

CBSE Class 12 Physics Question Paper 2025 with Solution PDF-Set 55/6/1



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 :

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

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

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

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

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

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

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

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

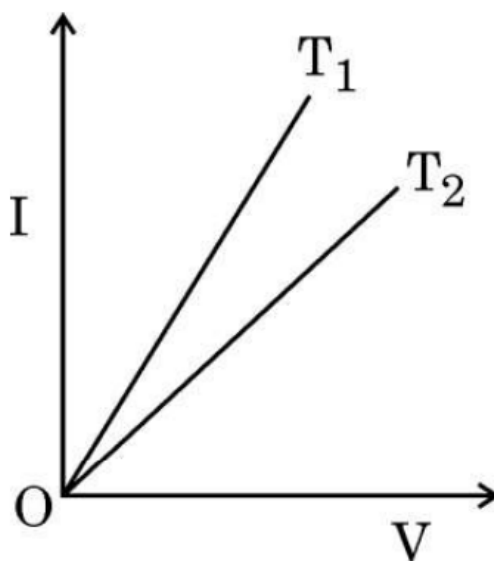
$$\text{Mass of proton} = 1.673 \times 10^{-27} \text{ kg}$$

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

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

Section A (16 marks)

1. The figure shows the voltage (V) versus the current (I) graphs for a wire at two temperatures T_1 and T_2 . One can conclude that: [1 mark]



- (A) $T_2 = 2T_1$
(B) $T_1 > T_2$
(C) $T_1 = T_2/3$
(D) $T_1 < T_2$

Correct Answer: (D) $T_1 < T_2$

Solution:

Concept:

- Ohm's law is $V = IR$, where R is resistance. For a graph with current on the vertical axis and voltage on the horizontal axis, the slope is $I/V = 1/R$.
- The resistance of an ordinary metallic wire increases with temperature, so a larger conductance $1/R$ means a lower temperature.

Step 1: Read the axes and compare slopes The printed graph has I vertically and V horizontally. The line labelled T_1 is steeper than the line labelled T_2 . Thus $1/R_1 > 1/R_2$, giving $R_1 < R_2$. Reading the slope as resistance would incorrectly reverse this comparison.

Step 2: Relate resistance to temperature For the same metallic wire, the smaller resistance corresponds to the lower temperature. The sketch gives no calibrated slopes or temperature coefficient, so exact temperature ratios in options (A) and (C) cannot be inferred. Option (B) reverses the temperature ordering.

Step 3: Conclusion $T_1 < T_2$. Hence, the correct option is (D).

Quick Tip to Solve: Check the axes first: an I -versus- V graph has slope $1/R$, so the steeper line represents the cooler metallic wire.

2. If R_s and R_p are the equivalent resistances of n resistors, each of value R , in series and parallel combinations respectively, then the value of $(R_s - R_p)$ is: [1 mark]

(A) $\left(\frac{n^2 - 1}{n^2}\right) R$

(B) $\left(\frac{n^2 + 1}{n^2 - 1}\right) R$

(C) $\left(\frac{n^2 - 1}{n}\right) R$

(D) $\frac{(n^2 + 1)R}{n^2}$

Correct Answer: (C) $\left(\frac{n^2 - 1}{n}\right) R$

Solution:

Concept:

- Series resistances add directly: for n equal resistors, each of resistance R , $R_s = nR$.
- Parallel conductances add: $1/R_p = n/R$, so the parallel equivalent resistance is $R_p = R/n$.

Step 1: Write the two equivalent resistances In series the same current passes through every resistor and the voltage drops add, giving $R_s = nR$. In parallel the voltage across each branch is the same and the currents add, giving $R_p = R/n$.

Step 2: Subtract with a common denominator Substitute both results and collect the terms over the denominator n :

$$R_s - R_p = nR - \frac{R}{n} = \frac{(n^2 - 1)R}{n}.$$

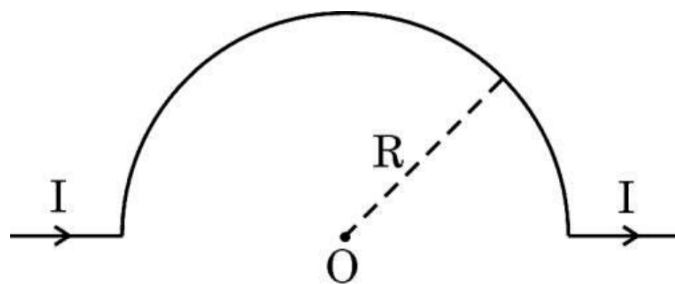
Option (A) introduces an extra factor of n in the denominator. Options (B) and (D) contain $n^2 + 1$, although a difference requires subtraction. For $n = 1$, the difference must vanish, as this expression does.

Step 3: Conclusion $R_s - R_p = \frac{n^2 - 1}{n} R$. Hence, the correct option is (C).

Quick Tip to Solve: Write nR and R/n first, then subtract; the single-resistor check $n = 1$ must give zero.

3. The value of magnetic field at point O in the given figure is:

[1 mark]



- (A) $\frac{\mu_0 I}{2\pi R}$
(B) $\frac{\mu_0 I}{\pi R}$
(C) $\frac{\mu_0 I}{4R}$
(D) $\frac{\mu_0 I}{R}$

Correct Answer: (C) $\frac{\mu_0 I}{4R}$

Solution:

Concept:

- By the Biot–Savart law, a current element contributes a field proportional to $I d\ell \sin \theta / r^2$, where θ is the angle between the element and its displacement toward the observation point.
- A circular arc of radius R , carrying current I and subtending angle ϕ radians at its centre, produces $B = \mu_0 I \phi / (4\pi R)$.

Step 1: Examine the straight portions The two straight wire portions lie along the diameter through O . For each element of either straight portion, the displacement to O is parallel or antiparallel to the current element. Hence $\sin \theta = 0$, and these portions produce no magnetic field at O .

Step 2: Evaluate the semicircular contribution The curved portion is a semicircle, so its angle is $\phi = \pi$. Its field magnitude is

$$B = \frac{\mu_0 I}{4\pi R} \pi = \frac{\mu_0 I}{4R}.$$

Current flows clockwise along the upper arc; the right-hand rule gives a field into the page. The other options use incorrect numerical factors for this semicircle; no extra field from the radial straight parts should be added.

Step 3: Conclusion The field magnitude at O is $\frac{\mu_0 I}{4R}$, directed into the page. Hence, the correct option is (C).

Quick Tip to Solve: At an arc's centre, discard radial straight segments and multiply the full-circle field by the fraction of a complete circle.

4. A piece of a diamagnetic material, free to move when placed in a uniform magnetic field: [1 mark]

- (A) moves along the field
- (B) moves opposite to the field
- (C) moves perpendicular to the field
- (D) does not move at all

Correct Answer: (D) does not move at all

Solution:

Concept:

- A diamagnetic material develops an induced magnetisation opposite to the applied magnetic field; its magnetic susceptibility χ is negative.
- Translational magnetic force requires spatial variation of the field. For a small linear material sample of volume $\mathcal{V}$, $\vec{F}$ is proportional to $\chi \mathcal{V} \vec{\nabla}(B^2)$.

Step 1: Identify the field condition The question explicitly specifies a uniform magnetic field. Its magnitude and direction are the same throughout the region, so there is no field gradient to produce a net translational force on the sample.

Step 2: Distinguish magnetisation from motion Magnetisation opposite to the applied field does not mean that the whole material moves opposite to the field. Diamagnetic material moves from stronger toward weaker field only in a non-uniform field. Here there is no preferred translational direction, excluding motion along, opposite to, or perpendicular to the field as in (A), (B), and (C).

Step 3: Conclusion The piece does not move under a net magnetic translational force in the uniform field. Hence, the correct option is (D).

Quick Tip to Solve: Before applying the rule that diamagnets move toward weaker fields, check whether the field is non-uniform; a uniform field supplies no such force.

5. A galvanometer can be converted into an ammeter of desired range by connecting a: [1 mark]

- (A) small resistance in series
- (B) large resistance in series
- (C) small resistance in parallel
- (D) large resistance in parallel

Correct Answer: (C) small resistance in parallel

Solution:

Concept:

- A galvanometer is sensitive to small currents and has a maximum safe full-scale current I_g , with coil resistance G .
- An ammeter uses a low resistance shunt S in parallel with the galvanometer to divert most of the measured current around the coil.

Step 1: Provide a parallel bypass Let the required current range be I . At full scale the galvanometer carries I_g , while the shunt carries $I - I_g$. The parallel branches have equal potential differences, so

$$I_g G = (I - I_g) S, \quad S = \frac{I_g G}{I - I_g}.$$

A small shunt resistance allows most of the total current to bypass the delicate galvanometer coil.

Step 2: Check the other connections A series resistance carries the same current as the coil and therefore cannot protect it by dividing current, ruling out (A) and (B). A large series resistance is used for a voltmeter. A large parallel resistance in (D) diverts too little current and does not provide the required low resistance ammeter connection.

Step 3: Conclusion Connect a small resistance in parallel with the galvanometer. Hence, the correct option is (C).

Quick Tip to Solve: For an ammeter, provide a low resistance parallel bypass; for a voltmeter, add a high resistance in series.

6. A proton and an α -particle enter with the same velocity $\vec{v}$ in a uniform magnetic field $\vec{B}$ such that $\vec{v} \perp \vec{B}$. The ratio of the radii of their paths is: [1 mark]

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

Correct Answer: (B) $\frac{1}{2}$

Solution:

Concept:

- For velocity perpendicular to a uniform magnetic field, the magnetic force supplies centripetal force: $qvB = mv^2/r$, so $r = mv/(qB)$.
- A proton has mass m_p and charge e . An alpha particle has approximately mass $4m_p$ and charge $2e$.

Step 1: Compare the mass-to-charge ratios The particles enter the same field with the same speed, so v and B cancel in the ratio. Therefore the radius is proportional to m/q , rather than to mass alone or to inverse charge alone.

Step 2: Form the ratio in the stated order Taking proton radius first and alpha-particle radius second gives

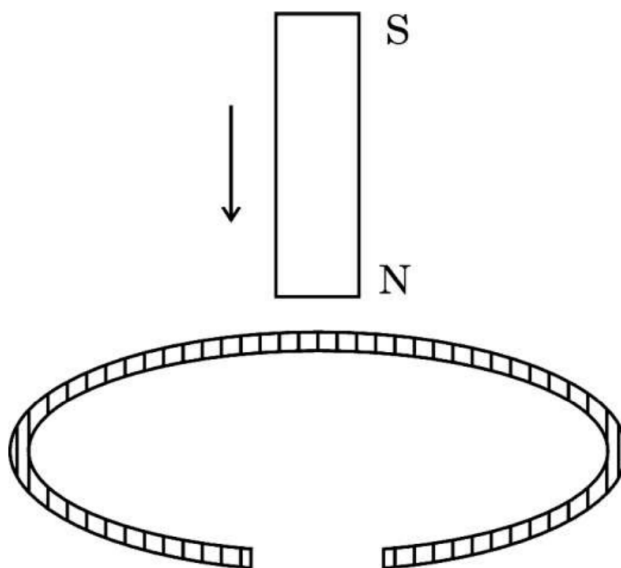
$$\frac{r_p}{r_\alpha} = \frac{m_p/e}{4m_p/(2e)} = \frac{1}{2}.$$

Option (A) is the reversed ratio. Option (C) compares only masses while ignoring the doubled alpha-particle charge; option (D) likewise cannot follow from the required mass-to-charge comparison.

Step 3: Conclusion The ratio of the proton's radius to the alpha particle's radius is $\frac{1}{2}$. Hence, the correct option is (B).

Quick Tip to Solve: For equal speeds in the same perpendicular magnetic field, compare m/q ; an alpha particle has twice the proton's mass-to-charge ratio.

7. A vertically held bar magnet is dropped along the axis of a copper ring having a cut as shown in the diagram. The acceleration of the falling magnet is: [1 mark]



- (A) zero
- (B) less than g
- (C) g
- (D) greater than g

Correct Answer: (C) g

Solution:

Concept:

- Faraday's law predicts an induced emf when the magnetic flux linked with a loop changes. A sustained current around the loop also requires a closed conducting path.
- Lenz's law makes the magnetic effect of an induced current oppose the change producing it. Magnetic braking of a falling magnet by a ring requires such a current.

Step 1: Notice the cut in the ring As the bar magnet falls toward the copper ring, the flux through the ring changes and an emf is induced. However, the cut breaks the conducting path, so no circulating current can flow around the ring in the ideal circuit model used here.

Step 2: Identify the force on the magnet Without a circulating induced current there is no opposing magnetic braking force from the ring. Neglecting air resistance, the only force responsible for the fall is its weight, so $ma = mg$. Acceleration below g , option (B), would apply to braking by a closed ring. There is neither a balancing upward force for (A) nor an additional downward force for (D).

Step 3: Conclusion The magnet falls with acceleration $a = g$, vertically downward. Hence, the correct option is (C).

Quick Tip to Solve: Before invoking Lenz's law to slow a falling magnet, check that the metal ring forms a closed path; a cut interrupts the circulating current.

8. An ac source is connected to a resistor and an inductor in series. The voltage across the resistor and inductor are 8 V and 6 V respectively. The voltage of the source is: [1 mark]

- (A) 10 V
- (B) 12 V
- (C) 14 V
- (D) 16 V

Correct Answer: (A) 10 V

Solution:

Concept:

- In a series resistor-inductor circuit, the same alternating current flows through both components.
- The resistor voltage V_R is in phase with the current, while the ideal inductor voltage V_L leads it by 90° . Thus $V = \sqrt{V_R^2 + V_L^2}$.

Step 1: Add the voltage phasors The two given voltages are perpendicular phasors, so their magnitudes cannot be added arithmetically. The source voltage is the magnitude of their vector sum, with $V_R = 8$ V and $V_L = 6$ V.

Step 2: Evaluate the resultant

$$V = \sqrt{8^2 + 6^2} = \sqrt{100} = 10 \text{ V.}$$

The value 14 V would apply to in-phase voltages and is therefore incorrect here. Neither 12 V nor 16 V satisfies the phasor relation.

Step 3: Conclusion The source voltage is 10 V. Hence, the correct option is (A).

Quick Tip to Solve: Recognise the scaled 3-4-5 triangle: perpendicular voltages of 6 V and 8 V give a resultant of 10 V.

9. Two coherent waves, each of intensity I_0 , produce interference pattern on a screen. The average intensity of light on the screen is: [1 mark]

- (A) zero
- (B) I_0
- (C) $2I_0$
- (D) $4I_0$

Correct Answer: (C) $2I_0$

Solution:

Concept:

- For two coherent waves, $I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \delta$, where δ is their phase difference at a point.
- Across a complete interference fringe cycle, the spatial average of $\cos \delta$ is zero; interference redistributes light energy.

Step 1: Write the intensity distribution Each wave has intensity I_0 . Substituting $I_1 = I_2 = I_0$, the intensity at a point is

$$I = 2I_0(1 + \cos \delta).$$

It ranges from zero at a dark fringe to $4I_0$ at a bright fringe.

Step 2: Average over the fringe pattern Over complete bright-dark fringe cycles, the positive and negative contributions of the cosine cancel:

$$\langle I \rangle = 2I_0(1 + \langle \cos \delta \rangle) = 2I_0.$$

Zero and $4I_0$ are the minimum and maximum, not the average; I_0 counts only one of the two incident waves.

Step 3: Conclusion The average intensity is $2I_0$. Hence, the correct option is (C).

Quick Tip to Solve: For equal coherent beams, distinguish the maximum $4I_0$ from the spatial average $2I_0$.

10. The work function of a material is 2.21 eV. Which of the following cannot produce photoelectrons from it? [1 mark]

- (A) Red light
- (B) Blue light
- (C) Violet light
- (D) Green light

Correct Answer: (A) Red light

Solution:

Concept:

- Photoelectric emission requires photon energy $E = h\nu = hc/\lambda$ to be at least the work function ϕ .
- The threshold wavelength is $\lambda_0 = hc/\phi$; photons with longer wavelengths cannot eject electrons, regardless of light intensity.

Step 1: Calculate the threshold wavelength Using $hc \simeq 1240 \text{ eV nm}$ and $\phi = 2.21 \text{ eV}$,

$$\lambda_0 = \frac{1240}{2.21} \text{ nm} \simeq 561 \text{ nm}.$$

Thus emission requires light of wavelength at most approximately 561 nm.

Step 2: Compare the listed colours Red light has a wavelength greater than this threshold, so its photons have insufficient energy. Blue and violet light have shorter wavelengths and can cause emission. Green light near its representative wavelength 550 nm also has sufficient photon energy. Although the broad green band can straddle the threshold, red is the listed colour whose band lies wholly beyond it.

Step 3: Conclusion Red light cannot produce photoelectrons from this material. Hence, the correct option is (A).

Quick Tip to Solve: Convert the work function to a threshold wavelength using $1240/\phi$ in nm, then compare colours by wavelength.

11. The momentum (in kg m/s) of a photon of frequency 6.0×10^{14} Hz is:

[1 mark]

- (A) 6.63×10^{-25}
- (B) 1.326×10^{-27}
- (C) 2.652×10^{-26}
- (D) 3.978×10^{-24}

Correct Answer: (B) 1.326×10^{-27}

Solution:

Concept:

- A photon of frequency ν has energy $E = h\nu$, where h is Planck's constant.
- For a photon, $E = pc$, so momentum $p = h\nu/c$, with c the speed of light in vacuum.

Step 1: Substitute the frequency in SI units Use $h = 6.63 \times 10^{-34}$ J s, $\nu = 6.0 \times 10^{14}$ Hz and $c = 3.0 \times 10^8$ m s⁻¹:

$$p = \frac{(6.63 \times 10^{-34})(6.0 \times 10^{14})}{3.0 \times 10^8}.$$

Step 2: Simplify and compare the options The numerical coefficient is $6.63 \times 6.0/3.0 = 13.26$, and the power is $10^{-34+14-8} = 10^{-28}$. Hence,

$$p = 13.26 \times 10^{-28} = 1.326 \times 10^{-27} \text{ kg m s}^{-1}.$$

Option (A) has an incorrect exponent and coefficient; (C) and (D) also do not match the required division of photon energy by c . Multiplying $h\nu$ alone would give energy, not momentum.

Step 3: Conclusion The photon momentum is 1.326×10^{-27} kg m s⁻¹. Hence, the correct option is (B).

Quick Tip to Solve: For photon momentum use $h\nu/c$, and subtract the exponent of c before normalising scientific notation.

12. Inside a nucleus, the nuclear forces between proton and proton, proton and neutron, neutron and neutron are F_{pp} , F_{pn} and F_{nn} respectively. Then:

[1 mark]

- (A) $F_{pp} > F_{pn} > F_{nn}$
- (B) $F_{pn} > F_{nn} > F_{pp}$
- (C) $F_{nn} > F_{pp} > F_{pn}$
- (D) $F_{pp} = F_{pn} = F_{nn}$

Correct Answer: (D) $F_{pp} = F_{pn} = F_{nn}$

Solution:

Concept:

- The nuclear force between nucleons is approximately charge independent: protons and neutrons interact through essentially the same strong nuclear interaction.
- At comparable separation and in the same spin state, its strength does not depend on whether the pair is proton-proton, proton-neutron or neutron-neutron.

Step 1: Identify the interaction being compared The question specifies nuclear forces, rather than total forces. A proton pair also experiences electrostatic repulsion, but that separate electrical interaction

must not be included in this comparison.

Step 2: Apply charge independence Under the standard charge-independent nuclear-force approximation,

$$F_{pp} = F_{pn} = F_{nn}.$$

The inequalities in (A), (B) and (C) incorrectly rank the nuclear interaction according to the charges of the nucleons. None expresses charge independence.

Step 3: Conclusion The three nuclear forces are equal in the stated approximation. Hence, the correct option is (D).

Quick Tip to Solve: When comparing nuclear forces, exclude Coulomb repulsion and recall the charge independence of the strong interaction.

13. Assertion (A): In a reflecting telescope, the image does not have chromatic aberration.

Reason (R): Chromatic aberration occurs only due to refraction of light through an optical medium.

Select the correct answer from the codes given below:

[1 mark]

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

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

Solution:

Concept:

- Chromatic aberration is the formation of different focal positions for different colours by a refracting lens because its refractive index depends on wavelength.
- A mirror focuses by reflection; the law of reflection is independent of wavelength, so its focal length does not vary with colour.

Step 1: Evaluate the assertion A reflecting telescope uses a concave mirror as its objective. Rays of different colours have the same objective focal position, so its image is free from the chromatic aberration associated with a refracting objective. Thus Assertion (A) is true in the usual ideal optical description.

Step 2: Evaluate the reason In the lens-and-mirror context of this question, chromatic aberration arises from wavelength-dependent refraction through an optical medium. Different colours are refracted by different amounts. Thus Reason (R) is true.

Step 3: Test the explanatory link The mirror objective uses reflection, so it avoids precisely the refractive dispersion described in the reason. Therefore R explains A. Option (B) misses this direct

explanation, and options (C) and (D) incorrectly classify one or both true statements as false.

Step 4: Conclusion Both A and R are true, and R is the correct explanation of A. Hence, the correct option is (A).

Quick Tip to Solve: For telescope colour errors, first identify the objective: a mirror has the same focal length for all colours.

14. Assertion (A): A hole is an apparent free particle with effective positive electronic charge.

Reason (R): A hole is not necessarily a vacancy left behind by an electron in the valence band.

Select the correct answer from the codes given below:

[1 mark]

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

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

Solution:

Concept:

- A hole is a vacancy created by the absence of an electron in the valence band of a semiconductor.
- Motion of neighbouring valence electrons into the vacancy makes the hole behave as a mobile positive charge carrier with charge $+e$, where e is the magnitude of electronic charge.

Step 1: Evaluate the assertion A hole is an effective carrier, rather than an independently existing elementary particle. When an electron fills a vacancy, another vacancy appears at its previous position. This makes the hole appear to move with effective positive charge. Assertion (A) is therefore true.

Step 2: Evaluate the reason In the semiconductor description used here, a hole is specifically the electron vacancy in the valence band. The reason denies that defining property by saying it is not necessarily such a vacancy. Reason (R) is therefore false.

Step 3: Relate the two statements A false reason cannot explain the true assertion. The positive-carrier behaviour is explained by the valence-electron vacancy and its motion, not by denying the vacancy. Options (A) and (B) require a true reason, while (D) incorrectly makes the assertion false.

Step 4: Conclusion A is true, but R is false. Hence, the correct option is (C).

Quick Tip to Solve: Identify a hole as a missing valence electron; its effective charge is positive, and its motion is opposite to electron hopping.

15. Assertion (A): X-rays are produced when slow moving electrons are stopped by a metal target of high atomic number.

Reason (R): X-rays consist of low-energy photons.

Select the correct answer from the codes given below:

[1 mark]

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

Correct Answer: (D) Both Assertion (A) and Reason (R) are false.

Solution:

Concept:

- X-rays are high-frequency electromagnetic waves; each photon has energy $E = h\nu = hc/\lambda$, where h is Planck's constant.
- An X-ray tube accelerates electrons through a large potential difference before they strike a metal target of high atomic number.

Step 1: Evaluate the assertion The assertion is false. X-rays are produced when fast, energetic electrons are suddenly decelerated in the target. The words “slow moving” make the printed assertion incorrect; a high atomic number target alone does not supply the required electron energy.

Step 2: Evaluate the reason The reason is false. X-ray photons have short wavelengths and therefore high energies, as follows from $E = hc/\lambda$. Calling them low-energy photons contradicts their position in the electromagnetic spectrum.

Step 3: Check the explanatory link Since neither statement is true, the reason cannot correctly explain the assertion. Options (A) and (B) both require two true statements, while option (C) requires a true assertion; each is excluded by the separate evaluations above.

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

Quick Tip to Solve: In X-ray tube questions, pair fast incident electrons with short-wavelength, high-energy photons.

16. Assertion (A): The binding energy per nucleon is practically constant for mass number in the range ($30 < A < 170$).

Reason (R): Nuclear forces between the nucleons for mass numbers in the range ($30 < A < 170$) are not short-range.

Select the correct answer from the codes given below:

[1 mark]

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

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

Solution:

Concept:

- Binding energy per nucleon is the total nuclear binding energy divided by mass number, B/A .
- Nuclear forces are short-range and show saturation: each nucleon interacts strongly mainly with its immediate neighbours.

Step 1: Evaluate the assertion The assertion is true. In the intermediate mass-number region $30 < A < 170$, the binding-energy curve is nearly flat, with B/A approximately 8 MeV. “Practically constant” allows the small changes along this portion of the curve; it does not mean exactly equal for every nucleus.

Step 2: Evaluate the reason The reason is false. Nuclear forces remain short-range in this mass-number region. They do not become long-range simply because the nucleus contains more nucleons.

Step 3: Check the explanatory link Saturation due to the short range means that adding nucleons adds roughly proportional binding energy, so B is approximately proportional to A . This explains the near constancy of B/A , but the printed reason denies short range and cannot explain it. Options (A) and (B) require a true reason, and option (D) requires a false assertion, so none fits.

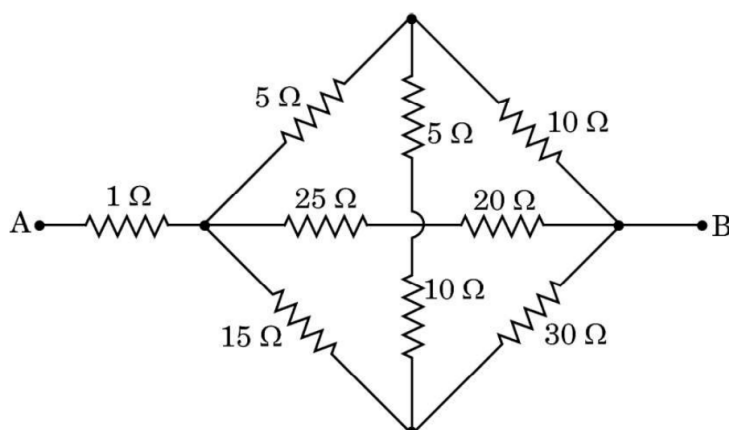
Step 4: Conclusion The assertion is true, but the reason is false. Hence, the correct option is (C).

Quick Tip to Solve: Link the nearly flat middle of the binding-energy curve to saturation of short-range nuclear forces.

Section B (10 marks)

17. Find the equivalent resistance between points A and B for the network shown in the figure.

[2 marks]



Solution:

Concept:

- A Wheatstone bridge is balanced when the ratios of its two pairs of arms are equal; the bridge branch then carries no current.
- Series resistances add, while parallel branches satisfy $1/R_p = \sum_i 1/R_i$, where R_p is their equivalent resistance.

Step 1: Identify the balanced bridge Let the left diamond vertex be L , and the top and bottom vertices be T and D . The curved crossing in the centre indicates that the horizontal and vertical wires are not connected. The outer arms satisfy

$$\frac{R_{LT}}{R_{TB}} = \frac{5}{10} = \frac{15}{30} = \frac{R_{LD}}{R_{DB}}.$$

Therefore T and D are at the same potential. No current flows through the vertical $5\ \Omega + 10\ \Omega$ branch, which can be omitted when finding the equivalent resistance.

Step 2: Combine the conducting branches Between L and B , the upper, lower and horizontal branches have resistances $5 + 10 = 15\ \Omega$, $15 + 30 = 45\ \Omega$, and $25 + 20 = 45\ \Omega$, respectively. They share the same two endpoints and are in parallel:

$$\frac{1}{R_{LB}} = \frac{1}{15} + \frac{1}{45} + \frac{1}{45} = \frac{5}{45}, \quad R_{LB} = 9\ \Omega.$$

The external $1\ \Omega$ resistor carries the entire current entering this network and is therefore in series with R_{LB} .

Step 3: Conclusion The equivalent resistance between A and B is $R_{AB} = 1 + 9 = \boxed{10\ \Omega}$.

Quick Tip to Solve: Check the outer-arm ratios first, and treat the curved wire crossing as a non-junction before combining resistors.

18(a). Find the intensity at a point on the screen in Young's double slit experiment, at which the interfering waves of intensity I_0 each, have a path difference of (i) $\frac{\lambda}{3}$ and (ii) $\frac{\lambda}{2}$. [2 marks]

Solution:

Concept:

- The interference intensity is $I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \phi$, where I_1, I_2 are the individual wave intensities and ϕ is their phase difference.
- A path difference Δ corresponds to phase difference $\phi = 2\pi\Delta/\lambda$. Here $I_1 = I_2 = I_0$, so $I = 2I_0(1 + \cos \phi)$.

Step 1: Substitute the first path difference For the printed case (i), $\Delta = \lambda/3$. The phase difference is neither zero nor π , so the waves interfere partially destructively:

$$\phi = \frac{2\pi \lambda}{\lambda} \frac{\lambda}{3} = \frac{2\pi}{3},$$

$$I = 2I_0 \left(1 + \cos \frac{2\pi}{3} \right) = 2I_0 \left(1 - \frac{1}{2} \right) = I_0.$$

The interference term is negative here, so simply adding the individual intensities would give an incorrect result.

Step 2: Substitute the second path difference For case (ii), $\Delta = \lambda/2$, giving

$$\phi = \frac{2\pi \lambda}{\lambda} \frac{\lambda}{2} = \pi, \quad I = 2I_0(1 + \cos \pi) = 2I_0(1 - 1) = 0.$$

The equal amplitudes arrive in opposite phase and cancel completely. Thus this point is a dark fringe in the ideal double-slit pattern.

Step 3: Conclusion The intensities are I_0 for path difference $\lambda/3$, and 0 for path difference $\lambda/2$.

Quick Tip to Solve: For equal beams, use $I = 4I_0 \cos^2(\pi\Delta/\lambda)$; a half-wavelength path difference gives zero immediately.

OR

18(b). A point source of light in air is kept at a distance of 12 cm in front of a convex spherical surface of glass of refractive index 1.5 and radius of curvature 30 cm. Find the nature and position of the image formed. [2 marks]

Solution:

Concept:

- For paraxial refraction at a spherical interface, $n_2/v - n_1/u = (n_2 - n_1)/R$, where n_1, n_2 are the incident and refracting media's refractive indices.
- Distances u, v, R are measured from the pole; the incident-light direction is positive. A negative image distance places the image on the incident side of the surface.

Step 1: Assign signed distances Take the light to travel from air into glass, from left to right. The object is on the left, so $u = -12$ cm. The convex surface has its centre of curvature inside the glass on the right, so $R = +30$ cm. Also, $n_1 = 1$ and $n_2 = 1.5$.

Step 2: Apply the refraction formula Substituting these signed quantities, using centimetres consistently, gives

$$\begin{aligned}\frac{1.5}{v} - \frac{1}{-12} &= \frac{1.5 - 1}{30}, \\ \frac{1.5}{v} + \frac{1}{12} &= \frac{1}{60}, \\ \frac{1.5}{v} &= \frac{1}{60} - \frac{1}{12} = -\frac{1}{15}, \\ v &= -22.5 \text{ cm}.\end{aligned}$$

The negative sign means the refracted rays do not actually converge in the glass. Their backward extensions meet in air, on the same side of the interface as the source, so the image is virtual.

Step 3: Conclusion The image is **virtual**, at 22.5 cm in front of the spherical surface in air; equivalently, $v = -22.5 \text{ cm}$.

Quick Tip to Solve: For a convex air-to-glass surface, use $u < 0$ and $R > 0$; interpret the sign of v only after solving.

19. A laser beam of frequency $3.0 \times 10^{14} \text{ Hz}$ produces average power of 9 mW. Find (i) the energy of photon of the beam, and (ii) the number of photons emitted per second on an average by the source. [2 marks]

Solution:

Concept:

- Each photon of frequency ν has energy $E_\gamma = h\nu$, where $h = 6.63 \times 10^{-34} \text{ J s}$ is Planck's constant.
- Power is the energy emitted per unit time. If $\dot{N}$ photons are emitted each second, the average beam power is $P = \dot{N}E_\gamma$.

Step 1: Calculate the energy of one photon The frequency is $\nu = 3.0 \times 10^{14} \text{ Hz}$. A photon's energy depends on this frequency, so

$$E_\gamma = h\nu = (6.63 \times 10^{-34})(3.0 \times 10^{14}) = 1.989 \times 10^{-19} \text{ J}.$$

This is the energy carried by each photon, not the total energy delivered by the beam in a second.

Step 2: Divide the energy emitted per second by the photon energy Convert the average power to SI units: $P = 9 \text{ mW} = 9 \times 10^{-3} \text{ J s}^{-1}$. Therefore,

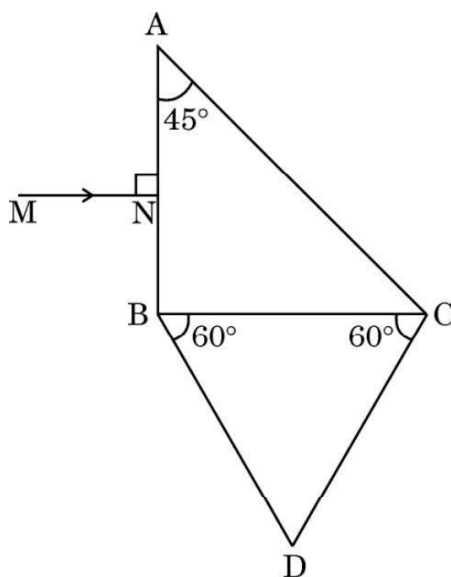
$$\dot{N} = \frac{P}{E_\gamma} = \frac{9 \times 10^{-3}}{1.989 \times 10^{-19}} = 4.52 \times 10^{16} \text{ s}^{-1}.$$

Using average power gives the average photon emission rate. The units follow from dividing joules per second by joules per photon.

Step 3: Conclusion (i) The photon energy is $1.99 \times 10^{-19} \text{ J}$. (ii) The source emits approximately 4.52×10^{16} photons per second on average.

Quick Tip to Solve: Convert milliwatts to watts before using $\dot{N} = P/(h\nu)$; keep photon energy and beam power as separate quantities.

20. A right angled isosceles glass prism ABC is kept in contact with an equilateral triangular prism DBC as shown in the figure. Both prisms are made of the same glass of refractive index 1.6. Trace the path of the ray MN incident normally on face AB as it passes through the combination. [2 marks]



Solution:

Concept:

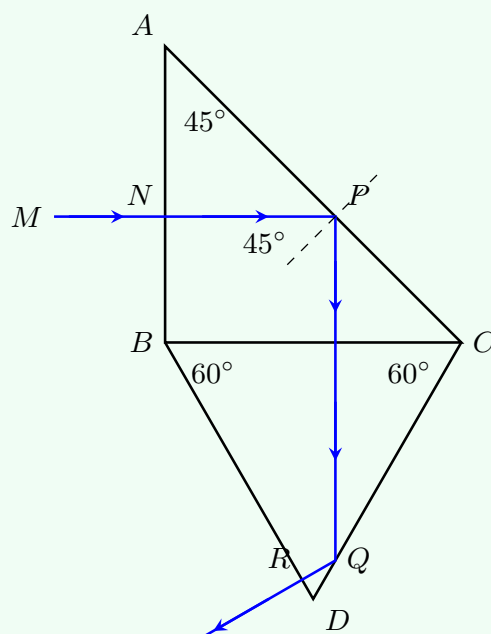
- A normally incident ray travels undeviated. At a boundary between two glasses of equal refractive index, the ray also continues straight.
- At a glass-air boundary, total internal reflection occurs for incidence $i > i_c$, where $\sin i_c = 1/\mu$. Angles of incidence are measured from the normal.

Step 1: Trace the ray through the upper prism For $\mu = 1.6$, the critical angle is

$$i_c = \sin^{-1}(1/1.6) \simeq 38.7^\circ.$$

The ray enters AB normally at N , continues horizontally, and strikes AC at P . Since ABC is right angled and isosceles, its incidence on AC is 45° . Thus $45^\circ > i_c$, and total internal reflection sends the ray vertically downward. It crosses the common face BC undeviated because the prisms are in optical contact and have the same refractive index.

Step 2: Trace reflection and emergence in the lower prism For the entry point shown, the downward ray meets face DC at Q . This face makes 60° with BC , so the ray makes 30° with the face and 60° with its normal. Since $60^\circ > 38.7^\circ$, it undergoes a second total internal reflection. The reflected ray travels downward to the left and strikes BD normally at R , emerging into air without further deviation. The traced path is shown below; arrows indicate propagation.



Ray path through the contacting prisms; total internal reflection occurs at P and Q .

Step 3: Conclusion The ray enters AB undeviated, is totally internally reflected at AC , crosses BC straight, is totally internally reflected at DC , and emerges normally through BD .

Quick Tip to Solve: Compare the incidence angles 45° and 60° with i_c ; do not treat the common glass-glass face BC as a glass-air boundary.

21. In an n -type semiconductor electron-hole combination is a continuous process at room temperature. Yet the electron concentration is always greater than the hole concentration in it. Explain.

[2 marks]

Solution:

Concept:

- Pentavalent donor impurities produce an n -type semiconductor: each ionised donor supplies an extra conduction electron without creating a corresponding hole in the valence band.
- Thermal generation creates electron-hole pairs, while recombination removes an electron and a hole together. At equilibrium, generation and recombination rates balance.

Step 1: Identify the unequal sources of the two carriers In a pure semiconductor, thermally generated electrons and holes occur in equal numbers. Doping with a pentavalent impurity changes this situation: four valence electrons participate in covalent bonds, while the weakly bound fifth electron can readily enter the conduction band at room temperature. This leaves a fixed positive donor ion, not a mobile hole. Thus, free electrons come from both donors and thermal pair generation, whereas holes arise from thermal generation.

Step 2: Explain why recombination preserves the electron excess Each recombination event removes one electron and one hole, so it does not remove the excess of electrons over holes. Continuous thermal generation replenishes pairs and an equilibrium is established. For uncompensated donor doping, electrical neutrality gives

$$n = p + N_D^+,$$

where n and p are free-electron and hole concentrations and N_D^+ is the concentration of ionised donors. Since $N_D^+ > 0$, the equilibrium electron concentration exceeds the hole concentration despite continuous recombination.

Step 3: Conclusion Electrons remain the majority carriers because donor atoms supply electrons without accompanying holes, while recombination removes the two mobile carrier types in equal numbers. The semiconductor as a whole remains electrically neutral.

Quick Tip to Solve: Distinguish the fixed positive donor ion from a mobile hole; donating an electron does not create an electron-hole pair.

Section C (21 marks)

22. What is the difference between ‘emf’ and ‘terminal voltage’ of a cell?

Two cells of emfs E_1 and E_2 and internal resistances r_1 and r_2 are connected in parallel. Derive an expression for the emf and internal resistance of the equivalent cell. [3 marks]

Solution:

Concept:

- The emf E is the energy supplied by the cell per unit charge in driving charge around a complete circuit. It equals the terminal potential difference when no current flows through the cell.
- Terminal voltage V is the potential difference between the cell's terminals. For a cell delivering current I through internal resistance r , $V = E - Ir$; both emf and terminal voltage are measured in volts.
- Cells connected in parallel share a common terminal voltage. Kirchhoff's current law gives the external current as the sum of the branch currents.

Step 1: Distinguish emf from terminal voltage Emf describes the cell's energy supply per unit charge, while terminal voltage describes the energy transferred per unit charge between its external terminals. During discharge, some energy is dissipated inside the cell, producing the drop Ir , so $V < E$. On open circuit, $I = 0$ and $V = E$. If a charging current of magnitude I enters the positive terminal, the relation is $V = E + Ir$.

Step 2: Write the branch-current equations Connect like terminals together, so the two cells support the same polarity. Let V be the common terminal voltage, and take I_1 and I_2 as positive when each cell supplies current to the external circuit. Then

$$I_1 = \frac{E_1 - V}{r_1}, \quad I_2 = \frac{E_2 - V}{r_2}, \quad I = I_1 + I_2.$$

These signed equations remain valid if one cell is charged by the other, in which case its branch current is negative.

Step 3: Compare the combination with a single equivalent cell Adding the two branch equations and rearranging gives

$$I = \frac{E_1}{r_1} + \frac{E_2}{r_2} - V \left(\frac{1}{r_1} + \frac{1}{r_2} \right),$$

$$V = \frac{E_1 r_2 + E_2 r_1}{r_1 + r_2} - I \frac{r_1 r_2}{r_1 + r_2}.$$

A single equivalent cell obeys $V = E_{\text{eq}} - Ir_{\text{eq}}$. Comparing the constant term and the coefficient of

I identifies its emf and internal resistance. The equivalent emf is the external open-circuit voltage; when the individual emfs differ, a circulating current may still flow between the parallel cells even with no external load.

Step 4: Conclusion Emf is the energy supplied per unit charge, whereas terminal voltage is the potential difference across the cell terminals. For cells joined in parallel with like terminals together,

$$E_{\text{eq}} = \frac{E_1 r_2 + E_2 r_1}{r_1 + r_2}, \quad r_{\text{eq}} = \frac{r_1 r_2}{r_1 + r_2}.$$

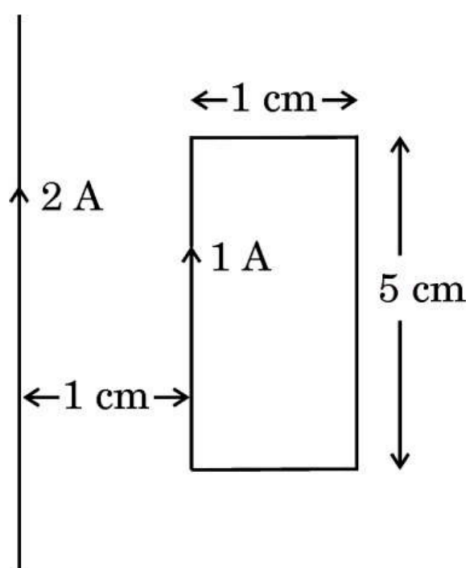
Quick Tip to Solve: First write both branch currents using the same terminal voltage, then collect terms into $V = E_{\text{eq}} - I r_{\text{eq}}$; for identical cells this gives $E_{\text{eq}} = E$ and $r_{\text{eq}} = r/2$.

23. A rectangular loop carries a current of 1 A. A straight long wire carrying 2 A current is kept near the loop in the same plane as shown in the figure.

Find:

- the torque acting on the loop, and
- the magnitude and direction of the net force on the loop.

[3 marks]



Solution:

Concept:

- The field at distance r from a long straight wire carrying current I_w is $B(r) = \mu_0 I_w / (2\pi r)$. On the right of an upward current it points into the paper.
- A current element experiences $d\vec{F} = I d\vec{l} \times \vec{B}$. Parallel currents attract and antiparallel currents repel; torque must be checked about the loop's centre because this field is nonuniform.

Step 1: Identify the dimensions and force directions The loop current is $I = 1$ A and the wire current is $I_w = 2$ A. The vertical sides have length $h = 5$ cm = 0.05 m. The nearer side is at $r_1 = 0.01$ m; adding the loop width gives $r_2 = 0.02$ m for the farther side. The near-side current is upward, so that side is attracted towards the wire. The far-side current is downward, so that side is repelled away from the wire.

Step 2: Check the torque and the horizontal sides On each vertical side, the field is constant along its length, so the horizontal resultant acts through its midpoint and has zero moment about the loop's centre. The top and bottom horizontal sides carry opposite currents. At corresponding points they experience equal, opposite vertical forces because their distances from the straight wire are identical. Their forces and their moments cancel pairwise. Thus the loop has no turning tendency, even though the field is stronger at its nearer side.

Step 3: Subtract the opposing vertical-side forces The vertical-side forces are $F_1 = IhB(r_1)$ and $F_2 = IhB(r_2)$. Since $r_1 < r_2$, the attraction is larger. Using $\mu_0 = 4\pi \times 10^{-7} \text{ N A}^{-2}$,

$$F_1 = \frac{\mu_0 I_w I h}{2\pi r_1} = 2.0 \times 10^{-6} \text{ N},$$

$$F_2 = \frac{\mu_0 I_w I h}{2\pi r_2} = 1.0 \times 10^{-6} \text{ N},$$

$$F_{\text{net}} = F_1 - F_2 = 1.0 \times 10^{-6} \text{ N}.$$

Step 4: Conclusion (i) The torque about the loop's centre is 0 N m . (ii) The net force is $1.0 \times 10^{-6} \text{ N}$, directed towards the straight wire.

Quick Tip to Solve: Add the loop width to the near distance before calculating the far-side force; equal horizontal sides cancel, but unequal vertical-side forces do not.

24(a). State Lenz's law. A rod MN of length L is rotated about an axis passing through its end M perpendicular to its length, with a constant angular velocity ω in a uniform magnetic field $\vec{B}$ parallel to the axis. Obtain an expression for emf induced between its ends. [3 marks]

Solution:

Concept:

- Lenz's law states that the induced emf, and the current if the circuit is closed, has a direction such that its magnetic effect opposes the change in magnetic flux that produces it.
- In a conductor moving through a magnetic field, the magnetic force on a charge is $q\vec{v} \times \vec{B}$. An element perpendicular to both $\vec{v}$ and $\vec{B}$ contributes motional emf $d\varepsilon = Bv dr$.

Step 1: State the physical meaning of Lenz's law The induced effect opposes the change in flux, rather than necessarily opposing the existing magnetic field. This opposition is represented by the negative sign in Faraday's law, $\varepsilon = -d\Phi_B/dt$ for a single closed loop. It is consistent with conservation of energy: if current is allowed to flow, external work is required to maintain the motion against the magnetic effect of that current.

Step 2: Divide the rod into elements Take a small element of length dr at distance r from the fixed end M . Since the rod rotates rigidly with angular speed ω , its tangential speed is $v = \omega r$. The magnetic field is along the rotation axis, so it is perpendicular to the plane of rotation. Hence $\vec{v} \times \vec{B}$ is along the rod, and the magnitude of the emf across this element is

$$d\varepsilon = B(\omega r) dr.$$

The speed varies along the rod, from zero at the pivot to ωL at the free end, so one must add the elemental emfs rather than use the tip speed for the whole rod.

Step 3: Integrate between the ends All elemental contributions have the same polarity along the rod. Integrating from M , where $r = 0$, to N , where $r = L$, gives

$$|\varepsilon| = \int_0^L B\omega r \, dr = B\omega \left[\frac{r^2}{2} \right]_0^L = \frac{1}{2}B\omega L^2.$$

If the angular velocity vector and $\vec{B}$ point in the same direction, positive charges are driven outwards and N is at higher potential than M . Reversing either the rotation or the field reverses this polarity. An open rod develops a potential difference without a sustained circuit current.

Step 4: Conclusion Lenz's law gives the direction that opposes the flux change producing the induced effect. The magnitude of the emf between the rotating rod's ends is $|\varepsilon| = \frac{1}{2}B\omega L^2$.

Quick Tip to Solve: Use $v = \omega r$ before integrating along the rod; using the free-end speed over the entire length incorrectly doubles the emf.

OR

24(b). Define 'self-inductance' of a coil. Derive an expression for self-inductance of a long solenoid of cross-sectional area A and length l , having n turns per unit length. [3 marks]

Solution:

Concept:

- Self-inductance $\mathcal{L}$ is the magnetic flux linkage per unit current in a coil: $\mathcal{L} = N\Phi_B/I$, where N is the number of turns and Φ_B is the flux through each turn.
- For a long air-core solenoid, the internal field is approximately uniform, $B = \mu_0 nI$, where n is the number of turns per unit length. End effects and the external field are neglected.

Step 1: Define self-inductance and its unit A change of current in a coil changes its own magnetic flux linkage and induces an emf in the same coil. For fixed geometry and a linear magnetic medium,

$$N\Phi_B = \mathcal{L}I, \quad \varepsilon = -\mathcal{L} \frac{dI}{dt}.$$

Thus self-inductance is also the magnitude of the induced emf when the current changes at unit rate. Its SI unit is the henry: a coil has inductance 1 H if a current changing at 1 A s^{-1} induces an emf of magnitude 1 V. The minus sign expresses opposition to the current change, not a negative inductance.

Step 2: Calculate the flux linked with the solenoid For length l and n turns per unit length, the total number of turns is $N = nl$. Let the current be I . The magnetic field is along the axis and therefore normal to the cross-sectional area A , giving flux per turn

$$\Phi_B = BA = \mu_0 nIA.$$

All turns of a sufficiently long solenoid link approximately this same flux. Consequently, the total flux linkage is

$$N\Phi_B = (nl)(\mu_0 nIA) = \mu_0 n^2 AlI.$$

Step 3: Divide the flux linkage by the current Substituting into the definition of self-inductance gives

$$\mathcal{L} = \frac{N\Phi_B}{I} = \frac{\mu_0 n^2 Al I}{I} = \mu_0 n^2 Al.$$

The current cancels because, for an air core and fixed geometry, the magnetic flux is proportional to current. Equivalently, using $n = N/l$, one obtains $\mathcal{L} = \mu_0 N^2 A/l$. If the solenoid is filled with a linear medium of permeability μ , replace μ_0 by μ .

Step 4: Conclusion Self-inductance is flux linkage per unit current. For the long air-core solenoid, $\mathcal{L} = \mu_0 n^2 Al$, with n the turns per unit length; its SI unit is henry.

Quick Tip to Solve: Multiply the flux of one turn by $N = nl$ before dividing by current; this is why the result contains n^2 , not just n .

25. Name the electromagnetic wave used (i) in radar, (ii) in eye surgery and (iii) as diagnostic tool in medicine. Write their wavelength range also. [3 marks]

Solution:

Concept:

- Electromagnetic waves are classified by wavelength λ ; all travel in vacuum at $c = \nu\lambda$, where ν is frequency and c is the speed of light.
- The application depends on the interaction of the radiation with matter. Spectral boundaries are approximate, and the wavelength actually used is a small part of the relevant band.

Step 1: Identify the radar band (i) **Microwaves** are used in radar. Their approximate wavelength range is

$$10^{-3} \text{ m to } 10^{-1} \text{ m} \quad (1 \text{ mm to } 10 \text{ cm}).$$

These short radio waves can be transmitted in narrow beams and reflected from distant objects. The time delay of the returning pulse gives the distance of the object; their directionality helps locate it.

Step 2: Identify the radiation used in eye surgery (ii) **Ultraviolet rays** are used in corrective eye surgery, for example in an excimer laser which precisely removes corneal tissue. Their approximate wavelength range is

$$10^{-9} \text{ m to } 4 \times 10^{-7} \text{ m} \quad (1 \text{ nm to } 400 \text{ nm}).$$

A particular surgical laser uses a selected wavelength within this band, rather than the entire ultraviolet range.

Step 3: Identify the diagnostic radiation (iii) **X-rays** are used as a diagnostic tool in medicine, such as in radiographs of bones. A commonly quoted approximate wavelength range is

$$10^{-12} \text{ m to } 10^{-9} \text{ m} \quad (0.001 \text{ nm to } 1 \text{ nm}).$$

Their penetrating power and differential absorption by bone and soft tissue produce contrast in the

image. The precise boundary of the X-ray band is conventional and may overlap neighbouring spectral regions.

Step 4: Conclusion The required waves are (i) microwaves, (ii) ultraviolet rays and (iii) X-rays, with the approximate wavelength ranges given above.

Quick Tip to Solve: Match radar to directional microwaves, corneal surgery to ultraviolet, and bone imaging to X-rays; their wavelengths decrease in that order.

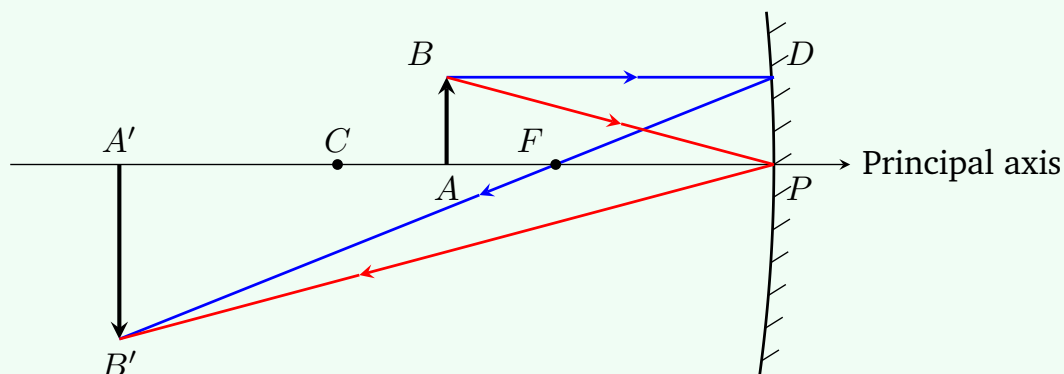
26. Draw a ray diagram showing the image formation when a concave mirror produces a real, inverted and magnified image of an object and hence obtain the mirror formula. [3 marks]

Solution:

Concept:

- A concave mirror gives a real, inverted and enlarged image when the object lies between its focus F and centre of curvature C . The image then lies beyond C .
- For a spherical mirror of small aperture, paraxial rays obey the mirror formula. We use similar triangles and then the Cartesian sign convention: distances measured opposite to incident light are negative.

Step 1: Construct the real enlarged image Place the upright object AB between C and F . A ray from its tip B , parallel to the principal axis, strikes the mirror at D and reflects through F . A second ray strikes the pole P and reflects with its angle of reflection equal to its angle of incidence. The reflected rays meet at B' , giving the inverted image $A'B'$ beyond C . The diagram uses the paraxial approximation, so D is treated as vertically above P .



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

Step 2: Relate the image and object heights First use positive lengths: let $AP = U$, $A'P = V$, $FP = F_0$, $AB = h$, and $A'B' = H$. Here H denotes the magnitude of the inverted image height. The equal angles at the pole give similar right triangles ABP and $A'B'P$, hence

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

Since the image is beyond the object, $V > U$, so this ratio also confirms magnification.

Step 3: Use the ray reflected through the focus In the small-aperture approximation, $DP \simeq h$. The right triangles DPF and $B'A'F$ are similar because their sloping sides lie along the same reflected

ray. With $A'F = V - F_0$,

$$\frac{H}{h} = \frac{V - F_0}{F_0}.$$

Equating the two height ratios and rearranging gives

$$\begin{aligned}\frac{V}{U} &= \frac{V - F_0}{F_0}, \\ VF_0 &= UV - UF_0, \\ UV &= F_0(U + V), \\ \frac{1}{F_0} &= \frac{1}{U} + \frac{1}{V}.\end{aligned}$$

Step 4: Apply the Cartesian sign convention Incident light travels towards the mirror from left to right. The real object, real image and focus are all to the left of the pole, so $u = -U$, $v = -V$ and $f = -F_0$. Substitution converts the positive-length relation into the signed mirror formula. This derivation assumes paraxial rays; large-aperture spherical mirrors suffer spherical aberration.

Step 5: Conclusion The image forms beyond C , and is real, inverted and magnified. With Cartesian distances, the mirror formula is

$$\boxed{\frac{1}{f} = \frac{1}{v} + \frac{1}{u}}.$$

Quick Tip to Solve: Derive with positive lengths first, then put $u, v, f < 0$ for this configuration; the two triangle ratios are V/U and $(V - F_0)/F_0$.

27. How is the necessary force provided to an electron to keep it moving in a circular orbit according to Bohr model of hydrogen atom? Derive an expression for the total energy of an electron moving in an orbit of radius r in hydrogen atom. Give the significance of negative sign in this expression.

[3 marks]

Solution:

Concept:

- In Bohr's hydrogen model the electrostatic attraction between the proton and electron supplies the centripetal force required for circular motion.
- The total mechanical energy is $E = K + U$, where $K = \frac{1}{2}m_e v^2$ is kinetic energy and U is electrostatic potential energy. Set $U = 0$ at infinite separation.

Step 1: Identify the force and obtain the kinetic energy Let e be the magnitude of the electronic charge, m_e the electron mass, v its orbital speed and r the orbital radius. Treating the much heavier proton as stationary, Coulomb attraction acts radially towards the proton. It supplies the centripetal force:

$$\frac{m_e v^2}{r} = \frac{e^2}{4\pi\epsilon_0 r^2}.$$

Multiplying by $r/2$ gives the positive kinetic energy

$$K = \frac{1}{2}m_e v^2 = \frac{e^2}{8\pi\epsilon_0 r}.$$

Step 2: Write the electrostatic potential energy For charges $+e$ and $-e$ at separation r , with the zero of potential energy at infinity,

$$U = \frac{(+e)(-e)}{4\pi\epsilon_0 r} = -\frac{e^2}{4\pi\epsilon_0 r}.$$

The interaction is attractive; bringing the electron in from infinity lowers the potential energy. Thus $U = -2K$.

Step 3: Add the energies and interpret the sign Adding the kinetic and potential energies yields

$$\begin{aligned} E &= K + U \\ &= \frac{e^2}{8\pi\epsilon_0 r} - \frac{e^2}{4\pi\epsilon_0 r} \\ &= -\frac{e^2}{8\pi\epsilon_0 r}. \end{aligned}$$

The energy is below that of the separated charges at rest at infinity, so the electron is bound. Removing it to infinity with zero final speed requires energy $-E = e^2/(8\pi\epsilon_0 r)$. Its kinetic energy remains positive.

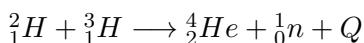
Step 4: Conclusion Electrostatic attraction provides the centripetal force. The orbital energy is

$$E = -\frac{e^2}{8\pi\epsilon_0 r}.$$

Its negative sign denotes a bound state relative to the separated electron and proton at rest at infinity.

Quick Tip to Solve: After balancing Coulomb and centripetal forces, use $U = -2K$; then $E = -K = U/2$, which prevents a factor-of-two or sign error.

28(a). Consider the so-called ‘D-T reaction’ (Deuterium-Tritium reaction). In a thermonuclear fusion reactor, the following nuclear reaction occurs:



Find the amount of energy released in the reaction.

Given:

$$m({}^2_1\text{H}) = 2.014102 \text{ u}$$

$$m({}^3_1\text{H}) = 3.016049 \text{ u}$$

$$m({}^4_2\text{He}) = 4.002603 \text{ u}$$

$$m({}^1_0\text{n}) = 1.008665 \text{ u}$$

$$1 \text{ u} = 931 \text{ MeV}/c^2$$

[3 marks total]

Solution:

Concept:

- In a nuclear reaction, the decrease in total rest mass appears as released energy. The reaction energy is $Q = (m_{\text{initial}} - m_{\text{final}})c^2$.
- With masses in atomic mass units, use the supplied conversion $1 \text{ u } c^2 = 931 \text{ MeV}$. The mass of every reactant and every product must be included.

Step 1: Add the masses on each side One deuterium nucleus and one tritium nucleus form one

helium nucleus and one neutron. Thus the initial and final masses, using the supplied values, are

$$m_{\text{initial}} = 2.014102 + 3.016049 = 5.030151 \text{ u},$$

$$m_{\text{final}} = 4.002603 + 1.008665 = 5.011268 \text{ u}.$$

The emitted neutron remains a material product; omitting its rest mass would give an incorrect, much larger energy. The supplied atomic masses may be used consistently because the two atomic electrons on the reactant side balance the two on the helium side.

Step 2: Convert the mass defect to energy Subtract the total product mass from the total reactant mass, retaining all given decimal places until the final multiplication:

$$\Delta m = 5.030151 - 5.011268 = 0.018883 \text{ u}.$$

Therefore,

$$Q = 0.018883 \times 931 = 17.580073 \text{ MeV}.$$

The mass defect is positive, so the reaction releases energy. This energy appears mainly as kinetic energy of the helium nucleus and neutron; it is the total for one fusion event.

Step 3: Conclusion The energy released per D-T reaction is $Q \simeq 17.58 \text{ MeV}$, approximately $2.81 \times 10^{-12} \text{ J}$.

Quick Tip to Solve: Add all product masses, including the neutron, before subtracting; multiply the mass defect in u directly by the given 931 to get MeV.

28(b). Show that the nuclear density is independent of mass number.

Solution:

Concept:

- Nuclear mass is approximately $M = Am_N$, where A is the mass number and m_N is the mean mass of a nucleon. Proton and neutron masses are nearly equal.
- The empirical nuclear radius law is $R = R_0 A^{1/3}$, where R_0 is a constant approximately $1.2 \times 10^{-15} \text{ m}$. The average density is mass divided by nuclear volume.

Step 1: Express the nuclear volume using the radius law Treat the nucleus as approximately spherical. Its volume is

$$\begin{aligned} V &= \frac{4}{3}\pi R^3 \\ &= \frac{4}{3}\pi \left(R_0 A^{1/3}\right)^3 \\ &= \frac{4}{3}\pi R_0^3 A. \end{aligned}$$

Thus nuclear volume increases directly in proportion to the number of nucleons. The cube on the radius is essential: cubing $A^{1/3}$ gives A , not A^3 .

Step 2: Divide nuclear mass by nuclear volume Using $M \simeq Am_N$, the average nuclear density becomes

$$\begin{aligned} \rho &= \frac{M}{V} = \frac{Am_N}{(4/3)\pi R_0^3 A} \\ &= \frac{3m_N}{4\pi R_0^3}. \end{aligned}$$

The factor A cancels because both mass and volume grow proportionally to A . The remaining quantities m_N and R_0 are approximately constant across nuclei. Consequently a heavier nucleus is larger, rather than having a systematically larger average density. Small binding-energy and nuclear-shape effects are neglected in this standard estimate.

Step 3: Conclusion $\rho = \frac{3m_N}{4\pi R_0^3}$ contains no mass number A . Hence the average nuclear density is approximately independent of mass number.

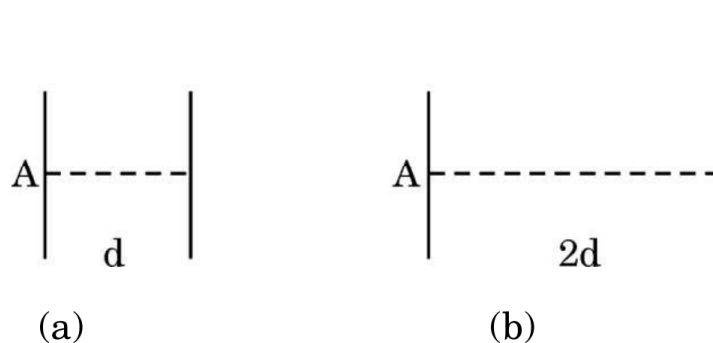
Quick Tip to Solve: Cube the radius law first: nuclear volume is proportional to A , so its A cancels the A in the nuclear mass.

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. A capacitor is a system of two conductors separated by an insulator. In practice, the two conductors have charges Q and $-Q$ with potential difference $V = V_1 - V_2$ between them. The ratio $\frac{Q}{V}$ is a constant, denoted by C and is called the capacitance of the capacitor. It is independent of Q or V . It depends only on the geometrical configuration (shape, size, separation) of the two conductors and the medium separating the conductors. When a parallel plate capacitor is charged, the electric field E_0 is localised between the plates and is uniform throughout. When a slab of a dielectric is inserted between the charged plates (charge density σ), the dielectric is polarised by the field. Consequently opposite charges appear on the faces of the slab, near the plates, with surface charge density of magnitude σ_p . For a linear dielectric σ_p is proportional to E_0 . Introduction of a dielectric changes the electric field, and hence, the capacitance of a capacitor, and hence, the energy stored in the capacitor. Like resistors, capacitors can also be arranged in series or in parallel or in a combination of series and parallel. [4 marks]

29(i). Consider a capacitor of capacitance C , with plate area A and plate separation d , filled with air [Fig. (a)]. The distance between the plates is increased to $2d$ and one of the plates is shifted as shown in Fig. (b). The capacitance of the new system now is: [1 mark]



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

Correct Answer: (A) $\frac{C}{4}$

Solution:

Concept:

- Neglecting fringing, an air-filled parallel-plate capacitor has capacitance $C = \epsilon_0 A/d$, where A is the overlapping plate area and d is the separation.
- A sideways displacement changes the facing area; increasing separation decreases capacitance independently of that area change.

Step 1: Read both geometrical changes In Fig. (b), the upper edge of one plate faces the midpoint of the other, so the overlap is half its original value: $A' = A/2$. The plate separation is also doubled: $d' = 2d$. Both changes must be included.

Step 2: Form the capacitance ratio

$$\frac{C'}{C} = \frac{A'}{A} \frac{d}{d'} = \frac{1}{2} \times \frac{1}{2} = \frac{1}{4}.$$

Option (B) includes only the doubled separation and misses the reduced overlap. Options (C) and (D) predict an increase, although each geometrical change reduces the capacitance.

Step 3: Conclusion $C' = C/4$. Hence, the correct option is (A).

Quick Tip to Solve: For a displaced capacitor, multiply the overlap-area ratio by the inverse separation ratio; here each contributes a factor of one-half.

29(ii). A slab (area A and thickness d_1) of a linear dielectric of dielectric constant K is inserted between charged plates (charge density σ) of a parallel plate capacitor [plate area A and plate separation $d (> d_1)$] and opposite charges with charge density of magnitude σ_p appear on the faces of the slab. The dielectric constant K is given by: [1 mark]

- (A) $\frac{\sigma + \sigma_p}{\sigma}$
 (B) $\frac{\sigma}{\sigma - \sigma_p}$
 (C) $\frac{\sigma + \sigma_p}{\sigma_p}$
 (D) $\frac{\sigma}{\sigma_p}$

Correct Answer: (B) $\frac{\sigma}{\sigma - \sigma_p}$

Solution:**Concept:**

- The field from free plate charge density σ is $E_0 = \sigma/\epsilon_0$. Polarisation of the slab produces an opposing field $E_p = \sigma_p/\epsilon_0$.
- Inside a linear dielectric, $E = E_0/K$, where K is the relative permittivity.

Step 1: Write the net field inside the dielectric Bound charges reduce the field within the slab, so

$$E = E_0 - E_p = \frac{\sigma - \sigma_p}{\epsilon_0}.$$

Step 2: Use the definition of dielectric constant

$$K = \frac{E_0}{E} = \frac{\sigma/\epsilon_0}{(\sigma - \sigma_p)/\epsilon_0} = \frac{\sigma}{\sigma - \sigma_p}.$$

Option (A) uses a sum and misses this field reduction. Options (C) and (D) have σ_p alone in the denominator and diverge when polarisation vanishes, instead of tending to $K = 1$.

Step 3: Conclusion $K = \frac{\sigma}{\sigma - \sigma_p}$. Hence, the correct option is (B).

Quick Tip to Solve: Write free-charge field minus polarisation field first, then take original field divided by net field to obtain K .

29(iii). An electric field E is established between the plates of an air filled parallel plate capacitor, with charges Q and $-Q$. V is the volume of the space enclosed between the plates. The energy stored in the capacitor is:

[1 mark]

- (A) $\frac{1}{2}\varepsilon_0 E^2$
- (B) $\varepsilon_0 Q^2 E$
- (C) $\frac{1}{2}\varepsilon_0 E^2 V$
- (D) $\varepsilon_0 EQV$

Correct Answer: (C) $\frac{1}{2}\varepsilon_0 E^2 V$

Solution:

Concept:

- A capacitor stores energy $U = \frac{1}{2}C(\Delta\phi)^2$, where $\Delta\phi$ is its potential difference. Here the question's symbol V denotes volume, not voltage.
- For air-filled plates, $C = \varepsilon_0 A/d$, $\Delta\phi = Ed$, and the field-filled volume is $V = Ad$, neglecting edge effects.

Step 1: Express capacitor energy in terms of field Substitute the parallel-plate capacitance and potential difference into the energy formula:

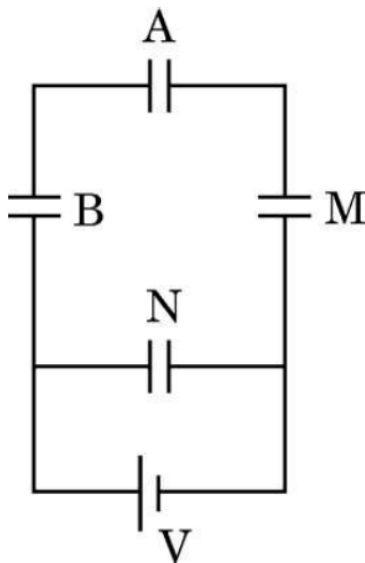
$$U = \frac{1}{2} \frac{\varepsilon_0 A}{d} (Ed)^2 = \frac{1}{2} \varepsilon_0 E^2 Ad.$$

Step 2: Identify the volume and compare the options Since $Ad = V$, the total energy is the field energy density $\frac{1}{2}\varepsilon_0 E^2$ multiplied by V . Option (A) is only energy per unit volume. Options (B) and (D) include incorrect powers of charge and field and do not have the required energy dimensions.

Step 3: Conclusion $U = \frac{1}{2}\varepsilon_0 E^2 V$. Hence, the correct option is (C).

Quick Tip to Solve: Check what V means before substituting: here it is volume, so multiply the electric-field energy density by V .

29(iv)(a). Three capacitors A , B and M , each of capacitance C are connected to a capacitor N of capacitance $2C$ and a battery as shown in the figure. If the charges on A and N are Q and Q' respectively, then $\frac{Q'}{Q}$ is: [1 mark]



- (A) $\frac{1}{6}$
- (B) $\frac{1}{3}$
- (C) 3
- (D) 6

Correct Answer: (D) 6

Solution:

Concept:

- Capacitors in series carry equal charge magnitudes, and their equivalent capacitance obeys $1/C_s = \sum_i 1/C_i$.
- Parallel branches have the same potential difference. For any capacitor, the charge magnitude is $q = C\Delta V$.

Step 1: Identify the two branches across the battery Following the upper path between the battery terminals, the capacitors B , A and M occur in series. Their intermediate junctions have no other connection. Each has capacitance C , so

$$\frac{1}{C_s} = \frac{1}{C} + \frac{1}{C} + \frac{1}{C}, \quad C_s = \frac{C}{3}.$$

If the battery voltage is V , the charge on each series capacitor, including A , is $Q = C_s V = CV/3$.

Step 2: Find the charge on the parallel capacitor Capacitor N is directly across the same battery terminals. Its capacitance is $2C$, so it carries charge $Q' = 2CV$. Therefore,

$$\frac{Q'}{Q} = \frac{2CV}{CV/3} = 6.$$

The reciprocal $1/6$ reverses the requested ratio. The values $1/3$ and 3 do not include both the three-capacitor series reduction and the doubled capacitance of N .

Step 3: Conclusion The required charge ratio is $Q'/Q = 6$. Hence, the correct option is (D).

Quick Tip to Solve: Trace the battery-to-battery paths first: B, A, M form one series branch, while N has the full battery voltage.

OR

29(iv)(b). A slab (area A and thickness $\frac{d}{2}$) of dielectric constant K is inserted in a parallel plate capacitor of plate area A and plate separation d . If C and C_0 are the capacitances of the capacitors with and without the dielectric, then $\frac{C}{C_0}$ is: [1 mark]

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

Correct Answer: (B) $\frac{2K}{K+1}$

Solution:

Concept:

- For layers perpendicular to the electric field, the air and dielectric regions act as capacitors in series, with the same free charge and additive potential drops.
- A uniform layer of area A , thickness t and relative permittivity K has capacitance $K\varepsilon_0 A/t$. Without dielectric, $C_0 = \varepsilon_0 A/d$.

Step 1: Identify the two series layers The slab fills the whole plate area but only half the plate separation. The remaining air thickness is $d/2$, so the two layer capacitances are

$$C_{\text{air}} = \frac{2\varepsilon_0 A}{d}, \quad C_{\text{slab}} = \frac{2K\varepsilon_0 A}{d}.$$

They are in series because the electric field passes successively through the air and dielectric, rather than through separate side-by-side areas.

Step 2: Combine the layers and check the alternatives Add the reciprocal capacitances:

$$\frac{1}{C} = \frac{d}{2\varepsilon_0 A} + \frac{d}{2K\varepsilon_0 A} = \frac{d(K+1)}{2K\varepsilon_0 A}.$$

Thus $C = 2K\varepsilon_0 A/[d(K+1)]$. Option (A) reverses the required ratio. Options (C) and (D) incorrectly contain $K-1$; in particular neither reproduces the unchanged capacitance when $K = 1$.

Step 3: Conclusion $\frac{C}{C_0} = \frac{2K}{K+1}$. Hence, the correct option is (B).

Quick Tip to Solve: For a slab filling the area but only part of the gap, add effective thicknesses: $d_{\text{eff}} = d - t + t/K$, then use $C/C_0 = d/d_{\text{eff}}$.

30. Extrinsic semiconductors are made by doping pure or intrinsic semiconductors with suitable impurity. There are two type of dopants used in doping, Si or Ge, and using them p-type and n-type semiconductors can be obtained. A p-n junction is the basic building block of many semiconductor devices. Two important processes occur during the formation of a p-n junction: diffusion and drift. When such a junction is formed, a 'depletion layer' is created consisting of immobile ion-cores. This is responsible for a junction potential barrier. The width of a depletion layer and the height of potential barrier changes when a junction is forward-biased or reverse-biased. A semiconductor diode is basically a p-n junction with metallic contacts provided at the ends for application of an external voltage. Using diodes, alternating voltages can be rectified. [4 marks]

30(i). Which of the following is a donor impurity atom for Ge? [1 mark]

- (A) Boron
- (B) Antimony
- (C) Aluminium
- (D) Indium

Correct Answer: (B) Antimony

Solution:

Concept:

- A donor impurity has five valence electrons and produces an n-type semiconductor when added to tetravalent germanium.
- Four impurity electrons form covalent bonds with neighbouring Ge atoms; the weakly bound fifth electron can become a conduction electron.

Step 1: Identify the pentavalent impurity Antimony has five valence electrons. After making the four bonds required by the germanium lattice, it has one extra electron available for donation. The ionised donor is positively charged, while the donated electron is mobile.

Step 2: Eliminate the acceptor impurities Boron, aluminium and indium are trivalent. Each lacks one electron for completing four covalent bonds and therefore acts as an acceptor, creating a hole. Consequently options (A), (C) and (D) describe acceptors rather than donors.

Step 3: Conclusion Antimony is the donor impurity for Ge. Hence, the correct option is (B).

Quick Tip to Solve: For a Si or Ge host, count valence electrons: five gives a donor and three gives an acceptor.

30(ii). When a pentavalent atom occupies the position of an atom in the crystal lattice of Si, four of its electrons form covalent bonds with four silicon neighbours, while the fifth remains bound to the parent atom. The energy required to set this electron free is about: [1 mark]

- (A) 0.5 eV
- (B) 0.1 eV
- (C) 0.05 eV
- (D) 0.01 eV

Correct Answer: (C) 0.05 eV

Solution:

Concept:

- A pentavalent impurity introduces a donor energy level just below the conduction band of silicon.
- The energy needed to free its fifth electron is the donor binding energy, approximately 0.05 eV in silicon; it is much smaller than the band gap.

Step 1: Identify the electron being released Four valence electrons participate in covalent bonds with the neighbouring silicon atoms. The fifth electron is only weakly bound to the donor. Releasing this electron therefore requires much less energy than breaking a normal covalent bond and promoting a valence electron across the band gap.

Step 2: Compare the stated energies The standard approximate donor ionisation energy for Si is 0.05 eV. Values 0.5 eV and 0.1 eV are too high for this approximation. The value 0.01 eV is associated with the smaller donor binding energy in germanium, not the silicon host specified here.

Step 3: Conclusion The required energy is about 0.05 eV. Hence, the correct option is (C).

Quick Tip to Solve: Check the host first: donor binding energies are about 0.05 eV for Si and 0.01 eV for Ge.

30(iii). During formation of a p-n junction: [1 mark]

- (A) a layer of negative charge on n-side and a layer of positive charge on p-side appear.
- (B) a layer of positive charge on n-side and a layer of negative charge on p-side appear.
- (C) the electrons on p-side of the junction move to n-side initially.
- (D) initially diffusion current is small and drift current is large.

Correct Answer: (B) a layer of positive charge on n-side and a layer of negative charge on p-side appear.

Solution:

Concept:

- On forming a p-n junction, majority carriers diffuse from the side of higher concentration to the side of lower concentration and recombine near the junction.
- Immobile positive donor ions on the n-side and negative acceptor ions on the p-side form the depletion region and its electric field.

Step 1: Track the initial diffusion Electrons initially diffuse from n to p, while holes diffuse from p to n. Electron loss exposes positive donor ions on the n-side. Hole loss leaves uncompensated negative acceptor ions on the p-side. These ions remain fixed in the crystal lattice.

Step 2: Check the alternative statements Option (A) reverses the ionic charges. Option (C) reverses the initial electron diffusion direction. Option (D) reverses the initial current balance: diffusion

is initially dominant, while drift increases as the space-charge field develops. At equilibrium the opposing diffusion and drift currents have equal magnitudes.

Step 3: Conclusion A positive-charge layer appears on the n-side and a negative-charge layer on the p-side. Hence, the correct option is (B).

Quick Tip to Solve: Follow the electrons leaving the n-side: their departure exposes fixed positive donor ions there.

30(iv)(a). In reverse-biased p-n junction:

[1 mark]

- (A) the drift current is of the order of few mA.
- (B) the applied voltage mostly drops across the depletion region.
- (C) the depletion region width decreases.
- (D) the current increases with increase in applied voltage.

Correct Answer: (B) the applied voltage mostly drops across the depletion region.

Solution:

Concept:

- Reverse bias connects the p-side to the negative terminal and the n-side to the positive terminal, increasing the junction barrier and depletion width.
- The depletion region contains very few mobile charge carriers and has much greater resistance than the neutral p and n regions. Reverse current below breakdown is a small minority-carrier drift current.

Step 1: Locate the main voltage drop The applied reverse voltage pulls majority carriers away from the junction. This widens the depletion region and reinforces its electric field. Since this region has the greatest resistance, most of the applied voltage drops across it; the voltage drops in the conducting neutral regions are comparatively small.

Step 2: Check the other statements Option (A) is incorrect: ordinary reverse saturation current is very small, typically of microampere order or less, rather than a few milliamperes. Option (C) gives the forward-bias change; reverse bias increases the depletion width. Option (D) is incorrect for the normal reverse-bias region: at fixed temperature, the reverse current remains approximately constant as voltage increases, until breakdown is reached.

Step 3: Conclusion The applied voltage mostly drops across the depletion region. Hence, the correct option is (B).

Quick Tip to Solve: For reverse bias, remember a wider depletion region, a larger barrier and a tiny nearly constant current before breakdown.

30(iv)(b). The output frequency of a full-wave rectifier with 50 Hz as input frequency is: [1 mark]

- (A) 25 Hz
- (B) 50 Hz
- (C) 100 Hz
- (D) 200 Hz

Correct Answer: (C) 100 Hz

Solution:

Concept:

- A full-wave rectifier makes current through the load flow in the same direction during both half-cycles of an alternating input.
- Two output pulses occur in each input cycle. Hence the output repetition frequency is $f_{\text{out}} = 2f_{\text{in}}$, where f_{in} is the input frequency.

Step 1: Compare input and output periods The positive half-cycle produces one output pulse, and the negative half-cycle is inverted to produce a second pulse of the same polarity. The rectified waveform therefore repeats after half the input period:

$$T_{\text{out}} = \frac{T_{\text{in}}}{2}, \quad f_{\text{out}} = \frac{1}{T_{\text{out}}} = 2f_{\text{in}}.$$

Step 2: Substitute the input frequency and test the options Using the given input frequency,

$$f_{\text{out}} = 2 \times 50 = 100 \text{ Hz}.$$

Option (A) halves the frequency instead of doubling it. Option (B) would describe the pulse frequency of a half-wave rectifier, which uses only one half-cycle. Option (D) incorrectly counts four pulses per input cycle; full-wave rectification produces only two.

Step 3: Conclusion The output frequency is 100 Hz. Hence, the correct option is (C).

Quick Tip to Solve: Count load-voltage pulses in one input cycle: two pulses for a full-wave rectifier mean twice the input frequency.

Section E (15 marks)

31(a). (i) Write the principle of working of an ac generator. Draw its labelled diagram and explain its working.

(ii) A resistor of 400Ω , an inductor of $\left(\frac{5}{\pi}\right)$ H and a capacitor of $\left(\frac{50}{\pi}\right) \mu\text{F}$ are joined in series across an ac source $v = 140 \sin(100\pi t)$ V. Find the rms voltages across these three circuit elements. The algebraic sum of these voltages is more than the rms voltage of source. Explain. [5 marks]

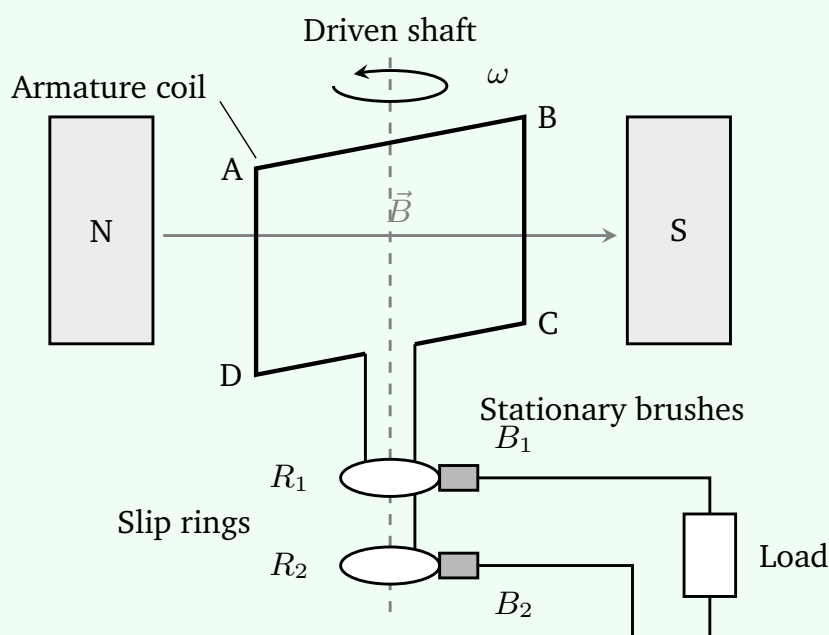
Solution:

Concept:

- Faraday's law gives the induced emf as $e = -d\Phi/dt$, where Φ is the flux linkage of the coil. Mechanical rotation in a magnetic field produces an alternating emf.

- For a series RLC circuit, $X_L = \omega L$, $X_C = 1/(\omega C)$ and $Z = \sqrt{R^2 + (X_L - X_C)^2}$. Here ω is the angular frequency and Z is the impedance.
- The rms values satisfy $V_{\text{rms}} = V_0/\sqrt{2}$ and $I_{\text{rms}} = V_{\text{rms}}/Z$. Element voltages must be added as phasors because their phases differ.

Step 1: (i) State the principle and identify the parts An ac generator works on electromagnetic induction: an emf is induced whenever the magnetic flux linked with a coil changes. A rectangular armature coil $ABCD$, having N turns and area A , rotates between the north and south poles of a magnet. The coil ends are connected separately to two continuous slip rings R_1, R_2 , insulated from each other and from the shaft. Stationary carbon brushes B_1, B_2 touch the rings and connect the rotating coil to an external load. An external mechanical drive rotates the shaft.



AC generator: separate continuous slip rings carry the coil output to stationary brushes and the load (schematic).

Step 2: Explain the alternating output Let the coil rotate with constant angular speed ω , and let its normal initially point along the uniform field B . At time t , the angle between the normal and the field is ωt , giving

$$\Phi = NBA \cos(\omega t), \quad e = -\frac{d\Phi}{dt} = NBA\omega \sin(\omega t).$$

Thus the peak emf is $e_0 = NBA\omega$. During rotation the two active sides cut magnetic field lines; their induced emfs add around the coil. After each half-turn their directions of motion reverse, so the emf and current in a resistive load reverse. The continuous slip rings preserve each coil end's connection to its brush, transmitting this alternating output. The generator converts mechanical energy into electrical energy; the induced current opposes the driving motion in accordance with Lenz's law.

Step 3: (ii) Calculate the reactances and the current From $v = 140 \sin(100\pi t)$ V, the peak voltage is

140 V, and $\omega = 100\pi \text{ rad s}^{-1}$. With the printed inductance $L = 5/\pi \text{ H}$,

$$\begin{aligned}X_L &= (100\pi) \frac{5}{\pi} = 500 \Omega, \\X_C &= \frac{1}{(100\pi)(50/\pi)10^{-6}} = 200 \Omega, \\Z &= \sqrt{400^2 + (500 - 200)^2} = 500 \Omega, \\V_{\text{rms}} &= \frac{140}{\sqrt{2}} = 70\sqrt{2} \text{ V}, \\I_{\text{rms}} &= \frac{70\sqrt{2}}{500} = 0.14\sqrt{2} \text{ A}.\end{aligned}$$

All three elements carry this same rms current because they are connected in series.

Step 4: Find each rms voltage and explain their sum Multiply the common rms current by each element's resistance or reactance:

$$\begin{aligned}V_R &= I_{\text{rms}}R = 56\sqrt{2} \text{ V} \simeq 79.2 \text{ V}, \\V_L &= I_{\text{rms}}X_L = 70\sqrt{2} \text{ V} \simeq 99.0 \text{ V}, \\V_C &= I_{\text{rms}}X_C = 28\sqrt{2} \text{ V} \simeq 39.6 \text{ V}.\end{aligned}$$

Their numerical sum is $154\sqrt{2} \simeq 217.8 \text{ V}$, exceeding the source rms voltage $70\sqrt{2} \simeq 99.0 \text{ V}$. This does not violate Kirchhoff's voltage law, which applies to the signed instantaneous voltages. Relative to the current, V_R is in phase, V_L leads by 90° , and V_C lags by 90° . Hence V_L and V_C oppose each other and their difference is perpendicular to V_R . The correct phasor sum is

$$V_{\text{rms}} = \sqrt{V_R^2 + (V_L - V_C)^2} = \sqrt{(56\sqrt{2})^2 + (42\sqrt{2})^2} = 70\sqrt{2} \text{ V}.$$

Step 5: Conclusion An ac generator produces $e = NBA\omega \sin(\omega t)$ by electromagnetic induction. The rms voltages are $V_R = 79.2 \text{ V}$, $V_L = 99.0 \text{ V}$, $V_C = 39.6 \text{ V}$. Their magnitudes exceed the source voltage when added arithmetically because the three voltages have different phases.

Quick Tip to Solve: Use the peak source voltage only after dividing by $\sqrt{2}$. For this series circuit subtract X_C from X_L before calculating the impedance; add element voltages as phasors.

31(b). (i) Write the principle of working of a transformer. With the help of a labelled diagram, explain the working of a step-up transformer.

(ii) An ideal transformer is designed to convert 50 V into 250 V. It draws 200 W power from an ac source whose instantaneous voltage is given by $v_i = 20 \sin(100\pi t)$ V.

Find:

(I) rms value of input current.

(II) expression for instantaneous output voltage.

(III) expression for instantaneous output current.

[5 marks]

Solution:

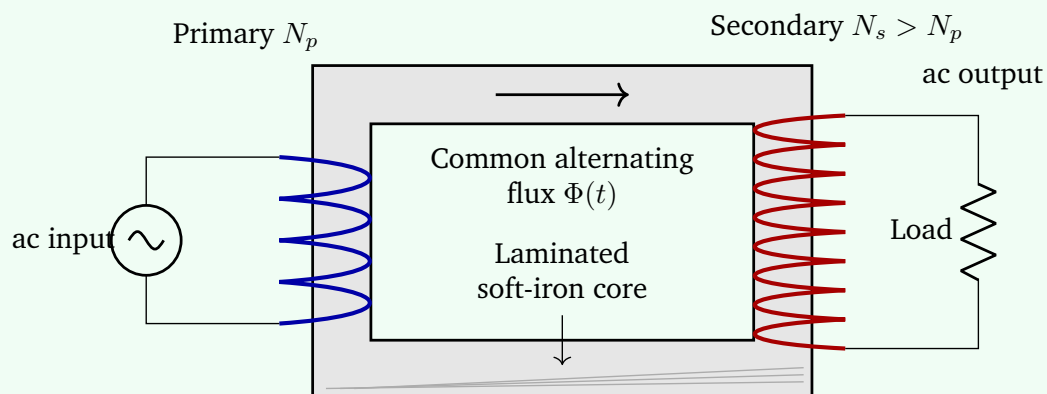
Concept:

- A transformer works on mutual induction: a changing primary current produces changing magnetic flux in the core and induces emf in the secondary coil.
- For an ideal transformer, both coils link the same flux Φ : $e_p = -N_p d\Phi/dt$, $e_s = -N_s d\Phi/dt$. Thus the voltage ratio is $k = N_s/N_p = V_s/V_p$.
- There is no power loss in an ideal transformer. With the usual resistive-load (unity-power-factor) assumption, $P = V_{p,\text{rms}} I_{p,\text{rms}} = V_{s,\text{rms}} I_{s,\text{rms}}$, and a sine wave has rms value equal to its peak divided by $\sqrt{2}$.

Step 1: (i) Explain mutual induction in a step-up transformer The primary coil, with N_p turns, is connected to an ac source. Its alternating current establishes an alternating magnetic flux in the closed soft-iron core. The secondary coil, electrically insulated from the primary, links this flux and acquires an alternating emf by Faraday's law. When a load is connected, current flows through it. The laminated core reduces eddy-current loss and provides a common magnetic path for both coils. Taking the ratio of the two induced emfs eliminates the common rate of change of flux:

$$\frac{|e_s|}{|e_p|} = \frac{N_s}{N_p}, \quad \frac{V_s}{V_p} = \frac{N_s}{N_p}.$$

In a step-up transformer $N_s > N_p$, so the secondary voltage exceeds the primary voltage. The secondary current is correspondingly smaller for the same transferred power. A steady dc supply cannot sustain the changing flux needed for continuous transformer action.



Step-up transformer: more secondary turns link the same alternating core flux (schematic).

Step 2: (ii) Establish the turns ratio and actual input voltage The design values specify the ratio, not

the voltage presently applied:

$$k = \frac{250}{50} = 5.$$

The actual waveform printed in the question is $v_i = 20 \sin(100\pi t)$ V. Therefore its peak voltage is 20 V, its angular frequency is $100\pi \text{ rad s}^{-1}$, and

$$V_{i,\text{rms}} = \frac{20}{\sqrt{2}} = 10\sqrt{2} \text{ V}.$$

Use this rms voltage in the power calculation; using the design voltage 50 V would conflict with the given waveform. For the numerical currents below, take the intended load to have unity power factor, so current and voltage are in phase.

Step 3: (I) Calculate the rms input current The average power drawn is 200 W. With the stated power-factor assumption,

$$I_{i,\text{rms}} = \frac{P}{V_{i,\text{rms}}} = \frac{200}{10\sqrt{2}} = 10\sqrt{2} \text{ A} \approx 14.14 \text{ A}.$$

The corresponding peak input current is $I_{i0} = \sqrt{2}I_{i,\text{rms}} = 20 \text{ A}$.

Step 4: (II) Write the instantaneous output voltage An ideal transformer multiplies the voltage amplitude by its turns ratio while preserving frequency. Choose corresponding terminal polarities so the two measured voltage waveforms have the same phase. Then

$$V_{o0} = kV_{i0} = 5 \times 20 = 100 \text{ V}, \quad v_o(t) = 100 \sin(100\pi t) \text{ V}.$$

The actual output rms voltage is $100/\sqrt{2} = 50\sqrt{2} \text{ V}$; the quoted 250 V would apply when the primary rms voltage is 50 V.

Step 5: (III) Write the instantaneous output current Conservation of average power gives the output rms current, and multiplying by $\sqrt{2}$ gives its peak:

$$I_{o,\text{rms}} = \frac{200}{50\sqrt{2}} = 2\sqrt{2} \text{ A}, \\ I_{o0} = \sqrt{2}(2\sqrt{2}) = 4 \text{ A}.$$

For current through the resistive load in the direction of its voltage drop,

$$i_o(t) = 4 \sin(100\pi t) \text{ A}.$$

Check: the average output power is $V_{o0}I_{o0}/2 = 100 \times 4/2 = 200 \text{ W}$. Strictly, ideal efficiency alone does not specify power factor. If a load phase angle ϕ were allowed, the input rms current would be $10\sqrt{2}/\cos \phi \text{ A}$ and output current would be $(4/\cos \phi) \sin(100\pi t - \phi) \text{ A}$; the printed problem supplies no such angle.

Step 6: Conclusion Mutual induction with $N_s > N_p$ raises the voltage. The turns ratio is 5. Under the intended unity-power-factor assumption, $I_{i,\text{rms}} = 10\sqrt{2} \text{ A}$, $v_o = 100 \sin(100\pi t) \text{ V}$, and $i_o = 4 \sin(100\pi t) \text{ A}$, with the chosen terminal polarity.

Quick Tip to Solve: Use 250/50 only for the turns ratio; use the actual peak 20 V to obtain rms voltage, and convert the calculated rms current back to peak before writing its sine expression.

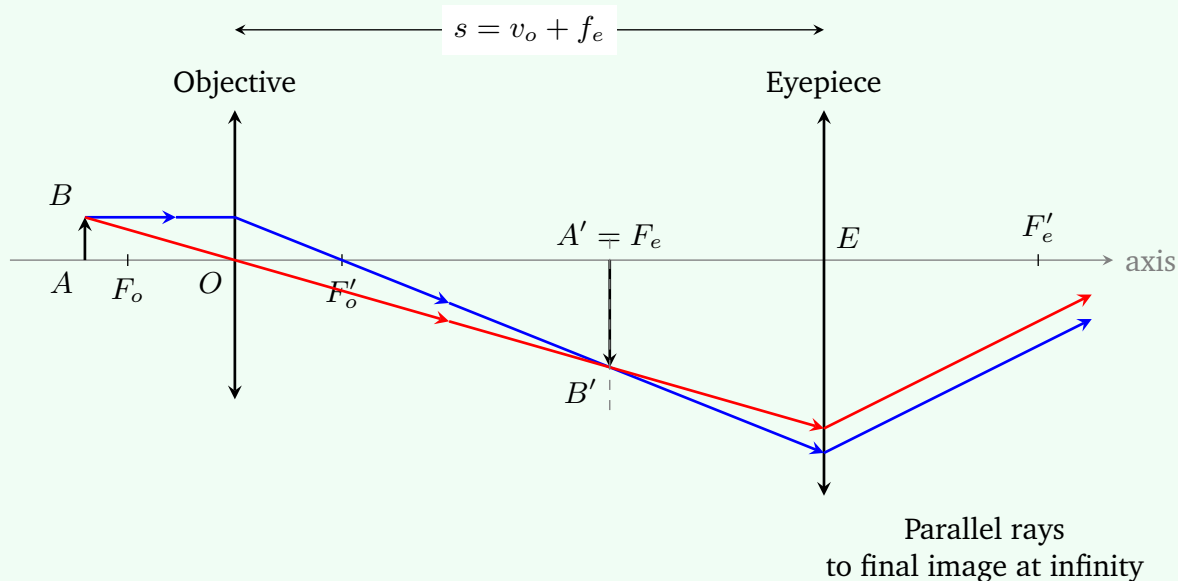
- 32(a).** (i) Draw a ray diagram to show the image formation by a compound microscope. Obtain the expression for the total magnification of the microscope when the final image is formed at infinity.
- (ii) In a compound microscope, an object is placed at a distance of 1.5 cm from the objective of focal length 1.25 cm. The eyepiece has a focal length of 5 cm. The final image is formed at infinity. Calculate the distance between the objective and the eyepiece. [5 marks]

Solution:

Concept:

- A compound microscope uses a short-focal-length objective to form a real, enlarged, inverted intermediate image; the eyepiece acts as a magnifier for this image.
- Total angular magnification is the product $M = m_o m_e$, where $m_o = v_o/u_o$ is the objective's signed linear magnification and $m_e = D/f_e$ for a final image at infinity. Here D is the least distance of distinct vision, conventionally 25 cm.
- For each thin lens, $1/f = 1/v - 1/u$ in the Cartesian sign convention. Normal adjustment requires the intermediate image to lie in the first focal plane of the eyepiece.

Step 1: (i) Construct the ray diagram for normal adjustment Place the object AB just beyond the objective's first focus F_o . The objective forms the real, inverted and enlarged image $A'B'$. Adjust the eyepiece so that A' coincides with its first focus F_e . Rays from B' emerge parallel after refraction by the eyepiece, so the final virtual image is at infinity and the eye views it without accommodation. In the diagram, one ray from B is initially parallel to the axis and refracts through F'_o ; the other passes undeviated through the objective's optical centre O .



Compound microscope in normal adjustment: $A'B'$ lies in the first focal plane of the eyepiece, and the emergent rays are parallel (schematic).

Step 2: Derive the angular magnification Let the object height be h and the magnitude of the intermediate-image height be h' . For small angles, the angle subtended by the unaided object at the near point is $\alpha \simeq h/D$. With the intermediate image in the eyepiece's focal plane, the angle seen through the eyepiece has magnitude $\beta \simeq h'/f_e$. Therefore,

$$|M| = \frac{\beta}{\alpha} = \frac{h'}{h} \frac{D}{f_e} = \frac{v_o}{|u_o|} \frac{D}{f_e}.$$

The final image remains inverted relative to the original object. Thus the signed magnification is

$$M = \frac{v_o}{u_o} \frac{D}{f_e}.$$

Define the optical tube length L as the distance from the objective's second focus F'_o to the intermediate-image plane F_e , so $L = v_o - f_o$. Multiplying the objective lens equation by v_o gives

$$\frac{v_o}{u_o} = 1 - \frac{v_o}{f_o} = -\frac{L}{f_o}, \quad M = -\frac{L}{f_o} \frac{D}{f_e}.$$

Hence the magnifying power is $LD/(f_o f_e)$. In the usual long-tube approximation, $v_o \simeq L$ and $|u_o| \simeq f_o$, giving the same familiar expression. The optical tube length must be distinguished from the actual separation of the two lenses.

Step 3: (ii) Locate the intermediate image numerically Light travels from the object to the objective, so the real object's distance is negative: $u_o = -1.5$ cm. The converging objective has $f_o = +1.25$ cm. Applying the lens formula,

$$\begin{aligned} \frac{1}{v_o} &= \frac{1}{f_o} + \frac{1}{u_o} \\ &= \frac{1}{1.25} - \frac{1}{1.5} = \frac{4}{5} - \frac{2}{3} = \frac{2}{15} \text{ cm}^{-1}, \\ v_o &= 7.5 \text{ cm}. \end{aligned}$$

The positive sign confirms that the intermediate image is real and lies to the right of the objective.

Step 4: Use the infinity condition to find the lens separation For the eyepiece, $v_e \rightarrow \infty$. Its lens formula then gives $u_e = -f_e = -5$ cm. Thus the intermediate image is 5 cm to the left of the eyepiece, whereas it is 7.5 cm to the right of the objective. The separation s is the sum of these positive distances:

$$s = v_o + f_e = 7.5 + 5 = 12.5 \text{ cm}.$$

Step 5: Conclusion For the final image at infinity, $M = -LD/(f_o f_e)$, where L is the optical tube length; its magnitude is $LD/(f_o f_e)$ and the image is inverted. The required objective-to-eyepiece distance is 12.5 cm.

Quick Tip to Solve: For normal adjustment, first calculate the objective image distance exactly and then add the eyepiece focal length; do not substitute the approximate optical tube length for the lens separation.

OR

32(b). (i) Using Huygens' principle, explain the refraction of a plane wavefront, propagating in air, at a plane interface between air and glass. Hence verify Snell's law.

(ii) Use mirror formula to deduce that a convex mirror always produces a virtual image of an object kept in front of it. [5 marks]

Solution:

Concept:

- Huygens' principle: every point on a wavefront emits secondary wavelets; their forward envelope forms the new wavefront. A ray is normal to its wavefront.

- The refractive index is $n = c/v$, where v is the speed in the medium. At an interface the frequency remains unchanged, while speed and wavelength can change.
- For a spherical mirror, $1/f = 1/v + 1/u$, where u , v and f are signed object distance, image distance and focal length in the Cartesian convention.

Step 1: (i) Construct the refracted wavefront Let AB be a plane wavefront incident obliquely from air on a plane air–glass interface. Point A reaches the interface first. Let v_1 be the speed in air and v_2 the speed in glass, with $v_2 < v_1$. In the time t taken by point B of the incident wavefront to reach the interface at C ,

$$BC = v_1 t.$$

Meanwhile the secondary wavelet emitted from A travels a distance $AD = v_2 t$ in glass. Draw the tangent CD from C to this wavelet. It is the common forward envelope of the secondary wavelets in glass, and hence is the refracted plane wavefront. The radius AD is perpendicular to this tangent. The incident ray BC is perpendicular to AB .

Step 2: Relate the geometry to Snell's law The angle between incident wavefront AB and the interface AC equals the angle of incidence i , because their respective normals form the same angle. Similarly, the angle between refracted wavefront CD and AC equals the angle of refraction r . Thus the right triangles ABC and ADC give

$$\sin i = \frac{BC}{AC} = \frac{v_1 t}{AC}, \quad \sin r = \frac{AD}{AC} = \frac{v_2 t}{AC}.$$

Dividing and using $n_1 = c/v_1$, $n_2 = c/v_2$,

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{n_2}{n_1}, \quad n_1 \sin i = n_2 \sin r.$$

This verifies Snell's law. Since glass has the larger refractive index, $r < i$; the rays bend towards the normal. For air, $n_1 \simeq 1$, so $\sin i / \sin r \simeq n_{\text{glass}}$.

Step 3: (ii) Apply the mirror formula with signs Take the pole as the origin and the direction of incident light as positive. A real object in front of a convex mirror has $u = -a$, where $a > 0$. The principal focus of a convex mirror lies behind it, so $f > 0$. Substitution into the mirror formula gives

$$\frac{1}{v} = \frac{1}{f} - \frac{1}{u} = \frac{1}{f} + \frac{1}{a} = \frac{a+f}{af}, \quad v = \frac{af}{a+f}.$$

Both numerator and denominator are positive for every real object position, and $a/(a+f) < 1$. Hence $0 < v < f$: the image is behind the mirror, between its pole and focus. Reflected rays do not actually meet there; only their backward extensions do. The positive image distance therefore establishes that the image is virtual. Also, $m = -v/u = f/(a+f)$ is positive and less than unity, consistent with an erect, diminished image.

Step 4: Conclusion (i) Huygens' construction gives $n_1 \sin i = n_2 \sin r$, verifying Snell's law for refraction from air into glass. (ii) For $u = -a < 0$ and $f > 0$, $v = af/(a+f) > 0$; a convex mirror always gives a virtual image of a real object in front of it.

Quick Tip to Solve: In Huygens' construction use the same time for both distances. For the mirror proof, write $u = -a$ first so the sign of v is evident.

33(a). (i) The electric field in a region is given by $\vec{E} = 40x \hat{i}$ N/C. Find the amount of work done in taking a unit positive charge from a point (0, 3 m) to the point (5 m, 0).

(ii) A charge Q is distributed over two concentric hollow spheres of radii r and R ($> r$) such that their surface charge densities are equal. Find:

(I) the electric field, and

(II) the potential

at their common centre.

[5 marks]

Solution:

Concept:

- Work done by an electric field is $W_{\text{field}} = q \int_A^B \vec{E} \cdot d\vec{l}$. For slow displacement with no change in kinetic energy, the external work is $W_{\text{ext}} = \Delta U = q(V_B - V_A) = -W_{\text{field}}$.
- A uniformly charged spherical shell of radius s and charge q_s produces zero electric field everywhere inside it, but a constant potential kq_s/s , with zero potential at infinity and $k = 1/(4\pi\epsilon_0)$.
- Equal surface charge densities mean $q_s = 4\pi s^2\sigma$. Electric fields add vectorially, whereas electrostatic potentials add algebraically.

Step 1: (i) Set up the work integral The unit positive charge is $q = 1$ C. Write the displacement as $d\vec{l} = dx \hat{i} + dy \hat{j}$. Since $\vec{E} = 40x \hat{i}$ N/C,

$$\vec{E} \cdot d\vec{l} = 40x dx.$$

The field has no y -component, so the change of y from 3 m to zero contributes no work. We integrate from the initial $x = 0$ to the final $x = 5$ m; the nonuniform field cannot be replaced by its final value over the entire displacement.

Step 2: Evaluate the work and specify its sign convention Work done by the field is

$$W_{\text{field}} = (1) \int_0^5 40x dx = 20[x^2]_0^5 = 20(25) = 500 \text{ J}.$$

The potential change is therefore

$$V_B - V_A = - \int_0^5 40x dx = -500 \text{ V}.$$

Thus the work done by an external agent in taking the charge slowly between these points is $W_{\text{ext}} = q(V_B - V_A) = -500$ J. Its negative sign means the field supplies energy and the external agent removes it. The amount of work has magnitude 500 J; specifying the agent distinguishes the two possible signed readings of the wording.

Step 3: (ii) Divide the total charge using equal surface densities Let q_r and q_R be the charges on the inner and outer hollow spheres, and σ their common uniform surface charge density. Then

$$q_r = 4\pi r^2\sigma, \quad q_R = 4\pi R^2\sigma, \quad Q = 4\pi\sigma(r^2 + R^2).$$

Eliminating σ gives

$$q_r = \frac{Qr^2}{r^2 + R^2}, \quad q_R = \frac{QR^2}{r^2 + R^2}.$$

The charges are proportional to the areas, not to the radii; their sum is the specified total charge Q .

Step 4: Find the field and potential at the common centre (I) The common centre lies inside both

uniformly charged spherical shells. The field due to each shell vanishes there by spherical symmetry, so superposition gives

$$\vec{E}_{\text{centre}} = \vec{0} + \vec{0} = \vec{0}.$$

(II) Every element of the inner shell is at distance r from the centre, and every element of the outer shell is at distance R . Their potentials therefore add as

$$\begin{aligned} V_{\text{centre}} &= k \left(\frac{q_r}{r} + \frac{q_R}{R} \right) \\ &= \frac{kQ}{r^2 + R^2} (r + R) = \frac{Q(r + R)}{4\pi\epsilon_0(r^2 + R^2)}. \end{aligned}$$

Zero field at the centre does not imply zero potential: the interior potential is constant, with its value set relative to infinity.

Step 5: Conclusion (i) The work magnitude is 500 J: the field does +500 J, while the external work for slow transfer is -500 J. (ii) At the common centre, $\vec{E} = \vec{0}$ and $V = Q(r + R)/[4\pi\epsilon_0(r^2 + R^2)]$, taking $V(\infty) = 0$.

Quick Tip to Solve: Integrate $E_x dx$ for a varying field and state who does the work. For equal shell densities first divide charge in the ratio $r^2 : R^2$, then add potentials.

OR

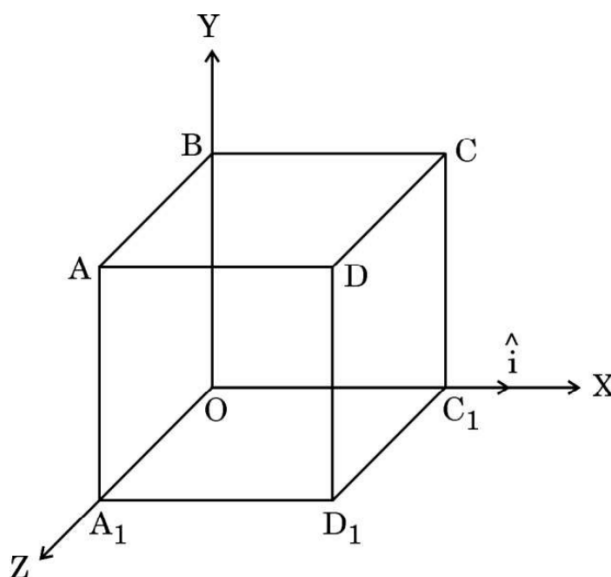
33(b). (i) Obtain an expression for the electric field $\vec{E}$ due to a dipole of dipole moment $\vec{p}$ at a point on its equatorial plane and specify its direction. Hence, find the value of electric field:

(I) at the centre of the dipole ($r = 0$), and

(II) at a point $r \gg a$,

where $2a$ is the length of the dipole.

(ii) An electric field $\vec{E} = (10x + 5)\hat{i}$ N/C exists in a region in which a cube of side L is kept as shown in the figure. Here x and L are in metres. Calculate the net flux through the cube. [5 marks]



Solution:

Concept:

- Superposition: the electric field of a dipole is the vector sum of the fields of its charges. For charges $-q$ and $+q$ separated by $2a$, $\vec{p} = 2qa \hat{p}$, where $\hat{p}$ points from the negative charge to the positive charge.
- Coulomb's law gives a point-charge field of magnitude kq/s^2 at distance s , where $k = 1/(4\pi\epsilon_0)$. Resolve both fields before adding them.
- Electric flux through a surface is $\Phi = \int \vec{E} \cdot d\vec{A}$, where $d\vec{A}$ points outwards for a closed surface. A field parallel to a face contributes zero flux through that face.

Step 1: (i) Set up the equatorial geometry Let O be the dipole midpoint and P a point on the equatorial plane with $OP = r$. Put the charges at position vectors $+a\hat{p}$ and $-a\hat{p}$. Write $\vec{r} = \overrightarrow{OP}$, so that $\vec{r} \cdot \hat{p} = 0$. Both charges are at distance $s = \sqrt{r^2 + a^2}$ from P . The field of the positive charge points away from it, whereas that of the negative charge points towards it. Thus,

$$\begin{aligned}\vec{E}_+ &= \frac{kq(\vec{r} - a\hat{p})}{(r^2 + a^2)^{3/2}}, \\ \vec{E}_- &= -\frac{kq(\vec{r} + a\hat{p})}{(r^2 + a^2)^{3/2}}.\end{aligned}$$

Step 2: (i) Add the fields and specify their direction The components along OP are equal and opposite, so they cancel. Both components parallel to the dipole axis point from $+q$ towards $-q$, and hence add:

$$\begin{aligned}\vec{E} &= \vec{E}_+ + \vec{E}_- \\ &= -\frac{2kqa \hat{p}}{(r^2 + a^2)^{3/2}} \\ &= -\frac{1}{4\pi\epsilon_0} \frac{\vec{p}}{(r^2 + a^2)^{3/2}}.\end{aligned}$$

The field is antiparallel to $\vec{p}$ everywhere on the equatorial plane. This expression is exact for the two separated point charges, without assuming that the observation point is far away.

Step 3: (i)(I) Evaluate the field at the centre At the midpoint, $r = 0$, while the distance from each charge remains a . Substitution in the exact expression gives

$$\vec{E}_O = -\frac{\vec{p}}{4\pi\epsilon_0 a^3}, \quad E_O = \frac{2q}{4\pi\epsilon_0 a^2}.$$

This is finite for a dipole of nonzero length and points from the positive charge to the negative charge. The individual fields at the midpoint reinforce each other; zero potential at the centre does not imply zero electric field.

Step 4: (i)(II) Take the far-field limit For $r \gg a$, the ratio a^2/r^2 is negligible. Therefore,

$$(r^2 + a^2)^{3/2} = r^3 \left(1 + \frac{a^2}{r^2}\right)^{3/2} \simeq r^3,$$

and the equatorial field becomes

$$\vec{E} \simeq -\frac{\vec{p}}{4\pi\epsilon_0 r^3}.$$

Its direction remains opposite to the dipole moment, and its magnitude decreases as the inverse cube of the distance.

Step 5: (ii) Calculate the flux through the cube's faces The cube in the figure extends from $x = 0$ to $x = L$. The field has only an x -component, so the four faces parallel to the x -axis have zero flux. On face $OBAA_1$, at $x = 0$, the outward normal is $-\hat{i}$. On the opposite face C_1CDD_1 , at $x = L$, it is $+\hat{i}$. Each face has area L^2 , and the field is constant over either face. Using the stated SI values,

$$\begin{aligned}\Phi_{x=0} &= -E(0)L^2 = -5L^2, \\ \Phi_{x=L} &= +E(L)L^2 = (10L + 5)L^2, \\ \Phi_{\text{net}} &= [(10L + 5) - 5]L^2 = 10L^3 \text{ N m}^2/\text{C}.\end{aligned}$$

Here L is the numerical side length in metres. The uniform contribution $5\hat{i}$ cancels between the opposing faces; the positive net flux comes from the increase in the field along $+x$.

Step 6: Conclusion The exact equatorial field is $\vec{E} = -\vec{p}/[4\pi\epsilon_0(r^2 + a^2)^{3/2}]$, directed opposite to $\vec{p}$. At the centre it is $-\vec{p}/(4\pi\epsilon_0 a^3)$; for $r \gg a$, it is approximately $-\vec{p}/(4\pi\epsilon_0 r^3)$. The cube's net outward flux is $10L^3 \text{ N m}^2/\text{C}$, with L in metres.

Quick Tip to Solve: Use the exact dipole expression before setting $r = 0$; the far-field formula is invalid there. For $\vec{E} = (Ax + B)\hat{i}$, opposite cube faces cancel B , giving net flux AL^3 .