

CBSE Class 12 Physics Question Paper 2024 with Solution PDF-Set 55/1/2



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 contains **33** questions. **All** questions are **compulsory**.
- (ii) This question paper is divided into **five** sections – **Sections A, B, C, D** and **E**.
- (iii) In **Section A** – Questions no. **1** to **16** are Multiple Choice type questions. Each question carries **1** mark.
- (iv) In **Section B** – Questions no. **17** to **21** are Very Short Answer type questions. Each question carries **2** marks.
- (v) In **Section C** – Questions no. **22** to **28** are Short Answer type questions. Each question carries **3** marks.
- (vi) In **Section D** – Questions no. **29** and **30** are case study-based questions. Each question carries **4** marks.
- (vii) In **Section E** – Questions no. **31** to **33** are Long Answer type questions. Each question carries **5** marks.
- (viii) There is no overall choice given in the question paper. However, an internal choice has been provided in few questions in all the Sections except Section A.
- (ix) Kindly note that there is a separate question paper for Visually Impaired candidates.
- (x) Use of calculators is not allowed.

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 (16 marks)

1. A thin plastic rod is bent into a circular ring of radius R . It is uniformly charged with charge density λ . The magnitude of the electric field at its centre is: [1 mark]

- (A) $\frac{\lambda}{2\epsilon_0 R}$
- (B) Zero
- (C) $\frac{\lambda}{4\pi\epsilon_0 R}$
- (D) $\frac{\lambda}{4\epsilon_0 R}$

Correct Answer: (B) Zero

Solution:

Concept:

- Electric fields obey vector superposition: the net field is the vector sum of the fields of all charge elements.
- A charge element dq at distance R produces a field of magnitude $dE = dq/(4\pi\epsilon_0 R^2)$, where ϵ_0 is the permittivity of free space.

Step 1: Pair opposite charge elements Uniform linear charge density means that equal small lengths at diametrically opposite points contain equal charges. Both elements are the same distance R from the centre, so their fields there have equal magnitudes.

Step 2: Add the fields as vectors The fields of each opposite pair point in opposite directions and cancel. Every element of the complete ring has such a partner, so no component survives. The nonzero expressions in options (A), (C) and (D) cannot apply at the centre of a complete uniformly charged ring; they ignore this vector cancellation.

Step 3: Conclusion The electric field at the centre is zero. Hence, the correct option is (B).

Quick Tip to Solve: For a complete uniformly charged ring, pair diametrically opposite elements before attempting an integral.

2. A charged sphere of radius r has surface charge density σ . The electric field on its surface is E . If the radius of the sphere is doubled, keeping charge density the same, the ratio of the electric field on the old sphere to that on the new sphere will be: [1 mark]

- (A) 1
- (B) $\frac{1}{2}$
- (C) $\frac{1}{4}$
- (D) 4

Correct Answer: (A) 1

Solution:

Concept:

- For a spherically symmetric charged sphere, the electric field just outside its surface is $E = Q/(4\pi\epsilon_0 r^2)$, where Q is its charge and r its radius.

- Surface charge density is charge per unit area, so $Q = \sigma(4\pi r^2)$, with σ the uniform surface charge density.

Step 1: Express the surface field using charge density Substitute the charge corresponding to the spherical surface area:

$$E_{\text{old}} = \frac{\sigma 4\pi r^2}{4\pi\epsilon_0 r^2} = \frac{\sigma}{\epsilon_0}.$$

The radius cancels; the surface field depends on the surface charge density.

Step 2: Compare the sphere of doubled radius At radius $2r$, the surface area and therefore the charge are four times as large, since σ is fixed. The squared distance in the field formula also increases fourfold. Thus the two changes cancel. Options (B), (C) and (D) incorrectly retain a radius dependence; in particular, $1/4$ would describe the new-to-old field ratio only if the total charge stayed fixed.

Step 3: Conclusion $E_{\text{old}}/E_{\text{new}} = 1$. Hence, the correct option is (A).

Quick Tip to Solve: Check what stays fixed: constant surface density makes the sphere's charge grow as the square of its radius.

3. A student is asked to connect four cells, each of emf E and internal resistance r , in series. But she/he connects one cell wrongly in series with the other cells. The equivalent emf and the equivalent internal resistance of the combination will be: [1 mark]

- (A) $4E$ and $2r$
- (B) $4E$ and $3r$
- (C) $3E$ and $4r$
- (D) $2E$ and $4r$

Correct Answer: (D) $2E$ and $4r$

Solution:

Concept:

- The equivalent emf of cells in series is their algebraic sum: a reversed cell contributes an emf opposite to the others.
- Internal resistances in series always add as positive resistances, independently of the polarity of each cell.

Step 1: Add the emfs with their polarities Choose the polarity of the three correctly connected cells as positive. Each contributes $+E$, while the incorrectly connected fourth cell contributes $-E$. Therefore,

$$E_{\text{eq}} = E + E + E - E = 2E.$$

Reversing a cell does not remove it: its emf opposes the other three, so $3E$ is not the equivalent emf.

Step 2: Add all four internal resistances All four cells still lie in the same series current path, including the reversed cell. Hence

$$r_{\text{eq}} = r + r + r + r = 4r.$$

Options (A) and (B) wrongly treat all four emfs as aiding and also omit resistance. Option (C) has the correct resistance but fails to subtract the reversed emf.

Step 3: Conclusion The equivalent emf is $2E$ and the equivalent internal resistance is $4r$. Hence, the correct option is (D).

Quick Tip to Solve: Reversing one series cell changes its emf contribution from $+E$ to $-E$, but leaves its resistance contribution $+r$.

4. A piece of wire bent in the form of a circular loop A carries a current I . The wire is then bent into a circular loop B of two turns and carries the same current. The ratio of magnetic fields at the centre of loop A to that of loop B will be: [1 mark]

- (A) $\frac{1}{16}$
(B) 16
(C) 4
(D) $\frac{1}{4}$

Correct Answer: (D) $\frac{1}{4}$

Solution:

Concept:

- The magnetic field at the centre of an N -turn circular coil of radius R , carrying current I , is $B = \mu_0 NI / (2R)$.
- When the same wire is rewound, its length remains fixed: $L = N(2\pi R)$, where L is the wire length and μ_0 the permeability of free space.

Step 1: Relate the radii of the loops Let the radius of the original single turn be R_A . With two turns of radius R_B , conservation of wire length gives

$$2\pi R_A = 2(2\pi R_B), \quad R_B = \frac{R_A}{2}.$$

Thus the second arrangement has both more turns and a smaller radius.

Step 2: Compare the central fields For the same current in both arrangements,

$$B_A = \frac{\mu_0 I}{2R_A}, \quad B_B = \frac{\mu_0 (2)I}{2(R_A/2)} = 4B_A.$$

Option (C) reverses the requested ratio. Options (A) and (B) introduce a factor of sixteen, whereas doubling the turn count at fixed wire length increases the field by only a factor of four.

Step 3: Conclusion $B_A/B_B = 1/4$. Hence, the correct option is (D).

Quick Tip to Solve: For fixed wire length and current, $R \propto 1/N$, so the central field grows as N^2 .

5. A 10 cm long wire lies along y-axis. It carries a current of 1.0 A in positive y-direction. A magnetic field $\vec{B} = (5 \text{ mT})\hat{j} - (8 \text{ mT})\hat{k}$ exists in the region. The force on the wire is: [1 mark]

- (A) $(0.8 \text{ mN})\hat{i}$
- (B) $-(0.8 \text{ mN})\hat{i}$
- (C) $(80 \text{ mN})\hat{i}$
- (D) $-(80 \text{ mN})\hat{i}$

Correct Answer: (B) $-(0.8 \text{ mN})\hat{i}$

Solution:

Concept:

- A straight wire in a uniform magnetic field experiences force $\vec{F} = I\vec{L} \times \vec{B}$, where $\vec{L}$ points along the current and has the wire's length as its magnitude.
- Only the magnetic field perpendicular to the current contributes: $\hat{j} \times \hat{j} = 0$ and $\hat{j} \times \hat{k} = \hat{i}$.

Step 1: Convert the data to SI units The wire length is 10 cm = 0.10 m, so $\vec{L} = (0.10 \text{ m})\hat{j}$. With $I = 1.0 \text{ A}$, use

$$\vec{B} = (5 \times 10^{-3} \text{ T})\hat{j} - (8 \times 10^{-3} \text{ T})\hat{k}.$$

The positive y -component of the field is parallel to the current and produces no force.

Step 2: Evaluate the cross product Using the negative z -component of the field,

$$\begin{aligned}\vec{F} &= (1.0)(0.10)(-8 \times 10^{-3})(\hat{j} \times \hat{k}) \text{ N} \\ &= -8.0 \times 10^{-4} \hat{i} \text{ N} = -0.8 \hat{i} \text{ mN}.\end{aligned}$$

Option (A) has the wrong direction. Printed options (C) and (D), of magnitude 80 mN, are a hundred times too large; the wire length must be converted from centimetres to metres.

Step 3: Conclusion The force is $\vec{F} = -(0.8 \text{ mN})\hat{i}$, along the negative x -axis. Hence, the correct option is (B).

Quick Tip to Solve: Drop the field component parallel to the wire, convert the length to metres, and then apply the cross-product sign.

6. A galvanometer of resistance $G \Omega$ is converted into an ammeter of range 0 to I A. If the current through the galvanometer is 0.1% of I A, the resistance of the ammeter is: [1 mark]

- (A) $\frac{G}{999} \Omega$
(B) $\frac{G}{1000} \Omega$
(C) $\frac{G}{1001} \Omega$
(D) $\frac{G}{100.1} \Omega$

Correct Answer: (B) $\frac{G}{1000} \Omega$

Solution:

Concept:

- An ammeter is formed by connecting a low shunt resistance S in parallel with a galvanometer of resistance G , so both branches have the same voltage.
- The effective resistance of the complete ammeter is $R_A = V/I$, where I is the total current and $V = I_g G$ is the terminal voltage; I_g is the galvanometer current.

Step 1: Convert the current percentage The current through the galvanometer is only 0.1% of the full ammeter current:

$$I_g = \frac{0.1}{100} I = \frac{I}{1000}.$$

Therefore the voltage across both the galvanometer and the complete ammeter is $V = IG/1000$.

Step 2: Find the resistance seen by the total current Dividing the terminal voltage by the total current gives

$$R_A = \frac{V}{I} = \frac{G}{1000}.$$

Option (A), $G/999$, is the shunt resistance because its current is $999I/1000$. It is not the parallel combination's resistance. Options (C) and (D) do not follow from the given current fraction and confuse the percentage or the division of current.

Step 3: Conclusion The resistance of the ammeter is $\frac{G}{1000} \Omega$. Hence, the correct option is (B).

Quick Tip to Solve: For the complete ammeter use $R_A/G = I_g/I$; distinguish its resistance from the shunt resistance.

7. A conducting circular loop is placed in a uniform magnetic field $B = 50 \text{ mT}$ with its plane perpendicular to the magnetic field. The radius of the loop is made to shrink at a constant rate of 1 mm s^{-1} . At the instant the radius of the loop is 4 cm , the induced emf in the loop is: [1 mark]

- (A) $\pi \mu\text{V}$
- (B) $2\pi \mu\text{V}$
- (C) $4\pi \mu\text{V}$
- (D) $8\pi \mu\text{V}$

Correct Answer: (C) $4\pi \mu\text{V}$

Solution:

Concept:

- Faraday's law gives the magnitude of induced emf as $|\mathcal{E}| = |d\Phi/dt|$, where Φ is the magnetic flux through the loop.
- When the plane of a circular loop is perpendicular to a uniform field B , its flux is $\Phi = B\pi r^2$; thus $|\mathcal{E}| = 2\pi Br|dr/dt|$ for constant B .

Step 1: Convert the field, radius and shrink rate The magnetic field is $B = 50 \times 10^{-3} \text{ T}$. At the specified instant, $r = 4 \times 10^{-2} \text{ m}$ and $|dr/dt| = 10^{-3} \text{ m s}^{-1}$. The area decreases because dr/dt is negative, but the answer options ask for the magnitude of the emf.

Step 2: Differentiate the area and substitute Since $d(\pi r^2)/dt = 2\pi r dr/dt$, the induced emf magnitude is

$$\begin{aligned} |\mathcal{E}| &= 2\pi(50 \times 10^{-3})(4 \times 10^{-2})(10^{-3}) \text{ V} \\ &= 4\pi \times 10^{-6} \text{ V} = 4\pi \mu\text{V}. \end{aligned}$$

Options (A), (B) and (D) have incorrect numerical factors. In particular, using $\pi r|dr/dt|$ would miss the factor of two from differentiating r^2 and lead to option (B).

Step 3: Conclusion The induced emf is $4\pi \mu\text{V}$. Hence, the correct option is (C).

Quick Tip to Solve: For a shrinking circle, differentiate its area first: the instantaneous area-change rate is circumference times radial speed.

8. The electric and magnetic fields of electromagnetic waves are: [1 mark]

- (A) In the same phase and perpendicular to each other.
- (B) In the same phase and not perpendicular to each other.
- (C) Not in the same phase but are perpendicular to each other.
- (D) Neither in the same phase nor perpendicular to each other.

Correct Answer: (A) In the same phase and perpendicular to each other.

Solution:

Concept:

- In a plane electromagnetic wave, the electric field $\vec{E}$, magnetic field $\vec{B}$ and propagation direction are mutually perpendicular.
- The fields oscillate in phase: $E = E_0 \sin(kx - \omega t)$ and $B = B_0 \sin(kx - \omega t)$, where k is the wave number and ω the angular frequency.

Step 1: Compare the time variation Both fields contain the same phase $kx - \omega t$. At a given position,

they pass through zero and attain their maxima together; their phase difference is zero.

Step 2: Check the field directions The electric and magnetic field vectors are perpendicular even though they oscillate in phase. Phase describes the timing of oscillation, whereas perpendicularity describes spatial directions. Thus (B) fails the direction condition, (C) fails the phase condition, and (D) fails both.

Step 3: Conclusion The electric and magnetic fields are in the same phase and perpendicular to each other. Hence, the correct option is (A).

Quick Tip to Solve: Check timing and direction separately: E and B peak together but their vectors meet at 90° .

9. Two beams, A and B whose photon energies are 3.3 eV and 11.3 eV respectively, illuminate a metallic surface (work function 2.3 eV) successively. The ratio of maximum speed of electrons emitted due to beam A to that due to beam B is: [1 mark]

- (A) 3
- (B) 9
- (C) $\frac{1}{3}$
- (D) $\frac{1}{9}$

Correct Answer: (C) $\frac{1}{3}$

Solution:

Concept:

- Einstein's photoelectric equation is $K_{\max} = E_\gamma - \phi$, where E_γ is photon energy and ϕ is the metal's work function.
- For emitted electrons, $K_{\max} = \frac{1}{2}m_e v_{\max}^2$. The speed ratio is the square root of the kinetic-energy ratio because both particles have the same mass m_e .

Step 1: Subtract the work function Both photon energies exceed $\phi = 2.3$ eV, so both beams eject electrons. Their maximum kinetic energies are

$$K_A = 3.3 - 2.3 = 1.0 \text{ eV}, \quad K_B = 11.3 - 2.3 = 9.0 \text{ eV}.$$

Step 2: Convert the energy ratio into a speed ratio Using the same energy unit in numerator and denominator,

$$\frac{v_A}{v_B} = \sqrt{\frac{K_A}{K_B}} = \sqrt{\frac{1}{9}} = \frac{1}{3}.$$

Option (D) gives the kinetic-energy ratio rather than the speed ratio. Options (A) and (B) exceed unity, although beam A supplies the smaller excess energy.

Step 3: Conclusion The ratio of maximum speeds is $v_A : v_B = 1 : 3$. Hence, the correct option is (C).

Quick Tip to Solve: First subtract the work function from each photon energy, then take the square root of their ratio.

10. The waves associated with a moving electron and a moving proton have the same wavelength λ . It implies that they have the same: [1 mark]

- (A) momentum
- (B) angular momentum
- (C) speed
- (D) energy

Correct Answer: (A) momentum

Solution:

Concept:

- The de Broglie relation is $\lambda = h/p$, where h is Planck's constant and p is the magnitude of particle momentum.
- For non-relativistic motion, $v = p/m$ and $K = p^2/(2m)$; equal momentum need not imply equal speed or kinetic energy for different masses.

Step 1: Apply the common wavelength The electron and proton have the same λ . Since h is universal, their momentum magnitudes are

$$p_e = \frac{h}{\lambda} = p_p.$$

The wavelength does not specify the direction of either momentum.

Step 2: Test the other choices Electron and proton masses differ, so at equal momentum their speeds and kinetic energies differ; hence (C) and (D) do not follow. Angular momentum $\vec{L} = \vec{r} \times \vec{p}$ also depends on position relative to the chosen origin, which is unspecified. Thus (B) does not follow either.

Step 3: Conclusion The moving electron and proton have equal momentum magnitudes. Hence, the correct option is (A).

Quick Tip to Solve: For equal de Broglie wavelengths, write $p = h/\lambda$ first; mass enters only when comparing speeds or energies.

11. Ge is doped with As. Due to doping, [1 mark]

- (A) the structure of Ge lattice is distorted.
- (B) the number of conduction electrons increases.
- (C) the number of holes increases.
- (D) the number of conduction electrons decreases.

Correct Answer: (B) the number of conduction electrons increases.

Solution:

Concept:

- Germanium is tetravalent, whereas arsenic is pentavalent. A small quantity of a pentavalent impurity acts as a donor in a group-14 semiconductor.
- Donor doping produces an n-type semiconductor in which electrons are the majority carriers and holes are the minority carriers.

Step 1: Account for the donor valence electrons An arsenic atom substitutes for a germanium atom

in the crystal. Four of its five valence electrons form covalent bonds with neighbouring Ge atoms; the fifth is weakly bound and can readily enter the conduction band.

Step 2: Identify the change in carrier number Donor ionisation therefore increases the number of conduction electrons. The substitution preserves the basic crystal structure, so lattice distortion is not the intended effect in (A). It does not produce the increase in holes in (C), and (D) reverses the actual change in conduction electrons.

Step 3: Conclusion Doping Ge with As increases the number of conduction electrons and makes it n-type. Hence, the correct option is (B).

Quick Tip to Solve: Compare valence counts: As has one more valence electron than Ge, so it donates an electron rather than creating a hole.

12. The transition of electron that gives rise to the formation of the second spectral line of the Balmer series in the spectrum of hydrogen atom corresponds to: [1 mark]

- (A) $n_f = 2$ and $n_i = 3$
- (B) $n_f = 3$ and $n_i = 4$
- (C) $n_f = 2$ and $n_i = 4$
- (D) $n_f = 2$ and $n_i = \infty$

Correct Answer: (C) $n_f = 2$ and $n_i = 4$

Solution:

Concept:

- All emission lines of the hydrogen Balmer series end at the level $n_f = 2$, where n_f is the final principal quantum number.
- The lines begin with $n_i = 3$ for the first line, $n_i = 4$ for the second, and so on; n_i is the initial principal quantum number.

Step 1: Fix the final energy level Balmer emission occurs when an electron falls from a higher level to $n_f = 2$. A transition ending at $n_f = 3$, as in (B), belongs to the Paschen series instead.

Step 2: Count from the first allowed transition The lowest initial level above 2 is 3, so $3 \rightarrow 2$ is the first Balmer line, not the second. The next transition is $4 \rightarrow 2$. Thus (A) is the first line; (D), with $n_i = \infty$, is the series limit rather than its second line.

Step 3: Conclusion The second Balmer line corresponds to $n_i = 4$ and $n_f = 2$. Hence, the correct option is (C).

Quick Tip to Solve: For the Balmer series fix the final level at 2, then count initial levels 3, 4, 5 for the first, second and third lines.

13. Assertion (A): Plane and convex mirrors cannot produce real images under any circumstance.

Reason (R): A virtual image cannot serve as an object to produce a real image.

[1 mark]

(A) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of the Assertion (A).

(B) Both Assertion (A) and Reason (R) are true, but Reason (R) is not the correct explanation of the Assertion (A).

(C) Assertion (A) is true, but Reason (R) is false.

(D) Assertion (A) is false and Reason (R) is also false.

Correct Answer: (D) Assertion (A) is false and Reason (R) is also false.

Solution:

Concept:

- A real image forms where outgoing rays actually converge. A virtual object for a mirror is a point towards which its incident rays are already converging.
- The mirror formula is $1/f = 1/v + 1/u$. With the Cartesian convention and incident light directed towards the mirror, a virtual object has $u > 0$, whereas a real reflected image has $v < 0$.

Step 1: Evaluate Assertion (A) The assertion is false because it says under any circumstance. For a plane mirror, $f \rightarrow \infty$, so $v = -u$: a converging incident beam with a virtual object $u > 0$ produces a real image. For a convex mirror, $f > 0$ and $v = fu/(u - f)$; a virtual object with $0 < u < f$ also gives $v < 0$. Ordinary real objects produce virtual images, but this does not cover all possible incident beams.

Step 2: Evaluate Reason (R) The reason is also false. A virtual image formed by one optical element can serve as the effective object for another. For example, a convex lens receiving rays that appear to diverge from a virtual image can form a real image when that effective object lies beyond the lens's focal length.

Step 3: Check the explanatory relationship Since both statements are false, R cannot correctly explain A. Codes (A) and (B) require both statements to be true, and code (C) requires A to be true; none fits these evaluations.

Step 4: Conclusion Both the assertion and the reason are false. Hence, the correct option is (D).

Quick Tip to Solve: The phrase under any circumstance requires checking converging incident rays, not only mirrors illuminated by a real object.

14. Assertion (A): Two long parallel wires, freely suspended and connected in series to a battery, move apart.

Reason (R): Two wires carrying current in opposite directions repel each other.

[1 mark]

(A) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of the Assertion (A).

(B) Both Assertion (A) and Reason (R) are true, but Reason (R) is not the correct explanation of the Assertion (A).

(C) Assertion (A) is true, but Reason (R) is false.

(D) Assertion (A) is false and Reason (R) is also false.

Correct Answer: (A) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of the Assertion (A).

Solution:

Concept:

- Two long parallel wires carrying currents in the same direction attract; currents in opposite directions cause repulsion.
- The magnetic force per unit length is $F/L = \mu_0 I_1 I_2 / (2\pi d)$, where d is the separation and I_1, I_2 are current magnitudes. Its direction follows from $\vec{F} = I\vec{L} \times \vec{B}$.

Step 1: Evaluate Assertion (A) In the stated series arrangement, the two parallel suspended wires form the outgoing and return sides of the circuit. Conventional current travels down one wire and back up the other, so their currents are opposite. The resulting repulsive force makes the freely suspended wires move apart. Assertion (A) is true.

Step 2: Evaluate Reason (R) Each wire lies in the magnetic field of the other. Applying the right-hand rule for that field and the force rule to opposite currents gives a force away from the other wire on each conductor. Thus opposite currents repel, and Reason (R) is true.

Step 3: Check whether the reason explains the assertion The opposite current directions in this series loop produce the very repulsive force responsible for the separation. R therefore correctly explains A. Code (B) denies this causal connection, while (C) and (D) incorrectly declare at least one of the statements false.

Step 4: Conclusion Both Assertion (A) and Reason (R) are true, and R correctly explains A. Hence, the correct option is (A).

Quick Tip to Solve: Trace current around the complete series loop: it passes one way through one parallel wire and returns through the other.

15. Assertion (A): In photoelectric effect, the kinetic energy of the emitted photoelectrons increases with increase in the intensity of the incident light.

Reason (R): Photoelectric current depends on the wavelength of the incident light.

[1 mark]

- (A) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of the Assertion (A).
- (B) Both Assertion (A) and Reason (R) are true, but Reason (R) is not the correct explanation of the Assertion (A).
- (C) Assertion (A) is true, but Reason (R) is false.
- (D) Assertion (A) is false and Reason (R) is also false.

Correct Answer: (D) Assertion (A) is false and Reason (R) is also false.

Solution:

Concept:

- Einstein's photoelectric equation is $K_{\max} = h\nu - \phi$, where h is Planck's constant, ν is the incident frequency and ϕ is the metal's work function.
- In the standard photoelectric experiment, for incident radiation above threshold and fixed collecting conditions, intensity controls the rate of electron emission and hence the photocurrent.

Step 1: Test the assertion At a fixed frequency, increasing intensity increases the number of incident photons per second, but leaves the energy $h\nu$ of each photon unchanged. Therefore the maximum kinetic energy of the emitted electrons does not increase. Assertion (A) is false.

Step 2: Test the reason In the usual CBSE description, photoelectric current depends on the intensity of incident light, whereas its wavelength determines the photon energy and thus the maximum electron kinetic energy. The comparison presumes light capable of causing emission; below threshold there is no photocurrent. Reason (R), as the stated explanation of the photocurrent dependence, is false.

Step 3: Choose the matching code Since both statements are false in the intended photoelectric-effect comparison, the explanation relationship does not arise. Codes (A) and (B) require both statements to be true, while code (C) requires the assertion to be true; none fits.

Step 4: Conclusion Both the assertion and the reason are false. Hence, the correct option is (D).

Quick Tip to Solve: Separate intensity from frequency: intensity changes the emission rate, while frequency changes $K_{\max}$, provided emission is possible.

16. Assertion (A): The mutual inductance between two coils is maximum when the coils are wound on each other.

Reason (R): The flux linkage between two coils is maximum when they are wound on each other.

[1 mark]

- (A) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of the Assertion (A).
(B) Both Assertion (A) and Reason (R) are true, but Reason (R) is not the correct explanation of the Assertion (A).
(C) Assertion (A) is true, but Reason (R) is false.
(D) Assertion (A) is false and Reason (R) is also false.

Correct Answer: (A) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of the Assertion (A).

Solution:

Concept:

- Mutual inductance is the magnetic flux linkage of one coil per unit current in the other: $M = N_2\Phi_{21}/I_1$. Here $N_2\Phi_{21}$ is the total flux linkage with coil 2 due to current I_1 in coil 1.
- For a given pair of coils, $M = k\sqrt{L_1L_2}$, where k is their coupling coefficient. Closer magnetic coupling reduces leakage of flux.

Step 1: Test the assertion When the two coils are wound on each other, they share essentially the same magnetic region and the coupling is greatest. For the given coils, mutual inductance is therefore maximum in this arrangement. Assertion (A) is true.

Step 2: Test the reason With the coils wound on each other, the largest fraction of the flux produced by either coil links the turns of the other. Thus, for the same current in the producing coil, flux linkage is maximum. Reason (R) is true.

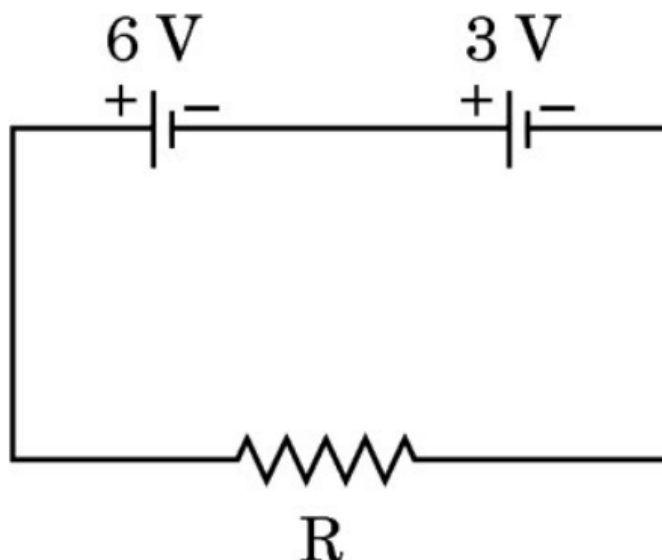
Step 3: Check the explanation The defining relation $M = N_2\Phi_{21}/I_1$ directly shows that maximum flux linkage at fixed current gives maximum mutual inductance. The reason therefore explains the assertion. Code (B) would deny this direct link, and codes (C) and (D) incorrectly classify at least one true statement as false.

Step 4: Conclusion Both statements are true, and the reason correctly explains the assertion. Hence, the correct option is (A).

Quick Tip to Solve: Compare flux linkage at the same current: the arrangement that links the most flux gives the largest mutual inductance.

Section B (10 marks)

17. Two batteries of emfs 6 V and 3 V and internal resistances $0.8\ \Omega$ and $0.2\ \Omega$ respectively are connected in series to an external resistance R , as shown in figure. Find the value of R so that the potential difference across the 6 V battery be zero. [2 marks]



Solution:

Concept:

- A cell delivering current I has terminal potential difference $V = \mathcal{E} - Ir$, where $\mathcal{E}$ is its emf and r its internal resistance.
- For series-aiding cells, the emfs add and the same current flows through both internal resistances and the external resistance: $I = (\mathcal{E}_1 + \mathcal{E}_2)/(R + r_1 + r_2)$.

Step 1: Use the zero terminal-voltage condition In the printed circuit the negative terminal of the 6 V battery connects to the positive terminal of the 3 V battery. The batteries therefore aid each other and both supply current. For the 6 V battery, its internal voltage drop must equal its emf:

$$0 = 6 - 0.8I \quad \Rightarrow \quad I = \frac{6}{0.8} = 7.5\text{ A.}$$

Zero terminal voltage does not imply zero current; here the entire emf of this battery is balanced by its own internal drop.

Step 2: Apply the loop equation The net emf is $6 + 3 = 9\text{ V}$, and the total internal resistance is $0.8 + 0.2 = 1.0\ \Omega$. Hence

$$\begin{aligned} 9 &= 7.5(R + 1.0), \\ R &= \frac{9}{7.5} - 1.0 = 0.20\ \Omega. \end{aligned}$$

As a check, the 3 V battery has terminal voltage $3 - 7.5(0.2) = 1.5\text{ V}$, equal to the external drop $IR = 7.5(0.20) = 1.5\text{ V}$.

Step 3: Conclusion The required external resistance is $R = 0.20\ \Omega$.

Quick Tip to Solve: Find the current from the specified cell's terminal voltage first, then use the total series emf to determine R .

18. Consider a neutron (mass m) of kinetic energy E and a photon of the same energy. Let λ_n and λ_p be the de Broglie wavelength of neutron and the wavelength of photon respectively. Obtain an expression for $\frac{\lambda_n}{\lambda_p}$. [2 marks]

Solution:

Concept:

- The de Broglie wavelength of a particle with momentum p is $\lambda = h/p$, where h is Planck's constant.
- For a non-relativistic neutron, kinetic energy is $E = p_n^2/(2m)$. A photon instead obeys $E = p_p c = hc/\lambda_p$, where c is the speed of light in vacuum.

Step 1: Express the neutron wavelength Use the usual non-relativistic kinetic-energy relation for the massive neutron. Solving for its momentum gives

$$p_n = \sqrt{2mE}, \quad \lambda_n = \frac{h}{\sqrt{2mE}}.$$

Here E denotes the neutron's kinetic energy, not its rest energy. The formula applies when this kinetic energy is small compared with mc^2 .

Step 2: Express the photon wavelength The photon has the same energy E , but its energy-momentum relation is linear. Therefore

$$E = \frac{hc}{\lambda_p} \Rightarrow \lambda_p = \frac{hc}{E}.$$

One must not use $p^2/(2m)$ for a photon, since it has zero rest mass.

Step 3: Divide the wavelengths Substitute both expressions and cancel Planck's constant:

$$\frac{\lambda_n}{\lambda_p} = \frac{h}{\sqrt{2mE}} \frac{E}{hc} = \frac{1}{c} \sqrt{\frac{E}{2m}}.$$

The factor $\sqrt{E/m}$ has dimensions of speed, so dividing by c gives the dimensionless wavelength ratio required.

Step 4: Conclusion In the non-relativistic regime, $\boxed{\frac{\lambda_n}{\lambda_p} = \sqrt{\frac{E}{2mc^2}}}.$

Quick Tip to Solve: Equal energy does not mean equal momentum: use $p_n = \sqrt{2mE}$ for the neutron and $p_p = E/c$ for the photon.

19(a). Monochromatic light of frequency 5.0×10^{14} Hz passes from air into a medium of refractive index 1.5. Find the wavelength of the light (i) reflected, and (ii) refracted at the interface of the two media. [2 marks]

Solution:

Concept:

- At a stationary interface, the frequency ν of light remains unchanged during reflection and refraction. Wavelength and speed are related by $\lambda = v/\nu$.
- In air, take $v = c = 3.0 \times 10^8$ m s⁻¹. In a medium of refractive index n , the speed is $v = c/n$.

Step 1: Find the reflected wavelength The reflected wave travels back into air. Its speed is therefore c , and its frequency remains $\nu = 5.0 \times 10^{14}$ Hz, the same as that of the incident wave. Hence

$$\lambda_{\text{reflected}} = \frac{c}{\nu} = \frac{3.0 \times 10^8}{5.0 \times 10^{14}} = 6.0 \times 10^{-7} \text{ m} = 600 \text{ nm}.$$

Reflection changes the direction of propagation, but does not change the wavelength in this same medium.

Step 2: Find the refracted wavelength In the second medium, the speed decreases while the frequency stays unchanged:

$$v = \frac{c}{n} = \frac{3.0 \times 10^8}{1.5} = 2.0 \times 10^8 \text{ m s}^{-1}.$$

Consequently,

$$\lambda_{\text{refracted}} = \frac{v}{\nu} = \frac{2.0 \times 10^8}{5.0 \times 10^{14}} = 4.0 \times 10^{-7} \text{ m} = 400 \text{ nm}.$$

This also follows by dividing the wavelength in air by the refractive index: $600/1.5 = 400 \text{ nm}$.

Step 3: Conclusion (i) Reflected light: 600 nm. (ii) Refracted light: 400 nm.

Quick Tip to Solve: Keep frequency fixed at the interface: the reflected wavelength stays unchanged, while the refracted wavelength is divided by n .

OR

19(b). A plano-convex lens of focal length 16 cm is made of a material of refractive index 1.4. Calculate the radius of the curved surface of the lens. [2 marks]

Solution:

Concept:

- For a thin lens in air, the lensmaker's formula is $\frac{1}{f} = (\mu - 1) \left(\frac{1}{R_1} - \frac{1}{R_2} \right)$, where μ is the lens material's refractive index and R_1, R_2 are the signed radii of its surfaces.
- A plane surface has infinite radius of curvature, so its reciprocal curvature is zero. A plano-convex lens in air is converging and has positive focal length.

Step 1: Identify the two surface curvatures Take light to travel from left to right and to enter the convex surface first. The centre of curvature of this surface lies to its right, so $R_1 = +R$, while the plane exit surface has $R_2 = \infty$. Thus the lensmaker's relation reduces to

$$\frac{1}{f} = (\mu - 1) \frac{1}{R}.$$

Here R is the positive magnitude of the radius being requested.

Step 2: Substitute the focal length and refractive index Using $f = 16 \text{ cm}$ and $\mu = 1.4$, rearrange before substitution:

$$R = f(\mu - 1) = 16(1.4 - 1) \text{ cm} = 6.4 \text{ cm}.$$

The index difference is dimensionless, so the radius has the same unit as the focal length. Reversing the lens changes the signed surface labels but leaves its focal length and this radius magnitude unchanged.

Step 3: Conclusion The radius of the curved surface is $R = 6.4 \text{ cm}$.

Quick Tip to Solve: For a plano-convex lens in air, put the plane surface's reciprocal radius equal to zero and use $R = (\mu - 1)f$.

20. An object is placed 30 cm in front of a concave mirror of radius of curvature 40 cm. Find the (i) position of the image formed and (ii) magnification of the image. [2 marks]

Solution:

Concept:

- For a spherical mirror, $f = R/2$, and the mirror formula is $1/f = 1/v + 1/u$. Here u , v and f are signed distances measured from the pole.
- The linear magnification is $m = h_i/h_o = -v/u$. Its sign gives image orientation and its magnitude gives the ratio of image height to object height.

Step 1: Assign Cartesian signs and calculate image distance Take incident light to travel towards the mirror from left to right. The object and the focus of the concave mirror lie to the left of the pole, hence

$$u = -30 \text{ cm}, \quad R = -40 \text{ cm}, \quad f = -20 \text{ cm}.$$

Substitute these signed values in the mirror formula:

$$\frac{1}{v} = \frac{1}{f} - \frac{1}{u} = -\frac{1}{20} + \frac{1}{30} = -\frac{1}{60} \text{ cm}^{-1},$$
$$v = -60 \text{ cm}.$$

The negative image distance places the image in front of the mirror, on the same side as the object.

Step 2: Calculate and interpret magnification Use both signed distances in the magnification expression:

$$m = -\frac{v}{u} = -\frac{-60}{-30} = -2.$$

The negative sign indicates an inverted image; $|m| = 2$ means that its height is twice the object height. This agrees with the object lying between the focus and the centre of curvature of a concave mirror, where the image is real and enlarged.

Step 3: Conclusion (i) The image forms 60 cm in front of the mirror ($v = -60 \text{ cm}$). (ii) Its magnification is $m = -2$; the image is real, inverted and twice the object's size.

Quick Tip to Solve: First halve the signed radius to obtain f , then use $1/v = 1/f - 1/u$; retain the minus sign in $m = -v/u$.

21. How does the conductivity of an intrinsic semiconductor vary with temperature? Explain. Show the variation in a plot. [2 marks]

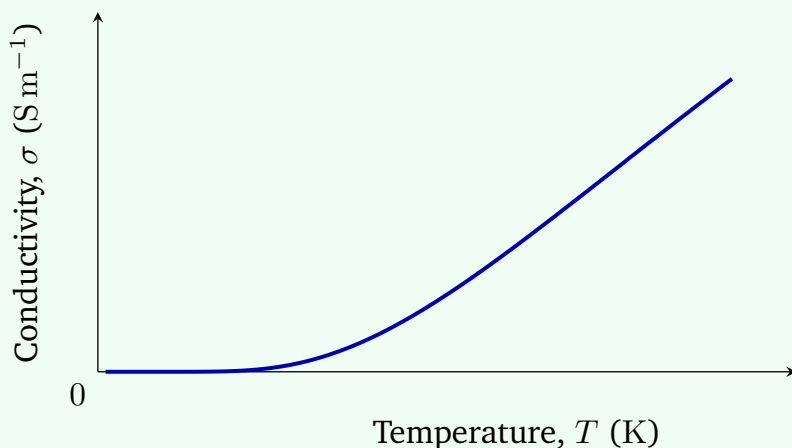
Solution:

Concept:

- In an intrinsic semiconductor the electron and hole concentrations are equal: $n = p = n_i$. Its conductivity is $\sigma = en_i(\mu_e + \mu_h)$, where e is the elementary charge and μ_e, μ_h are the electron and hole mobilities.
- Thermal energy excites electrons across the energy gap from the valence band to the conduction band, leaving holes behind. Each excitation creates one mobile electron-hole pair.

Step 1: Explain the effect of raising temperature At absolute zero, the valence band is full and the conduction band is empty, so an ideal intrinsic semiconductor has no mobile charge carriers. As temperature rises, more covalent bonds are broken by thermal excitation and the intrinsic carrier concentration increases rapidly. Both electrons in the conduction band and holes in the valence band contribute to current.

Step 2: Relate the carrier increase to the conductivity plot Although increasing lattice vibrations tend to reduce mobility, the rapid increase of n_i dominates in the intrinsic region. Therefore the conductivity increases with temperature, while resistivity decreases. The strong thermal dependence is commonly expressed by $n_i \propto T^{3/2} \exp[-E_g/(2k_B T)]$, where E_g is the band gap and k_B is Boltzmann's constant. The qualitative plot shows the conductivity rising nonlinearly as more carriers become available; it is not a straight-line metallic trend.



Qualitative variation of intrinsic semiconductor conductivity with temperature.

Step 3: Conclusion The conductivity σ of an intrinsic semiconductor increases rapidly with temperature because thermal excitation generates increasing numbers of electron-hole pairs. The semiconductor therefore has a negative temperature coefficient of resistivity.

Quick Tip to Solve: For an intrinsic semiconductor, connect higher temperature to more electron-hole pairs: draw σ rising with T , and remember that resistivity does the opposite.

Section C (21 marks)

22. Three point charges Q_1 , Q_2 and Q_3 are located in $x - y$ plane at points $(-d, 0)$, $(0, 0)$ and $(d, 0)$ respectively. Q_1 and Q_3 are identical and Q_2 is positive. What will be the nature and value of Q_1 so that the potential energy of the system is zero? [3 marks]

Solution:

Concept:

- The electrostatic potential energy of point charges, taking zero energy at infinite separation, is the sum over distinct pairs: $U = \sum_{i < j} kQ_i Q_j / r_{ij}$, where $k = 1/(4\pi\epsilon_0)$ and r_{ij} is their separation.
- Like-charge pairs contribute positive energy and unlike-charge pairs contribute negative energy. Each pair is counted exactly once; zero total energy requires cancellation of the signed pair energies.

Step 1: Identify all three pair separations The charges lie along the x -axis at $-d$, 0 and $+d$. Therefore

$$r_{12} = d, \quad r_{23} = d, \quad r_{13} = 2d.$$

Write the identical outer charges as $Q_1 = Q_3 = q$, and denote the positive central charge by $Q_2 = Q > 0$. In particular, the separation of the two outer charges is $2d$, not d .

Step 2: Add the pair energies and impose zero total energy The two central-outer interactions are equal, while the outer-outer interaction involves the longer separation. Thus

$$\begin{aligned} U &= \frac{kqQ}{d} + \frac{kQq}{d} + \frac{kq^2}{2d} \\ &= \frac{k}{2d} (4qQ + q^2) = \frac{k}{2d} q(q + 4Q). \end{aligned}$$

Since $d > 0$ and $k \neq 0$, requiring $U = 0$ gives $q(q + 4Q) = 0$. For nonzero outer point charges, the physically intended root is $q = -4Q$. The other algebraic root $q = 0$ merely removes both outer charges, leaving only the central charge.

Step 3: Check the sign and energy cancellation Because $Q > 0$, the nonzero outer charges must be negative. Substituting $q = -4Q$ makes the energy of each central-outer pair $-4kQ^2/d$, whereas the energy of the outer pair is $+8kQ^2/d$. Their sum is

$$U = -\frac{4kQ^2}{d} - \frac{4kQ^2}{d} + \frac{8kQ^2}{d} = 0,$$

confirming that attraction to the central charge cancels the positive interaction energy of the identical outer charges.

Step 4: Conclusion The required nonzero charge is $Q_1 = -4Q_2$, so Q_1 is negative and has magnitude four times the positive central charge. Since $Q_3 = Q_1$, it also equals $-4Q_2$. The trivial mathematical solution is $Q_1 = Q_3 = 0$.

Quick Tip to Solve: List the three distinct pairs first: the outer pair is separated by $2d$. Add energies as scalars with charge signs, then factor the common outer charge.

23(a). Define ‘current density’. Is it a scalar or a vector? An electric field $\vec{E}$ is maintained in a metallic conductor. If n be the number of electrons (mass m , charge $-e$) per unit volume in the conductor and τ its relaxation time, show that the current density $\vec{j} = \alpha \vec{E}$, where $\alpha = \left(\frac{ne^2}{m}\right) \tau$. [3 marks]

Solution:

Concept:

- Current density is current per unit area perpendicular to the flow. For uniform flow, $j = I/A$; its direction is that of conventional positive current.
- An electron has charge $-e$, so an electric field $\vec{E}$ produces force $-e\vec{E}$. Relaxation time τ is the mean time between successive collisions.
- For number density n and mean electron drift velocity $\vec{v}_d$, the current density is $\vec{j} = -ne\vec{v}_d$.

Step 1: Define current density and its nature At a point, current density is the electric current flowing per unit area of a small surface held perpendicular to the direction of current. For a uniform conductor of cross-sectional area A ,

$$\vec{j} = \frac{I}{A} \hat{n},$$

where $\hat{n}$ points along conventional current. Current density is a vector; its SI unit is A m^{-2} . More generally, current through an oriented surface is $I = \int \vec{j} \cdot d\vec{A}$, showing how the orientation of the surface matters.

Step 2: Obtain the mean electron drift velocity Without an applied field, random thermal velocities have zero vector average. Under the field, Newton’s second law gives the electron acceleration

$$\vec{a} = \frac{-e\vec{E}}{m}.$$

Collisions repeatedly randomise the electron velocity. Averaging the field-induced change over the relaxation time yields

$$\vec{v}_d = \vec{a}\tau = -\frac{e\tau}{m}\vec{E}.$$

Thus electrons drift opposite to the field, although conventional current flows along it.

Step 3: Relate drift velocity to current density In time dt , electrons in a cylinder of length $v_d dt$ and area A cross a normal section. Their number is $nAv_d dt$, so the magnitude of the current is $I = neAv_d$. Including the negative charge and the vector direction gives

$$\begin{aligned} \vec{j} &= -ne\vec{v}_d \\ &= -ne\left(-\frac{e\tau}{m}\vec{E}\right) \\ &= \frac{ne^2\tau}{m}\vec{E}. \end{aligned}$$

The two negative signs cancel, which is essential for the direction of conventional current in a metal.

Step 4: Conclusion Current density is a vector, directed along conventional current, and $\vec{j} = \alpha \vec{E}$, where $\alpha = ne^2\tau/m$ is the electrical conductivity. Its SI unit is S m^{-1} .

Quick Tip to Solve: Keep the electron’s negative charge in both $\vec{v}_d$ and $\vec{j} = -ne\vec{v}_d$; their signs cancel, so current density points along the field.

23(b). What is a Wheatstone bridge? Obtain the necessary conditions under which the Wheatstone bridge is balanced. [3 marks]

Solution:

Concept:

- A Wheatstone bridge is a four-resistance network used to determine an unknown resistance by comparison with known resistances.
- At balance, the galvanometer carries no current because its terminals have equal potential. Ohm's law then relates the voltage drops in the two branches.

Step 1: Specify the bridge arrangement Let the four resistances P, Q, R, S occupy arms AB, BC, AD, DC , respectively. Connect a cell across opposite junctions A and C , and a sensitive galvanometer across B and D . The branch ABC contains P, Q in series, and branch ADC contains R, S in series when the galvanometer current is zero. Adjust a known arm until the galvanometer shows null deflection; this is the balanced state.

Step 2: Apply the null-current condition At balance, $I_g = 0$, so $V_B = V_D$. Let I_1 flow from A to C through P, Q , and I_2 flow through R, S . Since no current leaves either branch through the galvanometer, the same branch current passes through both resistors in that branch. The equal drops from A to the galvanometer junctions give

$$V_A - V_B = V_A - V_D \Rightarrow I_1 P = I_2 R.$$

The equal drops from those junctions to C similarly give

$$V_B - V_C = V_D - V_C \Rightarrow I_1 Q = I_2 S.$$

Step 3: Eliminate the branch currents Divide the first voltage relation by the second, cancelling the nonzero branch currents:

$$\frac{I_1 P}{I_1 Q} = \frac{I_2 R}{I_2 S} \Rightarrow \frac{P}{Q} = \frac{R}{S}.$$

Conversely, this ratio makes the two junctions the same fractional potential between the battery terminals, and hence produces zero galvanometer current. For example, if S is unknown, the balance reading gives $S = QR/P$. The condition depends on resistance ratios, not on the cell emf or the galvanometer resistance.

Step 4: Conclusion A Wheatstone bridge measures an unknown resistance by a null comparison. With the arm labels defined above, it is balanced when $I_g = 0$, equivalently $V_B = V_D$ and $P/Q = R/S$ (or $PS = QR$).

Quick Tip to Solve: First name the four arms and the two diagonals; then equate voltage drops on either side of the zero-current galvanometer to obtain the correct ratio.

24. A bar magnet of magnetic moment 2.5 J T^{-1} lies aligned with the direction of a uniform magnetic field of 0.32 T .

(a) Find the amount of work done to turn the magnet so as to align its magnetic moment (i) normal to the field direction, and (ii) opposite to the field direction.

(b) What is the torque on the magnet in above cases (i) and (ii)?

[3 marks]

Solution:

Concept:

- A magnetic dipole of moment magnitude m in a uniform field B has potential energy $U = -mB \cos \theta$, where θ is the angle between its moment and the field.
- The work done by an external agent in turning the magnet slowly is the increase in potential energy, $W_{\text{ext}} = mB(\cos \theta_i - \cos \theta_f)$.
- The magnetic torque is $\vec{\tau} = \vec{m} \times \vec{B}$, of magnitude $\tau = mB \sin \theta$, and tends to align the moment with the field.

Step 1: Calculate the common energy factor Here $m = 2.5 \text{ J T}^{-1}$ and $B = 0.32 \text{ T}$. Thus

$$mB = (2.5)(0.32) = 0.80 \text{ J}.$$

Initially the magnet is aligned with the field, so $\theta_i = 0^\circ$ and $U_i = -mB = -0.80 \text{ J}$. The external work assumes no change of kinetic energy; field work has the opposite sign.

Step 2: Find the work for the two final orientations (a)(i) For a moment normal to the field, $\theta_f = 90^\circ$, and the final potential energy is zero. Consequently,

$$W_{\text{ext}} = 0 - (-0.80) = 0.80 \text{ J}.$$

(a)(ii) For a moment opposite to the field, $\theta_f = 180^\circ$, and $U_f = +mB = +0.80 \text{ J}$. Hence

$$W_{\text{ext}} = 0.80 - (-0.80) = 1.60 \text{ J}.$$

Both rotations start from the original aligned position.

Step 3: Evaluate the magnetic torque at each final position (b)(i) At the perpendicular orientation, the sine factor is unity:

$$\tau_{90^\circ} = mB \sin 90^\circ = 0.80 \text{ N m}.$$

This maximum torque tends to align the magnet; its direction follows $\vec{m} \times \vec{B}$. For (b)(ii), the antiparallel orientation has zero sine:

$$\tau_{180^\circ} = mB \sin 180^\circ = 0.$$

This is unstable equilibrium: a small angular displacement drives the magnet away from this position.

Step 4: Conclusion The required external work is (i) 0.80 J and (ii) 1.60 J . The corresponding magnetic torque magnitudes are (i) 0.80 N m , tending to align the magnet, and (ii) zero.

Quick Tip to Solve: Use cosine differences for work and sine for torque. At 180° , the torque is zero even though the work from the aligned state is maximum.

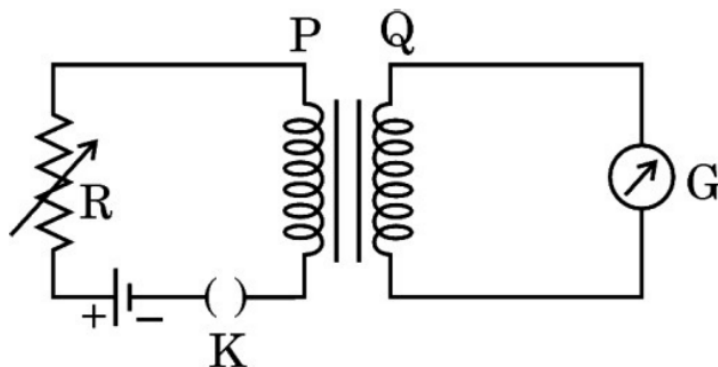
25. Consider the arrangement of two coils P and Q shown in the figure. When current in coil P is switched on or switched off, a current flows in coil Q .

(a) Explain the phenomenon involved in it.

(b) Mention two factors on which the current produced in coil Q depends.

(c) Give the direction of current in coil Q when there is a current in the coil P and (i) R is increased, and (ii) R is decreased.

[3 marks]



Solution:

Concept:

- Mutual induction is the production of an emf in one coil when the current in a neighbouring coil changes. The changing current changes the magnetic flux linked with the second coil.
- Faraday's law gives $\varepsilon_Q = -M dI_P/dt$, where M is the mutual inductance and I_P is the current in coil P . Lenz's law fixes the direction: the induced current opposes the change in flux.

Step 1: (a) Explain the momentary current Closing key K makes the current in P rise from zero, so the flux linked with Q increases. Opening the key makes that flux decrease. In either case, the changing flux induces an emf and hence a current in the closed circuit containing Q and the galvanometer. This is mutual induction. Once the current in P becomes steady, the flux becomes constant and the induced current disappears; merely having a magnetic field is insufficient.

Step 2: (b) State the factors controlling its magnitude Two factors are the rate of change of the current in P , $|dI_P/dt|$, and the mutual inductance M of the coils. For a fixed total resistance R_Q of the secondary circuit, the usual resistive-circuit expression is

$$|I_Q| = \frac{M}{R_Q} \left| \frac{dI_P}{dt} \right|.$$

A faster current change produces a larger induced emf. Stronger magnetic coupling, for example by bringing the coils closer or using a common iron core, increases M and hence the induced current under the same circuit conditions.

Step 3: (c) Apply Lenz's law to the two changes in resistance The battery sends conventional current from its positive terminal through R , then into the upper end of P , and out of its lower end. (i) Increasing R decreases this current and the flux linked with Q . The induced current must reinforce the original magnetic field. For the winding arrangement shown, it flows up through Q and down through the galvanometer: clockwise around the right-hand circuit as drawn. (ii) Decreasing R increases the primary current and linked flux. The induced current opposes this increase, so it reverses: down through Q , up through the galvanometer, and anticlockwise around the right-hand circuit. Each current lasts only while the primary current is changing.

Step 4: Conclusion The phenomenon is mutual induction. For a fixed secondary resistance, the current magnitude depends on the rate of change of primary current and on mutual inductance. Increasing R gives a clockwise induced current in the circuit of Q ; decreasing R gives an anticlockwise current, as viewed in the printed figure.

Quick Tip to Solve: Decide whether the primary flux increases or decreases first; the induced field opposes an increase but supports a decrease. Then trace the secondary winding to find the current direction.

26. Write the drawbacks of Rutherford's atomic model. How did Bohr remove them? Show that different orbits in Bohr's atom are not equally spaced. [3 marks]

Solution:

Concept:

- A charge accelerated in classical electrodynamics radiates electromagnetic energy. An orbiting electron has centripetal acceleration even when its speed is constant.
- Bohr postulated non-radiating stationary orbits with angular momentum $m_e v r = n\hbar$, where $n = 1, 2, \dots$ and $\hbar = h/(2\pi)$. Radiation occurs in transitions with $h\nu = E_i - E_f$ for emission.

Step 1: Identify Rutherford's two main difficulties Rutherford's orbiting electron is an accelerated charge. Classical theory therefore predicts continuous radiation, loss of energy and a shrinking orbit; the electron should spiral into the nucleus. The model cannot explain the observed stability of atoms. Moreover, it provides no allowed discrete energies or frequencies and therefore cannot explain the observed discrete line spectrum of hydrogen; a continuously changing orbit would instead emit a changing range of frequencies.

Step 2: Explain Bohr's remedies Bohr allowed only certain stationary orbits in which the electron does not radiate despite its acceleration. The lowest permitted orbit is a stable ground state, so continuous collapse is excluded. Quantisation of angular momentum gives discrete energies. An electron emits or absorbs a photon only when it changes between these levels, with $h\nu = |E_i - E_f|$. The allowed energy differences thus account for the discrete spectral lines of hydrogen. These are postulates replacing the classical radiation picture within the atom.

Step 3: Derive the radius of an allowed orbit For a hydrogen-like atom of nuclear charge $+Ze$, electrostatic attraction supplies the centripetal force. Combining this with angular-momentum quantisation gives

$$\begin{aligned} \frac{m_e v^2}{r_n} &= \frac{Ze^2}{4\pi\epsilon_0 r_n^2}, & m_e v r_n &= n\hbar, \\ \frac{n^2 \hbar^2}{m_e r_n^3} &= \frac{Ze^2}{4\pi\epsilon_0 r_n^2}, & r_n &= \frac{4\pi\epsilon_0 \hbar^2}{m_e Z e^2} n^2. \end{aligned}$$

Writing $a_0 = 4\pi\epsilon_0 \hbar^2 / (m_e e^2)$, the result is $r_n = (a_0/Z)n^2$, with $Z = 1$ for hydrogen.

Step 4: Compare neighbouring orbital separations The separation between successive radii is

$$r_{n+1} - r_n = \frac{a_0}{Z} [(n+1)^2 - n^2] = \frac{a_0}{Z} (2n+1).$$

Thus the first three radii are proportional to 1, 4, 9; their successive gaps are proportional to 3, 5. The radial gap depends on n and increases for higher orbits.

Step 5: Conclusion Rutherford's model fails to explain atomic stability and discrete line spectra. Bohr's stationary, quantised orbits and photon transitions address these problems for hydrogen-like

atoms. Since $r_n \propto n^2$ and $r_{n+1} - r_n \propto 2n + 1$, the orbits are not equally spaced.

Quick Tip to Solve: To test equal spacing, subtract successive radii; $r_n \propto n^2$ gives gaps proportional to the odd numbers 3, 5, 7, ...

27. (a) “The wavelength of the electromagnetic wave is often correlated with the characteristic size of the system that radiates.” Give two examples to justify this statement.

(b) (i) Long distance radio broadcasts use short-wave bands. Why?

(ii) Optical and radio telescopes are built on the ground, but X-ray astronomy is possible only from satellites orbiting the Earth. Why? [3 marks]

Solution:

Concept:

- Electromagnetic waves satisfy $c = \nu\lambda$, where c is their speed in vacuum, ν their frequency and λ their wavelength. Resonant radiating systems often have dimensions comparable to their emitted wavelength.
- The atmosphere transmits some wavelength bands, absorbs others, and can return suitable radio waves towards Earth through the ionosphere. The useful propagation path therefore depends on frequency.

Step 1: (a) Give two examples of size and wavelength correlation First, a radio transmitting antenna has a length comparable to the wavelength it radiates efficiently. For example, a half-wave dipole of length L is designed for approximately $\lambda = 2L$; a metre-scale antenna therefore radiates metre-scale waves. Second, the resonant cavities of microwave sources, such as magnetrons, have characteristic dimensions comparable to their operating microwave wavelength. Centimetre-scale cavities can thus be used to generate centimetre-wavelength radiation. These examples show a correlation of characteristic scales; the source size need not equal the wavelength exactly, since geometry and the resonant mode also matter.

Step 2: (b)(i) Explain the use of short-wave radio bands Short-wave radio signals in suitable frequency ranges can be returned to Earth by the ionosphere. This is called sky-wave propagation; the effect is commonly described as ionospheric reflection, arising from refraction in the ionised layers. The signals can reach a distant receiver beyond the direct line of sight. Repeated returns between the ionosphere and Earth’s surface permit communication over very long distances, which makes these bands useful for long-distance broadcasting. The usable frequency depends on ionospheric conditions.

Step 3: (b)(ii) Explain the locations of astronomical telescopes Earth’s atmosphere is sufficiently transparent in the visible band and in useful radio-frequency windows. Light and radio signals from astronomical objects can therefore reach suitable ground-based optical and radio telescopes. In contrast, the atmosphere strongly absorbs incoming astronomical X-rays before they can reach the ground. An X-ray telescope must consequently be carried above the absorbing atmosphere, for example on an Earth-orbiting satellite. This placement allows the detector to receive the X-rays directly.

Step 4: Conclusion Radio antennas and microwave resonant cavities provide examples of source dimensions correlated with wavelength. Short-wave broadcasts exploit ionospheric sky-wave propagation. Visible and radio atmospheric windows allow ground-based telescopes, whereas absorption of X-rays requires observing from above the atmosphere.

Quick Tip to Solve: For propagation questions, distinguish ionospheric return of short waves, atmospheric transmission of visible and selected radio bands, and atmospheric absorption of X-rays.

28. (a) Write two characteristic properties of nuclear force.

(b) Draw a plot of potential energy of a pair of nucleons as a function of their separation. Write two important conclusions that can be drawn from the plot. [3 marks]

Solution:

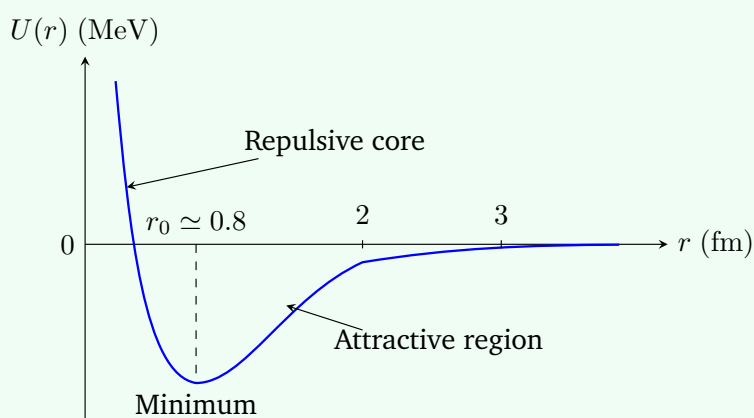
Concept:

- Nuclear force is the strong, short-range interaction that binds protons and neutrons inside a nucleus; a nucleon is either a proton or a neutron.
- The radial force and interaction potential energy are related by $F_r = -dU/dr$, where r is nucleon separation. An outward force is repulsive and an inward force is attractive. Choose $U(\infty) = 0$.

Step 1: State two characteristic properties (a) **Short range:** Nuclear force is appreciable only over distances of a few femtometres, where $1 \text{ fm} = 10^{-15} \text{ m}$. It becomes negligible when nucleons are separated by more than a few femtometres.

Approximate charge independence: After the electrostatic contribution between protons is excluded, the nuclear interaction between two protons, two neutrons or a proton and a neutron is approximately the same in corresponding states.

Step 2: Sketch the nuclear potential energy (b) At very small separation the potential rises steeply to a large positive value. It falls to a negative minimum near $r_0 \simeq 0.8 \text{ fm}$, then rises towards zero as the separation becomes a few femtometres. The curve below is schematic; the depth of the well is not assigned a numerical value.



Schematic potential energy of two nucleons; the minimum is near $r_0 \simeq 0.8 \text{ fm}$.

Step 3: Infer the force from the two slopes **First conclusion:** For $r < r_0$, the slope $dU/dr < 0$, so $F_r > 0$; the force is strongly repulsive. This repulsive core prevents nucleons from collapsing into one another.

Second conclusion: For $r > r_0$ within the interaction range, $dU/dr > 0$, so $F_r < 0$; the force is attractive and can bind nucleons. At large separation the graph becomes almost horizontal at $U = 0$, so the force tends to zero. At the minimum itself the force vanishes.

Step 4: Conclusion Nuclear force is short-ranged and approximately charge-independent. The potential-energy well shows a repulsive core at very small separation and attraction beyond the minimum, with negligible interaction beyond a few femtometres.

Quick Tip to Solve: Read nuclear force from the negative slope of the potential curve, not merely from whether the potential lies above or below zero.

Section D (8 marks)

Questions number 29 and 30 are case study-based questions. Read the following paragraphs and answer the questions that follow.

29. Junction Diode as a Rectifier:

The process of conversion of an ac voltage into a dc voltage is called rectification and the device which performs this conversion is called a rectifier. The characteristics of a p-n junction diode reveal that when a p-n junction diode is forward biased, it offers a low resistance and when it is reverse biased, it offers a high resistance. Hence, a p-n junction diode conducts only when it is forward biased. This property of a p-n junction diode makes it suitable for its use as a rectifier.

Thus, when an ac voltage is applied across a p-n junction, it conducts only during those alternate half cycles for which it is forward biased. A rectifier which rectifies only half cycle of an ac voltage is called a half-wave rectifier and one that rectifies both the half cycles is known as a full-wave rectifier.

[4 marks]

29(i). The root mean square value of an alternating voltage applied to a full-wave rectifier is $\frac{V_0}{\sqrt{2}}$.

Then the root mean square value of the rectified output voltage is:

[1 mark]

- (A) $\frac{V_0}{\sqrt{2}}$
(B) $\frac{V_0^2}{\sqrt{2}}$
(C) $\frac{2V_0}{\sqrt{2}}$
(D) $\frac{V_0}{2\sqrt{2}}$

Correct Answer: (A) $\frac{V_0}{\sqrt{2}}$

Solution:

Concept:

- An ideal full-wave rectifier changes both input half-cycles to the same output polarity: $v_o(t) = |V_0 \sin \omega t|$, where V_0 is the input peak voltage.
- The root mean square voltage is $V_{\text{rms}} = \sqrt{\langle v^2 \rangle}$; reversing a voltage's sign leaves its square

unchanged.

Step 1: Square the rectified waveform The negative half-cycle is inverted without changing its magnitude, assuming ideal diodes and no smoothing filter. Therefore $v_o^2 = V_0^2 \sin^2 \omega t$. The mean of $\sin^2 \omega t$ over one cycle is $1/2$.

Step 2: Calculate and compare the rms values

$$V_{o,\text{rms}} = \sqrt{\frac{V_0^2}{2}} = \frac{V_0}{\sqrt{2}}.$$

The rms output equals the rms input. Printed option (B), $V_0^2/\sqrt{2}$, has the dimensions of voltage squared. Options (C) and (D) respectively double and halve the rms voltage, although rectification itself does neither.

Step 3: Conclusion The root mean square output voltage is $V_0/\sqrt{2}$. Hence, the correct option is (A).

Quick Tip to Solve: For ideal full-wave rectification, square the waveform first: changing negative lobes to positive leaves the rms value unchanged.

29(ii). In a full-wave rectifier, the current in each of the diodes flows for:

[1 mark]

- (A) Complete cycle of the input signal
- (B) Half cycle of the input signal
- (C) Less than half cycle of the input signal
- (D) Only for the positive half cycle of the input signal

Correct Answer: (B) Half cycle of the input signal

Solution:

Concept:

- A diode conducts when forward biased and blocks current when reverse biased, in the ideal rectifier model.
- In the usual two-diode full-wave rectifier, the diodes conduct alternately, while the load current has the same direction during both input half-cycles.

Step 1: Follow the first half-cycle When one end of the centre-tapped secondary is positive relative to the centre tap, its diode is forward biased and carries the load current. The diode connected to the other, negative end is reverse biased and does not conduct.

Step 2: Reverse the input polarity In the next half-cycle the end polarities reverse. The previously conducting diode switches off and the other diode conducts. Thus each diode conducts for $T/2$, where T is the input period. Neither diode conducts for a complete cycle, and in the ideal model its conduction is not restricted to less than half a cycle. Option (D) is incorrect because the two diodes operate on opposite input half-cycles; both do not conduct only during the positive input half-cycle.

Step 3: Conclusion Current flows through each diode for half a cycle of the input signal. Hence, the correct option is (B).

Quick Tip to Solve: Distinguish a single diode's current from the load current: alternate diodes supply the two half-cycles of a full-wave output.

29(iii). In a full-wave rectifier:

[1 mark]

- (A) Both diodes are forward biased at the same time.
- (B) Both diodes are reverse biased at the same time.
- (C) One is forward biased and the other is reverse biased at the same time.
- (D) Both are forward biased in the first half of the cycle and reverse biased in the second half of the cycle.

Correct Answer: (C) One is forward biased and the other is reverse biased at the same time.

Solution:

Concept:

- A centre-tapped full-wave rectifier has opposite polarities at its secondary ends relative to the centre tap.
- An anode positive relative to its cathode gives forward bias; negative gives reverse bias.

Step 1: Compare biases In one half-cycle, the positive secondary end forward biases its diode, which conducts through the load. The negative end reverse biases the other diode, blocking it.

Step 2: Reverse the polarity The diodes exchange roles next half-cycle. Except at zero crossings, their biases are opposite: neither both forward (A) nor both reverse (B). Option (D) also assigns identical biases and wrongly blocks the entire second half-cycle.

Step 3: Conclusion One diode is forward biased and the other reverse biased. Hence, the correct option is (C).

Quick Tip to Solve: Mark opposite signs at the secondary ends; reverse them each half-cycle to identify the conducting diode.

29(iv)(a). An alternating voltage of frequency of 50 Hz is applied to a half-wave rectifier. Then the ripple frequency of the output will be:

[1 mark]

- (A) 100 Hz
- (B) 50 Hz
- (C) 25 Hz
- (D) 150 Hz

Correct Answer: (B) 50 Hz

Solution:

Concept:

- Ripple frequency measures repetition of the output's pulsating component.
- Half-wave rectification passes one half-cycle and blocks the next: one pulse per input cycle.

Step 1: Find the period For input frequency $f = 50$ Hz,

$$T = \frac{1}{f} = \frac{1}{50} \text{ s} = 0.02 \text{ s}.$$

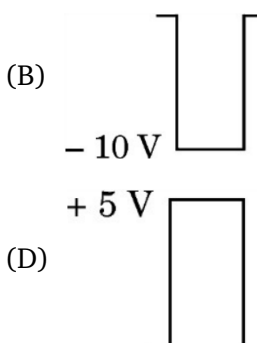
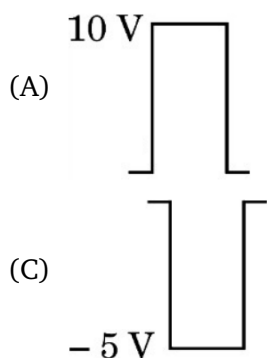
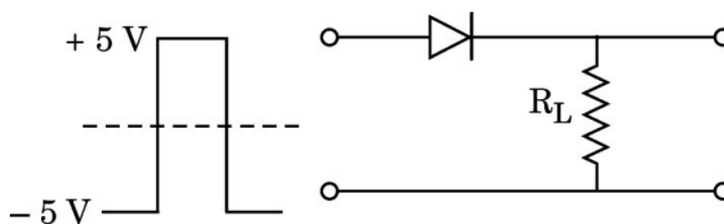
Step 2: Count pulses Pulses begin $T = 0.02 \text{ s}$ apart, giving $1/T = 50 \text{ Hz}$. Full-wave rectification gives two pulses per cycle and 100 Hz , ruling out (A). Blocking alternate half-cycles does not double the period to give 25 Hz (C); three pulses per cycle would be needed for 150 Hz (D).

Step 3: Conclusion The ripple frequency is 50 Hz . Hence, the correct option is (B).

Quick Tip to Solve: Count pulses per input cycle: one gives ripple frequency f ; two gives $2f$.

OR

29(iv)(b). A signal, as shown in the figure, is applied to a p-n junction diode. Identify the output across resistance R_L : [1 mark]



Correct Answer: (D)

Solution:

Concept:

- An ideal diode passes current from its anode to its cathode when forward biased and blocks reverse current.
- The output is the voltage across R_L , measured from the upper terminal to the lower terminal. The cathode bar in the printed circuit is on the right.

Step 1: Apply the positive input level When the upper input is at $+5 \text{ V}$ relative to the lower line, the left anode is positive and the diode conducts. Neglecting its forward voltage drop, the upper end of R_L is therefore at $+5 \text{ V}$. The output retains the positive rectangular pulse at its original height.

Step 2: Apply the negative input level and compare shapes At an input of -5 V , the diode is reverse biased. Current through R_L is zero, so its voltage is $IR_L = 0$. The output therefore alternates between zero and $+5 \text{ V}$. Options (B) and (C) show negative pulses, which this diode orientation blocks. Option (A) incorrectly uses 10 V , the input's peak-to-peak difference, as the output pulse height; the circuit provides no voltage doubling.

Step 3: Conclusion The output consists of positive rectangular pulses of height +5 V, with zero output during the negative input level. Hence, the correct option is (D).

Quick Tip to Solve: Locate the diode's cathode bar, then test the positive and negative input levels separately; do not confuse peak voltage with peak-to-peak voltage.

30. A lens is a transparent medium bounded by two surfaces, with one or both surfaces being spherical. The focal length of a lens is determined by the radii of curvature of its two surfaces and the refractive index of its medium with respect to that of the surrounding medium. The power of a lens is reciprocal of its focal length. If a number of lenses are kept in contact, the power of the combination is the algebraic sum of the powers of the individual lenses. [4 marks]

30(i). A double-convex lens, with each face having same radius of curvature R , is made of glass of refractive index n . Its power is: [1 mark]

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

Correct Answer: (A) $\frac{2(n-1)}{R}$

Solution:

Concept:

- For a thin lens in air, the lens-maker formula gives power $P = 1/f = (n-1)(1/R_1 - 1/R_2)$, where n is its refractive index.
- Radii have signs under the Cartesian convention. For a double-convex lens receiving light from the left, $R_1 = +R$ and $R_2 = -R$.

Step 1: Substitute the signed radii Although both faces have the same radius magnitude, their centres of curvature lie on opposite sides of their vertices. Thus

$$P = (n-1) \left(\frac{1}{R} - \frac{1}{-R} \right) = (n-1) \frac{2}{R}.$$

Step 2: Check the option factors Both curved surfaces contribute equally to the positive power. Options (B) and (D) contain $2n-1$, which would not vanish when $n = 1$. Option (C) is only one quarter of the derived power, so its numerical factor is incorrect.

Step 3: Conclusion The power is $P = 2(n-1)/R$, in dioptres when R is in metres. Hence, the correct option is (A).

Quick Tip to Solve: For an equiconvex lens, put opposite signs on its equal radii before subtracting their reciprocals.

30(ii). A double-convex lens of power P , with each face having same radius of curvature, is cut into two equal parts perpendicular to its principal axis. The power of one part of the lens will be: [1 mark]

(A) $2P$

(B) P

(C) $4P$

(D) $\frac{P}{2}$

Correct Answer: (D) $\frac{P}{2}$

Solution:

Concept:

- The original equiconvex lens has power $P = 2(n - 1)/R$, with R the magnitude of either radius and n the refractive index in air.
- A plane surface has infinite radius, so its contribution $1/R_{\text{plane}}$ in the lens-maker formula is zero.

Step 1: Identify the shape of each part A cut perpendicular to the principal axis through the middle produces two plano-convex lenses. Each has one original curved surface of radius magnitude R and one new plane surface. The refractive index of the material is unchanged.

Step 2: Compare the powers Applying the lens-maker formula to either part gives

$$P_{\text{part}} = (n - 1) \left(\frac{1}{R} - 0 \right) = \frac{n - 1}{R}.$$

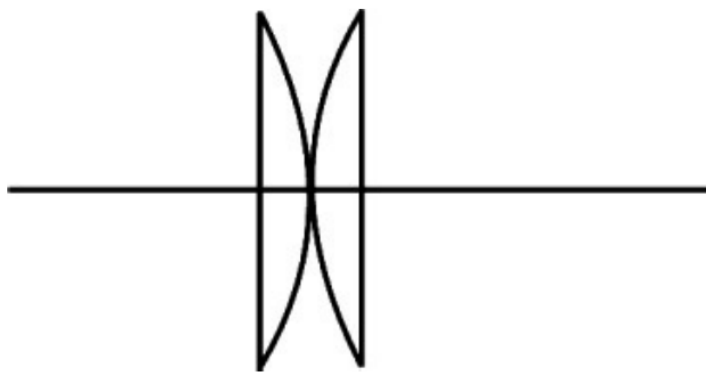
The original lens had two equal curved-surface contributions, whereas each part now has only one. Thus the power decreases; neither $2P$ nor $4P$ is possible, and retaining P would incorrectly count both original surfaces.

Step 3: Conclusion Each plano-convex part has power $\boxed{P/2}$. Hence, the correct option is (D).

Quick Tip to Solve: A perpendicular cut through an equiconvex lens replaces one curved face of each half by a plane face.

30(iii). The above two parts are kept in contact with each other as shown in the figure. The power of the combination will be:

[1 mark]



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

Correct Answer: (B) P

Solution:

Concept:

- Thin lenses placed in contact have equivalent power $P_{\text{eq}} = P_1 + P_2$, where each power retains its algebraic sign.
- Each plano-convex half of the original equiconvex lens has power $P/2$. Reversing a converging lens does not make its power negative.

Step 1: Read the arrangement in the figure The curved faces of the two plano-convex parts face one another, while the outer faces are plane. Each glass piece remains a converging lens in air. The central gap should not be mistaken for a concave glass lens: it is the two glass lenses whose powers must be added.

Step 2: Add the two positive powers Using the thin-lens contact approximation specified by the passage,

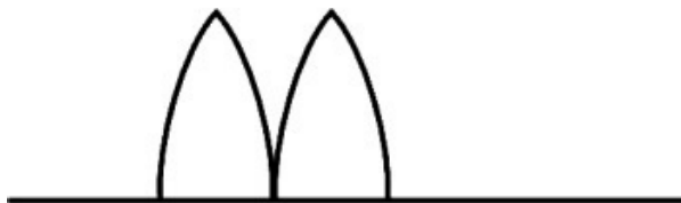
$$P_{\text{eq}} = \frac{P}{2} + \frac{P}{2}.$$

Option (A) counts just one part. Option (C) treats each part as retaining the full original power, and option (D) incorrectly halves the power a second time.

Step 3: Conclusion The combination has power $P_{\text{eq}} = P$. Hence, the correct option is (B).

Quick Tip to Solve: Add the positive powers of the actual glass pieces; an air gap drawn between them is not a concave glass lens.

30(iv)(a). A double-convex lens of power P , with each face having same radius of curvature, is cut along its principal axis. The two parts are arranged as shown in the figure. The power of the combination will be: [1 mark]



(A) Zero

(B) P

(C) $2P$

(D) $\frac{P}{2}$

Correct Answer: (C) $2P$

Solution:

Concept:

- The power $P = (n - 1)(1/R_1 - 1/R_2)$ of a thin lens depends on its surface curvatures and refractive index, not its aperture.
- When two thin lenses act successively in contact, their powers add: $P_{eq} = P_1 + P_2$.

Step 1: Determine the power of each axial half Cutting along the principal axis reduces the aperture but leaves both curved refracting surfaces of each half with their original radii. For rays passing through either half parallel to the original axis, its focal length therefore remains f , and its power remains $P = 1/f$. This differs from a perpendicular cut, which produces plano-convex lenses.

Step 2: Apply the contact-lens rule The figure places the two axial halves successively in the direction of light travel. Each contributes the same positive converging power, giving

$$P_{eq} = P + P.$$

Zero would require cancellation by a negative power. The option P counts only one half, while $P/2$ incorrectly treats reduced aperture as reduced power.

Step 3: Conclusion The power of the combination is $2P$. Hence, the correct option is (C).

Quick Tip to Solve: For a cut along the axis, retain each half's original power; then count how many halves a ray traverses successively.

30(iv)(b). Two convex lenses of focal lengths 60 cm and 20 cm are held coaxially in contact with each other. The power of the combination is: [1 mark]

- (A) 6.6 D
 (B) 15 D
 (C) $\frac{1}{15}$ D
 (D) $\frac{1}{80}$ D

Correct Answer: (A) 6.6 D

Solution:

Concept:

- The power of a lens is $P = 1/f$, measured in dioptres (D) when focal length f is expressed in metres.
- For two thin lenses held coaxially in contact, powers add: $P_{eq} = 1/f_1 + 1/f_2$. Both convex lenses have positive power.

Step 1: Convert the focal lengths to metres The given focal lengths are $f_1 = 60 \text{ cm} = 0.60 \text{ m}$ and $f_2 = 20 \text{ cm} = 0.20 \text{ m}$. Their individual powers are therefore

$$P_1 = \frac{1}{0.60} = \frac{5}{3} \text{ D}, \quad P_2 = \frac{1}{0.20} = 5 \text{ D}.$$

Step 2: Calculate the equivalent power and compare Adding the powers gives

$$P_{eq} = \frac{5}{3} + 5 = \frac{20}{3} \text{ D} = 6.666 \dots \text{ D}.$$

The printed 6.6 D is the intended approximate choice (the value rounded to one decimal place would be 6.7 D). The equivalent focal length is 15 cm, not a power of 15 D. Option (C) omits the conversion from centimetres, and option (D) incorrectly uses the sum of focal lengths in centimetres.

Step 3: Conclusion The power is $\frac{20}{3} \text{ D}$, corresponding to the printed approximate value 6.6 D. Hence, the correct option is (A).

Quick Tip to Solve: With focal lengths in centimetres, compute the combined power directly as $100/60 + 100/20$ dioptres.

Section E (15 marks)

31(a). (i) A ray of light passes through a triangular prism. Show graphically, how the angle of deviation varies with the angle of incidence? Hence define the angle of minimum deviation.

(ii) A ray of light is incident normally on a refracting face of a prism of prism angle A and suffers a deviation of angle δ . Prove that the refractive index n of the material of the prism is given by

$$n = \frac{\sin(A + \delta)}{\sin A}.$$

(iii) The refractive index of the material of a prism is $\sqrt{2}$. If the refracting angle of the prism is 60° , find the:

(1) Angle of minimum deviation, and

(2) Angle of incidence.

[5 marks]

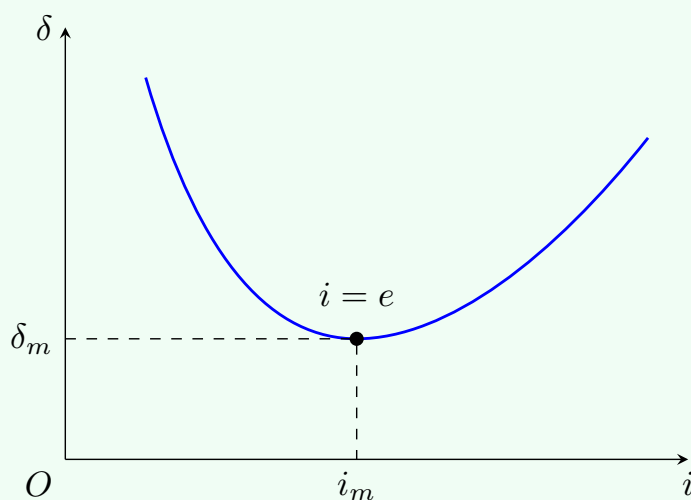
Solution:

Concept:

- For a prism in air, $r_1 + r_2 = A$ and $\delta = i + e - A$, where A is the prism angle, i and e are the incidence and emergence angles, and r_1, r_2 are the internal refraction angles. All ray angles are measured from the corresponding normal.
- Snell's law at entry and exit gives $\sin i = n \sin r_1$ and $n \sin r_2 = \sin e$, with n the refractive index of the prism relative to air.
- At minimum deviation δ_m , the path is symmetric: $i = e$, $r_1 = r_2 = A/2$, and $n = \frac{\sin[(A + \delta_m)/2]}{\sin(A/2)}$.

Step 1: (i) Plot deviation against incidence and identify its minimum For a fixed prism and a fixed wavelength, plot the angle of incidence i on the horizontal axis and the angle of deviation δ on the vertical axis. Over the range in which the ray emerges through the second refracting face, deviation first decreases as incidence increases, reaches a minimum, and then increases. The smooth curve below is schematic; the marked lowest point corresponds to the symmetric ray path.

The angle of minimum deviation δ_m is the least angle through which the prism deviates the ray, obtained by varying the angle of incidence. At this position, the incident and emergent rays make equal angles with their respective normals, so $i = e = i_m$ and $\delta_m = 2i_m - A$.



Schematic variation of deviation with incidence; the lowest point is minimum deviation.

Step 2: (ii) Apply normal incidence and the prism geometry Here the incident ray is normal to the first refracting face, so $i = 0$. Snell's law gives $\sin r_1 = 0$, hence $r_1 = 0$: there is no bending at entry.

The internal prism-angle relation therefore gives

$$r_1 + r_2 = A \Rightarrow r_2 = A.$$

The total deviation relation now becomes

$$\delta = 0 + e - A \Rightarrow e = A + \delta.$$

Applying Snell's law from prism to air at the second face,

$$n \sin r_2 = \sin e \Rightarrow n \sin A = \sin(A + \delta).$$

Dividing by $\sin A$ proves the required expression. This derivation refers to the normally incident ray in part (ii); it does not assume minimum deviation.

Step 3: (iii)(1) Calculate the minimum deviation With $n = \sqrt{2}$ and $A = 60^\circ$, use the minimum-deviation relation for the symmetric path:

$$\begin{aligned} \sin\left(\frac{A + \delta_m}{2}\right) &= n \sin \frac{A}{2} \\ &= \sqrt{2} \sin 30^\circ = \frac{1}{\sqrt{2}}. \end{aligned}$$

The angle $(A + \delta_m)/2$ is the physical incidence angle, between 0° and 90° ; therefore it is 45° , rather than the other mathematical sine solution. Thus $60^\circ + \delta_m = 90^\circ$.

Step 4: (iii)(2) Find the corresponding incidence angle The requested incidence angle is the angle at the minimum-deviation position. At that position, $r_1 = A/2 = 30^\circ$, so the entry-face law independently gives

$$\sin i_m = n \sin r_1 = \sqrt{2} \times \frac{1}{2} = \frac{1}{\sqrt{2}}.$$

Hence the physical incidence angle is 45° , in agreement with $i_m = (A + \delta_m)/2$. The emergence angle equals this incidence angle, which checks the symmetry condition used in the calculation.

Step 5: Conclusion (i) The deviation–incidence graph has a minimum δ_m , the least deviation produced by the prism for the chosen wavelength. (ii) For normal incidence, $n = \frac{\sin(A + \delta)}{\sin A}$. (iii) $\delta_m = 30^\circ$ and the corresponding $i_m = 45^\circ$.

Quick Tip to Solve: Keep the two ray conditions separate: normal incidence gives $r_1 = 0$, whereas minimum deviation gives $r_1 = r_2 = A/2$ and $i = e$.

31(b). (i) State Huygens' principle. A plane wave is incident at an angle i on a reflecting surface. Construct the corresponding reflected wavefront. Using this diagram, prove that the angle of reflection is equal to the angle of incidence.

(ii) What are the coherent sources of light? Can two independent sodium lamps act like coherent sources? Explain.

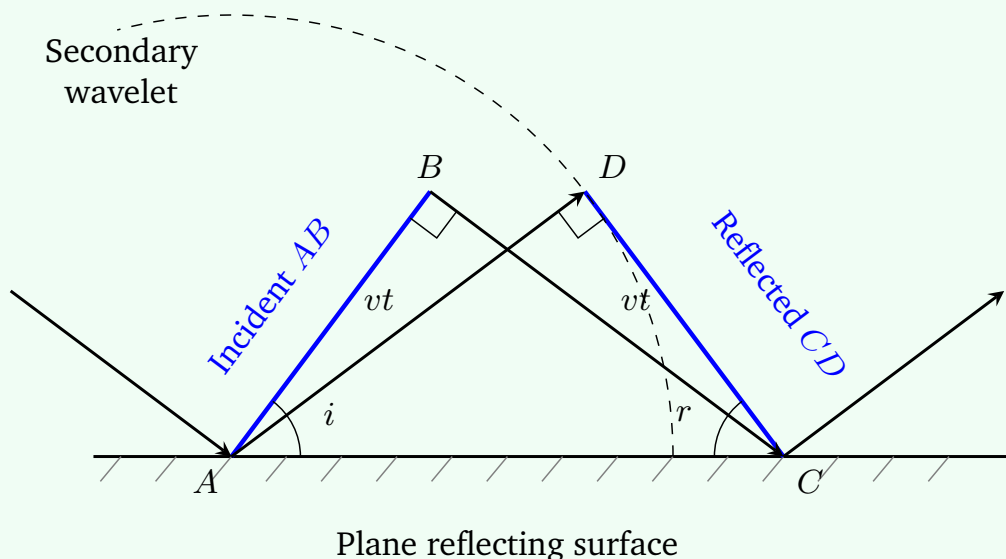
(iii) A beam of light consisting of a known wavelength 520 nm and an unknown wavelength λ , used in Young's double slit experiment produces two interference patterns such that the fourth bright fringe of unknown wavelength coincides with the fifth bright fringe of known wavelength. Find the value of λ . [5 marks]

Solution:

Concept:

- Huygens' principle: every point on a wavefront acts as a source of secondary wavelets, which spread with the speed of light in that medium. Their forward common envelope gives the new wavefront.
- A light ray is normal to its wavefront. During reflection the incident and reflected disturbances travel in the same medium, with the same speed v .
- Coherent sources emit waves of the same frequency with a constant phase difference. In Young's experiment the position of bright fringe of order m is $y_m = m\lambda D/d$, where D is screen distance and d is slit separation.

Step 1: (i) Construct the reflected wavefront Let the plane incident wavefront AB first touch the plane reflecting surface at A . The ray from B , perpendicular to AB , reaches the surface at C after time t , so $BC = vt$. In the same time, the secondary wavelet centred at A has radius $AD = vt$. Draw the tangent CD from C to this wavelet. This common envelope is the reflected plane wavefront; the reflected rays are perpendicular to CD . In the diagram $AB \perp BC$ and $AD \perp CD$.



Huygens construction: AB is incident, CD is reflected, and $BC = AD = vt$.

Step 2: Prove the law of reflection from the construction The angle between the incident ray and the surface normal equals the angle between incident wavefront AB and the surface AC ; hence $\angle BAC = i$. Similarly, $\angle ACD = r$, because reflected rays are perpendicular to CD . The two right

triangles ABC and ADC share hypotenuse AC , and have equal sides $BC = AD = vt$. Equivalently,

$$\sin i = \frac{BC}{AC} = \frac{vt}{AC}, \quad \sin r = \frac{AD}{AC} = \frac{vt}{AC}.$$

Thus $\sin i = \sin r$. Since the physical angles of incidence and reflection lie between 0° and 90° , this gives $i = r$. The construction lies in the plane of the incident ray and the normal.

Step 3: (ii) Test whether independent sodium lamps are coherent Coherent light sources must have the same frequency and maintain a constant phase difference. Two independent sodium lamps cannot act as coherent sources for a sustained interference pattern. Their atoms emit separate wave trains at random times, so the relative phase varies rapidly and randomly, even when the dominant wavelengths are the same. The interference term averages to zero during observation and no stable fringes remain. Coherent beams are therefore normally obtained by splitting light from a single source.

Step 4: (iii) Equate the positions of the coinciding bright fringes Measure fringe order from the common central maximum. Both patterns have the same D and d , so coincidence of the fourth bright fringe of the unknown wavelength with the fifth bright fringe of 520 nm gives

$$\begin{aligned} \frac{4\lambda D}{d} &= \frac{5(520 \text{ nm})D}{d}, \\ 4\lambda &= 2600 \text{ nm}, \\ \lambda &= 650 \text{ nm}. \end{aligned}$$

The longer wavelength has the larger fringe spacing, so its smaller order can coincide with a higher order of the known wavelength, consistent with the result.

Step 5: Conclusion The Huygens construction gives the reflected wavefront CD and proves $r = i$. Coherent sources have the same frequency and a constant phase difference; independent sodium lamps do not meet the phase condition. The unknown wavelength is 650 nm.

Quick Tip to Solve: For coinciding bright fringes equate order times wavelength. For the reflection proof use the equal distances $BC = AD = vt$ in the two right triangles sharing AC .

32(a). (i) Derive an expression for potential energy of an electric dipole $\vec{p}$ in an external uniform electric field $\vec{E}$. When is the potential energy of the dipole (1) maximum, and (2) minimum?

(ii) An electric dipole consists of point charges -1.0 pC and $+1.0 \text{ pC}$ located at $(0, 0)$ and $(3 \text{ mm}, 4 \text{ mm})$ respectively in $x - y$ plane. An electric field $\vec{E} = \left(\frac{1000 \text{ V}}{\text{m}}\right) \hat{i}$ is switched on in the region. Find the torque $\vec{\tau}$ acting on the dipole. [5 marks]

Solution:

Concept:

- The dipole moment is $\vec{p} = q(\vec{r}_+ - \vec{r}_-)$, directed from the negative charge to the positive charge. Here q is the magnitude of either charge.
- A uniform electric field exerts a couple on a dipole: $\vec{\tau} = \vec{p} \times \vec{E}$, with magnitude $pE \sin \theta$, where θ is the angle between $\vec{p}$ and $\vec{E}$.
- The increase in potential energy equals the work done by an external agent in rotating the dipole slowly against the electric torque. Choose $U = 0$ at $\theta = \pi/2$.

Step 1: (i) Calculate the work in rotating the dipole The electric torque tends to align the dipole with the field, reducing θ . For a slow rotation that increases θ , an external agent must apply an equal opposing torque. Taking the direction of increasing θ as positive, $\tau_{\text{ext}} = pE \sin \theta$. The infinitesimal work is therefore

$$dW_{\text{ext}} = pE \sin \theta d\theta = dU.$$

Integrate from the reference orientation $\pi/2$ to the desired orientation:

$$\begin{aligned} U(\theta) - U(\pi/2) &= \int_{\pi/2}^{\theta} pE \sin \theta' d\theta', \\ U(\theta) &= pE[-\cos \theta']_{\pi/2}^{\theta}, \\ U(\theta) &= -pE \cos \theta = -\vec{p} \cdot \vec{E}. \end{aligned}$$

An arbitrary reference choice could add a constant; the stated expression uses zero potential energy when the dipole is perpendicular to the field.

Step 2: Identify maximum and minimum potential energy Since $-1 \leq \cos \theta \leq 1$, the maximum potential energy is $U_{\text{max}} = +pE$, at $\theta = \pi$ or 180° : the dipole moment is antiparallel to the field. This is unstable equilibrium, because a small rotation lets the electric torque turn it farther away from that orientation. The minimum is $U_{\text{min}} = -pE$, at $\theta = 0$: the dipole is parallel to the field. This is stable equilibrium, because a small displacement produces a restoring torque. The torque is zero at both extrema, but their stability differs.

Step 3: (ii) Express the given dipole moment in SI units The charge separation vector points from $(0, 0)$ to $(3 \text{ mm}, 4 \text{ mm})$. Convert picocoulombs and millimetres before multiplying:

$$\begin{aligned} q &= 1.0 \times 10^{-12} \text{ C}, \\ \vec{r}_+ - \vec{r}_- &= (3\hat{i} + 4\hat{j}) \times 10^{-3} \text{ m}, \\ \vec{p} &= (3\hat{i} + 4\hat{j}) \times 10^{-15} \text{ C m}. \end{aligned}$$

The field printed in the question is $\vec{E} = 1000\hat{i} \text{ V m}^{-1} = 10^3\hat{i} \text{ N C}^{-1}$. Only the component of $\vec{p}$ perpendicular to this field contributes to the torque.

Step 4: Evaluate the vector torque and its direction Using $\hat{i} \times \hat{i} = 0$ and $\hat{j} \times \hat{i} = -\hat{k}$,

$$\begin{aligned} \vec{\tau} &= \vec{p} \times \vec{E}, \\ &= [(3\hat{i} + 4\hat{j}) \times 10^{-15}] \times (10^3\hat{i}), \\ &= -4.0 \times 10^{-12}\hat{k} \text{ N m}. \end{aligned}$$

Thus the torque points along the negative z -axis, into the $x - y$ plane as viewed from positive z . It rotates the dipole clockwise towards the positive x -direction. As a direct check, the force on the positive charge is $10^{-9}\hat{i} \text{ N}$, acting at vertical distance $4 \times 10^{-3} \text{ m}$, and hence has the same clockwise moment of magnitude $4 \times 10^{-12} \text{ N m}$.

Step 5: Conclusion With $U = 0$ at 90° , $U = -\vec{p} \cdot \vec{E} = -pE \cos \theta$. It is maximum ($+pE$) for antiparallel alignment and minimum ($-pE$) for parallel alignment. The given dipole experiences $\vec{\tau} = -4.0 \times 10^{-12}\hat{k} \text{ N m}$.

Quick Tip to Solve: Draw $\vec{p}$ from minus to plus, convert both pC and mm, then use $\hat{j} \times \hat{i} = -\hat{k}$. A field along x makes only the dipole's y -component contribute here.

32(b). (i) An electric dipole (dipole moment $\vec{p} = p\hat{i}$), consisting of charges $-q$ and q , separated by distance $2a$, is placed along the x-axis, with its centre at the origin. Show that the potential V , due to this dipole, at a point x , ($x \gg a$) is equal to $\frac{1}{4\pi\epsilon_0} \cdot \frac{\vec{p} \cdot \hat{i}}{x^2}$.

(ii) Two isolated metallic spheres S_1 and S_2 of radii 1 cm and 3 cm respectively are charged such that both have the same charge density $\left(\frac{2}{\pi} \times 10^{-9}\right) \text{ C/m}^2$. They are placed far away from each other and connected by a thin wire. Calculate the new charge on sphere S_1 . [5 marks]

Solution:

Concept:

- Electric potential is a scalar sum: a point charge q at distance r produces $V = kq/r$, where $k = 1/(4\pi\epsilon_0)$, taking zero potential at infinity.
- The dipole moment points from the negative charge to the positive charge and has magnitude $p = 2aq$. For an axial point far from the dipole, a^2/x^2 is negligible.
- A sphere of radius R and uniform surface charge density σ has charge $Q = 4\pi R^2\sigma$. Far-separated conducting spheres connected by a wire acquire equal potentials, $kQ'_1/R_1 = kQ'_2/R_2$, while total charge is conserved.

Step 1: (i) Add the potentials of the two dipole charges Since $\vec{p} = p\hat{i}$, place $-q$ at $x = -a$ and $+q$ at $x = +a$. The specified point $x \gg a$ lies on the positive axial side. Its distances from the positive and negative charges are $x - a$ and $x + a$, respectively. Therefore,

$$\begin{aligned} V(x) &= k \left(\frac{q}{x-a} - \frac{q}{x+a} \right) \\ &= kq \frac{(x+a) - (x-a)}{(x-a)(x+a)} = \frac{k(2aq)}{x^2 - a^2}. \end{aligned}$$

The minus sign belongs to the negative charge; potentials add algebraically rather than as vectors.

Step 2: (i) Apply the far-field approximation Using $2aq = p$, rewrite the exact axial potential as

$$V(x) = \frac{kp}{x^2} \frac{1}{1 - a^2/x^2}.$$

Since $x \gg a$, the factor $a^2/x^2 \ll 1$, so the denominator can be replaced by unity to leading order. Also, $\vec{p} \cdot \hat{i} = p$. Hence the required far-field expression follows:

$$V(x) \simeq \frac{1}{4\pi\epsilon_0} \frac{\vec{p} \cdot \hat{i}}{x^2}.$$

This is the distant-dipole approximation; the exact expression retains $x^2 - a^2$ in its denominator.

Step 3: (ii) Calculate the initial charge available Convert the radii to SI units: $R_1 = 0.01 \text{ m}$ and $R_2 = 0.03 \text{ m}$. With $\sigma = (2/\pi) \times 10^{-9} \text{ C m}^{-2}$,

$$\begin{aligned} Q_1 &= 4\pi(0.01)^2 \frac{2}{\pi} \times 10^{-9} = 8.0 \times 10^{-13} \text{ C}, \\ Q_2 &= 4\pi(0.03)^2 \frac{2}{\pi} \times 10^{-9} = 7.2 \times 10^{-12} \text{ C}, \\ Q_{\text{total}} &= Q_1 + Q_2 = 8.0 \times 10^{-12} \text{ C}. \end{aligned}$$

The spheres initially have equal charge densities, but unequal potentials, because $V = 4\pi k\sigma R$. Thus charge must flow when they are connected.

Step 4: (ii) Enforce equal final potentials and charge conservation The large separation lets us neglect mutual potential contributions, and the thin wire stores negligible charge. At equilibrium,

$$\frac{Q'_1}{R_1} = \frac{Q'_2}{R_2} \Rightarrow Q'_1 : Q'_2 = 1 : 3.$$

Combining this ratio with $Q'_1 + Q'_2 = Q_{\text{total}}$, the charge on the requested sphere S_1 is

$$Q'_1 = \frac{R_1}{R_1 + R_2} Q_{\text{total}} = \frac{1}{4} (8.0 \times 10^{-12}) = 2.0 \times 10^{-12} \text{ C}.$$

The companion value $Q'_2 = 6.0 \times 10^{-12} \text{ C}$ checks both the total charge and the required ratio.

Step 5: Conclusion (i) For $x \gg a$, $V \simeq (1/4\pi\epsilon_0)(\vec{p} \cdot \hat{i})/x^2$. (ii) The new charge on sphere S_1 is $+2.0 \times 10^{-12} \text{ C}$.

Quick Tip to Solve: Equal initial surface charge densities give charges in the ratio of squared radii; after connection, equal potentials give charges in the ratio of radii. Conserve the total charge between these two states.

33(a). (i) A resistor and a capacitor are connected in series to an ac source $v = v_m \sin \omega t$. Derive an expression for the impedance of the circuit.

(ii) When does an inductor act as a conductor in a circuit? Give reason for it.

(iii) An electric lamp is designed to operate at 110 V dc and 11 A current. If the lamp is operated on 220 V, 50 Hz ac source with a coil in series, then find the inductance of the coil. [5 marks]

Solution:

Concept:

- In a series circuit the same current flows through all elements. A resistor voltage is in phase with current, while a capacitor voltage lags current by $\pi/2$. Capacitive reactance is $X_C = 1/(\omega C)$, with C the capacitance and ω the angular frequency.
- An ideal inductor has reactance $X_L = \omega L = 2\pi fL$, where L is inductance and f is frequency. Its induced emf is $-L di/dt$.
- For a series resistor and ideal inductor, the rms supply voltage obeys $V^2 = (IR)^2 + (IX_L)^2$, since resistive and inductive voltage phasors are perpendicular.

Step 1: (i) Express the resistor and capacitor voltages Take the common current as the phasor reference. If its peak value is I_m , the resistor voltage has peak magnitude $V_{Rm} = I_m R$, along the current phasor. The capacitor voltage has peak magnitude $V_{Cm} = I_m X_C = I_m/(\omega C)$, directed 90° behind current. This follows also from $i = C dv_C/dt$: integration of a sinusoidal current gives a capacitor voltage lagging by a quarter-cycle. The applied voltage is the phasor sum of these two perpendicular voltages.

Step 2: (i) Derive the impedance and phase relation Pythagoras applied to the voltage phasors gives

$$\begin{aligned} v_m^2 &= V_{Rm}^2 + V_{Cm}^2 \\ &= I_m^2 \left[R^2 + \left(\frac{1}{\omega C} \right)^2 \right]. \end{aligned}$$

By definition, the impedance magnitude is the ratio of peak voltage to peak current, equivalently the ratio of their rms values. Therefore,

$$Z = \frac{v_m}{I_m} = \sqrt{R^2 + \frac{1}{\omega^2 C^2}}.$$

The current leads the applied voltage by ϕ , where $\tan \phi = X_C/R = 1/(\omega CR)$. For the given source $v = v_m \sin \omega t$, the current is $i = (v_m/Z) \sin(\omega t + \phi)$. The capacitive phase shift is why resistance and reactance cannot be added arithmetically.

Step 3: (ii) Identify when an inductor behaves as a conductor An ideal inductor acts as a conducting wire in a steady dc circuit, after the switching transient has ended. Then current is constant, so $di/dt = 0$ and its induced emf $-L di/dt$ vanishes. Equivalently, dc has $f = 0$, making $X_L = 2\pi fL = 0$. A real coil still offers its winding resistance. Immediately after switching, the current changes and the inductor does oppose that change, so the steady-state qualification is essential.

Step 4: (iii) Find the lamp resistance and required inductive reactance At its designed operating condition the lamp resistance is

$$R = \frac{110}{11} = 10 \Omega.$$

To operate the lamp at its rating, the ac rms current must be 11 A. Treat the series coil as an ideal inductor with negligible resistance. With the 220 V rms supply, the required total impedance is

$$Z_{RL} = \frac{220}{11} = 20 \Omega.$$

Since $Z_{RL}^2 = R^2 + X_L^2$,

$$X_L = \sqrt{20^2 - 10^2} = 10\sqrt{3} \Omega.$$

In particular, the coil voltage is perpendicular to the lamp voltage in the phasor sum; their magnitudes must not be subtracted directly from the supply voltage.

Step 5: (iii) Calculate the coil inductance Use $X_L = 2\pi fL$ at $f = 50$ Hz:

$$L = \frac{10\sqrt{3}}{2\pi(50)} = \frac{\sqrt{3}}{10\pi} \text{ H} \simeq 5.51 \times 10^{-2} \text{ H}.$$

As a check, the lamp voltage is $IR = 110$ V, and the coil voltage is $IX_L = 110\sqrt{3}$ V. Their quadrature sum is $\sqrt{110^2 + (110\sqrt{3})^2} = 220$ V, equal to the specified supply.

Step 6: Conclusion (i) The series RC impedance is $Z = \sqrt{R^2 + 1/(\omega^2 C^2)}$. (ii) An ideal inductor behaves as a conductor for steady dc because its induced emf and reactance vanish. (iii) The required inductance is $L \simeq 0.0551 \text{ H} = 55.1 \text{ mH}$.

Quick Tip to Solve: Keep RC and RL phasor relations distinct. For the lamp use its rated current, find $Z = V/I$, then obtain $X_L = \sqrt{Z^2 - R^2}$ before dividing by $2\pi f$.

33(b). (i) Draw a labelled diagram of a step-up transformer and describe its working principle. Explain any three causes for energy losses in a real transformer.

(ii) A step-up transformer converts a low voltage into high voltage. Does it violate the principle of conservation of energy? Explain.

(iii) A step-up transformer has 200 and 3000 turns in its primary and secondary coils respectively. The input voltage given to the primary coil is 90 V. Calculate:

(1) The output voltage across the secondary coil

(2) The current in the primary coil if the current in the secondary coil is 2.0 A.

[5 marks]

Solution:

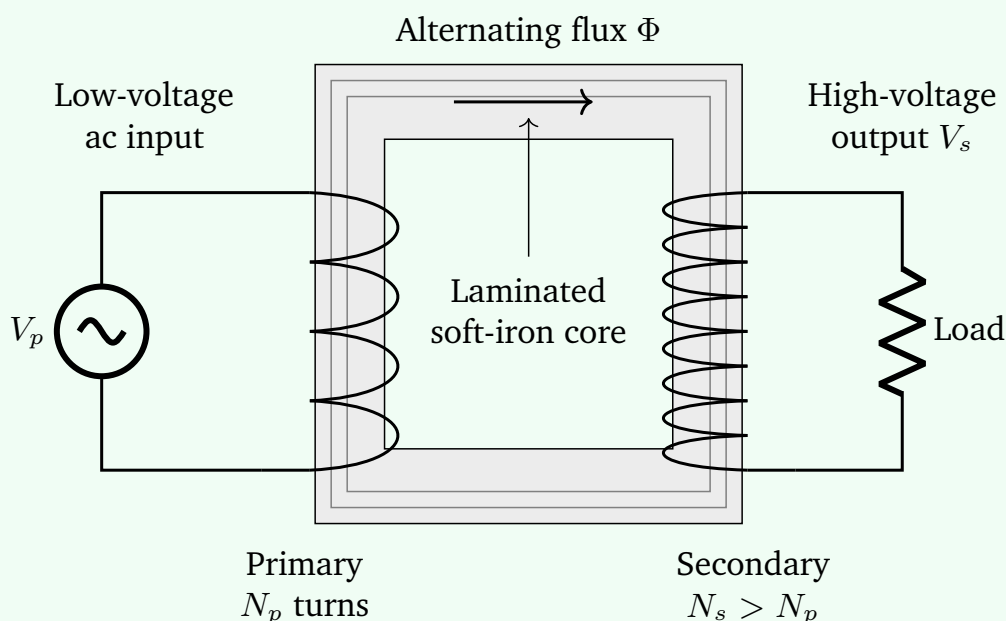
Concept:

- A transformer works by mutual induction: alternating current in the primary produces a changing magnetic flux Φ linking the primary and secondary windings.
- For an ideal transformer, $V_s/V_p = N_s/N_p$, where V is the rms voltage, N is the number of turns, and subscripts p and s denote primary and secondary.
- Conservation of energy gives $V_p I_p = V_s I_s$ for the ideal transformer with a resistive load; thus $I_p/I_s = N_s/N_p$. Real transformers lose some input power as heat.

Step 1: (i) Show the construction and explain mutual induction Two insulated coils are wound on a common laminated soft-iron core. The primary has fewer turns and is connected to the low-voltage ac supply; the secondary has more turns and supplies the load. The coils are electrically insulated from each other but magnetically linked through the core. The labelled schematic below shows $N_s > N_p$. Alternating primary current establishes an alternating flux in the core. The same changing flux links both windings and induces emfs according to Faraday's law:

$$e_p = -N_p \frac{d\Phi}{dt}, \quad e_s = -N_s \frac{d\Phi}{dt}.$$

Hence $e_s/e_p = N_s/N_p$. Neglecting winding resistance and flux leakage, the rms terminal voltages satisfy $V_s/V_p = N_s/N_p$. More secondary turns therefore give a higher secondary voltage. A steady dc input does not provide the continuously changing flux needed for normal transformer action.



Step-up transformer schematic: the secondary has more turns than the primary; both windings link the common core flux.

Step 2: (i) Explain three energy losses in a real transformer **Copper loss:** Both windings have resistance, so currents heat them at a rate $I_p^2 R_p + I_s^2 R_s$. Thick, low-resistance copper wire reduces this loss.

Eddy-current loss: The changing flux induces circulating currents within the conducting iron core; their resistance causes heating. Thin core laminations insulated from one another increase the resistance of these current paths and reduce the loss.

Hysteresis loss: Repeated reversal of the core's magnetisation consumes energy during each ac cycle, which appears as heat. A soft magnetic material with a narrow hysteresis loop reduces this loss.

Step 3: (ii) Apply conservation of energy Stepping up the voltage does not create energy. In an ideal transformer, output power equals input power:

$$V_p I_p = V_s I_s, \quad \frac{I_s}{I_p} = \frac{V_p}{V_s} = \frac{N_p}{N_s}.$$

The increase in voltage is accompanied by a corresponding decrease in current. In a real transformer, output power is less than input power because the difference is dissipated in the losses described above. Thus energy conservation is obeyed in both cases.

Step 4: (iii)(1) Calculate the secondary voltage Since no efficiency or winding losses are specified for the numerical part, use the ideal-transformer approximation. The turns ratio is

$$k = \frac{N_s}{N_p} = \frac{3000}{200} = 15.$$

Substituting $V_p = 90 \text{ V}$,

$$V_s = k V_p = 15 \times 90 = 1350 \text{ V}.$$

Step 5: (iii)(2) Calculate the primary current For $I_s = 2.0 \text{ A}$, the inverse voltage-current relation gives

$$I_p = \frac{V_s}{V_p} I_s = 15 \times 2.0 = 30 \text{ A}.$$

As a check, $P_{\text{in}} = 90 \times 30 = 2700 \text{ W}$, while $P_{\text{out}} = 1350 \times 2.0 = 2700 \text{ W}$. The equal powers confirm that the high secondary voltage is balanced by a smaller secondary current.

Step 6: Conclusion A step-up transformer uses mutual induction with $N_s > N_p$. Copper, eddy-current and hysteresis losses reduce its real efficiency. It obeys energy conservation; ideally, the given transformer has $V_s = 1350 \text{ V}$ and $I_p = 30 \text{ A}$.

Quick Tip to Solve: First find the turns ratio: here it is 15. Multiply the primary voltage by 15, but divide the primary current by 15 to obtain the secondary current.