

CBSE Class 12 Physics Question Paper 2020 with Solution PDF-Set 55/3/2



Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

- (i) This question paper comprises **four** Sections – **A, B, C** and **D**.
- (ii) There are **37** questions in the question paper. **All** questions are compulsory.
- (iii) **Section A** – Questions no. **1 to 20** are very short answer type questions, carrying **one** mark each.
- (iv) **Section B** – Questions no. **21 to 27** are short answer type questions, carrying **two** marks each.
- (v) **Section C** – Questions no. **28 to 34** are long answer type questions, carrying **three** marks each.
- (vi) **Section D** – Questions no. **35 to 37** are also long answer type questions, carrying **five** marks each.
- (vii) There is no overall choice in the question paper. However, an internal choice has been provided in 2 questions of 1 mark, 2 questions of 2 marks, 1 question of three marks and all the 3 questions of five marks. You have to attempt only one of the choices in such questions.
- (viii) In addition to this, separate instructions are given with each section and question, wherever necessary.
- (ix) Use of calculators and log tables is not permitted.

You may use the following values of physical constants wherever necessary.

$$c = 3 \times 10^8 \text{ m/s}$$

$$h = 6.63 \times 10^{-34} \text{ Js}$$

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

$$\mu_0 = 4\pi \times 10^{-7} \text{ T m A}^{-1}$$

$$\epsilon_0 = 8.854 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$$

$$\frac{1}{4\pi\epsilon_0} = 9 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$$

$$\text{Mass of electron } (m_e) = 9.1 \times 10^{-31} \text{ kg}$$

$$\text{Mass of neutron} = 1.675 \times 10^{-27} \text{ kg}$$

$$\text{Mass of proton} = 1.673 \times 10^{-27} \text{ kg}$$

$$\text{Avogadro's number} = 6.023 \times 10^{23} \text{ per gram mole}$$

$$\text{Boltzmann constant} = 1.38 \times 10^{-23} \text{ JK}^{-1}$$

Section A (20 marks)

Note : Select the most appropriate option from those given below each question :

1. A charge Q is kept at the centre of a circle of radius r . A test charge q_0 is carried from a point X to the point Y on this circle such that arc XY subtends an angle of 60° at the centre of the circle. The amount of work done in this process will be [1 mark]

- (A) $\frac{1}{4\pi\epsilon_0} \frac{Qq_0}{2r}$
(B) $\frac{1}{4\pi\epsilon_0} \frac{\sqrt{3}Qq_0}{2r}$
(C) Zero
(D) $\frac{\sqrt{3}Qq_0}{4\pi\epsilon_0 r}$

Correct Answer: (C) Zero

Solution:

Concept:

- The potential due to a point charge is $V = kQ/r$, where $k = 1/(4\pi\epsilon_0)$ and r is the distance from the charge.
- Work done by an external agent in a quasistatic displacement is $W = q_0(V_Y - V_X)$. Electrostatic work depends only on the endpoint potentials.

Step 1: Compare the endpoint potentials Both points lie on the same circle centred on Q , so both are at distance r from the source. Hence

$$V_X = V_Y = \frac{Q}{4\pi\epsilon_0 r}.$$

The angular separation of 60° changes the position, but not the distance determining the potential.

Step 2: Calculate the work The potential difference is zero. Therefore

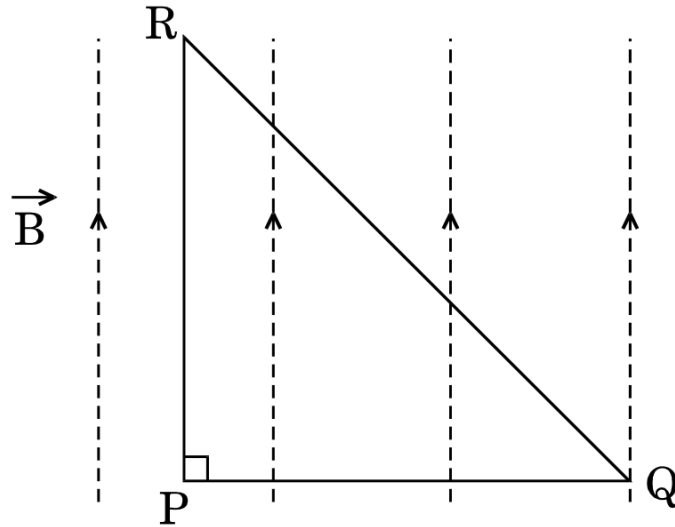
$$W = q_0(V_Y - V_X) = q_0(0) = 0.$$

Along the circular arc, the electric force is radial while the displacement is tangential, giving the same result. The nonzero expressions in (A), (B) and (D) incorrectly use a path length or chord length in place of a potential difference.

Step 3: Conclusion The work done is 0 J. Hence, the correct option is (C).

Quick Tip to Solve: For a point charge, compare the two radial distances first: equal distances mean equal potentials and zero electrostatic work.

2. An isosceles right angled current carrying loop PQR is placed in a uniform magnetic field $\vec{B}$ pointing along PR. If the magnetic force acting on the arm PQ is F , then the magnetic force which acts on the arm QR will be [1 mark]



- (A) F
- (B) $\frac{F}{\sqrt{2}}$
- (C) $\sqrt{2} F$
- (D) $-F$

Correct Answer: (D) $-F$

Solution:

Concept:

- The magnetic force on a straight current-carrying arm is $\vec{F} = I\vec{L} \times \vec{B}$, with $\vec{L}$ directed along its current.
- A closed current loop in a uniform magnetic field has zero resultant force because the vector sum of its directed arm lengths is zero.

Step 1: Find the force on PR The arm PR is parallel to the uniform magnetic field. Its angle to the field is either 0° or 180° , so

$$\vec{F}_{PR} = 0.$$

This remains true whichever direction the current circulates.

Step 2: Balance the two remaining forces For the complete loop,

$$\vec{F}_{PQ} + \vec{F}_{QR} + \vec{F}_{RP} = 0.$$

Thus $\vec{F}_{QR} = -\vec{F}_{PQ}$. The hypotenuse QR has length $\sqrt{2}$ times PQ, but its sine factor is $1/\sqrt{2}$, so its force magnitude equals that on PQ. The forces point in opposite directions perpendicular to the loop plane. Options (B) and (C) neglect one of these factors; (A) gives the magnitude but misses the

opposite direction represented by the signed answer.

Step 3: Conclusion The force on QR is $-F$: it has the same magnitude as that on PQ and the opposite direction. Hence, the correct option is (D).

Quick Tip to Solve: For a closed loop in uniform $\vec{B}$, first set the parallel arm force to zero; the other two arm forces must cancel as vectors.

3. An electric dipole consisting of charges $+q$ and $-q$ separated by a distance r , is kept symmetrically at the centre of an imaginary sphere of radius $R (> r)$. Another point charge Q is also kept at the centre of the sphere. The net electric flux coming out of the sphere will be [1 mark]

- (A) $-\frac{2q + Q}{4\pi\epsilon_0}$
(B) $\frac{Q}{\epsilon_0}$
(C) $\frac{2q + Q}{\epsilon_0}$
(D) $-\frac{Q}{\epsilon_0}$

Correct Answer: (B) $\frac{Q}{\epsilon_0}$

Solution:

Concept:

- Gauss's law gives the total outward electric flux through a closed surface as $\Phi_E = Q_{\text{enclosed}}/\epsilon_0$.
- Enclosed charges are added algebraically, including their signs. A dipole has zero net charge even though its electric field is not zero.

Step 1: Add the charges inside the sphere The sphere encloses both dipole charges and the central point charge. Its radius exceeds their separation, so neither dipole charge is outside. The total charge is

$$Q_{\text{enclosed}} = +q - q + Q = Q.$$

The separation and orientation of the dipole do not change this algebraic sum.

Step 2: Apply the closed-surface flux law Substituting the enclosed charge gives

$$\Phi_E = \frac{Q_{\text{enclosed}}}{\epsilon_0} = \frac{Q}{\epsilon_0}.$$

The positive and negative dipole contributions cancel in the total outward flux. Option (C) adds dipole magnitudes instead of signed charges. Option (A) also uses the point-charge field factor $1/(4\pi\epsilon_0)$ instead of the closed-surface flux law, and (D) reverses the sign of the central contribution.

Step 3: Conclusion The net outward electric flux is Q/ϵ_0 . Hence, the correct option is (B).

Quick Tip to Solve: For any closed-surface flux question, add all enclosed charges with their signs before considering distances or field geometry.

4. A parallel plate capacitor is charged to V volt by a battery. The battery is disconnected and the separation between the plates is halved. The new potential difference across the capacitor will be [1 mark]

- (A) $\frac{V}{2}$
- (B) V
- (C) $2V$
- (D) $\frac{V}{4}$

Correct Answer: (A) $\frac{V}{2}$

Solution:

Concept:

- For parallel plates of area A and separation d , neglecting edge effects, $C = \epsilon_0 A/d$.
- After the battery is disconnected, the isolated capacitor retains its charge Q , and its potential difference is $V = Q/C$.

Step 1: Find the new capacitance The area and medium remain unchanged while the separation becomes $d/2$. Thus

$$C' = \frac{\epsilon_0 A}{d/2} = 2C.$$

Bringing the plates closer increases the capacitance.

Step 2: Use constant charge The initial charge is $Q = CV$. Because the battery has been removed, it cannot supply or remove charge as the separation changes. Hence

$$V' = \frac{Q}{C'} = \frac{CV}{2C} = \frac{V}{2}.$$

Option (B) would apply if the battery stayed connected. Option (C) reverses the dependence on capacitance, while (D) incorrectly squares the factor of two.

Step 3: Conclusion The new potential difference is $V/2$. Hence, the correct option is (A).

Quick Tip to Solve: Check battery connection before using capacitor ratios: disconnected fixes Q , so doubling C halves V .

5. A region has a uniform magnetic field in it. A proton enters into the region with velocity making an angle of 45° with the direction of the magnetic field. In this region the proton will move on a path having the shape of a [1 mark]

- (A) straight line
- (B) circle
- (C) spiral
- (D) helix

Correct Answer: (D) helix

Solution:

Concept:

- The magnetic force is $\vec{F} = q\vec{v} \times \vec{B}$; it acts perpendicular to velocity and does no work.

- The velocity component parallel to the field stays constant, while the perpendicular component produces uniform circular motion.

Step 1: Resolve the entry velocity Let the proton enter with speed v . At 45° ,

$$v_{\parallel} = v \cos 45^\circ = \frac{v}{\sqrt{2}}, \quad v_{\perp} = v \sin 45^\circ = \frac{v}{\sqrt{2}}.$$

Both components are nonzero. The parallel component experiences no magnetic force.

Step 2: Combine the two motions The perpendicular component makes the proton circle with constant radius $r = mv_{\perp}/(eB)$, while the parallel component advances it uniformly along the field. Combining these motions gives a helix with constant radius and pitch. A straight line would require zero perpendicular component, and a circle would require zero parallel component. A spiral has a changing radius, which this uniform magnetic field alone does not produce.

Step 3: Conclusion The proton follows a helix around the magnetic-field direction. Hence, the correct option is (D).

Quick Tip to Solve: An oblique entry angle gives both parallel and perpendicular velocity components: uniform advance plus circular motion produces a helix.

6. n resistors, each of resistance R are connected (a) in series, and (b) in parallel. Each combination is then connected to a source of emf E . The ratio of heat produced per second in the two cases will be

[1 mark]

- (A) $n : 1$
 (B) $1 : n$
 (C) $n^2 : 1$
 (D) $1 : n^2$

Correct Answer: (D) $1 : n^2$

Solution:

Concept:

- The heat produced per second is electric power: $P = E^2/R_{\text{eq}}$ for a resistor combination connected across an ideal source of emf E .
- For n equal resistors each of resistance R , the series resistance is nR and the parallel resistance is R/n .

Step 1: Calculate the two heating rates Both arrangements are connected across the same source voltage. Therefore

$$P_s = \frac{E^2}{nR}, \quad P_p = \frac{E^2}{R/n} = \frac{nE^2}{R}.$$

The parallel arrangement draws more current because its equivalent resistance is smaller.

Step 2: Take the ratio in the stated order The question asks for series heating relative to parallel heating. Thus

$$\frac{P_s}{P_p} = \frac{E^2/(nR)}{nE^2/R} = \frac{1}{n^2}.$$

Options (A) and (B) overlook that the equivalent resistances differ by a factor of n^2 , while (C) reverses the requested order. The power formula at fixed current would be inappropriate because the current

changes between these arrangements.

Step 3: Conclusion The heat produced per second in series and parallel is in the ratio $1 : n^2$. Hence, the correct option is (D).

Quick Tip to Solve: At the same source voltage, heating rate is inversely proportional to equivalent resistance; preserve the series-to-parallel order.

7. A zener diode has

[1 mark]

- (A) heavily doped p-side and lightly doped n-side.
- (B) heavily doped n-side and lightly doped p-side.
- (C) heavily doped n-side as well as p-side.
- (D) lightly doped n-side as well as p-side.

Correct Answer: (C) heavily doped n-side as well as p-side.

Solution:

Concept:

- A Zener diode is designed to operate safely in reverse breakdown and maintain an approximately constant voltage over its operating current range.
- Heavy doping on both sides of its p–n junction produces a very thin depletion region and a strong electric field at a comparatively small reverse voltage.

Step 1: Identify the required junction construction Zener action requires a narrow depletion layer. Both the p-side and the n-side are heavily doped, so the strong junction field can produce breakdown at the specified reverse voltage. This construction distinguishes a Zener diode from an ordinary lightly doped junction.

Step 2: Compare the printed alternatives Options (A) and (B) heavily dope only one side and leave the other lightly doped, so the depletion region extends substantially into the lightly doped side. Option (D) lightly dopes both sides and gives a wider depletion layer. Only option (C) states that both sides are heavily doped, as required for the standard Zener-diode construction.

Step 3: Conclusion A Zener diode has a heavily doped n-side as well as a heavily doped p-side. Hence, the correct option is (C).

Quick Tip to Solve: Link Zener breakdown to a thin depletion layer: thin means heavy doping on both sides of the junction.

8. In Bohr's model of hydrogen atom, the total energy of the electron in n^{th} discrete orbit is proportional to

[1 mark]

- (A) n
- (B) $\frac{1}{n}$
- (C) n^2
- (D) $\frac{1}{n^2}$

Correct Answer: (D) $\frac{1}{n^2}$

Solution:

Concept:

- Bohr's stationary hydrogen orbits have total energy $E_n = -13.6/n^2$ eV, where n is the principal quantum number.
- The negative sign means that the electron is bound; the zero of energy is a free electron at rest infinitely far from the proton.

Step 1: Identify the orbit dependence The kinetic energy is positive, but the electrostatic potential energy is negative and twice its magnitude. Hence the total energy is negative. Using the Bohr energy expression, the only dependence on the orbit number is the factor n^{-2} . The constant factor -13.6 eV does not depend on n .

Step 2: Compare the printed options Options (A) and (C) increase as n increases, whereas the magnitude of the bound-state energy decreases. Option (B) decreases as $1/n$, giving the wrong power. Doubling n makes the energy magnitude one quarter, rather than one half, of its previous value.

Step 3: Conclusion The total energy is proportional to $1/n^2$, with a negative proportionality constant. Hence, the correct option is (D).

Quick Tip to Solve: For a hydrogen orbit, remember $r_n \propto n^2$ but $E_n \propto -1/n^2$; do not confuse radius and energy.

9. $\text{m}^2 \text{V}^{-1} \text{s}^{-1}$ is the SI unit of which of the following?

[1 mark]

- (A) Drift velocity
- (B) Mobility
- (C) Resistivity
- (D) Potential gradient

Correct Answer: (B) Mobility

Solution:

Concept:

- Mobility μ is drift speed per unit electric field: $\mu = v_d/E$, where v_d is the drift speed and E is the field magnitude.
- Drift speed has SI unit m s^{-1} , and electric field has SI unit V m^{-1} .

Step 1: Obtain the unit from the definition Dividing the unit of drift speed by the unit of field gives

$$[\mu] = \frac{\text{m s}^{-1}}{\text{V m}^{-1}} = \text{m}^2 \text{V}^{-1} \text{s}^{-1}.$$

The extra factor of metre appears because field is voltage per unit length.

Step 2: Check the other quantities Drift velocity, option (A), has unit m s^{-1} . Resistivity, option (C), has unit Ωm , as follows from $R = \rho L/A$. Potential gradient, option (D), has unit V m^{-1} . None matches the supplied unit.

Step 3: Conclusion The given SI unit belongs to mobility. Hence, the correct option is (B).

Quick Tip to Solve: Write mobility as speed divided by field; dividing by V m^{-1} supplies the second power of metre.

10. The electric flux emerging out from 1 C charge is

[1 mark]

- (A) $\frac{1}{\varepsilon_0}$
- (B) 4π
- (C) $\frac{4\pi}{\varepsilon_0}$
- (D) ε_0

Correct Answer: (A) $\frac{1}{\varepsilon_0}$

Solution:

Concept:

- Gauss's law gives the net outward electric flux through a closed surface as $\Phi_E = q_{\text{enc}}/\varepsilon_0$.
- Here q_{enc} is the enclosed charge and ε_0 is the permittivity of free space; flux has SI unit $\text{N m}^2\text{C}^{-1}$.

Step 1: Apply the closed-surface law Enclose the positive charge by any closed surface. Its field lines leave the surface, so the outward flux is positive. With $q_{\text{enc}} = 1 \text{ C}$,

$$\Phi_E = \frac{1 \text{ C}}{\varepsilon_0}.$$

The radius or shape of the enclosing surface does not alter this total.

Step 2: Check the factor of solid angle For a spherical surface, $E = q/(4\pi\varepsilon_0 r^2)$ and its area is $4\pi r^2$; their product cancels both 4π and r^2 . Therefore option (C) retains an extra factor 4π , option (B) omits charge and permittivity, and option (D) incorrectly uses permittivity in the numerator.

Step 3: Conclusion For a charge of 1 C, the printed expression for the emerging flux is $1/\varepsilon_0$. Hence, the correct option is (A).

Quick Tip to Solve: Use q/ε_0 for total flux; the 4π in the point-charge field cancels against the sphere area.

11. In Young's double slit experiment, when the monochromatic source is replaced by a source of white light, the central fringe becomes _____. [1 mark]

Solution:

Concept:

- In double-slit interference, the phase difference for wavelength λ is $\phi = 2\pi\Delta/\lambda$, where Δ is the path difference.
- White light contains the visible wavelengths. Their bright fringes coincide wherever the path difference is zero.

Step 1: Examine the central position At the centre of the screen, the point is equidistant from the two slits, so $\Delta = 0$. Consequently $\phi = 0$ for every visible wavelength. Both waves for each colour arrive in phase and reinforce one another at this same position.

Step 2: Combine the contributions of the colours The central maxima of all colours overlap, producing a bright white fringe. Away from the centre, the condition $\Delta = m\lambda$ selects different positions for different wavelengths, so coloured fringes occur there. This does not change the colour of the central fringe.

Step 3: Conclusion The central fringe becomes white (a bright white fringe).

Quick Tip to Solve: At the centre, set the path difference to zero first: zero phase difference holds for every colour of white light.

12. In photoelectric effect, the number of emitted photoelectrons is proportional to _____ of incident light. [1 mark]

Solution:

Concept:

- At a fixed frequency above threshold, incident photons carry the same energy $h\nu$; increasing intensity increases the photon arrival rate.
- In ordinary photoelectric emission, an electron absorbs energy from an individual photon; more incident photons give more emitted electrons under unchanged conditions.

Step 1: Relate intensity to photons Intensity is the incident energy per unit area per unit time. For illuminated area A and light frequency ν , the photon arrival rate is

$$\dot{N}_\gamma = \frac{IA}{h\nu}.$$

With A and ν fixed, this rate is proportional to I .

Step 2: Relate photons to emitted electrons For the same photosensitive surface and a fixed frequency exceeding its threshold, the emission efficiency stays fixed. Thus the number of photoelectrons emitted in a fixed interval increases in proportion to the intensity. Increasing intensity changes the number of emitted electrons, while their maximum kinetic energy depends on frequency.

Step 3: Conclusion The blank is intensity of incident light.

Quick Tip to Solve: Keep frequency above threshold fixed: intensity controls the electron count, whereas frequency controls maximum kinetic energy.

12. Light of frequency ν is incident on a photosensitive surface of threshold frequency ν_0 ($\nu > \nu_0$). The value of kinetic energy of the emitted photoelectrons will be _____. [1 mark]

Solution:

Concept:

- Einstein's photoelectric equation is $h\nu = \phi + K_{\max}$, where h is Planck's constant and ϕ is the work function.
- The threshold frequency ν_0 defines the minimum photon energy for emission: $\phi = h\nu_0$.

Step 1: Account for the work function An incident photon supplies energy $h\nu$. The electron must expend at least the work-function energy $h\nu_0$ to escape the surface. At the threshold itself no energy remains for the maximum kinetic energy, which is consistent with $K_{\max} = 0$ when $\nu = \nu_0$.

Step 2: Subtract the escape energy Substitute $\phi = h\nu_0$ into the energy balance:

$$K_{\max} = h\nu - h\nu_0 = h(\nu - \nu_0).$$

Since the printed question gives $\nu > \nu_0$, this quantity is positive. Electrons emerging after internal energy losses can have smaller kinetic energies; the expression requested is the maximum kinetic energy.

Step 3: Conclusion The blank is $h(\nu - \nu_0)$, the maximum kinetic energy of the emitted photoelectrons.

Quick Tip to Solve: Subtract the threshold photon energy from the incident photon energy; use frequency difference, not frequency ratio.

13. The phase difference between the two points on the same wavefront is _____. [1 mark]

Solution:

Concept:

- A wavefront is the locus of points of a wave that are in the same phase at a given instant.
- Phase indicates the stage of oscillation; a full cycle corresponds to 2π radians.

Step 1: Use the definition of a wavefront Take two points on the same wavefront at the same instant. By definition they are at the same stage of oscillation, so their phases are equal. The points need not occupy the same position; it is their phase, rather than their separation, that is shared.

Step 2: Find the phase difference If the phases are ϕ_1 and ϕ_2 , then

$$\Delta\phi = \phi_2 - \phi_1 = 0.$$

Physically, equal phases are also described modulo 2π , but the standard phase difference between points on one wavefront is zero. A distance measured along a wavefront does not create a phase

change.

Step 3: Conclusion The phase difference is zero (0 radians).

Quick Tip to Solve: Recall the defining phrase "same phase" for a wavefront before applying any phase-difference formula based on distance.

14. The refractive index of the material of a converging lens is 1.5. If air is replaced by a medium of refractive index 1.6, then the lens will now behave as a _____ lens. [1 mark]

Solution:

Concept:

- The power of a thin lens in a medium is $P = \left(\frac{n_l}{n_m} - 1 \right) \left(\frac{1}{R_1} - \frac{1}{R_2} \right)$, where n_l and n_m are the lens and medium refractive indices.
- For the same lens shape, the curvature factor stays fixed; positive power means convergence and negative power means divergence.

Step 1: Compare the refractive indices The lens material has $n_l = 1.5$, whereas the surrounding medium has $n_m = 1.6$. The relative refractive index is therefore $n_l/n_m = 1.5/1.6 = 0.9375$, which is less than unity.

Step 2: Determine the sign of the power The lens is converging in air, so its curvature factor is positive. In the new medium, $n_l/n_m - 1 = -0.0625$. Multiplication by the unchanged positive curvature factor makes its power negative; the emerging rays spread apart.

Step 3: Conclusion The lens now behaves as a diverging lens.

Quick Tip to Solve: Compare the lens index with the surrounding medium index before assigning a convex lens its optical behaviour.

15. The value of Brewster's angle for air-glass interface is $\frac{\pi}{3}$; hence the refractive index of glass is _____. [1 mark]

Solution:

Concept:

- Brewster's law gives $\tan i_B = n_2/n_1$, where i_B is the polarising angle and n_1, n_2 are the incident and transmitted media indices.
- For light incident from air, $n_1 \simeq 1$, so the glass refractive index equals $\tan i_B$.

Step 1: Identify the angle and incident medium The given Brewster angle is $i_B = \pi/3 = 60^\circ$. At an air-glass interface, the standard air-to-glass interpretation gives the refractive index of glass relative to air.

Step 2: Apply Brewster law Substitute the given angle:

$$n_{\text{glass}} = \tan\left(\frac{\pi}{3}\right) = \tan 60^\circ = \sqrt{3}.$$

The refractive index is a ratio of speeds and therefore has no unit; it is not the sine or cosine of the polarising angle.

Step 3: Conclusion The blank is $\sqrt{3}$, approximately 1.73.

Quick Tip to Solve: For an air-to-glass Brewster-angle question, take the tangent of the angle directly, not its sine.

16. A circuit element is connected across an ac source. It is observed that the voltage across the element leads the current flowing through it by a phase angle $\frac{\pi}{2}$. Identify the circuit element. [1 mark]

Solution:

Concept:

- In a pure inductance L , the applied voltage is $v = L di/dt$. Differentiation of a sinusoidal current advances its phase by $\pi/2$.
- An ideal resistor has voltage and current in phase; in an ideal capacitor, current leads voltage by $\pi/2$.

Step 1: Use the observed phase relation The stated voltage leads the current by $\pi/2 = 90^\circ$. Equivalently, the current lags the voltage by a quarter of a cycle. The direction of the lead is essential when identifying a reactive element.

Step 2: Check the inductive relation If $i = I_0 \sin \omega t$, an inductor gives

$$v = L \frac{di}{dt} = \omega L I_0 \cos \omega t = \omega L I_0 \sin(\omega t + \pi/2).$$

This has exactly the observed voltage lead. A resistor or capacitor does not have this phase relation.

Step 3: Conclusion The circuit element is a $\boxed{\text{pure inductor}}$.

Quick Tip to Solve: Remember that an inductor makes current lag; a capacitor makes current lead.

17. Write the impedance of a series LCR resonant circuit in terms of L , C and R . [1 mark]

Solution:

Concept:

- The impedance magnitude of a series LCR circuit is $Z = \sqrt{R^2 + (X_L - X_C)^2}$, with $X_L = \omega L$ and $X_C = 1/(\omega C)$.
- At series resonance the inductive and capacitive reactances are equal, so their net contribution

cancels.

Step 1: Write the general impedance For angular frequency ω , the resistance and net reactance combine as

$$Z = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}.$$

The reactances must first be subtracted, since their voltage contributions have opposite phase.

Step 2: Apply the resonance condition At $\omega = \omega_0 = 1/\sqrt{LC}$, $\omega_0 L = 1/(\omega_0 C)$. Thus the squared reactance term vanishes and the impedance is $\sqrt{R^2} = R$ for a nonnegative resistance. The values of L and C set the resonance frequency, but do not add to the impedance at resonance.

Step 3: Conclusion The resonant impedance is $Z_{\text{res}} = R$.

Quick Tip to Solve: Apply the resonance condition before calculating impedance: equal inductive and capacitive reactances cancel.

18. Mention the contribution of Indian physicist J.C. Bose in the production of electromagnetic waves. [1 mark]

Solution:

Concept:

- Electromagnetic waves can be produced by accelerated charges or oscillating electric currents; their wavelength identifies their region of the electromagnetic spectrum.
- Microwaves are short-wavelength electromagnetic waves, and laboratory generation and detection establish their physical properties.

Step 1: Identify the contribution asked for The question concerns J. C. Bose's work on producing electromagnetic waves. His relevant achievement was the production and experimental study of very short-wavelength radio waves, in the microwave region.

Step 2: State the experimental achievement Bose generated and detected millimetre-wavelength electromagnetic waves and used them in laboratory experiments. These experiments demonstrated their wave behaviour and supported their identification as electromagnetic radiation. The essential contribution here is the successful generation of short-wavelength microwaves, rather than a general statement about wireless communication.

Step 3: Conclusion J. C. Bose produced and detected very short-wavelength electromagnetic waves (millimetre-wave microwaves).

Quick Tip to Solve: For Bose's contribution to wave production, name short-wavelength microwaves explicitly.

19. In an ac circuit, the applied voltage and flowing current are $E = E_0 \sin \omega t$ and $I = I_0 \sin \left(\omega t + \frac{\pi}{2} \right)$ respectively. What is the average power consumed in one cycle in this circuit? [1 mark]

Solution:

Concept:

- The average ac power is $P_{av} = V_{rms} I_{rms} \cos \phi$, where ϕ is the voltage-current phase difference.
- For sinusoidal quantities, $V_{rms} = E_0/\sqrt{2}$ and $I_{rms} = I_0/\sqrt{2}$; the power factor is $\cos \phi$.

Step 1: Read the phase difference The voltage is $E = E_0 \sin \omega t$, and the current is $I = I_0 \sin(\omega t + \pi/2)$. Therefore current leads voltage by $\pi/2$, and the magnitude of their phase difference is 90° .

Step 2: Evaluate the cycle average Using the power-factor expression,

$$P_{av} = \frac{E_0 I_0}{2} \cos \frac{\pi}{2} = 0.$$

Equivalently, instantaneous power is $E_0 I_0 \sin \omega t \cos \omega t$, whose positive and negative contributions cancel over a complete cycle. Energy is stored and returned rather than dissipated on average.

Step 3: Conclusion The average power consumed in one cycle is 0 W.

Quick Tip to Solve: When voltage and current differ by a quarter-cycle, their power factor is zero regardless of the amplitudes.

OR

19. What happens when a block of metal is kept in a varying magnetic field? [1 mark]

Solution:

Concept:

- Faraday's law states that changing magnetic flux induces an emf: $\mathcal{E} = -d\Phi_B/dt$.
- A bulk metal contains conducting closed paths, so induced emfs drive circulating currents called eddy currents; resistance then dissipates energy as heat.

Step 1: Apply electromagnetic induction When the metal block is placed in a varying magnetic field, magnetic flux through conducting loops inside the block changes. An induced emf therefore develops along these paths even though the block is not connected to an external circuit.

Step 2: Describe the effect inside the metal The induced emf drives closed circulating eddy currents throughout the metal. By Lenz's law, their magnetic effect opposes the change of flux producing them. Because the metal has electrical resistance, these currents cause Joule heating, converting supplied electromagnetic energy into thermal energy.

Step 3: Conclusion Eddy currents are induced in the metal block, causing it to heat up.

Quick Tip to Solve: A changing field in a solid conductor produces internal current loops: name eddy currents and their heating effect.

20. Which physical quantity associated with an electromagnetic wave does not change when it propagates from one medium into another medium? [1 mark]

Solution:

Concept:

- The frequency ν of an electromagnetic wave is determined by its source and remains unchanged across a stationary interface between two media.
- Wave speed v , frequency ν , and wavelength λ obey $v = \nu\lambda$.

Step 1: Identify the quantity fixed by the source The electromagnetic disturbance must oscillate at the same rate on both sides of the interface. Therefore, the transmitted wave has the same frequency as the incident wave: $\nu_2 = \nu_1$.

Step 2: Distinguish frequency from speed and wavelength The speed depends on the optical properties of the medium and can change. Since $\lambda = v/\nu$, the wavelength changes with the speed while the frequency stays fixed. Thus neither speed nor wavelength is generally invariant between media.

Step 3: Conclusion The frequency of the electromagnetic wave remains unchanged when it passes from one medium into another.

Quick Tip to Solve: At a stationary boundary, keep frequency fixed and use $v = \nu\lambda$ to relate the changing speed and wavelength.

Section B (14 marks)

21. A battery of emf 12 V and internal resistance $4\ \Omega$ is connected to an external resistance R . If the current in the resistance is 0.5 A, calculate the value of (a) R , and (b) the terminal voltage of the battery. [2 marks]

Solution:

Concept:

- For a battery delivering current I , its internal resistance r is in series with the external resistance R . Hence $I = \mathcal{E}/(R + r)$, where $\mathcal{E}$ is its emf.
- The terminal voltage while the battery supplies current is $V = \mathcal{E} - Ir = IR$. The internal voltage drop Ir makes terminal voltage smaller than emf.

Step 1: Calculate the external resistance Given $\mathcal{E} = 12\text{ V}$, $r = 4\ \Omega$, and $I = 0.5\text{ A}$, the resistance of the complete circuit is

$$R + r = \frac{\mathcal{E}}{I} = \frac{12}{0.5}\ \Omega = 24\ \Omega.$$

Subtracting the battery's internal resistance gives $R = 24 - 4 = 20\ \Omega$. The external resistance must exclude the internal resistance, since both together account for the full emf.

Step 2: Calculate the terminal voltage The voltage lost inside the battery is $Ir = (0.5)(4) = 2\text{ V}$. Therefore,

$$V = \mathcal{E} - Ir = 12 - 2 = 10\text{ V}.$$

As a check, the voltage across the external resistance is $IR = (0.5)(20) = 10\text{ V}$, which agrees with the terminal voltage.

Step 3: Conclusion (a) The external resistance is $R = 20\ \Omega$. (b) The battery's terminal voltage is

$$V = 10 \text{ V}.$$

Quick Tip to Solve: Find total resistance from emf divided by current, subtract internal resistance, and check terminal voltage using IR .

22. A converging lens of focal length f_1 is placed coaxially in contact with a diverging lens of focal length f_2 ($f_1 > f_2$). Determine the power and nature of the combination in terms of f_1 and f_2 .

[2 marks]

Solution:

Concept:

- Powers of thin lenses placed coaxially in contact add: $P = P_1 + P_2 = 1/F$, where F is the equivalent focal length. Focal lengths must be in metres for power in dioptres.
- A converging lens has positive focal length and power, while a diverging lens has negative focal length and power. The sign of the resultant power determines the nature of the combination.

Step 1: Assign the signs and add powers Here f_1 and f_2 denote the positive magnitudes of the focal lengths of the converging and diverging lenses, respectively. Their signed focal lengths are therefore $+f_1$ and $-f_2$. The combined power is

$$P = \frac{1}{f_1} - \frac{1}{f_2} = \frac{f_2 - f_1}{f_1 f_2}.$$

This gives power in m^{-1} , or dioptres, when f_1 and f_2 are expressed in metres.

Step 2: Determine the nature from the resultant sign Since the given magnitudes satisfy $f_1 > f_2$, the numerator $f_2 - f_1$ is negative and the denominator is positive. Thus $P < 0$. The diverging lens has the larger power magnitude because it has the shorter focal length. Equivalently, $F = f_1 f_2 / (f_2 - f_1) < 0$, so parallel incident rays emerge diverging.

Step 3: Conclusion The power is $P = (f_2 - f_1)/(f_1 f_2)$ dioptres for focal-length magnitudes in metres. The combination is **diverging**.

Quick Tip to Solve: Attach the minus sign to the diverging lens before adding powers; the shorter focal-length magnitude dominates the combination.

OR

22. How is the resolving power of a compound microscope affected if (a) wavelength of light used is decreased, and (b) the diameter of its objective lens is increased? Justify your answers.

[2 marks]

Solution:

Concept:

- A microscope resolves two points when their diffraction patterns are sufficiently distinguishable. Its minimum resolvable separation is $d_{\min} = 1.22\lambda / (2\mu \sin \theta)$, where μ is the refractive index of the medium and θ is the half-angle subtended by the objective at the object.
- Resolving power is the reciprocal of the minimum resolvable separation: $\text{RP} = 1/d_{\min} = 2\mu \sin \theta / (1.22\lambda)$. Larger numerical aperture $\mu \sin \theta$ means better resolution.

Step 1: Decrease the wavelength of the light With the medium and objective aperture unchanged, $RP \propto 1/\lambda$. Decreasing the wavelength therefore increases the resolving power. The diffraction patterns become narrower, and two object points at a smaller separation can be distinguished. For example, halving the wavelength would double the resolving power under these conditions.

Step 2: Increase the objective diameter Keeping the wavelength, medium, and object-to-objective geometry otherwise the same, a larger objective diameter increases the angular aperture θ , and hence $\sin \theta$. Thus the numerical aperture increases. From the formula, resolving power increases and $d_{\min}$ decreases. The microscope can consequently distinguish points closer together.

Step 3: Conclusion Resolving power increases in both cases: (a) because it is inversely proportional to wavelength, and (b) because a larger objective diameter increases the numerical aperture.

Quick Tip to Solve: Use $RP \propto NA/\lambda$: shorter wavelength and larger numerical aperture both improve resolution.

23. The energy stored in a solenoid of inductance L is U . The number of turns per unit length of the solenoid is doubled. Keeping the current and all other factors same, find (a) change in inductance of the solenoid, and (b) the final energy stored in the inductor. [2 marks]

Solution:

Concept:

- The self-inductance of a long solenoid is $L = \mu n^2 A \ell$, where n is the number of turns per unit length, A is its cross-sectional area, ℓ is its length, and μ is the permeability of its core.
- The magnetic energy stored in an inductor carrying current I is $U = \frac{1}{2} L I^2$. At fixed current, the stored energy is directly proportional to inductance.

Step 1: Calculate the new inductance and its change The new turn density is $n' = 2n$, while μ , A , and ℓ remain the same. Hence

$$L' = \mu(2n)^2 A \ell = 4\mu n^2 A \ell = 4L.$$

Thus the final inductance is four times the initial inductance. The actual increase is $\Delta L = L' - L = 4L - L = 3L$. It is useful to distinguish the final value from the change requested in part (a).

Step 2: Calculate the final stored energy The current is explicitly kept unchanged, so only the inductance changes in the energy formula. Therefore,

$$U' = \frac{1}{2} L' I^2 = \frac{1}{2} (4L) I^2 = 4 \left(\frac{1}{2} L I^2 \right) = 4U.$$

The energy becomes four times its original value because the inductance is proportional to the square of the turn density.

Step 3: Conclusion (a) The final inductance is $L' = 4L$, an increase of $\Delta L = 3L$. (b) The final energy stored is $U' = 4U$.

Quick Tip to Solve: Square the factor by which turns per unit length change; at unchanged current, the same factor multiplies stored energy.

24. A hydrogen atom is in its third excited state.

(a) How many spectral lines can be emitted by it before coming to the ground state? Show these transitions in the energy level diagram.

(b) In which of the above transitions will the spectral line of shortest wavelength be emitted? [2 marks]

Solution:

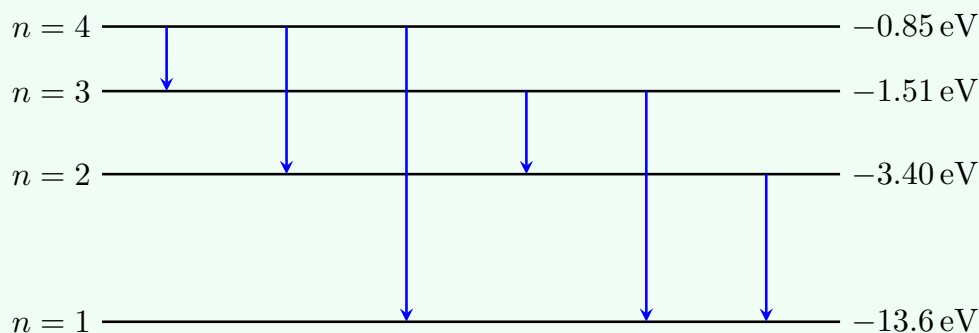
Concept:

- The ground state is $n = 1$; hence the third excited state is $n = 4$.
- Each distinct downward transition emits a photon with $hc/\lambda = E_i - E_f$, where $E_n = -13.6/n^2$ eV.

Step 1: (a) Count the possible spectral lines The levels available during de-excitation are $n = 4, 3, 2, 1$. A distinct line corresponds to a distinct pair of initial and final levels. There are three possible transitions from level 4, two from level 3 and one from level 2. Thus

$$N = 3 + 2 + 1 = \frac{4(4-1)}{2} = 6.$$

They are $4 \rightarrow 3$, $4 \rightarrow 2$, $4 \rightarrow 1$, $3 \rightarrow 2$, $3 \rightarrow 1$ and $2 \rightarrow 1$, shown below. These are all the possible lines over the alternative decay paths; a single atom following one path need not emit all six photons.



Four hydrogen levels and all six downward transitions (level spacing is schematic).

Step 2: (b) Identify the largest photon energy Since $\lambda = hc/(E_i - E_f)$, the shortest wavelength belongs to the greatest energy drop. Among these levels the largest drop is from $n = 4$ directly to $n = 1$:

$$E_4 - E_1 = 13.6 \left(1 - \frac{1}{16} \right) = 12.75 \text{ eV}.$$

Any transition ending above the ground state, or beginning below level 4, releases less energy and therefore has a longer wavelength.

Step 3: Conclusion (a) Six possible spectral lines are emitted. (b) The $n = 4 \rightarrow n = 1$ transition gives the shortest wavelength.

Quick Tip to Solve: Convert an excited-state number to the principal quantum number by adding one before using $n(n-1)/2$.

25. Two identical bars, one of paramagnetic material and other of diamagnetic material are kept in a uniform external magnetic field parallel to it. Draw diagrammatically the modifications in the magnetic field pattern in each case. [2 marks]

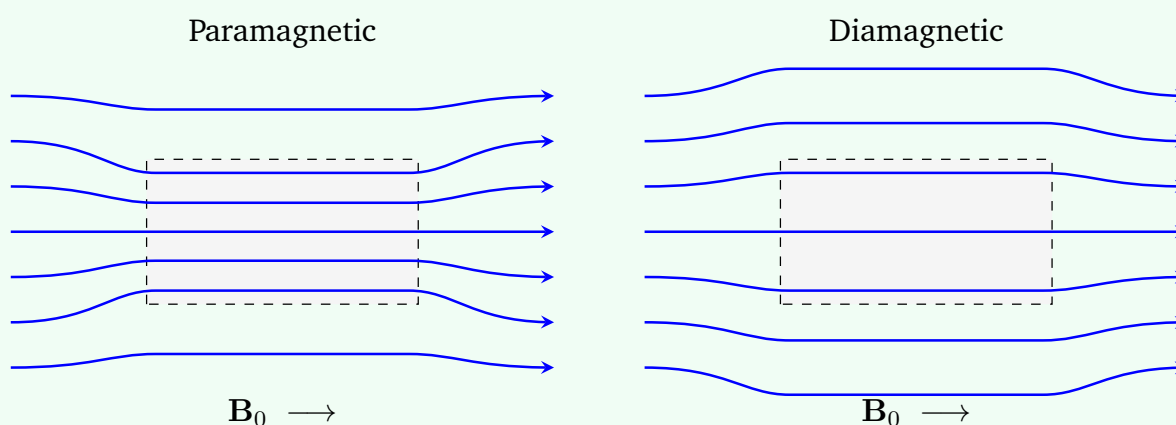
Solution:

Concept:

- A paramagnetic material has a small positive magnetic susceptibility χ_m ; its induced magnetisation is along the applied field.
- A diamagnetic material has a small negative χ_m ; its induced magnetisation opposes the applied field. The relative permeability is $\mu_r = 1 + \chi_m$.

Step 1: Draw the paramagnetic field pattern Take the uniform external field along the length of the bar, from left to right. In a paramagnetic bar the induced magnetisation reinforces that field. Therefore magnetic field lines bend towards the bar and become more closely spaced inside it than in the surrounding region. The sketch uses the same bar size and applied-field direction in both cases, so the difference in the density of lines is apparent.

Step 2: Draw the diamagnetic field pattern In a diamagnetic bar the induced magnetisation opposes the applied field, reducing the resultant field inside. Field lines tend to bend away from the bar, leaving fewer, more widely spaced lines within it. The field is reduced, rather than completely excluded: ordinary diamagnetic materials still have a nonzero internal field. Arrows in both sketches point in the direction of the resultant magnetic field, and closer line spacing indicates a stronger field.



Modifications of a left-to-right applied magnetic field; dashed rectangles show identical bars.

Step 3: Conclusion Paramagnetic: lines concentrate within the bar ($\mu_r > 1$). Diamagnetic: lines move away from the bar and are less dense inside it ($\mu_r < 1$), as drawn.

Quick Tip to Solve: Use the sign of susceptibility to decide whether the lines crowd into the bar or spread away from it.

26. The de Broglie wavelengths associated with an electron and a proton are equal. Prove that the kinetic energy of the electron is greater than that of the proton. [2 marks]

Solution:

Concept:

- The de Broglie relation is $\lambda = h/p$, with Planck's constant h and momentum magnitude p .
- For a nonrelativistic particle of mass m , kinetic energy $K = p^2/(2m)$; at a given momentum it is inversely proportional to mass.

Step 1: Use the equality of wavelengths Write the electron and proton wavelengths in terms of their momenta:

$$\lambda_e = \frac{h}{p_e}, \quad \lambda_p = \frac{h}{p_p}.$$

Since $\lambda_e = \lambda_p$, and the same constant h applies to both particles, their momentum magnitudes are equal: $p_e = p_p = p$. Equality of wavelengths does not imply equality of velocities or of kinetic energies.

Step 2: Compare kinetic energies at equal momentum Using the usual nonrelativistic kinetic-energy expression for each particle gives

$$K_e = \frac{p^2}{2m_e}, \quad K_p = \frac{p^2}{2m_p}, \quad \frac{K_e}{K_p} = \frac{m_p}{m_e}.$$

The proton is much heavier than the electron: $m_p \simeq 1836m_e$. Thus the energy ratio is about 1836 and exceeds unity. Physically, the lighter electron must move faster to have the same momentum, so it has the larger kinetic energy.

Step 3: Conclusion For equal de Broglie wavelengths, $K_e/K_p = m_p/m_e \simeq 1836 > 1$; hence the electron's kinetic energy is greater than the proton's.

Quick Tip to Solve: Equal de Broglie wavelengths mean equal momentum; compare energies using $p^2/(2m)$, not equal-speed reasoning.

27. How does an oscillating charge radiate an electromagnetic wave? Give the relation between the frequency of radiated wave and the frequency of oscillating charge. [2 marks]

Solution:

Concept:

- An accelerated charge radiates electromagnetic energy. An oscillating charge has a periodically changing velocity and therefore acceleration.
- Time-varying electric and magnetic fields are coupled and propagate through space as an electromagnetic wave; in vacuum its speed is $c = 1/\sqrt{\mu_0\epsilon_0}$.

Step 1: Explain the production of the wave An oscillating charge continually accelerates as its velocity changes in magnitude and direction. Its electric field therefore changes with time. This changing electric field is associated with a changing magnetic field; a changing magnetic field in turn produces an electric field. These coupled disturbances travel outwards from the accelerating charge, carrying energy away as electromagnetic radiation. In the radiation region the electric and magnetic fields are mutually perpendicular and both are perpendicular to the direction in which the wave propagates.

Step 2: Relate the two frequencies For a charge executing sinusoidal oscillations at frequency f , its

acceleration, and hence the radiated field, vary periodically at that same frequency. If the charge's period is T , the electric and magnetic fields repeat after T as well. Therefore

$$f_{\text{wave}} = \frac{1}{T} = f_{\text{charge}}.$$

Propagation introduces a time delay at a distant observation point, but this delay changes the phase, not the frequency of the emitted wave.

Step 3: Conclusion An oscillating charge radiates because it accelerates, producing coupled time-varying electric and magnetic fields. The radiated wave has the same frequency as the oscillating charge: $f_{\text{wave}} = f_{\text{charge}}$.

Quick Tip to Solve: Link radiation to acceleration first, then use the common oscillation period to establish equality of frequencies.

OR

27. (a) Explain briefly the fact that electromagnetic waves carry energy.

(b) Why do we not feel the pressure due to sunshine?

[2 marks]

Solution:

Concept:

- An electromagnetic wave consists of electric and magnetic fields. Both fields store energy and transport it through space.
- In vacuum the energy densities are $u_E = \frac{1}{2}\epsilon_0 E^2$ and $u_B = B^2/(2\mu_0)$, where E and B are the field magnitudes. Radiation also carries momentum.

Step 1: (a) Explain energy transport The electric and magnetic fields of an electromagnetic wave exert forces on charges in matter. On absorption, the wave transfers energy to the material, producing effects such as heating. For example, sunlight warms an absorbing surface even though no material medium carries heat from the Sun to that surface. The field energy density is

$$u = \frac{1}{2}\epsilon_0 E^2 + \frac{B^2}{2\mu_0}.$$

This energy travels with the wave; hence electromagnetic waves carry energy.

Step 2: (b) Account for the imperceptible sunshine pressure Absorbed light transfers momentum to a surface and therefore exerts radiation pressure. If I is the incident intensity and c the speed of light, the pressure on a normally illuminated, perfectly absorbing surface is $p = I/c$. For perfect reflection it is $2I/c$. Since c is extremely large, the pressure associated with ordinary sunshine is extremely small, of order 10^{-6} Pa. The resulting force on the body is too small to be felt.

Step 3: Conclusion (a) Electromagnetic waves transport energy stored in their electric and magnetic fields and transfer it on absorption. (b) Sunshine exerts radiation pressure, but its magnitude is far too small for us to feel.

Quick Tip to Solve: Distinguish noticeable heating from radiation pressure: the latter is intensity divided by the very large speed of light.

Section C (21 marks)

28. (a) Write the relationship between mobility and drift velocity in a current carrying conductor.
(b) Two aluminium wires have their lengths in the ratio 2 : 3 and radii in the ratio 1 : 3. These are connected in parallel across a battery of emf E and of negligible internal resistance. Find the ratio of drift velocities of the electrons in the two wires. [3 marks]

Solution:

Concept:

- Electron mobility is $\mu = v_d/\mathcal{E}$, where v_d is the magnitude of drift velocity and $\mathcal{E}$ is the electric field magnitude inside the conductor.
- Across a uniform wire of length L and potential difference V , $\mathcal{E} = V/L$. Identical materials under the same conditions have the same mobility.
- Current and drift speed satisfy $I = neAv_d$, where n is the free-electron number density, e the electron charge magnitude and A the cross-sectional area.

Step 1: (a) State the mobility relation Mobility is the drift speed acquired per unit electric field:

$$\mu = \frac{v_d}{\mathcal{E}}, \quad v_d = \mu\mathcal{E}.$$

For electron velocity as a vector, $\mathbf{v}_d = -\mu\mathbf{\mathcal{E}}$, because electrons drift opposite to the electric field. The scalar relation above uses positive magnitudes.

Step 2: (b) Use the common parallel voltage Let the first and second wires have lengths L_1, L_2 , with $L_1 : L_2 = 2 : 3$. Since the wires are connected in parallel to a battery of negligible internal resistance, each has the same potential difference, equal to the battery emf E . The internal electric fields therefore have magnitudes E/L_1 and E/L_2 . Both wires are aluminium, so their mobilities are equal. Thus

$$\frac{v_{d1}}{v_{d2}} = \frac{\mu E/L_1}{\mu E/L_2} = \frac{L_2}{L_1} = \frac{3}{2}.$$

Step 3: Check why the radius ratio cancels The areas obey $A_1 : A_2 = 1 : 9$. With the same resistivity, $R = \rho L/A$, so $R_1/R_2 = (2/3) \times 9 = 6$ and $I_1/I_2 = 1/6$. Using $v_d = I/(neA)$, with the same n in both wires, gives $v_{d1}/v_{d2} = (1/6) \times 9 = 3/2$, confirming the electric-field method. Radius changes the current and the number of carriers crossing the section in matching proportions.

Step 4: Conclusion (a) $v_d = \mu\mathcal{E}$ for magnitudes. (b) The electron drift-speed ratio, in the order of the two stated wires, is $v_{d1} : v_{d2} = 3 : 2$.

Quick Tip to Solve: For wires of the same material connected in parallel, use $v_d = \mu V/L$; the drift-speed ratio is the inverse length ratio.

29. (a) Why is an intrinsic semiconductor deliberately converted into an extrinsic semiconductor by adding impurity atoms?

(b) Explain briefly the two processes that occur in p-n junction region to create a potential barrier.

[3 marks]

Solution:

Concept:

- Doping is the controlled addition of impurity atoms to an intrinsic semiconductor to increase and control its free charge-carrier concentration and hence its conductivity.
- Diffusion is carrier movement from a region of higher carrier concentration to a region of lower concentration. Drift is carrier movement caused by an electric field.
- In an unbiased p-n junction at thermal equilibrium, the drift and diffusion currents balance, leaving a built-in potential barrier across the depletion region.

Step 1: (a) Explain the purpose of adding impurities An intrinsic semiconductor has relatively few free electrons and holes, so its conductivity is low. A small, controlled amount of suitable impurity greatly increases the concentration of mobile carriers, making the conductivity useful and controllable in electronic devices. Pentavalent donor impurities produce an n-type semiconductor with electrons as majority carriers, while trivalent acceptor impurities produce a p-type semiconductor with holes as majority carriers. The bulk doped material remains electrically neutral.

Step 2: (b) Describe diffusion and depletion-region formation On joining p-type and n-type regions, the carrier concentrations differ across the junction. Electrons diffuse from the n side to the p side, and holes diffuse from the p side to the n side. Near the junction they recombine, removing mobile carriers there. The n side is left with immobile positive donor ions, while the p side is left with immobile negative acceptor ions. This region depleted of mobile majority carriers is called the depletion region.

Step 3: Explain drift and the establishment of the barrier The exposed ions create an electric field directed from the positive n-side ions towards the negative p-side ions. This field opposes further majority-carrier diffusion and establishes a potential barrier. It also drives electrons towards the n side and holes towards the p side, producing a drift current opposite to the diffusion current. As charge separation builds up, the opposing electric field increases. At thermal equilibrium, drift and diffusion currents have equal magnitudes, so the net current is zero and a stable built-in potential barrier remains across the junction.

Step 4: Conclusion (a) Doping increases and controls the carrier concentration and electrical conductivity. (b) Diffusion creates a depleted region with fixed ions; its electric field produces opposing drift, and their equilibrium establishes the junction's potential barrier.

Quick Tip to Solve: Track the fixed ions after recombination: positive on the n side and negative on the p side, so the barrier field points from n to p.

30. (a) The density of the nuclear matter is tremendously larger than the physical density of the material. Explain.
- (b) The nuclear forces are not coulomb forces between nucleons. Explain.
- (c) Draw a plot of the potential energy between a pair of nucleons as a function of distance between them inside a nucleus. [3 marks]

Solution:

Concept:

- Nearly all the mass of an atom is concentrated in its nucleus; most of the atomic volume lies outside the nucleus.
- The nuclear radius is $R = R_0 A^{1/3}$, where $R_0 \simeq 1.2 \times 10^{-15} \text{ m}$ and A is the mass number. A nucleon's mass is approximately $m_N = 1.67 \times 10^{-27} \text{ kg}$.
- The strong nuclear interaction is approximately charge independent, attractive over a short range and strongly repulsive at very small separations. Its radial force satisfies $F_r = -dU/dr$.

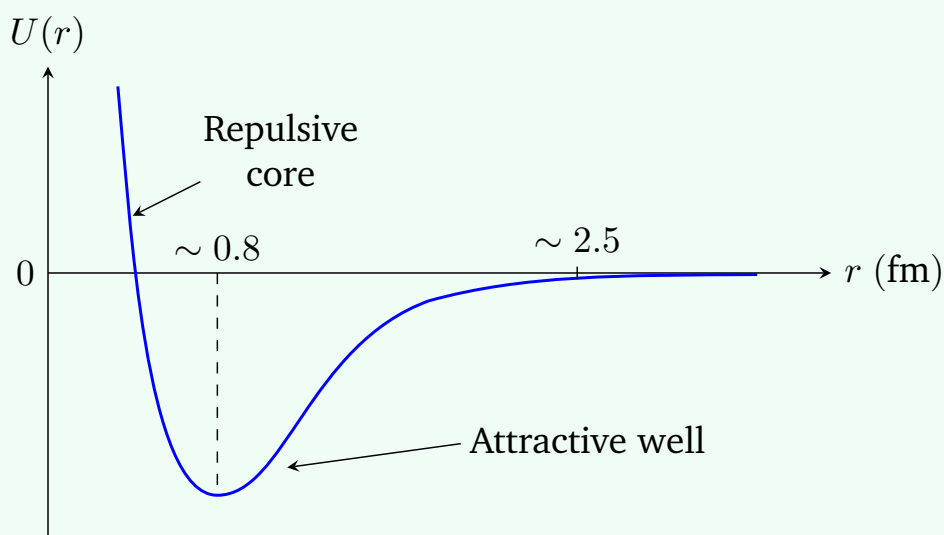
Step 1: (a) Compare nuclear and material densities An atom has a radius of order 10^{-10} m , whereas its nucleus has a radius of order 10^{-15} to 10^{-14} m . The electrons contribute very little mass, so almost the entire atomic mass is confined to this extremely small nuclear volume. The physical density of a material uses the much larger volume occupied by its atoms, including the space outside their nuclei. Thus the nuclear density is tremendously greater.

$$\rho_N = \frac{Am_N}{(4\pi/3)R^3} = \frac{3m_N}{4\pi R_0^3} \simeq 2.3 \times 10^{17} \text{ kg m}^{-3}.$$

The cancellation of A also shows why nuclear density is approximately the same for different nuclei. Ordinary condensed materials typically have densities of order 10^3 to 10^4 kg m^{-3} , many orders of magnitude smaller.

Step 2: (b) Distinguish nuclear forces from Coulomb forces Coulomb forces act between electric charges: two protons repel, while a neutron has no net electric charge. Nevertheless, strong attractive interactions occur between neutron–neutron and proton–neutron pairs, as well as between proton–proton pairs at nuclear distances. The nuclear interaction is approximately charge independent and can bind a nucleus despite the Coulomb repulsion between its protons. Also, nuclear forces have a range of only a few femtometres, whereas the Coulomb force varies as $1/r^2$ and has long range. These properties show that the binding nuclear force is a distinct interaction, not the Coulomb force.

Step 3: (c) Sketch and interpret the nucleon potential Take $U = 0$ at infinite separation. The schematic curve rises steeply to positive values at very small separation, representing the repulsive core. It has a negative minimum near $r \sim 0.8 \text{ fm}$, then rises towards zero and is negligible beyond a few femtometres. On the outer side of the minimum, $dU/dr > 0$, so $F_r < 0$: the force is attractive. On the inner side, $dU/dr < 0$, so $F_r > 0$: the force is repulsive. The negative well indicates binding; the axes and distance values in the sketch are schematic.



Schematic potential energy of a pair of nucleons, with zero at infinite separation.

Step 4: Conclusion Nuclear matter is exceptionally dense because nearly all atomic mass occupies the minute nuclear volume. Nuclear binding is caused by the short-range strong interaction. Its potential has a steep repulsive core and a negative attractive well that approaches zero outside the nuclear-force range.

Quick Tip to Solve: Use the same mass but compare nuclear and atomic volumes for density; for the potential graph, draw the positive core before the negative well and label the zero-energy line.

31. What are matter waves? Find the ratio of de Broglie wavelengths associated with proton and alpha particles when both particles

(a) are accelerated through the same potential difference.

(b) have same velocity.

[3 marks]

Solution:

Concept:

- Matter waves are the de Broglie waves associated with moving material particles. Their wavelength is $\lambda = h/p$, where h is Planck's constant and p is the particle's momentum.
- For nonrelativistic motion, $p = mv$ and the kinetic energy is $K = p^2/(2m)$. A particle of charge q , accelerated from rest through a potential difference V , gains kinetic energy qV .
- A proton has charge e and mass m_p . An alpha particle has charge $2e$ and mass approximately $4m_p$.

Step 1: Define matter waves According to de Broglie's hypothesis, a moving material particle is associated with a wave having wavelength $\lambda = h/p$. These matter waves explain particle diffraction; they are not electromagnetic waves. Larger momentum gives a smaller wavelength.

Step 2: (a) Use the same accelerating potential difference For both particles accelerated from rest through the same positive potential difference V , use the usual nonrelativistic relation

$$\frac{p^2}{2m} = qV \quad \Rightarrow \quad \lambda = \frac{h}{\sqrt{2mqV}}.$$

The proton gains energy eV , while the alpha particle gains $2eV$. Substituting both mass and charge

gives

$$\lambda_p = \frac{h}{\sqrt{2m_p eV}},$$
$$\lambda_\alpha = \frac{h}{\sqrt{2(4m_p)(2e)V}},$$
$$\frac{\lambda_p}{\lambda_\alpha} = \sqrt{\frac{(4m_p)(2e)}{m_p e}} = \sqrt{8} = 2\sqrt{2}.$$

Thus the wavelength ratio in the requested order, proton to alpha particle, is $2\sqrt{2} : 1$.

Step 3: (b) Use the same velocity Let the common speed be v . Then $p_p = m_p v$ and $p_\alpha = m_\alpha v \simeq 4m_p v$. Since wavelength is inversely proportional to momentum,

$$\frac{\lambda_p}{\lambda_\alpha} = \frac{h/(m_p v)}{h/(4m_p v)} = 4.$$

At equal velocity, only the masses determine the momentum ratio; the charges do not enter. The wavelength ratio is $4 : 1$.

Step 4: Conclusion Matter waves are the de Broglie waves associated with moving particles, with $\lambda = h/p$. The ratios $\lambda_p : \lambda_\alpha$ are (a) $2\sqrt{2} : 1$ for the same accelerating potential and (b) $4 : 1$ for the same velocity.

Quick Tip to Solve: For equal accelerating voltage, include both mass and charge under the square root; for equal velocity, compare only the masses and invert the momentum ratio.

32. (a) Using the necessary ray diagram, derive the mirror formula for a concave mirror.

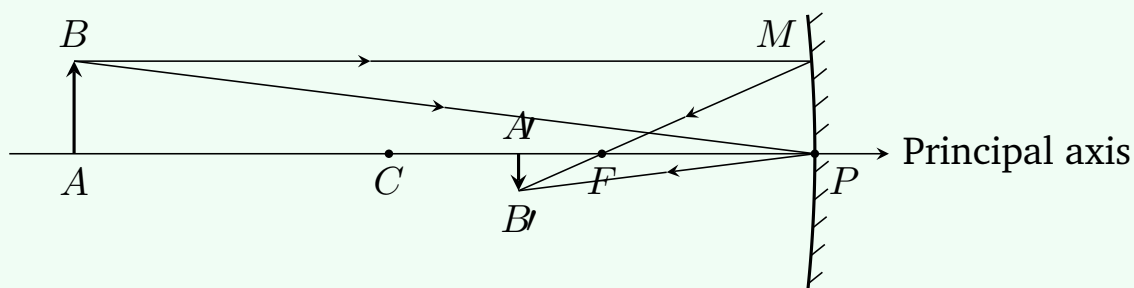
(b) In the magnified image of a measuring scale (with equidistant markings) lying along the principal axis of a concave mirror, the markings are not equidistant. Explain. [3 marks]

Solution:

Concept:

- A spherical mirror obeys the paraxial approximation: rays make small angles with the principal axis and strike close to the pole. Its focal length is $f = R/2$, where R is its radius of curvature.
- In the Cartesian sign convention, distances are measured from the pole P , positive in the direction of incident light. For the real-object, real-image arrangement shown, $u < 0$, $v < 0$ and $f < 0$.

Step 1: (a) Draw two principal rays and define distances Let AB be an upright object beyond the centre of curvature C , and $A'B'$ its inverted real image. Write the positive magnitudes as $U = PA$, $V = PA'$, $F = PF$, object height $h = AB$, and image-height magnitude $h_i = A'B'$. A ray from B parallel to the principal axis strikes the mirror at M and is reflected through the focus. A second ray incident at the pole is reflected with equal angles to the axis. Their intersection gives B' .



Paraxial ray diagram: object beyond C and inverted image between C and F.

Step 2: (a) Use similar triangles to derive the formula The triangles formed by the ray reflected at the pole give

$$\frac{h_i}{h} = \frac{V}{U}.$$

For a small aperture, M lies nearly in the transverse plane through P , so its height is h . The similar triangles along the ray reflected through F then give

$$\frac{h_i}{h} = \frac{V - F}{F}.$$

Equating these ratios,

$$\begin{aligned}\frac{V}{U} &= \frac{V - F}{F}, \\ VF &= UV - UF, \\ \frac{1}{F} &= \frac{1}{U} + \frac{1}{V}.\end{aligned}$$

Substituting $U = -u$, $V = -v$, $F = -f$ gives the Cartesian mirror formula $1/f = 1/u + 1/v$. Although derived using a real image, it applies to other paraxial arrangements with the proper signs.

Step 3: (b) Explain unequal spacings in the scale image Different scale markings lie at different object distances, so their image positions follow

$$v = \frac{fu}{u - f}.$$

This relation is nonlinear. For neighbouring markings,

$$\frac{dv}{du} = -\frac{f^2}{(u - f)^2}, \quad |\Delta v| \simeq \frac{f^2}{(u - f)^2} |\Delta u|.$$

Thus, even when each object interval $|\Delta u|$ is the same, its image interval varies with the location u along the scale. Markings closer to the focus have greater longitudinal magnification; hence the magnified image markings are not equidistant.

Step 4: Conclusion (a) For a concave spherical mirror and paraxial rays, $\boxed{1/f = 1/u + 1/v}$. (b) Image spacing varies because longitudinal magnification depends on object distance.

Quick Tip to Solve: For a scale placed along the axis, compare image distances using the mirror formula; transverse magnification alone does not give the spacing between its markings.

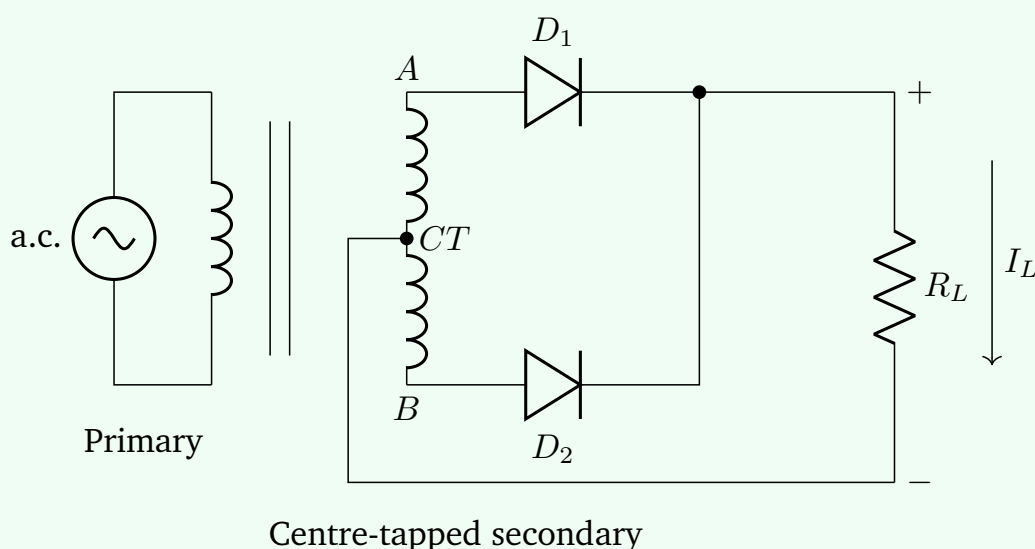
33. With the help of a circuit diagram, explain how two p-n junction diodes along with a centre tapped transformer can be used as a full wave rectifier. [3 marks]

Solution:

Concept:

- A p-n junction diode conducts appreciably when forward biased and blocks current when reverse biased. Rectification converts an alternating voltage into a unidirectional output.
- The two halves of a centre-tapped transformer secondary have equal voltages of opposite polarity relative to the centre tap CT . Two diodes use these halves on alternate half-cycles.

Step 1: Connect the centre-tapped rectifier Connect the anodes of D_1 and D_2 to the secondary ends A and B , respectively. Join their cathodes at the positive output terminal, and connect the load resistor R_L between that junction and the centre tap CT . The primary receives the a.c. supply. The load current is defined from the common cathodes through R_L towards CT .



Centre-tapped full-wave rectifier; both diode cathodes join the positive output.

Step 2: Operation during the first half-cycle When A is positive relative to CT , B is negative relative to CT . Diode D_1 is forward biased and conducts, while D_2 is reverse biased. The closed current path is $A \rightarrow D_1 \rightarrow R_L \rightarrow CT \rightarrow A$, returning through the upper half of the secondary. The upper end of the load is positive.

Step 3: Operation during the next half-cycle On reversal of the secondary voltage, B becomes positive relative to CT and A becomes negative. Now D_2 conducts and D_1 blocks. The current path is $B \rightarrow D_2 \rightarrow R_L \rightarrow CT \rightarrow B$, returning through the lower half of the secondary. The current through R_L still flows in the same direction as in the first half-cycle.

Step 4: Identify the full-wave output Both halves of the input cycle therefore produce positive load-voltage pulses. For ideal diodes, if either half-secondary has peak voltage V_m , the load voltage is $v_o = V_m |\sin \omega t|$. The output is pulsating d.c.; its ripple frequency is twice the supply frequency, $f_{\text{ripple}} = 2f_{\text{input}}$. It is not a constant voltage unless a suitable smoothing filter is added.

Step 5: Conclusion The two diodes conduct alternately, but drive current through the load in one direction during both half-cycles. Thus the centre-tapped circuit is a full-wave rectifier with pulsating d.c. output.

Quick Tip to Solve: Trace each half-cycle from the positive secondary end through its diode and the load back to the centre tap; the load-current arrows must agree.

34. A series LCR ac circuit has $L = 2.0 \text{ H}$, $C = 32 \mu\text{F}$ and $R = 10 \Omega$.

(a) At what angular frequency of ac will it resonate?

(b) Calculate the Q value of the circuit.

[3 marks]

Solution:

Concept:

- In a series LCR circuit the inductive reactance is $X_L = \omega L$ and the capacitive reactance is $X_C = 1/(\omega C)$, where ω is the angular frequency of the supply.
- At resonance the opposite reactive voltage contributions cancel: $X_L = X_C$. The impedance then equals the resistance R , and the current is maximum for a fixed supply voltage.
- The dimensionless quality factor is $Q = \omega_0 L/R = (1/R)\sqrt{L/C}$. It measures the sharpness of the current resonance; ω_0 denotes the resonant angular frequency.

Step 1: (a) Apply the resonance condition The given values are $L = 2.0 \text{ H}$, $C = 32 \mu\text{F} = 32 \times 10^{-6} \text{ F}$ and $R = 10 \Omega$. Equating the two reactances gives

$$\omega_0 L = \frac{1}{\omega_0 C} \Rightarrow \omega_0^2 = \frac{1}{LC}.$$

Choose the positive root because the driving angular frequency is positive. Thus

$$\omega_0 = \frac{1}{\sqrt{2.0 \times 32 \times 10^{-6}}} = \frac{1}{8.0 \times 10^{-3}} = 125 \text{ rad s}^{-1}.$$

The question asks for angular frequency, so this value should not be divided by 2π in the answer to part (a).

Step 2: (b) Evaluate the quality factor Use the series-circuit expression with the angular frequency already found:

$$Q = \frac{\omega_0 L}{R} = \frac{125 \times 2.0}{10} = 25.$$

As a numerical check, the two reactances at resonance are

$$X_L = 125 \times 2.0 = 250 \Omega, \quad X_C = \frac{1}{125 \times 32 \times 10^{-6}} = 250 \Omega.$$

Their equality verifies the resonance calculation. Their common value divided by R is $250/10 = 25$, consistent with the calculated quality factor. Because Q is a ratio of reactance to resistance, it has no unit.

Step 3: Conclusion (a) The circuit resonates at $\omega_0 = 125 \text{ rad s}^{-1}$. (b) Its quality factor is $Q = 25$, a dimensionless quantity.

Quick Tip to Solve: Convert microfarads to farads before taking the square root; after finding ω_0 , obtain Q directly from $\omega_0 L/R$.

OR

34. An ideal inductor of $\frac{5}{\pi}$ H inductance is connected to a 200 V, 50 Hz ac supply.

(a) Calculate the rms and peak value of current in the inductor.

(b) What is the phase difference between current through the inductor and the applied voltage? How will it change if a small resistance is connected in series with this inductor in the circuit? [3 marks]

Solution:

Concept:

- For an ideal inductor, the inductive reactance is $X_L = \omega L = 2\pi fL$, where f is the supply frequency and L is the inductance.
- The rms current is $I_{\text{rms}} = V_{\text{rms}}/X_L$. For a sinusoidal current its peak value is $I_0 = \sqrt{2} I_{\text{rms}}$; an ac supply rating gives the rms voltage.
- In a pure inductor the current lags the voltage by $\pi/2$. With series resistance R , the current lag ϕ satisfies $\tan \phi = X_L/R$, with $0 < \phi < \pi/2$.

Step 1: (a) Find the inductive reactance and rms current The printed inductance is $L = 5/\pi$ H. The voltage rating is $V_{\text{rms}} = 200$ V, and the frequency is $f = 50$ Hz. Hence

$$X_L = 2\pi \times 50 \times \frac{5}{\pi} = 500 \Omega.$$

An ideal inductor has zero resistance, so its impedance magnitude equals X_L . Using rms voltage and rms current consistently gives

$$I_{\text{rms}} = \frac{V_{\text{rms}}}{X_L} = \frac{200}{500} = 0.40 \text{ A}.$$

Step 2: Convert the rms current to its peak value For sinusoidal ac, the peak is $\sqrt{2}$ times the rms value. Therefore

$$I_0 = \sqrt{2} I_{\text{rms}} = 0.40\sqrt{2} \text{ A} \simeq 0.566 \text{ A}.$$

Equivalently, the peak supply voltage is $200\sqrt{2}$ V; dividing that by 500Ω gives the same peak current.

Step 3: (b) Determine the current lag and the effect of resistance The relation $v = L di/dt$ makes the voltage lead the sinusoidal current by a quarter cycle. If $v = V_0 \sin \omega t$, then $i = I_0 \sin(\omega t - \pi/2)$. Thus the current lags the applied voltage by 90° , or $\pi/2$ rad.

A series resistance adds a voltage component in phase with the current. The applied voltage is the

phasor sum of this resistive component and the inductive component, giving

$$\phi = \tan^{-1} \left(\frac{X_L}{R} \right) = \tan^{-1} \left(\frac{500 \Omega}{R} \right).$$

For a positive, small resistance, the current still lags the voltage, but the lag becomes slightly less than 90° . A numerical new angle cannot be calculated without the resistance value.

Step 4: Conclusion (a) $I_{\text{rms}} = 0.40 \text{ A}$ and $I_0 = 0.40\sqrt{2} \text{ A} \approx 0.566 \text{ A}$. (b) Initially the current lags the voltage by 90° ; adding a small series resistance reduces this lag to a value slightly below 90° .

Quick Tip to Solve: Cancel π in $2\pi f(5/\pi)$ before calculating, and use rms voltage to find rms current before multiplying by $\sqrt{2}$.

Section D (15 marks)

35. (a) Derive the expression for the force acting per unit length between two long straight parallel current carrying conductors. Hence define one ampere.

(b) Two long parallel straight conductors are placed 12 cm apart in air. They carry equal currents of 3 A each. Find the magnitude and direction of the magnetic field at a point midway between them (drawing a figure) when the currents in them flow in opposite directions. [5 marks]

Solution:

Concept:

- The magnetic field at perpendicular distance d from a long straight wire carrying current I in air or vacuum is $B = \mu_0 I / (2\pi d)$. Its direction follows the right-hand thumb rule.
- A straight conductor of length L , carrying current I , experiences magnetic force $F = ILB \sin \theta$, where θ is the angle between its current and the magnetic field.
- Magnetic fields obey vector superposition. At a point between wires carrying opposite currents, the two fields point in the same direction and therefore add.

Step 1: (a) Field of the first conductor at the second Consider two very long, straight, parallel conductors separated by distance d , carrying currents I_1 and I_2 . Ignore end effects. The field produced by conductor 1 at conductor 2 has magnitude

$$B_1 = \frac{\mu_0 I_1}{2\pi d}.$$

This field is perpendicular to the second conductor because the field lines are circles around the first conductor. Therefore the angle between I_2 and $\vec{B}_1$ is 90° .

Step 2: (a) Force per unit length and its direction The force on a length L of conductor 2 is

$$\begin{aligned} F_{21} &= I_2 L B_1 \sin 90^\circ \\ &= \frac{\mu_0 I_1 I_2 L}{2\pi d}, \\ \frac{F}{L} &= \frac{\mu_0 I_1 I_2}{2\pi d}. \end{aligned}$$

Interchanging the conductors gives an equal force on conductor 1 in the opposite direction. Applying $\vec{F} = I\vec{L} \times \vec{B}$ shows that currents flowing in the same direction attract, whereas currents flowing in

opposite directions repel. The result concerns the mutual force, so the magnetic field of a wire itself is not used to calculate its force.

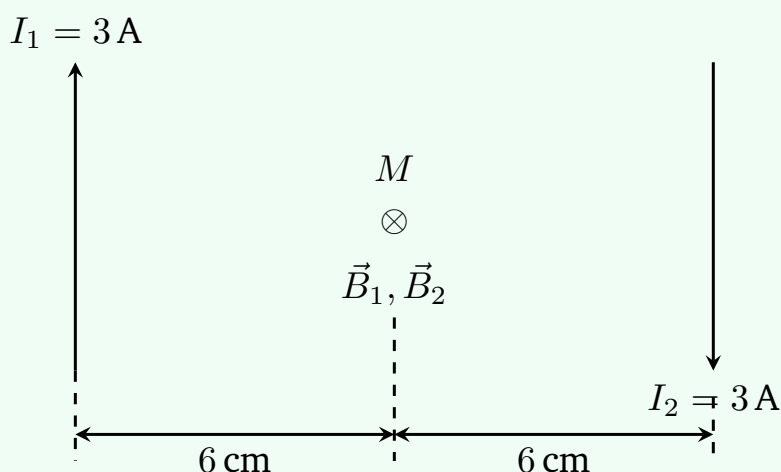
Step 3: (a) Define one ampere using the force between wires Using the force-based definition intended in this paper, one ampere is the constant current which, when maintained in each of two straight parallel conductors of infinite length and negligible circular cross-section, placed one metre apart in vacuum, produces a force of $2 \times 10^{-7} \text{ N}$ per metre of length between them. Indeed, with $I_1 = I_2 = 1 \text{ A}$, $d = 1 \text{ m}$ and $\mu_0 = 4\pi \times 10^{-7} \text{ N A}^{-2}$,

$$\frac{F}{L} = \frac{4\pi \times 10^{-7} \times 1 \times 1}{2\pi \times 1} = 2 \times 10^{-7} \text{ N m}^{-1}.$$

Step 4: (b) Determine the fields at the midpoint Let the left conductor carry 3 A upwards and the right conductor carry 3 A downwards, both in the plane of the figure. The midpoint M is at distance

$$r = \frac{12}{2} \text{ cm} = 0.06 \text{ m}$$

from each conductor. By the right-hand thumb rule, the field of the left conductor at M is into the plane of the figure. The field of the right conductor at M is also into that plane. The diagram uses $\otimes$ for this direction. Thus the fields add, even though the currents are opposite.



Opposite currents produce reinforcing fields into the page at midpoint M .

Step 5: (b) Calculate the resultant magnetic field Each wire contributes

$$B_1 = B_2 = \frac{4\pi \times 10^{-7} \times 3}{2\pi \times 0.06} = 1.0 \times 10^{-5} \text{ T}.$$

Hence the resultant magnitude is

$$B_{\text{net}} = B_1 + B_2 = 2.0 \times 10^{-5} \text{ T}.$$

It is perpendicular to the plane containing the conductors and directed into the page for the current directions chosen in the drawing. Reversing both currents reverses the field, giving the same magnitude out of the page.

Step 6: Conclusion The mutual force per unit length is $F/L = \mu_0 I_1 I_2 / (2\pi d)$; it is attractive for parallel currents and repulsive for opposite currents. The force-based definition of one ampere corresponds to $2 \times 10^{-7} \text{ N m}^{-1}$ between the specified conductors one metre apart in vacuum. At the midpoint in part

(b), $B = 2.0 \times 10^{-5} \text{ T}$, into the page for the directions drawn.

Quick Tip to Solve: At the midpoint use half the wire separation, then apply the right-hand rule to each field before adding: opposite currents give reinforcing fields between the wires.

OR

35. (a) Draw the schematic sketch of a cyclotron. Explain the shape of the path on which charged particle moves when the particle is accelerated by it.

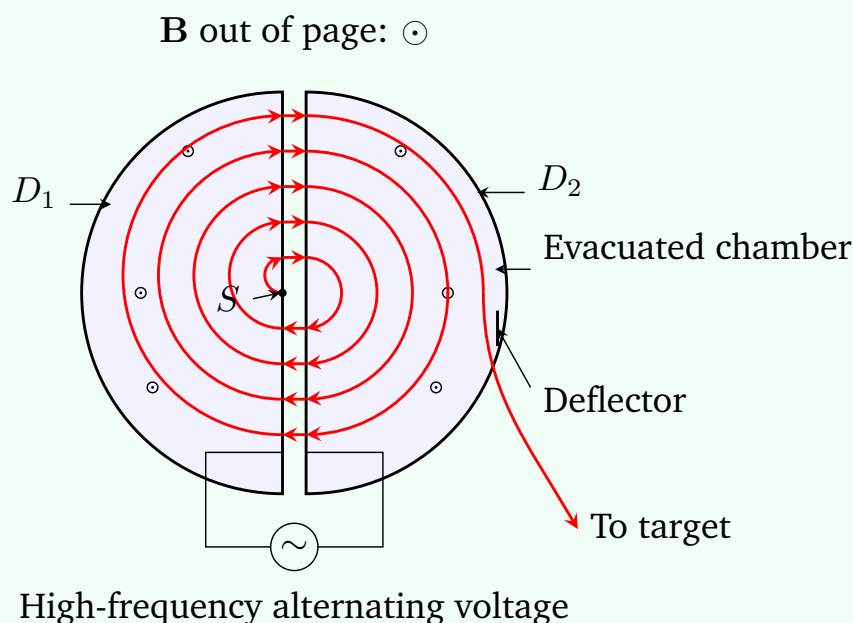
(b) To convert a given galvanometer into a voltmeter of ranges $2V$, V and $\frac{V}{2}$ volt, resistances R_1 , R_2 and R_3 ohm respectively, are required to be connected in series with the galvanometer. Obtain the relationship between R_1 , R_2 and R_3 . [5 marks]

Solution:

Concept:

- A cyclotron accelerates a charged particle using an alternating electric field across the gap between two hollow D-shaped electrodes (dees). A uniform magnetic field perpendicular to the dees bends the particle's motion inside them.
- For a non-relativistic particle of mass m , charge magnitude $|q|$ and speed v , magnetic force provides the centripetal force: $|q|vB = mv^2/r$. Thus $r = mv/(|q|B)$ and the cyclotron frequency is $f = |q|B/(2\pi m)$.
- A galvanometer of resistance G and full-scale current I_g , connected in series with resistance R , has voltmeter range $U = I_g(G + R)$.

Step 1: (a) Schematic arrangement of the cyclotron The two hollow metal dees D_1 and D_2 are enclosed in an evacuated chamber between the poles of an electromagnet. The magnetic field is perpendicular to their plane. An ion source S is placed near the centre, in the narrow gap, and a high-frequency alternating voltage is applied between the dees. The following plan view uses dots to indicate a magnetic field out of the page; the path is drawn for a positively charged particle. A deflector near the outer edge directs the energetic particles towards a target.



Cyclotron plan view: increasing semicircular paths in two dees, alternating gap voltage, and magnetic field out of the page. The paths are schematic.

Step 2: (a) Explain the successive semicircular paths When an ion crosses the gap, the electric field accelerates it towards the oppositely charged dee. Inside a dee the electric field is effectively zero, so the magnetic force alone bends the trajectory; it does no work and the speed remains constant during that semicircle. From

$$|q|vB = \frac{mv^2}{r}, \quad r = \frac{mv}{|q|B},$$

each part of the path inside a dee is a semicircle. The time spent in one dee is

$$t_{1/2} = \frac{\pi r}{v} = \frac{\pi m}{|q|B},$$

independent of speed and radius. Therefore the applied voltage reverses polarity every half revolution. On reaching the gap again, the ion experiences an accelerating electric field towards the other dee. Each crossing increases its kinetic energy (by $|q|\Delta V$ for an accelerating potential difference ΔV), hence its speed and its next semicircle's radius increase. The overall trajectory is an outward-growing, approximately spiral path made of successive larger semicircles, rather than a single fixed circle. Resonance is maintained at $f = |q|B/(2\pi m)$ while relativistic changes in mass are negligible. At the outer edge the beam is extracted towards the target.

Step 3: (b) Write the three full-scale voltage equations The same galvanometer is used in every case, so both G and I_g remain unchanged. At full-scale deflection the voltage across the series combination is the current times its total resistance. Denoting the common voltage parameter by V , the three stated ranges give

$$\begin{aligned} 2V &= I_g(G + R_1), \\ V &= I_g(G + R_2), \\ \frac{V}{2} &= I_g(G + R_3). \end{aligned}$$

The internal resistance must be retained: the external series resistances alone are not in the ratio of the voltage ranges.

Step 4: (b) Eliminate the galvanometer constants Subtract the second voltage equation from the first, and the third from the second:

$$V = I_g(R_1 - R_2),$$

$$\frac{V}{2} = I_g(R_2 - R_3).$$

Dividing the first difference by the second eliminates V and I_g , giving

$$R_1 - R_2 = 2(R_2 - R_3).$$

This also shows that $R_1 > R_2 > R_3$, as expected because a larger voltmeter range requires more series resistance.

Step 5: Conclusion (a) The accelerated particle follows successive semicircles of increasing radius, forming an outward-growing spiral-like path. (b) The required relationship is $R_1 + 2R_3 = 3R_2$.

Quick Tip to Solve: Subtract the full-scale voltage equations before taking ratios: this removes the galvanometer's internal resistance and prevents the incorrect ratio $R_1 : R_2 : R_3 = 4 : 2 : 1$.

36. (a) What is meant by plane polarised light? An unpolarised light is incident at an angle θ on the surface of glass of refractive index μ . If the reflected and refracted rays are perpendicular to each other, then obtain the relationship between μ and θ .

(b) Two polaroids P_1 and P_2 are placed in a crossed position. Unpolarised light of intensity I_0 is incident on P_1 . If P_2 is rotated through an angle θ about the direction of propagation of light, keeping P_1 fixed, plot the graph of intensity of light for $0^\circ < \theta < 360^\circ$ which is (i) transmitted by P_1 , and (ii) transmitted by P_2 . [5 marks]

Solution:

Concept:

- Plane polarised light has its electric-field vibrations restricted to one fixed direction in the plane perpendicular to its direction of propagation. In unpolarised light these transverse directions vary randomly.
- Snell's law for incidence from air into glass is $\mu = \sin \theta / \sin r$, where θ and r are measured from the normal. At the polarising angle the reflected and refracted rays are perpendicular.
- An ideal polariser transmits half the intensity of incident unpolarised light. Malus's law gives $I = I_{\text{in}} \cos^2 \alpha$ for incident plane polarised light, where α is the angle between its electric-field direction and the analyser's transmission axis.

Step 1: (a) Define plane polarisation and identify the ray angles In plane polarised light the electric vector oscillates along a single fixed transverse direction; it does not have randomly changing orientations as in unpolarised light. Let the angle of refraction in glass be r . By the law of reflection the reflected ray makes angle θ with the normal on the air side. The angle between the outgoing reflected and refracted rays is $180^\circ - (\theta + r)$. The stated perpendicularity therefore implies

$$180^\circ - (\theta + r) = 90^\circ, \quad r = 90^\circ - \theta.$$

All these angles are measured from the normal, rather than from the glass surface.

Step 2: (a) Apply Snell's law to obtain Brewster's relation Taking the refractive index of air as unity,

Snell's law at the interface gives $\sin \theta = \mu \sin r$. Substitute the complementary ray angles:

$$\mu = \frac{\sin \theta}{\sin(90^\circ - \theta)} = \frac{\sin \theta}{\cos \theta} = \tan \theta.$$

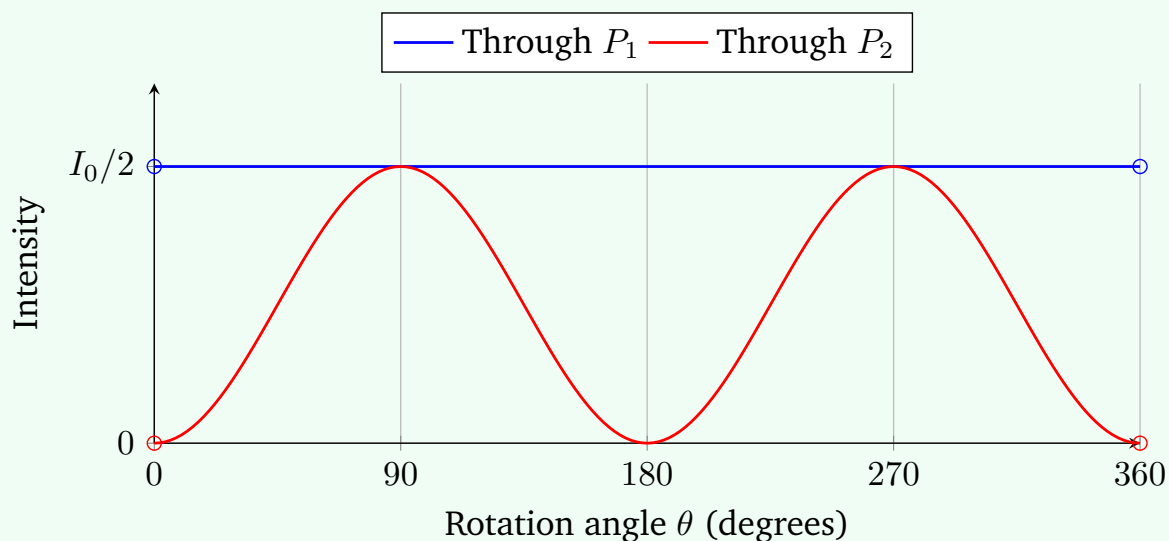
This incidence angle is Brewster's angle, or the polarising angle θ_B . Thus the reflected beam is plane polarised and $\theta_B = \tan^{-1} \mu$. The given geometry determines the index relation without requiring an intensity calculation.

Step 3: (b)(i) Find the light transmitted by the fixed first polaroid Initially unpolarised light has intensity I_0 . Averaging its electric-field directions gives $\langle \cos^2 \alpha \rangle = 1/2$, so the intensity immediately after the first ideal polaroid is $I_1 = I_0/2$. Rotating P_2 leaves both the incident light and the fixed axis of P_1 unchanged. Consequently I_1 remains constant throughout $0^\circ < \theta < 360^\circ$; its graph is a horizontal line at $I_0/2$.

Step 4: (b)(ii) Apply Malus's law to the rotated second polaroid At $\theta = 0^\circ$ the two axes are crossed. If the analyser turns towards the first axis, their angle is $\alpha = 90^\circ - \theta$; turning the other way gives the same squared projection. Hence

$$I_2 = I_1 \cos^2(90^\circ - \theta) = \frac{I_0}{2} \sin^2 \theta.$$

The transmitted intensity has maxima $I_0/2$ at 90° and 270° , and is zero at 180° . Its limiting values at 0° and 360° are also zero; these boundary points are excluded by the printed interval. The graph has period 180° . The largest possible I_2 is only $I_0/2$, because half the original intensity was already removed by P_1 .



Intensity through each polaroid against rotation of the second polaroid. Open circles indicate the excluded endpoints.

Step 5: Conclusion (a) Plane polarised light has electric vibrations along one fixed transverse direction, and the required relationship is $\mu = \tan \theta$. (b) The graphs represent $I_1 = I_0/2$ and $I_2 = (I_0/2) \sin^2 \theta$ for $0^\circ < \theta < 360^\circ$.

Quick Tip to Solve: Since rotation starts with crossed axes, use sine squared of the rotation angle; check that transmission initially tends to zero before drawing the graph.

36. (a) Briefly describe the Young's double slit experiment of interference of light. Derive the expression for fringe width in the pattern.

(b) Monochromatic light of wavelength 588 nm is incident from air to water interface. Find the wavelength and speed of the refracted light. The refractive index of water is $\frac{4}{3}$. [5 marks]

Solution:

Concept:

- Coherent sources have the same frequency and a constant phase difference; their superposition produces stable interference fringes.
- For slit separation d , screen distance D and transverse position y , the path difference is $\Delta \simeq dy/D$ when $D \gg d$ and $y \ll D$.
- Refractive index $\mu = c/v$, with c the speed in air and v the speed in the medium. Frequency remains unchanged at refraction, so wavelength becomes λ/μ .

Step 1: (a) Describe the experiment A narrow monochromatic source illuminates two close, narrow parallel slits S_1 and S_2 . The two slits act as coherent secondary sources because they receive light from the same source. A screen is placed at distance D , much larger than the slit separation d . The waves from the two slits overlap on the screen. They reinforce where the path difference is an integral multiple of the wavelength and cancel where it is an odd multiple of half a wavelength. Alternate bright and dark fringes appear parallel to the slits. With equal illumination of the slits, dark fringes ideally have zero intensity. The central point on the perpendicular bisector of the slits is bright because its path difference is zero.

Step 2: (a) Derive fringe width Consider a screen point P at transverse distance y from the central bright fringe. If its direction makes angle α with the screen normal, the distant-screen and small-angle approximations give

$$\Delta = S_2P - S_1P \simeq d \sin \alpha \simeq d \tan \alpha = \frac{dy}{D}.$$

For a bright fringe, $\Delta = n\lambda$, where n is an integer. Hence $y_n = n\lambda D/d$. The spacing of successive bright fringes is

$$\beta = y_{n+1} - y_n = \frac{(n+1)\lambda D - n\lambda D}{d} = \frac{\lambda D}{d}.$$

A dark fringe satisfies $\Delta = (n + \frac{1}{2})\lambda$, so its position is $y_n^{\text{dark}} = (n + \frac{1}{2})\lambda D/d$. Successive dark fringes have the same spacing β ; neighbouring bright and dark fringes are separated by $\beta/2$. Thus the fringe width is approximately independent of fringe order within the small-angle region.

Step 3: (b) Calculate the refracted wavelength and speed Given $\mu = 4/3$ and $\lambda_{\text{air}} = 588 \text{ nm}$, use $c = 3.0 \times 10^8 \text{ m s}^{-1}$:

$$v = \frac{c}{\mu} = \frac{3.0 \times 10^8}{4/3} = 2.25 \times 10^8 \text{ m s}^{-1},$$

$$\lambda_{\text{water}} = \frac{588}{4/3} \text{ nm} = 441 \text{ nm}.$$

Frequency is determined by the source and does not change at the interface. From $v = f\lambda$, the speed

and wavelength must therefore decrease by the same factor.

Step 4: Conclusion The fringe width is $\beta = \lambda D/d$. In water, the wavelength is 441 nm and the speed is $2.25 \times 10^8 \text{ m s}^{-1}$.

Quick Tip to Solve: Subtract adjacent bright-fringe positions to find width; at refraction keep frequency fixed and divide speed and wavelength by the refractive index.

37. (a) An electric dipole of dipole moment $\vec{p}$ is placed in a uniform electric field $\vec{E}$ at an angle θ with it. Derive the expression for torque ($\vec{\tau}$) acting on it. Find the orientation of the dipole relative to the electric field for which torque on it is (i) maximum, and (ii) half of maximum.

(b) Two point charges $q_1 = +1 \mu\text{C}$ and $q_2 = +4 \mu\text{C}$ are placed 2 m apart in air. At what distance from q_1 along the line joining the two charges, will the net electric field be zero? [5 marks]

Solution:

Concept:

- For charges $-q$ and $+q$ separated by distance $2a$, the dipole moment $\vec{p}$ points from negative to positive charge and has magnitude $p = q(2a)$.
- A charge in a uniform electric field experiences force $\vec{F} = q\vec{E}$. Equal opposite forces on a dipole form a couple, whose torque is force times perpendicular separation.
- The electric field of a point charge has magnitude kq/r^2 , where $k = 1/(4\pi\epsilon_0)$. A positive charge produces a field directed away from itself.

Step 1: (a) Derive the torque of the dipole Let the separation of the charges be $2a$, with the dipole axis making angle θ with the uniform field $\vec{E}$. The positive charge experiences force $+q\vec{E}$ and the negative charge experiences $-q\vec{E}$. These forces are equal, opposite and parallel, so the resultant force vanishes. Their lines of action are separated by perpendicular distance $2a \sin \theta$. Hence the magnitude of the couple is

$$\tau = qE(2a \sin \theta) = pE \sin \theta.$$

Equivalently, relative to the dipole centre the position vectors are $\vec{r}_+ = a\hat{p}$ and $\vec{r}_- = -a\hat{p}$. Thus

$$\begin{aligned}\vec{\tau} &= \vec{r}_+ \times (q\vec{E}) + \vec{r}_- \times (-q\vec{E}) \\ &= 2aq\hat{p} \times \vec{E} = \vec{p} \times \vec{E}.\end{aligned}$$

Its direction follows the right-hand rule and the torque tends to align the dipole moment with the field. The force cancellation requires a uniform field; the torque need not vanish even though the net force does.

Step 2: (a) Determine the required orientations Since $\tau = pE \sin \theta$, the largest torque magnitude occurs when $\sin \theta = 1$. Thus $\tau_{\max} = pE$ at $\theta = 90^\circ$, when the dipole is perpendicular to the field. Half the maximum requires

$$pE \sin \theta = \frac{pE}{2}, \quad \sin \theta = \frac{1}{2}.$$

For the angle between two vectors, $0^\circ \leq \theta \leq 180^\circ$, both $\theta = 30^\circ$ and $\theta = 150^\circ$ satisfy this condition. Parallel and antiparallel orientations have zero torque and therefore do not satisfy either requested nonzero value.

Step 3: (b) Identify where cancellation is possible Both charges are positive. Outside the interval joining them, their electric fields point in the same direction, so their sum cannot vanish. Between them, the field due to q_1 points towards q_2 , and the field due to q_2 points towards q_1 ; cancellation is possible there. Let the null point be a distance x from q_1 towards q_2 . Its distance from q_2 is $2 - x$, with $0 < x < 2$.

Step 4: (b) Equate the field magnitudes Use the inverse-square law and cancel the common factor k :

$$\begin{aligned}\frac{k(1 \times 10^{-6})}{x^2} &= \frac{k(4 \times 10^{-6})}{(2 - x)^2}, \\ (2 - x)^2 &= 4x^2, \\ 2 - x &= 2x, \\ x &= \frac{2}{3} \text{ m}.\end{aligned}$$

The positive square root is required because both distances are positive inside the interval. The distance from q_2 is $4/3$ m, twice the distance from q_1 . Consequently its four-times-larger charge produces an equal field, confirming the cancellation. The point lies closer to the smaller charge, as expected.

Step 5: Conclusion The torque is $\vec{\tau} = \vec{p} \times \vec{E}$, with magnitude $pE \sin \theta$. It is maximum at 90° and half maximum at 30° or 150° . The zero-field point is $2/3$ m from q_1 , between the charges towards q_2 .

Quick Tip to Solve: For like charges, first restrict cancellation to the interval between them; the null-point distances are proportional to the square roots of the charge magnitudes.

OR

37. (a) Derive an expression for the energy stored in a parallel plate capacitor of capacitance C when charged up to voltage V . How is this energy stored in the capacitor?

(b) A capacitor of capacitance $1 \mu\text{F}$ is charged by connecting a battery of negligible internal resistance and emf 10V across it. Calculate the amount of charge supplied by the battery in charging the capacitor fully. [5 marks]

Solution:

Concept:

- The capacitance is $C = q/v$, where q is the charge on either plate and v is the instantaneous potential difference between the plates. For a fixed parallel plate capacitor, C remains constant during charging.

- Moving an infinitesimal positive charge dq from the negative plate to the positive plate against a potential difference v requires work $dW = v dq$. The accumulated work becomes electrostatic potential energy.
- The stored energy resides in the electric field between the plates. For air or vacuum, its energy density is $u = \frac{1}{2}\epsilon_0 E^2$, where E is the electric field and ϵ_0 is the permittivity of free space.

Step 1: (a) Work required during charging Initially the capacitor is uncharged, so its potential difference is zero. Let its plates carry charges $+q$ and $-q$ at an intermediate stage. The potential difference at this stage is

$$v = \frac{q}{C}.$$

Transferring a further small charge dq to the positive plate requires work

$$dW = v dq = \frac{q}{C} dq.$$

The potential difference rises as charge accumulates, so the final voltage cannot be used as the voltage for every charge increment. The total work is obtained by adding the successive infinitesimal contributions.

Step 2: (a) Integrate to obtain the stored energy If the final charge on either plate has magnitude Q , integrate from the initial charge zero to Q :

$$U = \int_0^Q dW = \int_0^Q \frac{q}{C} dq = \frac{1}{C} \left[\frac{q^2}{2} \right]_0^Q = \frac{Q^2}{2C}.$$

At the final potential difference V , the capacitor relation gives $Q = CV$. Substitution expresses the energy entirely in terms of the specified capacitance and voltage:

$$U = \frac{(CV)^2}{2C} = \frac{1}{2}CV^2 = \frac{1}{2}QV.$$

The factor $1/2$ follows because the voltage rises from zero to V ; equivalently, the average voltage during this charge transfer is $V/2$.

Step 3: (a) Explain where the energy is stored Separating positive and negative charges creates an electric field in the space between the plates. The work performed against the electric forces is stored as the energy of this field. For plates of area A separated by distance d , neglecting edge effects in air or vacuum, $C = \epsilon_0 A/d$ and $V = Ed$. Thus

$$U = \frac{1}{2} \frac{\epsilon_0 A}{d} (Ed)^2 = \frac{1}{2} \epsilon_0 E^2 (Ad).$$

The field occupies volume Ad , so the stored energy per unit volume is $U/(Ad) = \frac{1}{2}\epsilon_0 E^2$. This identifies the electric field between the plates as the location of the stored energy.

Step 4: (b) Calculate the charge supplied by the battery On full charging, the potential difference across the capacitor equals the battery emf because its internal resistance is negligible. Convert the

capacitance to SI units:

$$C = 1 \mu\text{F} = 1 \times 10^{-6} \text{ F}, \quad V = 10 \text{ V}.$$

The charge transferred through the battery while charging is the magnitude of the charge on either capacitor plate:

$$Q = CV = (1 \times 10^{-6})(10) = 1 \times 10^{-5} \text{ C} = 10 \mu\text{C}.$$

The plates acquire equal and opposite charges. Their magnitudes are not added to calculate the charge supplied by the battery, because the same transferred charge produces both plate charges.

Step 5: Conclusion (a) The energy stored is $U = \frac{1}{2}CV^2$, equivalently $Q^2/(2C)$ or $QV/2$. It is stored in the electric field between the capacitor plates. (b) The charge supplied by the battery is $10 \mu\text{C} = 1.0 \times 10^{-5} \text{ C}$.

Quick Tip to Solve: During the energy derivation use the changing voltage q/C inside the integral; for the charge supplied by a battery, use $Q = CV$ once, without doubling the two plate charges.