon

Rubbing a balloon on hair transfers electrons to the balloon, giving it a negative charge. The balloon sticks to a wall due to attraction between unlike charges.

Example 2: Lightning

Lightning in clouds occurs due to charge separation. When the potential difference becomes large, air breaks down as an insulator, resulting in a spark—i.e., lightning.

Example 3: Electric Field of a Point Charge

If a charge of 2 Cis placed 1 maway in vacuum, the electric field at that point is:

$$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2} = 9 \times 10^9 \frac{2}{1^2} = 1.8 \times 10^{10} \text{ N/C}$$

Example 4: Parallel Plate Capacitor

A capacitor made from two parallel plates separated by an insulator can store charge for use in circuits, cameras, and filters.

Example 5: Using Gauss's Law

To find the electric field outside a uniformly charged sphere (like a metal ball), use Gauss's Law and symmetry for simple calculation.

Practice Questions

Basic Level (Board Exam)

1. State Coulomb’s law and give its mathematical form.
2. What is quantization of charge?
3. Define electric field intensity.
4. How does the force between two charges change if the distance is doubled?
5. What does the principle of superposition state?
6. What is an electric dipole?
7. Describe the direction of electric field lines around a positive charge.
8. Write the formula for potential at a point due to a point charge.
9. Explain what is meant by equipotential surfaces.
10. What is capacitance? Write its SI unit.

Moderate Level (Bridging Board & JEE)

11. Calculate the electrostatic force between two charges, 3 μC and 6 μC, placed 2 m apart in air.
12. A 1 μC charge experiences a force of 3 N in an electric field. What is the field strength at its location?
13. Find the potential at a distance of 5 cm from a 1 nC charge.
14. State Gauss’s law and use it to derive the electric field of a charged spherical shell.
15. A parallel plate capacitor has plates of area 1 m^2, separated by 1 mm in vacuum. Calculate its capacitance.
16. Draw and explain electric field lines between two like charges.
17. Describe the torque on an electric dipole in a uniform electric field.
18. If three equal charges are placed at the corners of an equilateral triangle, find the net force on one charge.

Advanced Level (JEE Main/Advanced, MCQ included)

19. A solid sphere of radius Rcarries a uniform charge density. Using Gauss’s Law, what is the electric field at a distance $r < R$from the center?
20. Four charges $+q, +q, -q, -q$are placed at corners of a square. Find the electric field at its center.
21. (MCQ) The work done to move a 2 μC charge from point A to B is 0.06 J. The potential difference $V_A - V_B$is:
    - (A) 0.03 V
    - (B) 30 V
    - (C) 3 V

- (D) 300 V

22. (MCQ) A capacitor of 2 μF is charged to 100 V. The energy stored is:
    - (A) 0.01 J
    - (B) 0.02 J
    - (C) 0.005 J
    - (D) 10 J
23. (MCQ) Two charges $+2q$and $-q$are kept 1 m apart. The point where electric field is zero is:
    - (A) 1/√2 m from +2q
    - (B) 1/2 m from -q
    - (C) 1/3 m from +2q
    - (D) 1 m from +2q
24. A bamboo rod of length 2 m is uniformly charged. Calculate the field at a point 1 m from its center along its axis.
25. (MCQ) The unit of electric flux is:
    - (A) Volt
    - (B) Volt/meter
    - (C) Newton-meter
    - (D) Newton-meter^2/Coulomb

Answers and Detailed Explanations

1. Coulomb's law: The force between two point charges is directly proportional to the product of charges and inversely proportional to the square of the distance. $F = k\frac{|q_1 q_2|}{r^2}$

2. Charge exists only in discrete amounts (integral multiples of e): $q = ne$, with $n$integer.

3. Electric field intensity at a point is the force per unit positive charge at that point: $E = F/q$.

4. If distance doubles ($r \to 2r$), Fbecomes $1/4$its original value ($F' = F/4$).

5. Superposition: The net force on a charge equals the vector sum of forces from all other charges considered separately.

6. An electric dipole is a pair of equal and opposite charges separated by a distance.

7. Field lines point radially outward from positive, radially inward toward negative charges.

8. $V = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}$

9. A surface where electric potential is the same everywhere; no work done moving charge along it.

10. Capacitance is the ability of a system to store charge per unit voltage; SI unit is Farad (F).

11. Use $F = k\frac{q_1 q_2}{r^2}$, $q_1 = 3 \times 10^{-6}$C, $q_2 = 6 \times 10^{-6}$C, $r = 2$m.

$$F = 9 \times 10^9 \frac{3 \times 10^{-6} \times 6 \times 10^{-6}}{4} = 0.0405 \text{ N}$$

12. $E = \frac{F}{q} = \frac{3}{1\times10^{-6}} = 3 \times 10^6$N/C.

13. $V = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}$, $q = 1 \times 10^{-9}$C, $r = 0.05$m:

$$V = 9 \times 10^9 \frac{1 \times 10^{-9}}{0.05} = 180 \text{ V}$$

14. Gauss's Law: The field outside is $E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$(like a point charge). For $r < R$, $E = 0$(for hollow shell).

15. $C = \varepsilon_0 \frac{A}{d} = 8.85 \times 10^{-12} \frac{1}{1\times10^{-3}} = 8.85 \times 10^{-9}$F = 8.85nF.

16. Draw field lines curving outward from both charges, never touching.

17. $\tau = pE\sin\,\theta$: The dipole experiences torque turning it to align with the field.

18. The net force is the vector sum due to other two charges, solved geometrically using symmetry and vector addition.

19. Use Gauss's Law:

$$E = \frac{1}{4\pi\varepsilon_0}\frac{Qr}{R^3}$$

where $r < R$.

20. The net field at the center is zero due to symmetry.

21. Work ($W = q\Delta V$):

$$\Delta V = \frac{W}{q} = \frac{0.06}{2 \times 10^{-6}} = 30 \text{ V}$$

Correct answer: (B).

22. $U = \frac{1}{2}CV^2 = \frac{1}{2} \times 2 \times 10^{-6} \times (100)^2 = 0.01$J.
Correct: (A).

23. Use field formula and set resultant field to zero, solve for x; correct answer: (C).

24. Use integration (linear charge distribution) for field on axis; detailed calculation involves calculus and is standard in JEE material.

25. The unit is (D) Newton-meter^2/Coulomb.