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NEET UG · STUDY MODULE

Physics · Class 12

Electric Charges and Fields

Theory · Illustrations · Try Yourself · Summary · Section A · Section B · Section C

6	30	30+	3
Topics	Colour figures	Try-yourself	Graded sections



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10. Section C: Challenge problems (HCV / Irodov style, original)
11. Answer keys and solutions

How to study this module. Read each topic once, note the TRICK and EXAM ALERT boxes, copy the formulas to your formula page, then do every Illustration yourself before reading the solution. Attempt the TRY YOURSELF box immediately after each topic. After the chapter summary, work through Section A (standard), Section B (difficult), and Section C (pattern of questions that NEET has been asking). Use $g = 10\ \mathrm{m\,s^{-2}}$, $k = 9 \times 10^9\ \mathrm{N\,m^2C^{-2}}$ unless told otherwise.

1 Electric charge and its properties

Charge is the property of matter due to which it experiences a force in an electric or magnetic field. It is a **scalar** with SI unit **coulomb (C)**. Matter is electrically neutral because it contains equal numbers of protons and electrons. A body becomes **positively charged** by *losing* electrons and **negatively charged** by *gaining* electrons. Only electrons move; protons stay locked in the nucleus.

Particle	Charge	Mass
Electron	-1.6×10^{-19} C	9.1×10^{-31} kg
Proton	$+1.6 \times 10^{-19}$ C	1.67×10^{-27} kg
Neutron	0	1.675×10^{-27} kg

Properties of charge

1. **Additivity:** total charge = algebraic sum of all charges.
2. **Conservation:** charge can be neither created nor destroyed; it only moves from one body to another (pair production creates $+e$ and $-e$ together, net zero).
3. **Quantisation:** $q = \pm ne$ with $n = 1, 2, 3\ldots$ The charge $e = 1.6 \times 10^{-19}$ C is the least free charge. (Quarks carry $\pm e/3$, $\pm 2e/3$ but are never found free.)
4. **Invariance:** charge does not change with speed, unlike mass.

Methods of charging

- **Friction:** two different materials rubbed together transfer electrons; both acquire equal and opposite charges (glass rubbed with silk: glass $+$, silk $-$; ebonite rubbed with fur: ebonite $-$).
- **Conduction (contact):** a charged body touches a conductor; the conductor gets the *same kind* of charge.
- **Induction:** a charged body is only *brought near* a conductor; the near end gets the *opposite* charge, the far end the *same*. If the far end is earthed and then the earth connection is removed before the rod, the body is left with the opposite charge.

Conductors (metals, human body, earth) allow charge to flow; insulators (glass, plastic, rubber) do not. The **gold-leaf electroscope** detects charge: leaves diverge when charged, and the divergence increases when a like charge is brought near.

⚡ TRICK Number of electrons in charge q: $n = \dfrac{q}{e} = \dfrac{q}{1.6 \times 10^{-19}}$. One coulomb contains 6.25×10^{18} electrons. A body that gains n electrons also gains mass nm_e.

⚠ EXAM ALERT A charged body is **never** a fraction of e. If an option gives $1.5e$ or 2.4×10^{-19} C, reject it. A positively charged body has slightly *less* mass; a negatively charged body slightly *more*.

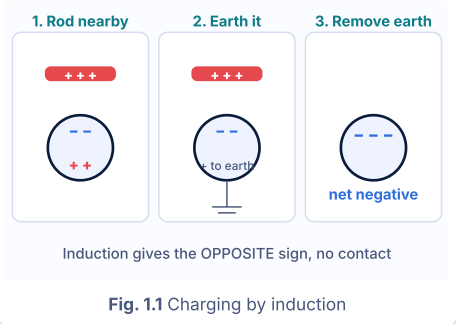


Fig. 1.1 Charging by induction

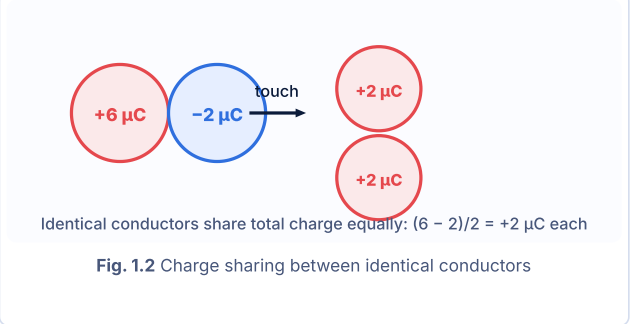


Fig. 1.2 Charge sharing between identical conductors

Illustration 1.1

A body carries 2.5×10^{13} excess electrons. Find its charge and the mass gained.

Solution. $q = ne = 2.5 \times 10^{13} \times 1.6 \times 10^{-19} = 4 \times 10^{-6}$ C $= -4\,\mu$C. Mass gained $= nm_e = 2.5 \times 10^{13} \times 9.1 \times 10^{-31} = 2.3 \times 10^{-17}$ kg.

Illustration 1.2

How many electrons make up 1 C of charge, and what is their mass?

Solution. $n = \dfrac{1}{1.6 \times 10^{-19}} = 6.25 \times 10^{18}$. Mass $= 6.25 \times 10^{18} \times 9.1 \times 10^{-31} = 5.7 \times 10^{-12}$ kg.

TRY YOURSELF 1

1. Which property of charge is violated by a body having 2.4×10^{-19} C?
   (A) Quantisation **(B)** Invariance **(C)** Conservation **(D)** Additivity

2. A glass rod is rubbed with silk and becomes positive. This happens because:
   (A) protons move from glass to silk
   (B) electrons move from glass to silk
   (C) electrons move from silk to glass
   (D) protons move from silk to glass

3. The number of electrons in $-1\,\mu$C of charge is:
   (A) 6.25×10^{18} **(B)** 6.25×10^{6} **(C)** 6.25×10^{12} **(D)** 1.6×10^{13}

4. Two identical conducting spheres carrying $+q$ and $-3q$ are touched and separated. Each now carries:
   (A) $-2q$ **(B)** $-q/2$ **(C)** $+q$ **(D)** $-q$

5. When a body is charged positively, its mass:
   (A) decreases slightly **(B)** becomes zero
   (C) increases slightly **(D)** remains exactly the same

2 Coulomb's law and superposition

Coulomb's law. The force between two stationary point charges is directly proportional to the product of the charges and inversely proportional to the square of the distance, acting along the line joining them:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2} = k\frac{q_1 q_2}{r^2}, \qquad k = 9 \times 10^9\ \mathrm{N\,m^2 C^{-2}},\ \varepsilon_0 = 8.85 \times 10^{-12}\ \mathrm{C^2 N^{-1} m^{-2}}$$

In vector form $\vec{F}_{12} = k\dfrac{q_1 q_2}{r^2}\hat{r}_{12}$ is the force on q_1 due to q_2. Like charges repel, unlike attract, and $\vec{F}_{12} = -\vec{F}_{21}$.

In a medium. $F_{\text{medium}} = \dfrac{1}{4\pi\varepsilon_0 K}\dfrac{q_1 q_2}{r^2} = \dfrac{F_{\text{air}}}{K}$, where $K = \varepsilon_r$ is the dielectric constant ($K = 1$ for air/vacuum, $K = 80$ for water, $K = \infty$ for a conductor).

Superposition principle. The force on a charge due to several charges is the *vector sum* of the individual forces. Pairwise forces are unaffected by other charges.

Electric force	Gravitational force
Attractive or repulsive	Always attractive
Depends on the medium	Independent of the medium
$F_e/F_g \approx 10^{36}$ for two protons	Weakest of the fundamental forces
Both are central, conservative and follow the inverse-square law.	

TRICK **Null point of two charges** (distance d apart, $q_1 > q_2$ in magnitude). For *like* charges the null point lies between them at $x = \dfrac{d\sqrt{q_1}}{\sqrt{q_1}+\sqrt{q_2}}$ from q_1. For *unlike* charges it lies outside, beyond the smaller charge, at $x = \dfrac{d\sqrt{q_2}}{\sqrt{q_1}-\sqrt{q_2}}$ from q_2.

TRICK **Equilibrium of a third charge.** For two like charges q_1, q_2, a third charge placed at the null point is in equilibrium if $q_3 = -\dfrac{q_1 q_2}{(\sqrt{q_1}+\sqrt{q_2})^2}$. For $q_1 = q_2 = q$ this gives $q_3 = -q/4$ at the midpoint.

TRICK **Two identical hanging spheres in a liquid.** If the angle between the threads is the same in air and in a liquid of density σ and dielectric constant K, then the density of the sphere material is $\rho = \dfrac{K\sigma}{K-1}$ (since $K(1-\sigma/\rho) = 1$).

EXAM ALERT When identical conducting spheres are touched, the total charge is shared **equally**. The force may change in size and even in nature (attractive to repulsive).

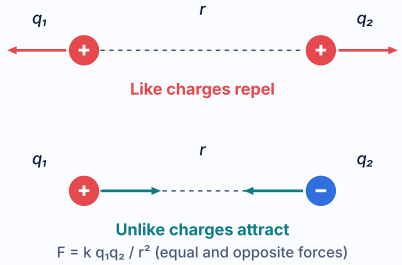


Fig. 2.1 Forces between two point charges

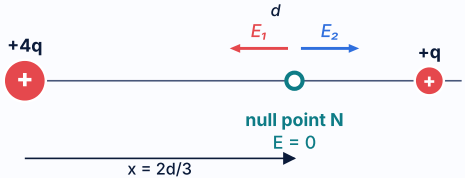


Fig. 2.2 Null point between +4q and +q

Illustration 2.1

Two charges $+5\,\mu\text{C}$ and $-3\,\mu\text{C}$ are 0.3 m apart in air. Find the force between them.

Solution. $F = \dfrac{9\times10^{9}\times5\times10^{-6}\times3\times10^{-6}}{(0.3)^2} = 1.5$ N (attractive).

Illustration 2.2

Charges $+9\,\mu\text{C}$ and $+4\,\mu\text{C}$ are 50 cm apart. Locate the point on the line joining them where the field is zero.

Solution. $x = \dfrac{d\sqrt{q_1}}{\sqrt{q_1}+\sqrt{q_2}} = \dfrac{0.5\times3}{3+2} = 0.3$ m from the $9\,\mu$C charge. Check: $\dfrac{9}{0.3^2} = \dfrac{4}{0.2^2} = 100$.

Illustration 2.3

Charges $+4q$ and $+q$ are d apart. Find the charge and position of a third charge that keeps all three in equilibrium.

Solution. Position (null point): $x = \dfrac{d\cdot2\sqrt{q}}{2\sqrt{q}+\sqrt{q}} = \dfrac{2d}{3}$ from $4q$. Charge: $q_3 = -\dfrac{4q\cdot q}{(2\sqrt{q}+\sqrt{q})^2} = -\dfrac{4q}{9}$.

Illustration 2.4

Two identical spheres of density $1.5\ \text{g cm}^{-3}$ hang by threads. They keep the same angle between the threads when immersed in a liquid of density $0.5\ \text{g cm}^{-3}$. Find K of the liquid.

Solution. $K(1-\sigma/\rho) = 1 \Rightarrow K = \dfrac{\rho}{\rho-\sigma} = \dfrac{1.5}{1.0} = 1.5$.

TRY YOURSELF 2

1. If the distance between two charges is increased by 20%, the force between them:
   (A) decreases by about 30.6% **(B)** decreases by 44%
   (C) decreases by 36% **(D)** decreases by 20%

2. Charges $5\,\mu$C and $20\,\mu$C are 30 cm apart. The field is zero at a distance ___ from the $5\,\mu$C charge.
   (A) 6 cm **(B)** 15 cm **(C)** 20 cm **(D)** 10 cm

3. Two equal charges q are fixed. The charge to be placed at the midpoint so that the system is in equilibrium is:
   (A) $-q$ **(B)** $-q/4$ **(C)** $-q/2$ **(D)** $+q/4$

4. The ratio F_e/F_g between two protons varies with the separation r as:
   (A) r^{-4} **(B)** r^{-2} **(C)** r^{0} (independent of r) **(D)** r^{2}

5. Spheres carrying $+3\,\mu$C and $-1\,\mu$C are touched and separated by the same distance as before. The new force is ___ of the old one and is ___.
   (A) $\frac{1}{3}$, repulsive **(B)** equal, attractive **(C)** $\frac{1}{3}$, attractive
   (D) 3 times, repulsive

3 Electric field and field lines

Electric field at a point is the force per unit positive test charge placed there (test charge so small it does not disturb the source):

$$\vec{E} = \lim_{q_0\to0}\frac{\vec{F}}{q_0}, \qquad \text{unit: N C}^{-1}\ (=\text{V m}^{-1}),\ [E] = MLT^{-3}A^{-1}$$

For a point charge q: $E = \dfrac{kq}{r^2}$, directed away from $+q$ and towards $-q$. For many charges, $\vec{E} = \sum\vec{E}_i$ (vector sum).

Force and motion in a field. A charge q feels $\vec{F} = q\vec{E}$ (along $\vec{E}$ for $+q$, opposite for $-q$). A free charge released from rest in a uniform field moves in a straight line with $a = \dfrac{qE}{m}$. If it enters perpendicular to the field with speed v_0 it follows a parabola, just like a projectile:

$$y = \frac{1}{2}\frac{qE}{m}t^2, \quad t = \frac{x}{v_0} \Rightarrow y = \frac{qE\,x^2}{2mv_0^2}.$$

Field lines are imaginary curves whose tangent gives the direction of the field. (1) They start on $+$ charges and end on $-$ charges. (2) They never cross (two tangents would mean two directions). (3) They never form closed loops in electrostatics. (4) Their density (closeness) shows field strength. (5) They are perpendicular to the surface of a conductor. (6) They tend to contract along their length (attraction) and repel sideways (repulsion).

⚡ **TRICK** Field due to a system: if charges are arranged symmetrically (regular polygon of equal charges) the field at the centre is **zero**. Removing one charge q from such a polygon leaves a field $\dfrac{kq}{R^2}$ at the centre, directed *away* from the removed charge's position if q was positive.

⚠ **EXAM ALERT** Field lines show the path of a particle only if it starts from rest and the lines are straight. In a curved field the particle does not follow the line.

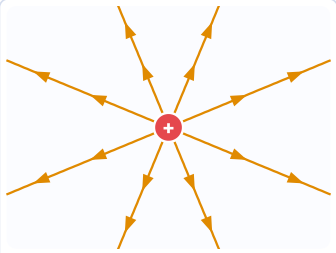


Fig. 3.1 Field of +q

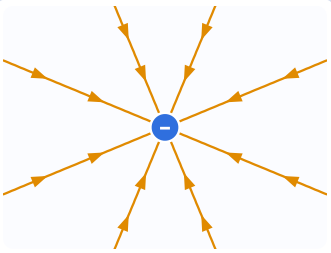


Fig. 3.2 Field of −q

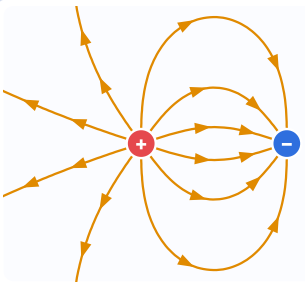


Fig. 3.3 Field lines of a dipole

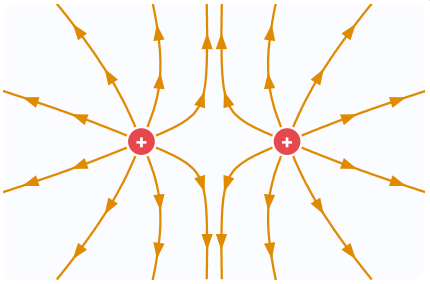


Fig. 3.4 Two equal positive charges

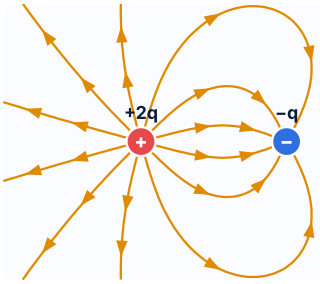


Fig. 3.5 Unequal charges: more lines from +2q

Illustration 3.1

Charges $+4\,\mu$C and $-4\,\mu$C are 20 cm apart. Find the field at the midpoint.

Solution. Both fields point from $+$ to $-$, so they add: $E = 2 \times \dfrac{9\times10^{9}\times4\times10^{-6}}{(0.1)^2} = 7.2\times10^{6}\ \mathrm{N\,C^{-1}}$.

Illustration 3.2

An electron enters a uniform field $E = 10^{3}\ \mathrm{N\,C^{-1}}$ at right angles with speed $2\times10^{6}\ \mathrm{m\,s^{-1}}$. The field region is 5 cm long. Find the deflection.

Solution. $a = \dfrac{eE}{m} = 1.76\times10^{14}\ \mathrm{m\,s^{-2}}$, $t = \dfrac{0.05}{2\times10^{6}} = 2.5\times10^{-8}$ s. $y = \tfrac{1}{2}at^2 = 0.0549\ \mathrm{m} \approx 5.5\ \mathrm{cm}$.

TRY YOURSELF 3

1. The field at 3 cm from a point charge of 2 nC is:
   (A) $2\times10^{4}\ \mathrm{N\,C^{-1}}$ **(B)** $6\times10^{4}\ \mathrm{N\,C^{-1}}$ **(C)** $6\times10^{2}\ \mathrm{N\,C^{-1}}$
   (D) $2\times10^{2}\ \mathrm{N\,C^{-1}}$

2. A charge $-2\,\mu$C is in a field of $5\times10^{4}\ \mathrm{N\,C^{-1}}$. The force on it is:
   (A) 10 N opposite to the field **(B)** 0.1 N along the field
   (C) 0.01 N along the field **(D)** 0.1 N opposite to the field

3. Which statement about field lines is wrong?
   (A) They can intersect
   (B) They are perpendicular to a conductor's surface
   (C) Closer lines mean stronger field
   (D) They start on positive charges

4. A proton is placed in a field of $10^{4}\ \mathrm{N\,C^{-1}}$. Its acceleration is nearly:
   (A) $1.76\times10^{15}\ \mathrm{m\,s^{-2}}$ **(B)** $9.6\times10^{8}\ \mathrm{m\,s^{-2}}$ **(C)** $9.6\times10^{11}\ \mathrm{m\,s^{-2}}$
   (D) $1.6\times10^{-15}\ \mathrm{m\,s^{-2}}$

5. Four equal charges $+q$ are at the corners of a square. The field at the centre is:
   (A) $2\sqrt{2}\,kq/a^2$ **(B)** zero **(C)** $4kq/a^2$ **(D)** kq/a^2

4 Electric dipole

An **electric dipole** is a pair of equal and opposite charges $\pm q$ separated by a small distance $2a$. Its **dipole moment** is $\vec{p} = q\,(2\vec{a})$, a vector pointing from $-q$ to $+q$. Unit: C m. Total charge of a dipole is zero, but it still produces and responds to a field.

Field of a dipole (point dipole, $r \gg a$)

Position	Field	Direction
Axial (on the line through the dipole)	$E = \dfrac{2kp}{r^3}$	along $\vec{p}$
Equatorial (perpendicular bisector)	$E = \dfrac{kp}{r^3}$	opposite to $\vec{p}$

Both fall as $1/r^3$, faster than the $1/r^2$ of a single charge, because the two fields nearly cancel. Axial field is exactly twice the equatorial field at the same distance.

Dipole in a uniform field

- Net force $= 0$.
- Torque $\vec{\tau} = \vec{p} \times \vec{E}$, $\tau = pE\sin\theta$ (maximum at 90°, zero at 0° and 180°).
- Potential energy $U = -\vec{p}\cdot\vec{E} = -pE\cos\theta$. Stable equilibrium at $\theta = 0^\circ$ ($U = -pE$), unstable at 180° ($U = +pE$).
- Work to rotate from θ_1 to θ_2: $W = pE(\cos\theta_1 - \cos\theta_2)$.
- For small angular displacement it executes SHM: $T = 2\pi\sqrt{\dfrac{I}{pE}}$.

In a **non-uniform** field the dipole also feels a net force and tends to move towards the stronger-field region.

TRICK Work to rotate a dipole from 0° to 90° is pE; from 0° to 180° is $2pE$; from 90° to 180° is pE. The torque at 30° is half the maximum torque.

EXAM ALERT $2kp/r^3$ and kp/r^3 are valid only for $r \gg 2a$ (short dipole). Do not use them for points near the dipole.

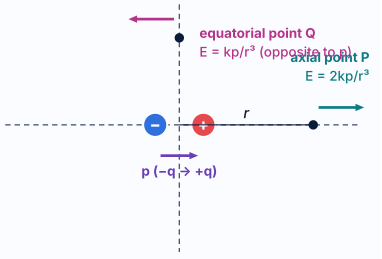


Fig. 4.1 Axial and equatorial fields of a dipole

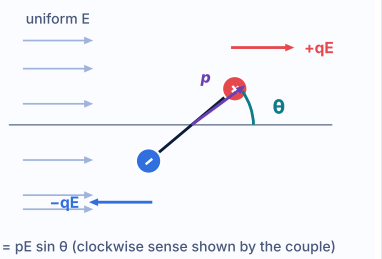


Fig. 4.2 Dipole in a uniform field: torque

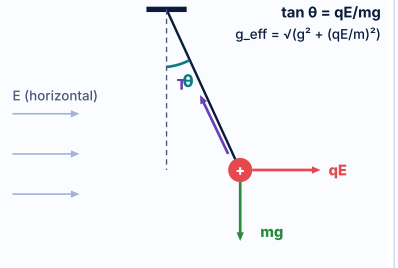


Fig. 4.3 Charged pendulum in a field

Illustration 4.1

A dipole of moment 4×10^{-9} C m is in a field of 5×10^{4} N C^{-1}. Find the maximum torque and the work done in turning it from 0° to 180°.

Solution. $\tau_{\max} = pE = 2 \times 10^{-4}$ N m. $W = 2pE = 4 \times 10^{-4}$ J.

Illustration 4.2

A dipole of moment 2×10^{-8} C m. Find the field at 0.5 m on its axis.

Solution. $E = \dfrac{2kp}{r^3} = \dfrac{2 \times 9 \times 10^{9} \times 2 \times 10^{-8}}{(0.5)^3} = 2880$ N C^{-1}.

Illustration 4.3

A dipole of moment 4×10^{-9} C m and moment of inertia 10^{-9} kg m^2 oscillates in a field of 10^{4} N C^{-1} through a small angle. Find the period.

Solution. $T = 2\pi\sqrt{\dfrac{I}{pE}} = 2\pi\sqrt{\dfrac{10^{-9}}{4 \times 10^{-5}}} = 0.0314$ s.

TRY YOURSELF 4

1. The direction of the dipole moment is from:
(A) $-q$ to $+q$ **(B)** $+q$ to $-q$ **(C)** it has no direction
(D) perpendicular to the axis

2. The torque on a dipole in a uniform field is maximum when the angle between $\vec{p}$ and $\vec{E}$ is:
(A) 90° **(B)** 45° **(C)** 0° **(D)** 180°

3. In a uniform electric field a dipole experiences:
(A) neither always **(B)** both **(C)** torque but no net force
(D) net force but no torque

4. A dipole of moment 1.6×10^{-8} C m. The axial field at 40 cm is:
(A) 9000 N C^{-1} **(B)** 2250 N C^{-1} **(C)** 360 N C^{-1}
(D) 4500 N C^{-1}

5. Work to rotate a dipole ($p = 4 \times 10^{-8}$ C m) from 0° to 60° in $E = 10^{5}$ N C^{-1}:
(A) 8×10^{-3} J **(B)** 2×10^{-3} J **(C)** 4×10^{-3} J
(D) 3.5×10^{-3} J

5 Electric flux and Gauss's law

Electric flux through a surface is the number of field lines passing normally through it: $\Phi = \int \vec{E}\cdot d\vec{A} = EA\cos\theta$ for a uniform field (θ is the angle between $\vec{E}$ and the area vector $\vec{A}$, which is normal to the surface and, for a closed surface, points outward). Unit: N m^2 C^{-1}. Flux is a scalar: positive for lines leaving, negative for lines entering a closed surface.

Gauss's law. The net flux through any closed surface equals $\dfrac{1}{\varepsilon_0}$ times the net charge enclosed:

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