

# CBSE Class 12 Physics Question Paper 2025 with Solution PDF-Set 55/6/3



## 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 :

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

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

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

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

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

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

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

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

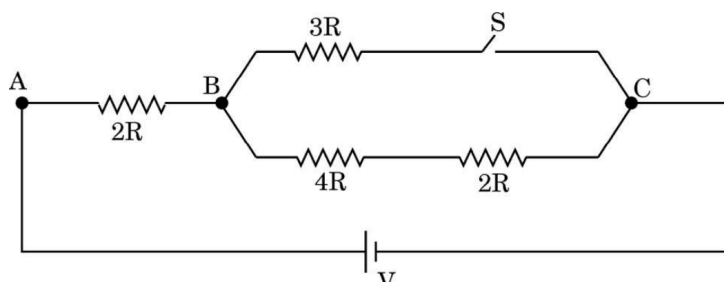
$$\text{Mass of proton} = 1.673 \times 10^{-27} \text{ kg}$$

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

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

### Section A (16 marks)

1. The ratio of potential difference across  $AB$  in the circuit shown for the case (i) when switch  $S$  is closed and (ii) when  $S$  is open is: [1 mark]



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

**Correct Answer:** (D) 2

#### Solution:

##### Concept:

- Series resistances add, while parallel resistances satisfy  $R_p = R_1 R_2 / (R_1 + R_2)$ .
- The potential difference across a resistor is  $V_R = IR$ , where  $I$  is its current. The battery maintains the same voltage  $V$  in both switch positions.

**Step 1: Reduce the circuit with the switch closed** Between B and C, the lower branch has resistance  $4R + 2R = 6R$ . With S closed, it is in parallel with  $3R$ , giving

$$R_{BC} = \frac{3R \times 6R}{3R + 6R} = 2R.$$

This is in series with the  $2R$  between A and B. Hence the total resistance is  $4R$ , the current is  $V/(4R)$ , and  $V_{AB, \text{closed}} = V/2$ .

**Step 2: Reduce the circuit with the switch open** Opening S removes the upper branch. The total resistance becomes  $2R + 4R + 2R = 8R$ , so the current is  $V/(8R)$  and  $V_{AB, \text{open}} = V/4$ . Thus the required closed-to-open ratio is  $(V/2)/(V/4)$ . The value  $1/2$  reverses the requested order;  $1/4$  is the open-case fraction of battery voltage, and unity wrongly assumes the current stays unchanged.

**Step 3: Conclusion**  $V_{AB, \text{closed}}/V_{AB, \text{open}} = 2$ . Hence, the correct option is (D).

**Quick Tip to Solve:** Since the same AB resistor is used in both cases, its voltage ratio equals the current ratio: compare the inverse total resistances.

2. 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:**

- Two coherent waves of intensities  $I_1$  and  $I_2$  give  $I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \phi$ , where  $\phi$  is their phase difference at a point.
- Across a complete fringe pattern, the spatial average of  $\cos \phi$  is zero: bright fringes redistribute light from dark fringes without changing its average energy.

**Step 1: Write the intensity for equal incident waves** Substitute  $I_1 = I_2 = I_0$  in the interference formula:

$$I = 2I_0 + 2I_0 \cos \phi.$$

The phase difference changes with position on the screen, so the intensity ranges from zero at dark fringes to  $4I_0$  at bright fringes.

**Step 2: Average over the fringe pattern** Taking the spatial average over complete fringes gives  $\langle I \rangle = 2I_0 + 2I_0 \langle \cos \phi \rangle$ . The interference term averages to zero. Thus option (A) describes a minimum, option (D) a maximum, and option (B) only one incident wave's intensity; none is the average of the combined pattern.

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

**Quick Tip to Solve:** For the average over a full interference pattern, add the individual intensities; do not substitute only the bright-fringe phase.

3. A particle of mass  $m$  and charge  $q$  moving with velocity  $v\hat{i}$  is subjected to a uniform electric field  $E\hat{j}$ . The particle will initially have a tendency to move in a circle of radius: [1 mark]

- (A)  $\left(\frac{mv}{qE}\right)$  in x-y plane  
(B)  $\left(\frac{mv^2}{qE^2}\right)$  in x-z plane  
(C)  $\left(\frac{mv^2}{qE}\right)$  in x-y plane  
(D)  $\left(\frac{mv}{qE^2}\right)$  in y-z plane

**Correct Answer:** (C)  $\left(\frac{mv^2}{qE}\right)$  in x-y plane

**Solution:**

**Concept:**

- The electric force is  $\vec{F} = q\vec{E}$ . Initially the force along the y-axis is perpendicular to the velocity along the x-axis.
- The instantaneous radius of curvature satisfies  $mv^2/r = |q|E$ , where  $v$  is the initial speed and  $|q|$  the charge magnitude.

**Step 1: Identify the initial plane of bending** The initial velocity is  $v\hat{i}$  and the acceleration is  $(qE/m)\hat{j}$ . Both lie in the x-y plane, and there is no z-component of acceleration or velocity. Therefore the initial bending cannot be in the x-z or y-z plane, excluding (B) and (D).

**Step 2: Calculate the instantaneous curvature** At entry the entire electric acceleration is normal to the velocity. Equating its magnitude to the normal acceleration gives

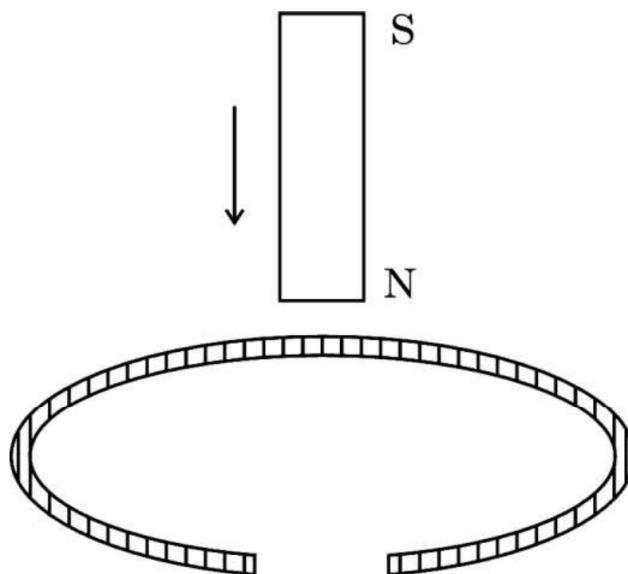
$$r = \frac{v^2}{|q|E/m} = \frac{mv^2}{|q|E}.$$

The printed options use  $q$  as the positive charge magnitude. Option (A) lacks one power of  $v$  and is dimensionally not a length. This is the initial radius of curvature: a constant electric force subsequently produces a parabola, not sustained circular motion.

**Step 3: Conclusion** The initial radius of curvature is  $mv^2/(qE)$  in the x-y plane, with  $q$  understood as the charge magnitude. Hence, the correct option is (C).

**Quick Tip to Solve:** For an initial bend, use only the acceleration perpendicular to the initial velocity in  $r = v^2/a_{\perp}$ ; a circular initial curvature does not imply a circular trajectory.

4. 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:**

- A changing magnetic flux produces an induced emf according to Faraday's law,  $\varepsilon = -d\Phi_B/dt$ , where  $\Phi_B$  is magnetic flux.
- A sustained current around a conducting ring requires a closed path. Lenz's law gives a magnetic force opposing motion only when the induced current can flow.

**Step 1: Check whether an induced ring current can flow** As the magnet falls, its flux through the copper ring changes. However, the visible cut makes the ring an open circuit. An emf can appear across the cut, but a circulating induced current cannot flow in the ideal ring model.

**Step 2: Identify the force on the magnet** With no induced ring current, there is no magnetic braking force from the ring. Neglecting air resistance, the force on the magnet is its weight  $mg$ , so Newton's law gives  $ma = mg$ . A value less than  $g$  would apply to a closed conducting ring that opposes the falling motion. Neither zero acceleration nor acceleration greater than  $g$  follows from the forces here.

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

**Quick Tip to Solve:** Before using Lenz's law to predict magnetic braking, check that the conducting ring is closed; a cut prevents the circulating current.

5. 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 binds nucleons and is approximately charge independent: at comparable separations, its strength is the same for proton-proton, proton-neutron and neutron-neutron pairs.
- Nuclear force must be distinguished from electrostatic force. Protons also repel electrically, but that Coulomb contribution is not part of the nuclear force being compared.

**Step 1: Identify the interaction requested** The question explicitly compares the nuclear forces  $F_{pp}$ ,  $F_{pn}$  and  $F_{nn}$ . It does not ask for the total force after adding the Coulomb repulsion between two protons. Hence the presence or absence of electric charge does not rank these nuclear-force strengths.

**Step 2: Apply charge independence** In the standard nuclear-force model used here, replacing a proton by a neutron does not change the nuclear interaction strength for comparable nucleon configurations. Therefore no strict inequality among the three given nuclear forces is justified. All of (A), (B) and (C) incorrectly assign a charge-based ordering.

**Step 3: Conclusion**  $F_{pp} = F_{pn} = F_{nn}$ , expressing charge independence of nuclear forces. Hence, the correct option is (D).

**Quick Tip to Solve:** Underline the word nuclear: do not add the extra proton-proton Coulomb repulsion when comparing only nuclear-force strengths.

6. 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 current, while the ideal inductor voltage  $V_L$  leads it by  $90^\circ$ .
- Perpendicular voltage phasors add by  $V = \sqrt{V_R^2 + V_L^2}$ , where all voltage magnitudes must be expressed consistently, such as rms values.

**Step 1: Identify the phase relation** The given 8 V across the resistor and 6 V across the inductor are not in phase. The source voltage is the vector sum of their perpendicular phasors, not the arithmetic

sum of their magnitudes.

**Step 2: Add the voltage phasors** Apply the Pythagorean relation:

$$V^2 = (8\text{ V})^2 + (6\text{ V})^2 = 100\text{ V}^2.$$

The arithmetic sum 14 V, option (C), would require in-phase voltages. Options (B) and (D) also fail the squared-magnitude relation; 16 V even exceeds the sum of the two magnitudes.

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

**Quick Tip to Solve:** Recognise the 6-8-10 right triangle whenever resistor and inductor voltages are 6 V and 8 V; their phasors are perpendicular.

**7. A proton and an  $\alpha$ -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 motion perpendicular to a uniform magnetic field, magnetic force supplies the centripetal force:  $|q|vB = mv^2/r$ , hence  $r = mv/(|q|B)$ .
- 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** Both particles enter the same field with the same speed, so the factors  $v$  and  $B$  cancel when comparing radii. Radius is therefore proportional to  $m/|q|$ , not mass alone or charge alone.

**Step 2: Form the proton-to-alpha radius ratio** In the order given in the question,

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

The alpha-particle has twice the mass-to-charge ratio and thus twice the radius. Option (A) reverses the requested ratio. Option (C) incorrectly retains only the mass ratio, while (D) ignores both the charge factor and the requested order.

**Step 3: Conclusion** The ratio of the proton radius to the alpha-particle radius is  $1/2$ . Hence, the correct option is (B).

**Quick Tip to Solve:** At equal speeds in the same magnetic field, compare mass divided by charge: the alpha-particle gives  $4/2 = 2$  times the proton radius.

8. 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:**

- For resistors in series, the same current flows through each and their resistances add:  $R_s = R_1 + R_2 + \dots + R_n$ .
- For resistors in parallel, each has the same potential difference and the reciprocal resistances add:  $1/R_p = 1/R_1 + 1/R_2 + \dots + 1/R_n$ .

**Step 1: Calculate the two equivalent resistances** Since all  $n$  resistors have resistance  $R$ , the series combination gives  $R_s = nR$ . In parallel,  $1/R_p = n/R$ , so  $R_p = R/n$ . Increasing the number therefore increases the series resistance but reduces the parallel resistance.

**Step 2: Subtract using a common denominator** The required difference is

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

Option (A) has an extra factor of  $n$  in the denominator. Options (B) and (D) contain  $n^2 + 1$ , whereas subtraction requires  $n^2 - 1$ ; neither represents this difference.

**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  $R/n$  before subtracting; the common denominator is  $n$ , not  $n^2$ .

9. 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:**

- Diamagnetic materials acquire a weak induced magnetisation opposite to the applied magnetic field; their magnetic susceptibility  $\chi$  is negative.
- A magnetic force causing translational motion requires a field gradient. For a small isotropic

specimen of volume  $V$ ,  $F_x = \chi V d(B^2)/dx / (2\mu_0)$ , where  $B$  is the applied magnetic field.

**Step 1: Use the uniformity of the field** A uniform magnetic field has the same magnitude throughout the region occupied by the material. Therefore  $d(B^2)/dx = 0$ , and similarly for the other directions. The net translational magnetic force on the specimen is consequently zero.

**Step 2: Distinguish magnetisation from displacement** Opposite magnetisation does not mean motion opposite to the field. A diamagnet moves towards a weaker field only when a field gradient exists. Thus motion along the field, opposite to it, or perpendicular to it cannot follow here; options (A), (B), and (C) all wrongly predict translational motion in a uniform field.

**Step 3: Conclusion** The material does not move under the action of the uniform magnetic field. Hence, the correct option is (D).

**Quick Tip to Solve:** Underline the word “uniform”: a diamagnet needs a field gradient to move towards a weaker-field region.

**10. The wavelength of a photon is equal to the wavelength associated with an electron. Both will have the same value of:** [1 mark]

- (A) energy
- (B) angular momentum
- (C) velocity
- (D) linear momentum

**Correct Answer:** (D) linear momentum

**Solution:**

**Concept:**

- For a particle of momentum magnitude  $p$ , the de Broglie wavelength is  $\lambda = h/p$ , where  $h$  is Planck's constant.
- A photon also obeys  $p = h/\lambda$ , and its energy is  $E = pc$ , where  $c$  is the speed of light in vacuum.

**Step 1: Compare the momenta at the common wavelength** Denote the common wavelength by  $\lambda$ . The photon momentum is  $p_\gamma = h/\lambda$ , and the electron momentum is  $p_e = h/\lambda$ . Therefore the magnitudes of their linear momenta are equal, regardless of their different masses.

**Step 2: Check the other proposed equalities** Equal momenta do not imply equal energies: a nonrelativistic electron has kinetic energy  $p^2/(2m_e)$ , whereas a photon has energy  $pc$ . The photon travels at  $c$ , but the massive electron travels slower than  $c$ . Angular momentum depends on additional information such as position and direction, so equality of wavelengths does not ensure equal angular momentum. Hence (A), (B), and (C) are not implied.

**Step 3: Conclusion** Both have the same magnitude of linear momentum,  $h/\lambda$ . Hence, the correct option is (D).

**Quick Tip to Solve:** Whenever wavelengths of different particles are equal, apply  $p = h/\lambda$  first; their energy formulae can differ.

11. 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 carries only a small full-scale current  $I_g$ . An ammeter must measure a larger total current while offering a small resistance to the circuit.
- A shunt resistance  $S$  in parallel with a galvanometer of resistance  $G$  diverts the excess current; equal branch voltages give  $I_g G = (I - I_g)S$ , where  $I$  is the desired range.

**Step 1: Provide a path for the excess current** At full-scale deflection only  $I_g$  should flow through the galvanometer. The remaining current  $I - I_g$  must bypass it. A parallel connection supplies this separate path, while a series resistance would still make the entire circuit current flow through the galvanometer.

**Step 2: Choose the resistance of the parallel path** From equal potential differences,

$$S = \frac{I_g G}{I - I_g}.$$

The shunt is small so that it carries most of the current and keeps the effective meter resistance low. A large parallel resistance would not bypass enough current. A large series resistance is instead used for conversion to a voltmeter; neither series option gives the required ammeter arrangement.

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

**Quick Tip to Solve:** An ammeter needs a low-resistance bypass: remember “small shunt in parallel” and use  $S = I_g G / (I - I_g)$ .

12. The momentum (in kg m/s) of a photon of frequency  $6.0 \times 10^{14}$  Hz is: [1 mark]

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

**Correct Answer:** (B)  $1.326 \times 10^{-27}$

**Solution:**

**Concept:**

- A photon of frequency  $\nu$  has energy  $E = h\nu$ , where  $h = 6.63 \times 10^{-34}$  J s is Planck's constant.
- Photon energy and momentum obey  $E = pc$ , so  $p = h\nu/c$ , with  $c = 3.0 \times 10^8$  m s<sup>-1</sup>.

**Step 1: Calculate the photon energy** Substitute the stated frequency  $\nu = 6.0 \times 10^{14}$  Hz:

$$E = (6.63 \times 10^{-34})(6.0 \times 10^{14}) = 3.978 \times 10^{-19} \text{ J.}$$

**Step 2: Divide the energy by the speed of light** Since a photon has zero rest mass, use  $p = E/c$ , not the massive-particle expression  $mv$ :

$$p = \frac{3.978 \times 10^{-19}}{3.0 \times 10^8} = 1.326 \times 10^{-27} \text{ kg m s}^{-1}.$$

The exponent becomes  $-19 - 8 = -27$ , and the coefficient is  $3.978/3 = 1.326$ . Option (A) has an incorrect exponent and coefficient; (C) and (D) also fail this substitution. The stated options retain the coefficient to four significant figures.

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

**Quick Tip to Solve:** For a photon use  $h\nu/c$  directly, and subtract the denominator exponent after multiplying  $h$  by  $\nu$ .

**13. 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:**

- In an X-ray tube, electrons accelerated through a large potential difference acquire high kinetic energy and strike a metal target of high atomic number.
- X-rays have high frequencies and short wavelengths. Their photon energy is  $E = h\nu = hc/\lambda$ , with  $h$  Planck's constant,  $\nu$  frequency and  $\lambda$  wavelength.

**Step 1: Evaluate Assertion (A)** The assertion specifies slow-moving electrons. X-rays are produced when fast, energetic electrons are rapidly decelerated on striking the target. Slow electrons lack the necessary kinetic energy for the usual X-ray emission process. The target's high atomic number alone cannot supply this energy, so Assertion (A) is false.

**Step 2: Evaluate Reason (R)** X-ray photons have high energy compared with visible and lower-frequency electromagnetic radiation because their frequency is high. Calling them low-energy photons is therefore incorrect in this context. Reason (R) is false.

**Step 3: Check the proposed explanatory relation** Since both statements are false, the reason cannot explain the assertion. Options (A) and (B) require both statements to be true, while (C) requires a

true assertion; all three conflict with the separate evaluations.

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

**Quick Tip to Solve:** Check the two key adjectives: X-ray production needs fast electrons, and X-rays consist of high-energy photons.

**14. 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  $B/A$ , where  $B$  is the energy needed to separate the nucleus into its nucleons and  $A$  is its mass number.
- Nuclear forces are short-range and exhibit saturation: a nucleon interacts strongly mainly with its nearest neighbours, not with every nucleon in a large nucleus.

**Step 1: Evaluate Assertion (A)** For intermediate nuclei in the stated range  $30 < A < 170$ , the binding energy per nucleon varies only moderately around roughly 8 MeV. The word “practically” allows this small variation, including the broad maximum near iron. Therefore the assertion is true.

**Step 2: Evaluate Reason (R)** Nuclear forces remain short-range in these nuclei, acting appreciably only over distances of a few femtometres. The claim that they are not short-range is false; the mass-number interval does not turn the nuclear interaction into a long-range force.

**Step 3: Test whether the reason explains the assertion** The near constancy actually follows from saturation caused by the short range: each interior nucleon has approximately the same number of strongly interacting neighbours. Thus the total binding energy grows approximately with  $A$ . The printed reason denies this property, so it cannot explain the true assertion. Options requiring a true reason or a false assertion are excluded.

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

**Quick Tip to Solve:** Link a nearly flat  $B/A$  curve to saturation: short-range forces give each nucleon only a limited set of neighbours.

**15. 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 failure of different colours to focus at the same point because a refracting lens has a wavelength-dependent refractive index.
- A reflecting telescope uses a concave mirror as its objective; its focal length  $f = R/2$ , where  $R$  is the radius of curvature, is independent of colour.

**Step 1: Evaluate the assertion** The objective forms the image by reflection. The law of reflection is the same for all wavelengths, so the objective brings different colours to the same focus. Assertion (A) is true.

**Step 2: Evaluate the reason** In the geometrical-optics context of this question, chromatic aberration arises from dispersion during refraction through an optical medium. Different colours have different refractive indices and hence different focal lengths in a lens. Reason (R) is true.

**Step 3: Check the explanatory link** The mirror objective avoids the colour-dependent refraction responsible for chromatic aberration. Thus the reason explains the assertion; the choice saying there is no explanatory link is incorrect, as are choices declaring either statement false.

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

**Quick Tip to Solve:** Identify the telescope objective: a mirror has a common geometrical focus for all colours, whereas a lens disperses them.

**16. 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 vacant electronic state in an otherwise nearly filled valence band, produced when a valence electron leaves that state.
- Motion of neighbouring valence electrons into a vacancy is described as motion of a hole with effective charge  $+e$ , where  $e$  is the magnitude of electronic charge.

**Step 1: Evaluate the assertion** A hole is not a separate positively charged atom or an actual free proton. It is a useful apparent carrier: successive electron transfers make the vacancy move through the crystal and carry conventional current as if it had positive electronic charge. Assertion (A) is true.

**Step 2: Evaluate the reason** In the semiconductor band model, a hole is precisely the vacancy left in the valence band by a missing electron. The statement that it is not necessarily such a vacancy contradicts this definition. Reason (R) is false.

**Step 3: Check the explanatory link** Since the reason itself is false, it cannot explain the true assertion. Both choices requiring a true reason are excluded; the choice declaring the assertion false is also excluded.

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

**Quick Tip to Solve:** Track an electron moving into an adjacent vacancy: the vacancy moves oppositely and behaves as a positive carrier.

**Section B (10 marks)**

**17. 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:**

- An  $n$ -type semiconductor is obtained by adding pentavalent donor impurities. Each ionised donor supplies a conduction electron without producing a valence-band hole.
- Thermal generation creates electron-hole pairs, while recombination removes an electron and a hole together. At thermal equilibrium these processes balance.

**Step 1: Identify the source of excess electrons** Four valence electrons of a donor atom form covalent bonds with neighbouring semiconductor atoms. Its loosely bound fifth electron can enter the conduc-

tion band at room temperature, leaving an immobile positive donor ion. This produces an additional conduction electron, but no corresponding hole in the valence band.

**Step 2: Compare the effects of generation and recombination** Thermal generation adds one electron and one hole at a time, and recombination removes one of each. Neither process removes the excess of electrons contributed by the donor atoms. For an uncompensated sample, charge neutrality gives

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

where  $n$  and  $p$  are the electron and hole concentrations and  $N_D^+$  is the concentration of ionised donors. The positive donor ions balance the extra electrons, so the material remains electrically neutral even though  $n > p$ .

**Step 3: Conclusion** Donor impurities supply electrons without supplying holes. Thus electrons remain the majority carriers and holes the minority carriers despite continuous electron-hole recombination and thermal generation.

**Quick Tip to Solve:** Separate donor ionisation from pair generation: only pair generation creates equal numbers of mobile electrons and holes.

**18. (a)** What is the difference between ‘velocity’ and ‘drift velocity’ of electrons in a current-carrying conductor.

**(b)** A copper wire of uniform cross-sectional area carries a current of 3.4 A. The drift velocity of conduction electrons is 0.2 mm/s. If the number density of electrons in copper is  $8.5 \times 10^{28} \text{ m}^{-3}$ , find the area of cross-section of the wire. [2 marks]

**Solution:**

**Concept:**

- Electron velocity is the instantaneous velocity of an individual electron. Drift velocity is the small average velocity acquired by the ensemble of electrons under an applied electric field.
- The magnitude of current in a uniform wire is  $I = neAv_d$ , where  $n$  is the free-electron number density,  $e$  is the magnitude of electronic charge,  $A$  is the cross-sectional area and  $v_d$  is the drift speed.

**Step 1: Distinguish the velocities in part (a)** An electron has a rapidly changing instantaneous velocity because of its random motion and collisions. Without an electric field the random velocities average to zero. In a current-carrying conductor, a small directed average is superposed on this motion. This average is the drift velocity; for electrons it is opposite to the electric field and to conventional current. It is much smaller than the typical speed of the random motion.

**Step 2: Convert the drift speed in part (b)** Use SI units before substituting. The stated drift speed is

$$v_d = 0.2 \text{ mm s}^{-1} = 2.0 \times 10^{-4} \text{ m s}^{-1}.$$

Also,  $I = 3.4 \text{ A}$ ,  $n = 8.5 \times 10^{28} \text{ m}^{-3}$ , and  $e = 1.6 \times 10^{-19} \text{ C}$ .

**Step 3: Calculate the cross-sectional area** Rearranging the current relation gives

$$\begin{aligned} A &= \frac{I}{nev_d} \\ &= \frac{3.4}{(8.5 \times 10^{28})(1.6 \times 10^{-19})(2.0 \times 10^{-4})} \\ &= \frac{3.4}{2.72 \times 10^6} \text{ m}^2 = 1.25 \times 10^{-6} \text{ m}^2. \end{aligned}$$

**Step 4: Conclusion** (a) Instantaneous electron velocity varies randomly, whereas drift velocity is its directed average due to the applied field. (b) The wire's cross-sectional area is  $1.25 \times 10^{-6} \text{ m}^2 = 1.25 \text{ mm}^2$ .

**Quick Tip to Solve:** Convert millimetres per second to metres per second before using  $I = neAv_d$ ; the area then comes out directly in square metres.

**19(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:**

- For two coherent waves of individual intensities  $I_1$  and  $I_2$ , the resultant intensity is  $I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \phi$ , where  $\phi$  is their phase difference.
- A path difference  $\Delta$  produces phase difference  $\phi = 2\pi\Delta/\lambda$ . For  $I_1 = I_2 = I_0$ , this gives  $I = 2I_0(1 + \cos \phi)$ .

**Step 1: Evaluate the first path difference** In part (i), the printed path difference is  $\Delta = \lambda/3$ . Its phase difference is

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

Since  $\cos(2\pi/3) = -1/2$ , the interference term reduces the sum of the individual intensities:

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

This is partial destructive interference; the waves are not exactly opposite in phase.

**Step 2: Evaluate the second path difference** In part (ii), the printed path difference is  $\Delta = \lambda/2$ , so

$$\phi = \frac{2\pi}{\lambda} \frac{\lambda}{2} = \pi.$$

The waves now have equal amplitudes and opposite phases. Therefore,

$$I = 2I_0(1 + \cos \pi) = 2I_0(1 - 1) = 0.$$

This point lies on a dark fringe. Complete cancellation is possible because the two incident intensities are equal.

**Step 3: Conclusion** The resultant intensity is (i)  $I_0$  for path difference  $\lambda/3$ , and (ii) zero for path difference  $\lambda/2$ .

**Quick Tip to Solve:** Convert path difference into phase first:  $\lambda/3$  means  $120^\circ$ , while  $\lambda/2$  means  $180^\circ$  and a dark fringe.

OR

**19(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:**

- Refraction at a spherical surface obeys  $\frac{n_2}{v} - \frac{n_1}{u} = \frac{n_2 - n_1}{R}$ , where  $n_1, n_2$  are the refractive indices of the incident and refracting media.
- Measure all distances from the pole. Taking the incident light direction as positive, a real object has  $u < 0$ ; a negative image distance indicates a virtual image on the incident side.

**Step 1: Assign the signed distances** Light travels from air into glass, so  $n_1 = 1$  and  $n_2 = 1.5$ . The source is in front of the surface, giving  $u = -12$  cm. The centre of curvature of the convex glass surface lies inside the glass, along the incident light direction, so  $R = +30$  cm.

**Step 2: Apply the spherical refraction formula** Using centimetres consistently for all three distances,

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

The refracted rays diverge; their backward extensions meet on the air side of the surface. Thus the sign of the computed distance determines the image nature directly.

**Step 3: Conclusion** The image is virtual and is formed 22.5 cm in front of the spherical surface, on the same side as the source ( $v = -22.5$  cm).

**Quick Tip to Solve:** For air-to-glass refraction at a convex surface, write  $u < 0$  and  $R > 0$  before substitution; the sign of  $v$  then tells you the image side.

**20.** An alpha particle and a deuterium ion are accelerated through the same potential difference. These are then directed towards a target nucleus to make head-on collision. It is observed that their distance of closest approach is the same. Justify it theoretically. [2 marks]

**Solution:**

**Concept:**

- A positive ion of charge  $q$ , accelerated from rest through a potential difference  $V$ , gains kinetic energy  $K = qV$ .
- In a head-on approach to a heavy target nucleus of charge  $Ze$ , electrostatic repulsion converts the ion's kinetic energy into electric potential energy. At closest approach  $r_0$ ,  $K = \frac{1}{4\pi\epsilon_0} \frac{qZe}{r_0}$ .

**Step 1: Derive the closest-approach distance** Treat the heavy target nucleus as stationary and take the initial electrostatic potential energy far from it as zero. At the turning point, the incident particle is momentarily at rest. Conservation of energy gives

$$qV = \frac{1}{4\pi\epsilon_0} \frac{qZe}{r_0} \Rightarrow r_0 = \frac{Ze}{4\pi\epsilon_0 V}.$$

The incident charge cancels because increasing it increases both the accelerating energy and the repulsive potential energy by the same factor. The particle mass also does not appear.

**Step 2: Compare the two incident ions** The alpha particle has charge  $2e$  and kinetic energy  $2eV$ ; the deuterium ion has charge  $e$  and kinetic energy  $eV$ . Therefore,

$$r_\alpha = \frac{(2e)(Ze)}{4\pi\epsilon_0(2eV)}, \quad r_d = \frac{e(Ze)}{4\pi\epsilon_0(eV)}.$$

Both expressions reduce to the same value for the same target and accelerating potential, although the two particles need not have equal speeds.

**Step 3: Conclusion** Their distances of closest approach are equal:  $r_\alpha = r_d = \frac{Ze}{4\pi\epsilon_0 V}$ , since their kinetic energies and Coulomb repulsions scale in the same proportion with their charges.

**Quick Tip to Solve:** For ions accelerated through the same voltage, substitute  $K = qV$  into the closest-approach formula before comparing charges or masses.

**21.** A tank is filled with a liquid of refractive index  $\sqrt{2}$ , up to a height of 30 cm. A tiny bulb is glowing at the bottom of the tank. Calculate the diameter of an opaque disc floating symmetrically on the liquid surface that can cut off completely the light from the bulb that comes out of the liquid surface. [2 marks]

**Solution:**

**Concept:**

- Light travelling from a denser liquid into air can escape only for incidence angles up to the critical angle  $C$ , where  $\sin C = 1/\mu$  and  $\mu$  is the liquid's refractive index relative to air.
- For a point source at depth  $h$ , the limiting cone of escaping rays meets the horizontal surface in a circle of radius  $r = h \tan C$ . A centred opaque disc must cover this circle.

**Step 1: Calculate the critical angle** Here  $\mu = \sqrt{2}$ , so Snell's law for a refracted ray grazing the surface

gives

$$\sqrt{2} \sin C = \sin 90^\circ = 1 \Rightarrow C = 45^\circ.$$

Rays incident at angles greater than this value undergo total internal reflection and do not emerge into air. The disc needs to block only the surface region reached by rays within this limiting cone.

**Step 2: Find the radius of the escape circle** Consider the right triangle formed by the bulb, the point vertically above it on the liquid surface, and a point on the edge of the escape circle. The angle between the limiting ray and the vertical normal is  $C$ . With  $h = 30$  cm,

$$\tan C = \frac{r}{h} \Rightarrow r = 30 \tan 45^\circ = 30 \text{ cm}.$$

The disc must be centred vertically above the bulb. Covering the entire circle ensures that every ray which could leave the liquid through the upper surface encounters the opaque disc.

**Step 3: Conclusion** The minimum diameter of the opaque disc is  $D = 2r = 2(30) = 60$  cm.

**Quick Tip to Solve:** First calculate  $C$ , then use  $D = 2h \tan C$ ; remember that  $h \tan C$  gives the radius, not the requested diameter.

### Section C (21 marks)

**22. 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 their wavelength  $\lambda$  or frequency  $\nu$ , related in vacuum by  $c = \nu\lambda$ . Their wavelength influences their interaction with matter and therefore their applications.
- The approximate conventional wavelength bands are used here; their boundaries are not perfectly sharp. Microwaves have longer wavelengths than ultraviolet radiation, while X-rays have still shorter wavelengths.

**Step 1: Identify the waves used in radar** (i) **Microwaves** are used in radar. They can be directed into narrow beams and reflected from objects; the delay of the reflected signal is used to find the target distance. Their approximate wavelength range is

$$1 \text{ mm to } 0.1 \text{ m} \quad (10^{-3} \text{ m to } 10^{-1} \text{ m}).$$

**Step 2: Identify the waves used in eye surgery** (ii) **Ultraviolet radiation** is used in procedures such as laser reshaping of the cornea. A focused ultraviolet laser can remove very thin layers of corneal tissue with precision. The ultraviolet band has an approximate wavelength range of

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

A particular surgical laser operates at a selected wavelength within this band.

**Step 3: Identify the waves used in medical diagnosis** (iii) **X-rays** are used as a diagnostic tool in medicine. Their penetration and the different absorption by bone and soft tissue allow internal structures to be imaged. Their approximate wavelength range is

$$10^{-3} \text{ nm to } 1 \text{ nm} \quad (10^{-12} \text{ m to } 10^{-9} \text{ m}).$$

Medical imaging uses a suitable part of the X-ray band depending on the required penetration.

**Step 4: Conclusion** The required waves are (i) microwaves:  $10^{-3}$  to  $10^{-1}$  m; (ii) ultraviolet:  $10^{-9}$  to  $4 \times 10^{-7}$  m; and (iii) X-rays:  $10^{-12}$  to  $10^{-9}$  m, with approximate band limits.

**Quick Tip to Solve:** Match the applications in order: radar–microwaves, corneal surgery–ultraviolet, diagnostic radiography–X-rays; use  $1 \text{ nm} = 10^{-9} \text{ m}$  to check the ranges.

**23. (a) Differentiate between ‘nuclear fission’ and ‘nuclear fusion’. Briefly discuss one example of each.**

**(b) Draw a graph of potential energy between a pair of nucleons as a function of their separation.**

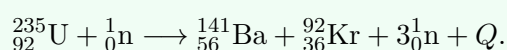
[3 marks]

**Solution:**

**Concept:**

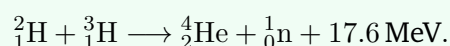
- Nuclear fission splits a heavy nucleus; nuclear fusion combines light nuclei. Energy is released when the products have greater binding energy per nucleon, with the mass decrease supplying  $Q = \Delta mc^2$ .
- For nucleon separation  $r$ , the nuclear potential energy  $U(r)$  is taken as zero at large separation. The force is  $F_r = -dU/dr$ ; its sign follows the slope of the potential curve.

**Step 1: (a) Explain fission with an example** In fission a heavy nucleus splits into two lighter nuclei, usually after absorbing a neutron, releasing energy and additional neutrons. One possible uranium reaction is



Both charge and nucleon number are conserved:  $92 = 56 + 36$  and  $236 = 141 + 92 + 3$ . The released neutrons can induce further fissions, producing a chain reaction; controlled fission supplies energy in nuclear reactors.

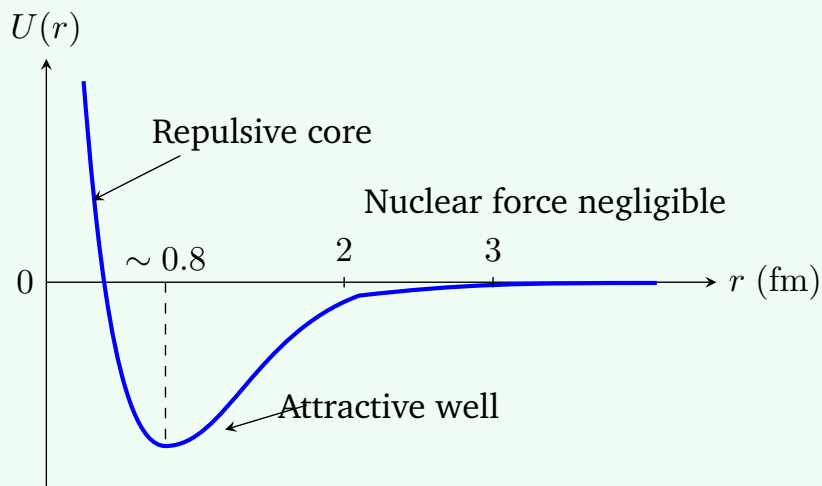
**Step 2: (a) Explain fusion with an example** In fusion two light nuclei combine to form a heavier nucleus. For example, deuterium and tritium can fuse as



Unlike neutron-induced fission, fusion of positively charged nuclei requires extremely high temperature to overcome their electrostatic repulsion and bring them within the range of nuclear attraction. Fusion reactions are the source of stellar energy.

**Step 3: (b) Sketch and interpret the nuclear potential** The schematic graph has a steep positive core at very small separation, a negative potential well at intermediate separation, and approaches zero beyond a few femtometres. Here  $1 \text{ fm} = 10^{-15} \text{ m}$ . The minimum occurs at a separation of order  $0.8 \text{ fm}$ . On the inner side the slope is negative and the force is repulsive; outside the minimum the slope is

positive and the force is attractive. At large separation the slope and hence the nuclear force become negligible. This short range explains why a nucleon interacts strongly only with nearby nucleons.



*Schematic nuclear potential energy versus nucleon separation (not to scale).*

**Step 4: Conclusion** Fission breaks a heavy nucleus into lighter nuclei, whereas fusion joins light nuclei; both can release binding energy. The nucleon potential has a repulsive core, an attractive well and a negligible long-range tail, as shown.

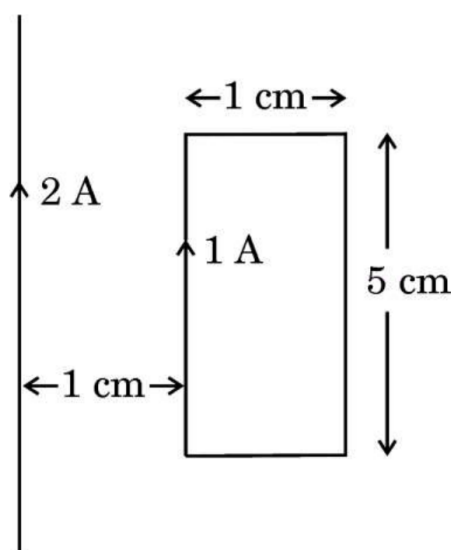
**Quick Tip to Solve:** For the potential graph, draw the positive core, negative well and zero tail; use the negative slope rule to identify the force direction.

**24.** 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:

- A long straight wire carrying current  $I_w$  produces magnetic field  $B(r) = \mu_0 I_w / (2\pi r)$  at perpendicular distance  $r$ . The right-hand rule fixes its direction.
- A current element experiences  $d\mathbf{F} = I d\boldsymbol{\ell} \times \mathbf{B}$ . Parallel currents attract and opposite currents repel. Net torque is found by adding moments of these forces about the loop centre.

**Step 1: Read the geometry and field direction** The loop current is  $I = 1$  A, the straight-wire current is  $I_w = 2$  A, and each vertical side has length  $L = 5$  cm  $= 0.05$  m. The near side is at  $a = 0.01$  m; the loop width is  $0.01$  m, so the far side is at  $b = 0.02$  m. Because the straight-wire current points upwards, its field is into the page throughout the loop. The loop current is clockwise, as shown by the upward arrow on its near side.

**Step 2: (i) Add the force moments about the centre** Forces on the two vertical sides are horizontal, and each side's resultant acts through its midpoint along the horizontal line through the loop centre. Each therefore has zero moment about that centre. On corresponding elements of the top and bottom sides, the field magnitudes are equal because their distances from the wire are equal. Their forces are equal and opposite, directed upwards and downwards, respectively, along the same vertical line. Their moments cancel pairwise. Thus the nonuniform field exerts no net turning moment on the loop.

**Step 3: (ii) Subtract the forces on the vertical sides** The near side carries current parallel to the straight wire and is attracted towards it. The far side carries opposite current and is repelled. Their force magnitudes are

$$F_{\text{near}} = \frac{\mu_0 I_w I L}{2\pi a} = \frac{(2 \times 10^{-7})(2)(1)(0.05)}{0.01} = 2.0 \times 10^{-6} \text{ N},$$
$$F_{\text{far}} = \frac{\mu_0 I_w I L}{2\pi b} = \frac{(2 \times 10^{-7})(2)(1)(0.05)}{0.02} = 1.0 \times 10^{-6} \text{ N}.$$

The top and bottom forces cancel exactly, even though the field varies along each side. The stronger near-side attraction therefore determines the direction of the net force.

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

**Quick Tip to Solve:** Add the gap and loop width to get the far-side distance; then subtract the two vertical-side forces, since their directions are opposite.

**25. (a)** A concave mirror has radius of curvature 20 cm. Calculate the distance of an object from the mirror so as to form an image of magnification  $-2$ . Also find the location of the image.

**(b)** If the silver coating around the centre of a concave mirror is removed, will the mirror still form the image of an object? Justify your answer. [3 marks]

### Solution:

#### Concept:

- For a spherical mirror, the focal length has magnitude half the radius of curvature. With the Cartesian sign convention, a concave mirror has  $f = -R/2$ , and an object in front has  $u < 0$ .
- The mirror formula is  $1/f = 1/v + 1/u$ , and transverse magnification is  $m = h_i/h_o = -v/u$ , where  $u$  and  $v$  are measured from the pole.

- Every reflecting region of a mirror receives rays from all points of the object. Reducing the reflecting area lowers the light collected without removing corresponding portions of the image.

**Step 1: (a) Relate the image and object distances** The radius of curvature is  $R = 20$  cm. The principal focus lies in front of the concave mirror, so its signed focal length is

$$f = -\frac{20}{2} = -10 \text{ cm.}$$

The specified magnification is negative, indicating an inverted image. Substituting it in the magnification formula gives

$$-2 = -\frac{v}{u} \Rightarrow v = 2u.$$

Thus the signed image distance is twice the signed object distance; both will be negative for this real-image arrangement.

**Step 2: (a) Apply the mirror formula** Substitute  $v = 2u$  and  $f = -10$  cm:

$$\begin{aligned} -\frac{1}{10} &= \frac{1}{2u} + \frac{1}{u} = \frac{3}{2u}, \\ 2u &= -30 \text{ cm}, \quad u = -15 \text{ cm}, \\ v &= 2(-15) = -30 \text{ cm.} \end{aligned}$$

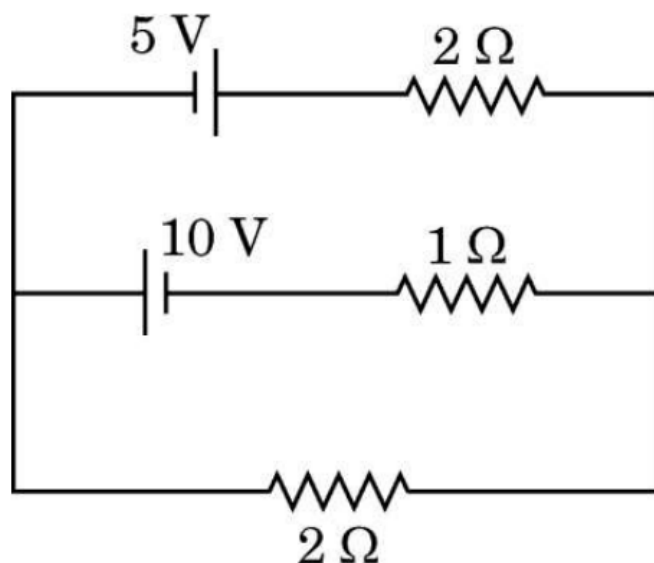
This places the object between the focus at 10 cm and centre of curvature at 20 cm, both in front of the mirror. A real, inverted and enlarged image beyond the centre of curvature is therefore consistent with the ray-optics prediction. Checking gives  $-v/u = -(-30)/(-15) = -2$ .

**Step 3: (b) Examine the effect of removing the central coating** Yes, the remaining silvered portion still forms the complete image. Rays from each object point strike the remaining reflecting surface and converge to the corresponding image point. Removing the coating around the centre reduces the effective reflecting area and hence the amount of reflected light, so the image becomes less bright. Within the usual paraxial treatment, the mirror curvature and focal length remain the same; consequently the image position and magnification also remain the same. There is no missing central portion of the image.

**Step 4: Conclusion** (a) Place the object 15 cm in front of the mirror; the image forms 30 cm in front and is real, inverted and twice the object's size. (b) The remaining mirror forms a complete image of the same size and position, with reduced brightness.

**Quick Tip to Solve:** Use  $m = -v/u$  first to eliminate one distance; removing part of a mirror changes image brightness, not which part of the object is imaged.

26. State Kirchhoff's laws. Apply these laws to find the values of current flowing in the three branches of the given circuit. [3 marks]



**Solution:**

**Concept:**

- Kirchhoff's junction law: the algebraic sum of currents at a junction is zero,  $\sum I = 0$ ; total incoming current equals total outgoing current. This expresses conservation of charge.
- Kirchhoff's loop law: the algebraic sum of potential changes around a closed loop is zero,  $\sum \Delta V = 0$ . This expresses conservation of energy.
- Across a resistor, the potential falls by  $IR$  in the current direction. Across an ideal cell, going from its short plate to its long plate gives a rise equal to its emf.

**Step 1: Assign branch currents and read the cell polarities** Call the left junction  $A$  and the right junction  $B$ . Initially take all three branch currents from  $A$  to  $B$ :  $I_1$  in the upper branch,  $I_2$  in the middle branch and  $I_3$  in the lower branch. A negative answer will mean current actually flows from right to left. The 5V cell is positive on its right, whereas the 10V cell is positive on its left. The junction rule therefore gives

$$I_1 + I_2 + I_3 = 0.$$

**Step 2: Apply the loop law to two independent loops** Go left to right through the upper branch and return through the lower branch. The cell gives a rise of 5V, so

$$5 - 2I_1 + 2I_3 = 0, \quad I_1 - I_3 = 2.5.$$

Next go left to right through the middle branch and return through the lower branch. This traversal crosses the 10V cell from positive to negative:

$$-10 - I_2 + 2I_3 = 0, \quad I_2 = 2I_3 - 10.$$

The positive resistor term on the return path occurs because that path is opposite to the assumed lower-branch current.

**Step 3: Solve the simultaneous equations** Substitute  $I_1 = I_3 + 2.5$  and  $I_2 = 2I_3 - 10$  into the junction

equation:

$$\begin{aligned}(I_3 + 2.5) + (2I_3 - 10) + I_3 &= 0, \\ 4I_3 &= 7.5, \\ I_3 &= 1.875 \text{ A}, \\ I_1 &= 4.375 \text{ A}, \\ I_2 &= -6.25 \text{ A}.\end{aligned}$$

The magnitude entering the left junction through the middle branch equals the total leaving it:  $6.25 = 4.375 + 1.875$ , as required.

**Step 4: Conclusion** The upper-branch current is 4.375 A from left to right, the middle-branch current is 6.25 A from right to left, and the lower-branch current is 1.875 A from left to right.

**Quick Tip to Solve:** Mark each cell's long plate first: the two cells here face opposite ways. Keep assumed current directions fixed until the algebra supplies their signs.

**27. In Bohr model of hydrogen atom, an electron is revolving in second orbit. Find the value of:**

- (i) angular momentum of electron,
- (ii) radius of the orbit, and
- (iii) kinetic energy of electron.

Take radius of first orbit of hydrogen atom as  $0.5 \text{ \AA}$ .

[3 marks]

**Solution:**

**Concept:**

- Bohr's angular-momentum quantisation is  $L_n = m_e v_n r_n = nh/(2\pi)$ , where  $n$  is the orbit number and  $h$  is Planck's constant.
- For hydrogen, the radius varies as  $r_n = n^2 r_1$ . Here the supplied first-orbit radius is  $r_1 = 0.5 \text{ \AA}$ , with  $1 \text{ \AA} = 10^{-10} \text{ m}$ .
- Coulomb attraction provides the centripetal force:  $m_e v_n^2 / r_n = ke^2 / r_n^2$ . Thus the kinetic energy is  $K_n = ke^2 / (2r_n)$ , where  $k = 1/(4\pi\epsilon_0)$  and  $e$  is the elementary charge.

**Step 1: Find the angular momentum in the second orbit** Set  $n = 2$  in Bohr's quantisation condition and use  $h = 6.63 \times 10^{-34} \text{ J s}$ :

$$L_2 = \frac{2h}{2\pi} = \frac{h}{\pi} = \frac{6.63 \times 10^{-34}}{3.1416} \simeq 2.11 \times 10^{-34} \text{ J s}.$$

This is the magnitude of orbital angular momentum; its SI unit is equivalently  $\text{kg m}^2 \text{ s}^{-1}$ .

**Step 2: Calculate the second-orbit radius** The orbit radius scales with the square of the orbit number, not directly with it. Using the first-orbit radius explicitly supplied in the question,

$$r_2 = 2^2 r_1 = 4(0.5 \text{ \AA}) = 2.0 \text{ \AA} = 2.0 \times 10^{-10} \text{ m}.$$

**Step 3: Calculate kinetic energy from the given radius** Multiplying the centripetal-force equation by

$r_2/2$  gives  $K_2 = ke^2/(2r_2)$ . Therefore,

$$\begin{aligned} K_2 &= \frac{(9 \times 10^9)(1.6 \times 10^{-19})^2}{2(2.0 \times 10^{-10})} \\ &= 5.76 \times 10^{-19} \text{ J} \\ &= \frac{5.76 \times 10^{-19}}{1.6 \times 10^{-19}} \text{ eV} = 3.6 \text{ eV}. \end{aligned}$$

Kinetic energy is positive. This calculation uses the printed rounded radius  $0.5 \text{ \AA}$ . The familiar value  $13.6/2^2 = 3.4 \text{ eV}$  instead uses the more precise Bohr radius, approximately  $0.529 \text{ \AA}$ ; the small numerical difference reflects the rounded input.

**Step 4: Conclusion** (i)  $L_2 = 2.11 \times 10^{-34} \text{ J s}$ ; (ii)  $r_2 = 2.0 \times 10^{-10} \text{ m}$ ; (iii) using the given radius,  $K_2 = 5.76 \times 10^{-19} \text{ J} = 3.6 \text{ eV}$ .

**Quick Tip to Solve:** In the second orbit, angular momentum doubles and radius quadruples. For the energy calculation, retain the radius supplied in this question.

**28(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  $\omega$  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 an induced current has a direction such that its magnetic effect opposes the change in magnetic flux that produces it. The minus sign in  $\mathcal{E} = -d\Phi_B/dt$  expresses this opposition.
- A conducting element of length  $dr$ , moving perpendicular to a magnetic field with speed  $v$ , has motional emf  $d\mathcal{E} = Bv dr$  when the magnetic force acts along the element.
- In uniform rotation about an end, a point at distance  $r$  from the axis has tangential speed  $v = \omega r$ . The rod's different elements therefore contribute different amounts of emf.

**Step 1: Identify the magnetic force along the rod** The axis passes through  $M$ , and the rod rotates in the plane perpendicular to the uniform magnetic field. Consider a small element at distance  $r$  from  $M$ . Its velocity is tangential, its speed is  $\omega r$ , and  $\vec{v}$  is perpendicular to  $\vec{B}$ . The magnetic force  $q\vec{v} \times \vec{B}$  on a charge is radial, along the rod, so charges separate between its ends. An emf exists even when the rod is not part of a closed circuit; a sustained current requires a closed conducting path.

**Step 2: Add the emf contributions of all elements** For the element of radial length  $dr$ , the magnitude of motional emf is

$$d\mathcal{E} = Bv dr = B\omega r dr.$$

Integrate along the rod from the fixed end  $M$ , where  $r = 0$ , to the outer end  $N$ , where  $r = L$ :

$$\begin{aligned} |\mathcal{E}_{MN}| &= \int_0^L B\omega r dr \\ &= B\omega \left[ \frac{r^2}{2} \right]_0^L = \frac{1}{2} B\omega L^2. \end{aligned}$$

The factor  $1/2$  arises because speed increases linearly from zero at  $M$  to  $\omega L$  at  $N$ . Using the tip speed for the entire rod would incorrectly double the result.

**Step 3: Determine the polarity and interpret Lenz's law** If the rotation vector points along  $\vec{B}$ ,  $\vec{v} \times \vec{B}$  points radially outwards. Positive charge accumulates at  $N$ , so  $V_N > V_M$ . If the rotation is reversed, the polarity reverses. When a closed path is provided, the induced current's magnetic torque opposes the imposed rotation, consistent with Lenz's law and conservation of energy.

**Step 4: Conclusion** The induced emf between the rod's ends has magnitude  $|\mathcal{E}_{MN}| = \frac{1}{2}B\omega L^2$ . For rotation with its angular-velocity vector along  $\vec{B}$ ,  $N$  is positive relative to  $M$ .

**Quick Tip to Solve:** For a rod rotating about one end, use  $v = \omega r$  and integrate along its length; the mean speed is half the tip speed.

OR

**28(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  $L$  is the magnetic flux linkage of a coil per unit current through it:  $L = N\Phi/I$ , where  $N$  is the number of turns and  $\Phi$  is the flux through each turn.
- A changing current induces a self-induced emf  $\varepsilon = -L dI/dt$ ; its sign expresses opposition to the change in current. The SI unit of inductance is henry (H).
- Inside a long air-core solenoid, the magnetic field is approximately uniform:  $B = \mu_0 nI$ , where  $n$  is the number of turns per unit length and  $\mu_0$  is the permeability of free space.

**Step 1: State the definition and identify the turns** The self-inductance measures the flux linked with the entire coil when unit current flows through it. Equivalently, a coil has inductance 1 H if a current changing at  $1 \text{ A s}^{-1}$  induces an emf of magnitude 1 V. For a solenoid of length  $l$  and turn density  $n$ , the total number of turns is  $N = nl$ .

**Step 2: Calculate the flux through each turn** Neglect end effects for the long solenoid. Its axial magnetic field is perpendicular to each turn's cross-sectional area  $A$ , so the flux through one turn is

$$\Phi = BA = \mu_0 nIA.$$

Every turn links essentially this same flux. We must therefore multiply by the total number of turns to find flux linkage; using the single-turn flux alone would omit a factor  $N$ .

**Step 3: Obtain the flux linkage and inductance** Substituting  $N = nl$  gives

$$N\Phi = (nl)(\mu_0 nIA) = \mu_0 n^2 AII.$$

Comparing this with  $N\Phi = LI$ , we divide by the current. For fixed geometry and a linear medium,

the resulting inductance is independent of the current. If a uniform magnetic core of permeability  $\mu$  completely fills the solenoid, the same derivation replaces  $\mu_0$  by  $\mu$ .

**Step 4: Conclusion** Self-inductance is flux linkage per unit current, and the long air-core solenoid has  $L = \mu_0 n^2 Al = \mu_0 N^2 A/l$ . Its SI unit is henry.

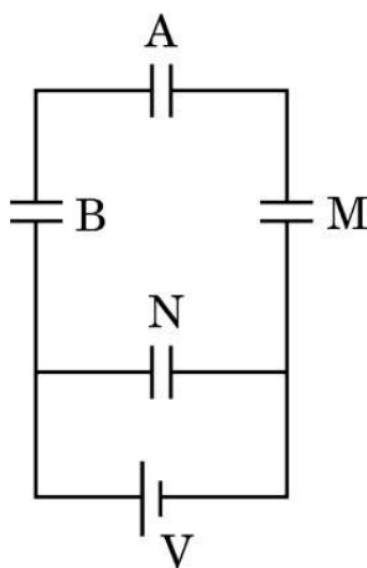
**Quick Tip to Solve:** First calculate flux through one turn, then multiply by  $N = nl$ ; forgetting this factor loses the square of the turn density.

### 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  $\sigma$ ), 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  $\sigma_p$ . For a linear dielectric  $\sigma_p$  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)(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, and their equivalent capacitance satisfies  $1/C_s = \sum 1/C_i$ .
- Parallel branches share the same potential difference  $V$ . The charge stored by a capacitor is

$$Q = CV.$$

**Step 1: Identify the series branch** Trace the upper path between the battery terminals: it passes successively through  $B$ ,  $A$  and  $M$ , each of capacitance  $C$ . Their internal junctions have no additional branch, so these three capacitors are in series. Their equivalent capacitance and the charge on each are

$$C_s = \left( \frac{1}{C} + \frac{1}{C} + \frac{1}{C} \right)^{-1} = \frac{C}{3}, \quad Q = \frac{CV}{3}.$$

**Step 2: Compare the charge on the parallel capacitor** Capacitor  $N$ , of capacitance  $2C$ , is directly across the battery, so  $Q' = 2CV$ . Thus

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

Option (A) reverses the requested ratio. Options (B) and (C) cannot account for both the three-capacitor series branch and the doubled capacitance of  $N$ .

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

**Quick Tip to Solve:** Trace wires to identify branches first: three equal capacitors in series carry  $CV/3$ , while the parallel  $2C$  capacitor carries  $2CV$ .

OR

**29(i)(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 a parallel-plate capacitor without dielectric,  $C_0 = \epsilon_0 A/d$ , where  $A$  is the plate area and  $d$  the separation.
- Layers encountered successively along the electric field act as capacitors in series. A dielectric of relative permittivity  $K$  has permittivity  $K\epsilon_0$ .

**Step 1: Represent the two layers as series capacitors** The slab covers the full plate area and occupies thickness  $d/2$ . The remaining air layer also has total thickness  $d/2$ . Thus the individual layer capacitances are

$$C_{\text{air}} = \frac{\epsilon_0 A}{d/2} = 2C_0, \quad C_{\text{slab}} = \frac{K\epsilon_0 A}{d/2} = 2KC_0.$$

**Step 2: Add reciprocal capacitances** The two layers carry the same free charge and their voltage drops add. Therefore

$$\frac{1}{C} = \frac{1}{2C_0} + \frac{1}{2KC_0} = \frac{K+1}{2KC_0}.$$

Option (A) is the reciprocal of the requested ratio. Options (C) and (D) fail the check  $K = 1$ : replacing air with a material of the same permittivity must leave the capacitance unchanged.

**Step 3: Conclusion** The capacitance ratio is  $C/C_0 = 2K/(K+1)$ . Hence, the correct option is (B).

**Quick Tip to Solve:** For a slab of thickness  $t$ , use the effective air gap  $d - t + t/K$ ; here it is  $d/2 + d/(2K)$ .

**29(ii).** 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:**

- The energy density of a uniform electric field in air is  $u = \frac{1}{2}\varepsilon_0 E^2$ , where  $\varepsilon_0$  is the permittivity of free space.
- Total stored energy equals energy density times the volume occupied by the field:  $U = uV$ . Here  $V$  denotes volume, not voltage.

**Step 1: Express capacitor energy using the field** Write the potential difference as  $\Delta\varphi = Ed$ , where  $d$  is the plate separation. For plate area  $A$ ,  $C = \varepsilon_0 A/d$ . Thus

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

**Step 2: Identify the volume and compare the options** The volume between the plates is  $V = Ad$ . Substitution supplies the volume factor multiplying the field energy density. Option (A) gives energy per unit volume and therefore omits a necessary factor. Options (B) and (D) have extra charge factors and do not follow the energy formula; they also fail the dimensions of energy.

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

**Quick Tip to Solve:** When  $V$  means volume, multiply  $\frac{1}{2}\varepsilon_0 E^2$  by  $V$ ; do not substitute this  $V$  into the voltage formula.

**29(iii).** A slab (area  $A$  and thickness  $d_1$ ) of a linear dielectric of dielectric constant  $K$  is inserted between charged plates (charge density  $\sigma$ ) of a parallel plate capacitor [plate area  $A$  and plate separation  $d (> d_1)$ ] and opposite charges with charge density of magnitude  $\sigma_p$  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 due to free surface charge density  $\sigma$  is  $E_0 = \sigma/\epsilon_0$  for large parallel plates, neglecting edge effects.
- Polarisation produces an opposing field of magnitude  $E_p = \sigma_p/\epsilon_0$  inside the dielectric. The dielectric constant is  $K = E_0/E$ , where  $E$  is the net field within the slab.

**Step 1: Determine the field inside the dielectric** Bound charges on the two slab faces oppose the field from the free charges on the metal plates. Consequently their fields subtract:

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

The air gaps outside the slab do not change this local relation within the dielectric.

**Step 2: Form the dielectric constant** Using the definition of  $K$ ,

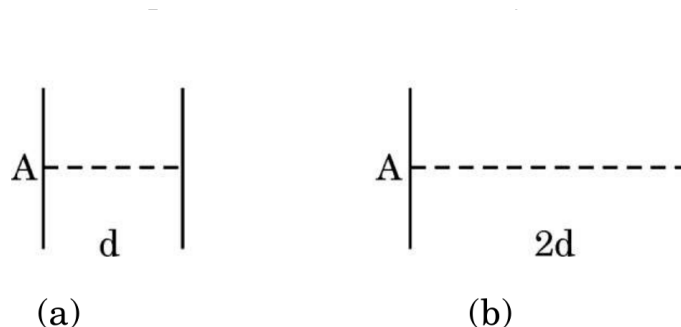
$$K = \frac{\sigma/\epsilon_0}{(\sigma - \sigma_p)/\epsilon_0} = \frac{\sigma}{\sigma - \sigma_p}.$$

The slab thickness affects the overall capacitance, but cancels from this field ratio. Options (A) and (C) add the opposing charge densities; option (D) divides by the polarisation density alone, instead of the density that produces the net field.

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

**Quick Tip to Solve:** First subtract the polarisation field from the free-charge field, then form  $E_0/E$ ; the denominator must contain  $\sigma - \sigma_p$ .

**29(iv).** 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, the capacitance of air-filled parallel plates is  $C = \epsilon_0 A_{\text{overlap}}/d$ , where  $A_{\text{overlap}}$  is their facing area and  $d$  is their separation.
- Only the overlapping portions contribute in the ideal parallel-plate model; increasing separation reduces capacitance.

**Step 1: Read the overlap in the shifted arrangement** Initially the full plate area  $A$  overlaps, so  $C = \epsilon_0 A/d$ . In Fig. (b), one plate has been shifted upward by half its height: its lower edge lies at the level of the other plate's midpoint. The facing area is therefore  $A/2$ , and the new separation is  $2d$ .

**Step 2: Apply both geometrical changes** Substitute the reduced overlap and increased separation together:

$$C_{\text{new}} = \frac{\epsilon_0 (A/2)}{2d} = \frac{1}{4} \frac{\epsilon_0 A}{d}.$$

Option (B) accounts for only one of the two changes. Options (C) and (D) predict an increase, although both changes reduce capacitance.

**Step 3: Conclusion** The new capacitance is  $C/4$ . Hence, the correct option is (A).

**Quick Tip to Solve:** For shifted capacitor plates, multiply the overlap-area ratio by the inverse separation ratio: here  $(1/2)(1/2)$ .

**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)(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 raises the potential barrier and widens the depletion region of a p-n junction.
- Below breakdown, the small reverse current is mainly the drift of thermally generated minority carriers and is nearly independent of reverse voltage at fixed temperature.

**Step 1: Locate the main voltage drop** The depletion region contains immobile ion cores but very few mobile carriers. It therefore has a much greater resistance than the neutral p and n regions. Most of the applied reverse voltage drops across this depletion region, making statement (B) correct.

**Step 2: Check the remaining statements** The normal reverse current is very small, typically on a microampere or smaller scale rather than a few milliamperes, so (A) is incorrect. Reverse bias pulls majority carriers away from the junction and increases its depletion width, excluding (C). Before breakdown, raising the reverse voltage does not substantially increase the saturation current, excluding (D). The sharp current rise at breakdown is not the ordinary reverse-bias regime meant here.

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

**Quick Tip to Solve:** For normal reverse bias, remember a wider depletion region and an almost constant, very small minority-carrier current.

**30(i)(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 sends current through the load in the same direction during both half-cycles of an alternating input.
- Its pulsating output has two pulses per input cycle, so its ripple frequency is  $f_{\text{out}} = 2f_{\text{in}}$ .

**Step 1: Relate the periods of input and output** The input frequency is  $f_{\text{in}} = 50$  Hz, so its period is  $T_{\text{in}} = 1/50 = 0.020$  s. Full-wave rectification reverses the negative half-cycle at the load; the rectified waveform repeats after half an input period. Thus  $T_{\text{out}} = 0.010$  s.

**Step 2: Calculate the pulse frequency and compare options** Taking the reciprocal gives

$$f_{\text{out}} = \frac{1}{0.010} = 2(50) = 100 \text{ Hz.}$$

The value 50 Hz would apply to the pulse frequency of a half-wave rectifier. Neither 25 Hz nor 200 Hz matches the two-pulses-per-cycle operation of a full-wave rectifier. The frequency here refers to the pulsations in the unfiltered rectified output.

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

**Quick Tip to Solve:** Count pulses in one input cycle: a full-wave rectifier makes two, so double the input frequency.

**30(ii).** 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:**

- Diffusion moves majority carriers from high concentration to low concentration: electrons move from the n-side to the p-side, and holes from the p-side to the n-side.
- Recombination near the junction leaves immobile ionised donors on the n-side and ionised acceptors on the p-side, forming the depletion region.

**Step 1: Identify the charges left near the junction** Electrons initially diffuse out of the n-region near the junction. The donor ions left behind have positive charge. Holes diffuse out of the neighbouring

p-region; the acceptor ions left behind carry negative charge. These immobile charges create the junction electric field.

**Step 2: Compare each statement with junction formation** Option (B) gives the correct positive n-side and negative p-side layers. Option (A) reverses their signs. Option (C) reverses the initial net electron diffusion direction. Option (D) reverses the initial current behaviour: diffusion is initially dominant, while drift develops as the depletion-region field builds up. At thermal equilibrium, the opposing drift and diffusion currents balance.

**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 carriers that leave each side: losing electrons exposes positive donors, while losing holes exposes negative acceptors.

**30(iii).** 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:**

- Silicon is tetravalent. A pentavalent impurity uses four of its five valence electrons to form covalent bonds with neighbouring silicon atoms.
- The extra electron is weakly bound and occupies a donor level just below the conduction band. The donor ionisation energy is approximately 0.05 eV in silicon.

**Step 1: Identify the electron that is released** The question concerns the fifth electron of the donor atom, rather than an electron belonging to a silicon covalent bond. Releasing it does not require exciting an electron across the full silicon band gap. Its small binding energy lets thermal agitation create mobile conduction electrons readily.

**Step 2: Compare the listed energies** For a pentavalent donor in silicon, the standard approximate donor ionisation energy is 0.05 eV. The values 0.5 eV and 0.1 eV are too large for the stated approximation. The smaller value 0.01 eV is the usual approximate donor binding energy in germanium, not silicon. The host crystal named in the question therefore distinguishes the two tempting small energies.

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

**Quick Tip to Solve:** Check the host material before choosing a donor energy: remember about 0.05 eV for Si and 0.01 eV for Ge.

30(iv). 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:**

- Germanium is tetravalent: each Ge atom contributes four valence electrons to covalent bonds in its crystal.
- A pentavalent substitutional impurity supplies an extra electron and acts as a donor, producing n-type material. A trivalent impurity acts as an acceptor.

**Step 1: Identify the electron donor** Antimony has five valence electrons. When an antimony atom replaces a Ge atom, four electrons form covalent bonds with neighbouring atoms. The fifth electron is weakly bound and can be donated to the conduction band, leaving a positively charged immobile donor ion. Therefore antimony is the required donor impurity.

**Step 2: Eliminate the other choices** Boron, aluminium and indium each have three valence electrons. Each leaves one covalent bond short of an electron when substituted into tetravalent Ge. These impurities accept an electron and create a mobile hole; they are acceptors producing p-type material. Thus options (A), (C) and (D) cannot provide the donor action asked for.

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

**Quick Tip to Solve:** Compare impurity valency with Ge's four: five donates an electron, while three produces a hole.

**Section E (15 marks)**

31(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:**

- The work done by an electrostatic field on charge  $q$  is  $W_{\text{field}} = q \int_A^B \vec{E} \cdot d\vec{l}$ . The potential difference is  $V_B - V_A = - \int_A^B \vec{E} \cdot d\vec{l}$ .
- For slow transport without a change in kinetic energy, external work equals the change in potential energy:  $W_{\text{ext}} = q(V_B - V_A) = -W_{\text{field}}$ .
- A uniformly charged spherical shell of radius  $a$  and charge  $q_s$  produces zero electric field and constant potential  $q_s/(4\pi\epsilon_0 a)$  everywhere inside, taking potential zero at infinity.

- Equal surface charge density  $\sigma$  means that each shell's charge equals  $\sigma$  times its area. Electric fields add as vectors, whereas potentials add as scalars.

**Step 1: (i) Set up the line integral** The unit positive charge is  $q = 1$  C, initially at  $A = (0, 3 \text{ m})$  and finally at  $B = (5 \text{ m}, 0)$ . Since the field has only an  $x$ -component,

$$\vec{E} \cdot d\vec{l} = (40x \hat{i}) \cdot (dx \hat{i} + dy \hat{j}) = 40x dx.$$

Hence the change in  $y$  contributes no work. The electrostatic work depends only on the endpoint coordinates, so we may integrate directly from  $x = 0$  to  $x = 5 \text{ m}$ .

**Step 2: (i) Evaluate the work and identify its sign** Substituting the field and the charge gives

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

The displacement has a component along the field, so the electric field does positive work. Equivalently,

$$V_B - V_A = -500 \text{ V}, \quad \Delta U = q(V_B - V_A) = -500 \text{ J}.$$

Thus, if “work done in taking” means work by an external agent in a slow transfer, that signed work is negative. The magnitude of the work is 500 J; distinguishing the agent removes any sign ambiguity in the wording.

**Step 3: (ii) Divide the total charge between the shells** Let the charges on the inner and outer shells be  $q_r$  and  $q_R$ , respectively. Their common surface charge density gives

$$\frac{q_r}{4\pi r^2} = \frac{q_R}{4\pi R^2} = \sigma, \quad q_r + q_R = Q.$$

Combining the total charge with the two areas,

$$\sigma = \frac{Q}{4\pi(r^2 + R^2)}, \quad q_r = \frac{Qr^2}{r^2 + R^2}, \quad q_R = \frac{QR^2}{r^2 + R^2}.$$

In particular, equal densities do not mean equal charges: the larger shell carries the larger share for positive  $Q$ .

**Step 4: (ii) (I) Add the electric fields at the centre** The common centre  $O$  lies inside both uniformly charged spherical shells. For each shell, diametrically opposite surface elements give equal and opposite field contributions there. Therefore

$$\vec{E}(O) = \vec{E}_r(O) + \vec{E}_R(O) = \vec{0} + \vec{0}.$$

The shell theorem also gives this result throughout the region inside the smaller shell. No singular point-charge formula may be used at the centre of an extended shell.

**Step 5: (ii) (II) Add the potentials at the centre** Every element of the inner shell is a distance  $r$  from  $O$ , and every element of the outer shell is a distance  $R$  from  $O$ . With the potential zero at infinity,

their scalar contributions give

$$\begin{aligned} V(O) &= \frac{1}{4\pi\epsilon_0} \left( \frac{q_r}{r} + \frac{q_R}{R} \right) \\ &= \frac{1}{4\pi\epsilon_0} \left( \frac{Qr}{r^2 + R^2} + \frac{QR}{r^2 + R^2} \right) \\ &= \frac{Q(r + R)}{4\pi\epsilon_0(r^2 + R^2)}. \end{aligned}$$

Zero electric field does not require zero potential: it requires spatially constant potential in the inner region.

**Step 6: Conclusion** (i) The work magnitude is 500 J: the field does +500 J, while a slow external transfer requires -500 J. (ii)(I)  $\vec{E}(O) = \vec{0}$ ; (ii)(II)  $V(O) = \frac{Q(r + R)}{4\pi\epsilon_0(r^2 + R^2)}$ , with zero potential at infinity.

**Quick Tip to Solve:** For  $\vec{E} = E_x(x)\hat{i}$ , integrate only over  $x$  and specify whose work you calculate. For equal shell densities, split  $Q$  in the ratio  $r^2 : R^2$  before adding the shell potentials.

OR

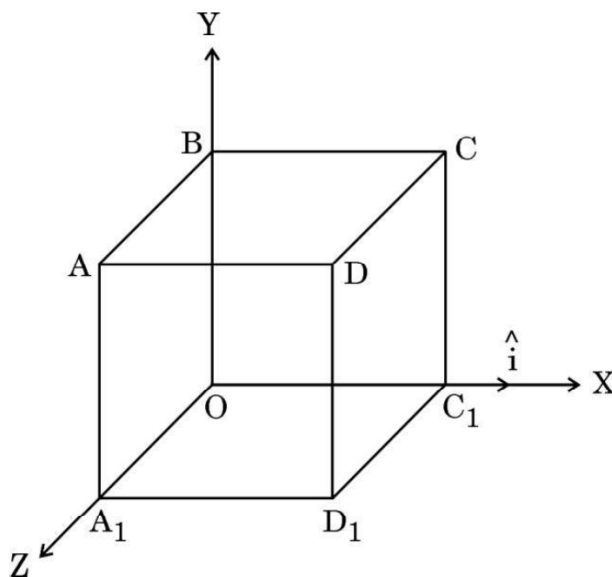
**31(b).** (i) Obtain an expression for the electric field  $\vec{E}$  due to a dipole of dipole moment  $\vec{p}$  at a point on its equatorial plane and specify its direction. Hence, find the value of electric field:

(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:

- An electric dipole consists of charges  $-q$  and  $+q$  separated by  $2a$ . Its dipole moment is  $\vec{p} = 2qa \hat{p}$ , directed from the negative charge towards the positive charge.
- Coulomb's law gives the field magnitude of either charge at distance  $R$  as  $kq/R^2$ , where  $k = 1/(4\pi\epsilon_0)$ . Add the fields vectorially using superposition.
- Electric flux is  $\Phi = \oint \vec{E} \cdot d\vec{A}$ , with each area vector directed outwards. For a uniform field over a plane face, its flux is  $EA \cos \theta$ .

**Step 1: (i) Resolve the fields on the equatorial plane** Place the dipole centre at  $O$ , with the charges at position vectors  $-a\hat{p}$  and  $+a\hat{p}$ . Let  $P$  lie in the equatorial plane at distance  $OP = r$ , and write its position vector as  $\vec{r}$ , so  $\vec{r} \cdot \hat{p} = 0$ . The distance from either charge to  $P$  is the same:

$$R = \sqrt{r^2 + a^2}.$$

The positive charge's field points away from it, whereas the negative charge's field points towards it. Their components along  $OP$  cancel; their components opposite to  $\hat{p}$  add. Explicitly,

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

Thus the field on the equatorial plane is antiparallel to the dipole moment, from the positive-charge side towards the negative-charge side.

**Step 2: (i)(I) Evaluate the field at the centre** At the centre,  $r = 0$ , while each charge is still a finite distance  $a$  away. Substitution in the exact expression gives

$$\vec{E}_O = -\frac{\vec{p}}{4\pi\epsilon_0 a^3}.$$

Its magnitude is  $kp/a^3 = 2kq/a^2$ . The field is not zero: at the centre, both individual fields point from  $+q$  towards  $-q$ , so they reinforce each other. Although the potentials cancel there, the electric fields do not.

**Step 3: (i)(II) Obtain the distant-point approximation** For  $r \gg a$ , the ratio  $a^2/r^2$  is negligible. Therefore,

$$(r^2 + a^2)^{3/2} = r^3 \left(1 + \frac{a^2}{r^2}\right)^{3/2} \simeq r^3, \quad \vec{E} \simeq -\frac{\vec{p}}{4\pi\epsilon_0 r^3}.$$

This field still points opposite to  $\vec{p}$ ; its magnitude falls as the inverse cube of the distance. This approximation cannot be used at the centre.

**Step 4: (ii) Calculate the signed flux through the cube's faces** The cube shown extends from  $x = 0$  to  $x = L$ , and each face has area  $L^2$ . Since  $\vec{E} = (10x + 5)\hat{i}$ , the four faces whose outward normals are along  $\pm\hat{j}$  or  $\pm\hat{k}$  have zero flux. The field is parallel to those faces. On face  $ABOA_1$ , at  $x = 0$ , the

outward normal is  $-\hat{i}$ ; on the opposite face  $DCC_1D_1$ , at  $x = L$ , it is  $+\hat{i}$ . Consequently,

$$\begin{aligned}\Phi_{x=0} &= -5L^2, \\ \Phi_{x=L} &= (10L + 5)L^2, \\ \Phi_{\text{net}} &= (10L + 5)L^2 - 5L^2 = 10L^3.\end{aligned}$$

The flux is positive because more field leaves the right face than enters the left face. The spatially constant contribution  $5\hat{i}$  cancels between the opposite faces. With  $L$  expressed in metres, the net flux is  $10L^3 \text{ N m}^2/\text{C}$ .

**Step 5: Conclusion** (i)  $\vec{E}_{\text{eq}} = -\frac{\vec{p}}{4\pi\epsilon_0(r^2 + a^2)^{3/2}}$ , opposite to  $\vec{p}$ . At the centre,  $\vec{E}_O = -\frac{\vec{p}}{4\pi\epsilon_0 a^3}$ ; for  $r \gg a$ ,  $\vec{E} \simeq -\frac{\vec{p}}{4\pi\epsilon_0 r^3}$ . (ii) The net outward flux is  $10L^3 \text{ N m}^2/\text{C}$ , for  $L$  in metres.

**Quick Tip to Solve:** Use the exact finite-dipole expression before setting  $r = 0$ . For a field along the cube's  $x$ -axis, subtract the entering-face field from the leaving-face field and multiply by  $L^2$ .

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

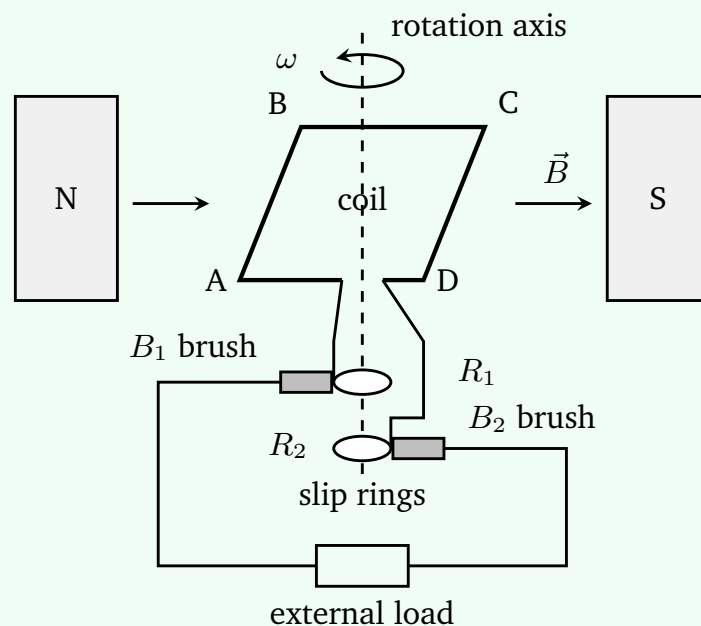
(ii) A resistor of  $400 \Omega$ , an inductor of  $\left(\frac{5}{\pi}\right) \text{ H}$  and a capacitor of  $\left(\frac{50}{\pi}\right) \mu\text{F}$  are joined in series across an ac source  $v = 140 \sin(100\pi t) \text{ V}$ . Find the rms voltages across these three circuit elements. The algebraic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

**Solution:**

**Concept:**

- An ac generator works on electromagnetic induction: changing the magnetic flux linked with a coil induces an emf,  $e = -d(N\Phi)/dt$ , where  $N$  is the number of turns.
- In a series RLC circuit,  $X_L = \omega L$ ,  $X_C = 1/(\omega C)$ , and  $Z = \sqrt{R^2 + (X_L - X_C)^2}$ . The same rms current flows through all three elements.
- For a sinusoidal voltage,  $V_{\text{rms}} = V_0/\sqrt{2}$ . Component rms voltages are  $IR$ ,  $IX_L$  and  $IX_C$ ; their phase differences require vector addition.

**Step 1: (i) Describe the generator construction** A rectangular armature coil  $ABCD$ , with  $N$  turns and area  $A$ , rotates mechanically between the north and south poles of a magnet. Its two ends connect to separate continuous slip rings  $R_1$  and  $R_2$ , insulated from each other and from the shaft. Stationary carbon brushes  $B_1$  and  $B_2$  touch the rings and connect the rotating coil to the external load. The schematic shows the two separate ring contacts; the rings and coil rotate together.



*AC generator: rotating armature, separate slip rings, stationary brushes and external load (schematic).*

**Step 2: Explain the induced alternating emf** Let the coil rotate with angular speed  $\omega$ , with its normal initially parallel to the uniform magnetic field  $B$ . The angle between the normal and the field is  $\omega t$ , giving

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

Thus the peak emf is  $e_0 = NBA\omega$ . The induced emf is zero when the coil's plane is perpendicular to the field and maximum in magnitude when its plane is parallel to the field. After each half revolution the direction of motion of each active side reverses relative to the field, so the induced emf and load current reverse. Fleming's right-hand rule gives their instantaneous direction. Slip rings maintain the two separate electrical connections without reversing them, so the output is alternating. Mechanical energy supplied to rotate the coil is converted into electrical energy.

**Step 3: (ii) Calculate the reactances and impedance** From  $v = 140 \sin(100\pi t)$  V, the peak voltage is 140 V and  $\omega = 100\pi \text{ rad s}^{-1}$ . Using the printed inductance  $L = 5/\pi \text{ H}$  and  $C = (50/\pi) \times 10^{-6} \text{ F}$ ,

$$\begin{aligned} X_L &= (100\pi) \frac{5}{\pi} = 500 \Omega, \\ X_C &= \frac{1}{(100\pi)(50/\pi) \times 10^{-6}} = 200 \Omega, \\ Z &= \sqrt{400^2 + (500 - 200)^2} = 500 \Omega. \end{aligned}$$

The net reactance is inductive, because  $X_L > X_C$ .

**Step 4: Obtain the rms current and component voltages** The rms supply voltage and common rms current are

$$V = \frac{140}{\sqrt{2}} = 70\sqrt{2} \text{ V}, \quad I = \frac{V}{Z} = \frac{70\sqrt{2}}{500} \text{ A} \simeq 0.198 \text{ A}.$$

Hence the individual rms voltages are

$$V_R = IR = 56\sqrt{2}\text{ V} \simeq 79.2\text{ V},$$

$$V_L = IX_L = 70\sqrt{2}\text{ V} \simeq 99.0\text{ V},$$

$$V_C = IX_C = 28\sqrt{2}\text{ V} \simeq 39.6\text{ V}.$$

**Step 5: Explain why the sum exceeds the supply voltage** The arithmetic sum of the rms magnitudes is  $154\sqrt{2} \simeq 217.8\text{ V}$ , exceeding the source rms value  $70\sqrt{2} \simeq 99.0\text{ V}$ . These voltages are not in phase:  $V_R$  is in phase with current,  $V_L$  leads current by  $90^\circ$ , and  $V_C$  lags it by  $90^\circ$ . The inductor and capacitor voltages therefore oppose each other as phasors. The correct combination is

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

Kirchhoff's voltage law applies to the instantaneous signed voltages. It does not imply that the separate positive rms magnitudes must add arithmetically.

**Step 6: Conclusion** The generator produces alternating emf  $e = NBA\omega \sin(\omega t)$  by electromagnetic induction. The rms voltages are  $V_R = 79.2\text{ V}$ ,  $V_L = 99.0\text{ V}$ , and  $V_C = 39.6\text{ V}$ . Their phasor sum, rather than the sum of their magnitudes, equals the source rms voltage  $99.0\text{ V}$ .

**Quick Tip to Solve:** Read the printed inductance as  $5/\pi\text{ H}$ , convert microfarads to farads, and subtract  $X_C$  from  $X_L$  before finding impedance; add rms voltages as phasors.

OR

**32(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  $50\text{ V}$  into  $250\text{ V}$ . It draws  $200\text{ W}$  power from an ac source whose instantaneous voltage is given by  $v_i = 20 \sin(100\pi t)\text{ V}$ .

Find:

(I) rms value of input current.

(II) expression for instantaneous output voltage.

(III) expression for instantaneous output current.

[5 marks]

**Solution:**

**Concept:**

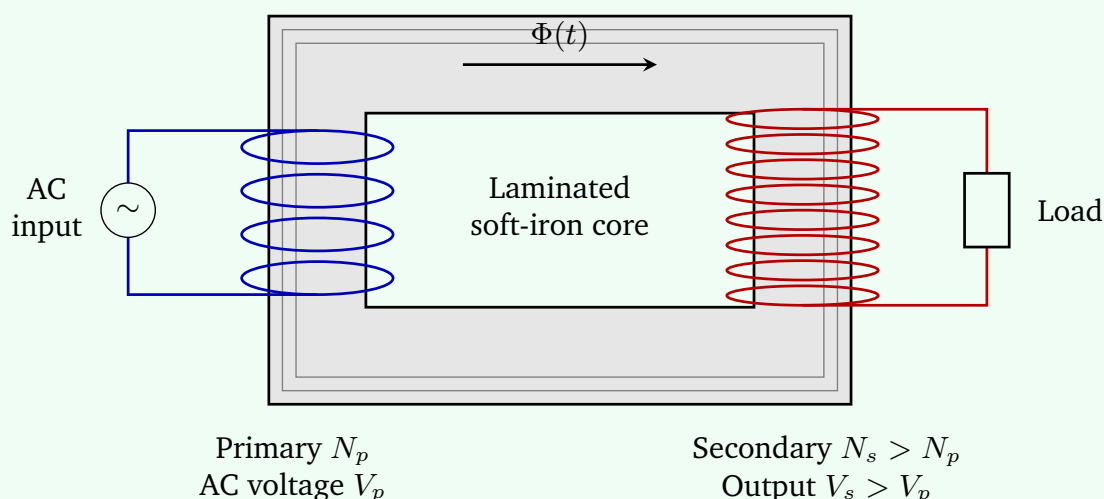
- A transformer works on mutual induction: alternating current in the primary produces a changing magnetic flux  $\Phi$  linking the secondary, inducing an emf in it.
- For an ideal transformer,  $V_s/V_p = N_s/N_p = k$ , where  $N_p, N_s$  are the primary and secondary turn counts. The frequency is unchanged; a step-up transformer has  $N_s > N_p$ .
- A sinusoidal voltage has  $V_{\text{rms}} = V_0/\sqrt{2}$ . With a resistive load,  $P = V_{\text{rms}}I_{\text{rms}}$ ; ideal power transfer gives  $P_{\text{in}} = P_{\text{out}}$ .

**Step 1: (i) Explain mutual induction using the labelled transformer** Two electrically insulated coils are wound on a common laminated soft-iron core. The primary has fewer turns and is connected to an ac supply. Its alternating current sets up an alternating flux in the core; this flux links both

windings. By Faraday's law, their induced emfs are

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

Dividing the emf magnitudes gives  $E_s/E_p = N_s/N_p$ . In the ideal case, winding resistance and leakage flux are negligible, so the same ratio holds for terminal voltages. Thus  $N_s > N_p$  produces a larger secondary voltage. Connecting a load to the secondary allows an output current to flow, transferring energy by magnetic coupling without electrical contact between the coils. The laminated core limits eddy currents. The increased voltage is accompanied by reduced current, so power is not multiplied.



*Step-up transformer: the secondary has more turns than the primary; both link the alternating core flux.*

**Step 2: (ii) Identify the turns ratio and actual input voltage** The design values specify the fixed turns ratio, not the rms voltage of the source used in this calculation:

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

The given source is  $v_i = 20 \sin(100\pi t)$  V, so its peak voltage is 20 V, angular frequency is  $100\pi \text{ rad s}^{-1}$ , and frequency is 50 Hz. Therefore

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

**Step 3: (I) Calculate the rms input current** Use the usual resistive-load (unity-power-factor) interpretation of the numerical. The power drawn is  $P_i = 200 \text{ W}$ , giving

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

Ideal operation by itself guarantees conservation of power; the unity power factor used here is the conventional additional assumption when no load phase angle is supplied.

**Step 4: (II) Write the instantaneous output voltage** Choose corresponding terminal polarities for the primary and secondary voltages. The instantaneous voltage is multiplied by the turns ratio, while its frequency remains unchanged:

$$v_o(t) = kv_i(t) = 100 \sin(100\pi t) \text{ V}.$$

Its rms value is  $100/\sqrt{2} = 50\sqrt{2} \text{ V}$ . The value 250 V would apply when the primary rms voltage were

50 V, whereas the stated waveform has a different rms voltage.

**Step 5: (III) Write the instantaneous output current** For the ideal transformer, output power equals the 200 W input power. With the same resistive-load assumption,

$$I_{o,\text{rms}} = \frac{200}{50\sqrt{2}} = 2\sqrt{2} \text{ A},$$
$$I_{o,0} = \sqrt{2} I_{o,\text{rms}} = 4 \text{ A}.$$

The current through the resistive load is in phase with its voltage, hence  $i_o(t) = 4 \sin(100\pi t) \text{ A}$ . As a check,  $\langle v_o i_o \rangle = 400 \langle \sin^2(100\pi t) \rangle = 200 \text{ W}$ . If a reactive load were intended, its power factor would also be required to determine the total rms current and current phase; the printed data do not specify these.

**Step 6: Conclusion** A step-up transformer uses mutual induction with  $N_s > N_p$ . Here  $N_s/N_p = 5$ . Under the standard unity-power-factor interpretation,

$$I_{i,\text{rms}} = 10\sqrt{2} \text{ A} \simeq 14.14 \text{ A},$$
$$v_o(t) = 100 \sin(100\pi t) \text{ V},$$
$$i_o(t) = 4 \sin(100\pi t) \text{ A}.$$

**Quick Tip to Solve:** Use 250/50 only to find the turns ratio; obtain the actual input rms voltage from the 20 V peak in the given waveform before using the power.

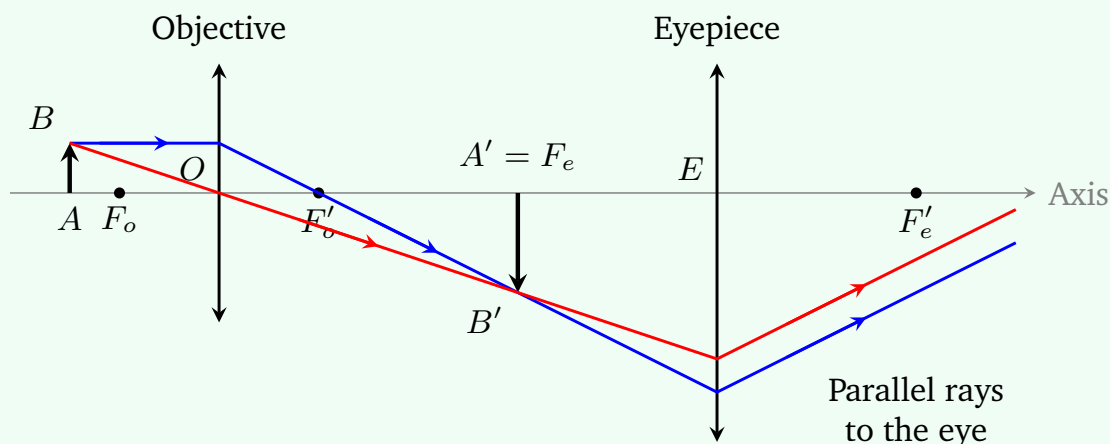
- 33(a). (i)** Draw a ray diagram to show the image formation by a compound microscope. Obtain the expression for the total magnification of the microscope when the final image is formed at infinity.
- (ii)** In a compound microscope, an object is placed at a distance of 1.5 cm from the objective of 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 produce a real enlarged intermediate image, and an eyepiece to magnify its angular size.
- For normal adjustment, the intermediate image lies in the first focal plane of the eyepiece, so the final image is at infinity. The total angular magnification is  $M = m_o m_e$ , where  $m_o$  is the objective's transverse magnification and  $m_e$  is the eyepiece's angular magnification.
- With Cartesian signs, the thin-lens formula is  $1/f = 1/v - 1/u$ . Here  $u$  and  $v$  are signed object and image distances. The least distance of distinct vision is  $D = 25 \text{ cm}$ .

**Step 1: (i) Construct the image in normal adjustment** Place the small object  $AB$  just beyond the objective's first focal point  $F_o$ . A ray from  $B$  parallel to the principal axis refracts through  $F'_o$ ; a second ray passes undeviated through the objective's optical centre. They meet at  $B'$ , forming a real, inverted and enlarged intermediate image  $A'B'$ . Adjust the eyepiece so that  $A'$  coincides with its first focal point  $F_e$ . The rays from  $B'$  then emerge parallel from the eyepiece: the final image is at infinity and the eye is relaxed. The diagram is schematic, with the eye situated to the right.



Compound microscope in normal adjustment:  $A' = F_e$ ; parallel emergent rays give the final image at infinity.

**Step 2: Derive the objective and eyepiece magnifications** Let the object height be  $h$  and the magnitude of the intermediate-image height be  $h'$ . If the objective's image distance is  $v_o$  and its object distance is  $u_o < 0$ , similar triangles give

$$m_o = \frac{v_o}{u_o}, \quad |m_o| = \frac{h'}{h} = \frac{v_o}{|u_o|}.$$

For an intermediate image in the eyepiece's focal plane, its angular size through the eyepiece is approximately  $\beta = h'/f_e$ . The same intermediate image viewed directly at distance  $D$  subtends  $\alpha' = h'/D$ . Thus the eyepiece's angular magnification is

$$m_e = \frac{\beta}{\alpha'} = \frac{D}{f_e}.$$

Multiplying the two factors gives the signed total magnification

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

The negative sign of  $M$  indicates that the final image is inverted relative to  $AB$ . For the usual microscope approximation  $|u_o| \simeq f_o$  and  $v_o \simeq L$ , where  $L$  is the effective tube length, this becomes  $M \simeq -LD/(f_o f_e)$ . The magnitude is conventionally quoted as  $LD/(f_o f_e)$ . The approximation is used for this familiar magnification expression; the numerical separation below uses the lens equation directly.

**Step 3: (ii) Find the objective's image distance** The given object is to the left of the converging objective, so  $u_o = -1.5$  cm, while  $f_o = +1.25$  cm. Substitute these signed values:

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

Therefore the real intermediate image forms 7.5 cm to the right of the objective.

**Step 4: Use the eyepiece's focal-plane condition** To form the final image at infinity, the intermediate image must lie  $f_e = 5$  cm to the left of the eyepiece. Consequently, the eyepiece is beyond the

intermediate image and the lens separation is the sum

$$\ell = v_o + f_e = 7.5 + 5.0 = 12.5 \text{ cm.}$$

Subtracting these distances would place the eyepiece on the wrong side of the intermediate image for normal adjustment.

**Step 5: Conclusion** For the final image at infinity,  $|M| = \frac{v_o}{|u_o|} \frac{D}{f_e} \simeq \frac{LD}{f_o f_e}$ , with inversion represented by a negative signed magnification. For the given microscope, the objective-to-eyepiece distance is 12.5 cm.

**Quick Tip to Solve:** For a microscope adjusted to infinity, first find the objective's real image distance exactly, then add the eyepiece focal length to obtain the lens separation.

OR

**33(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.

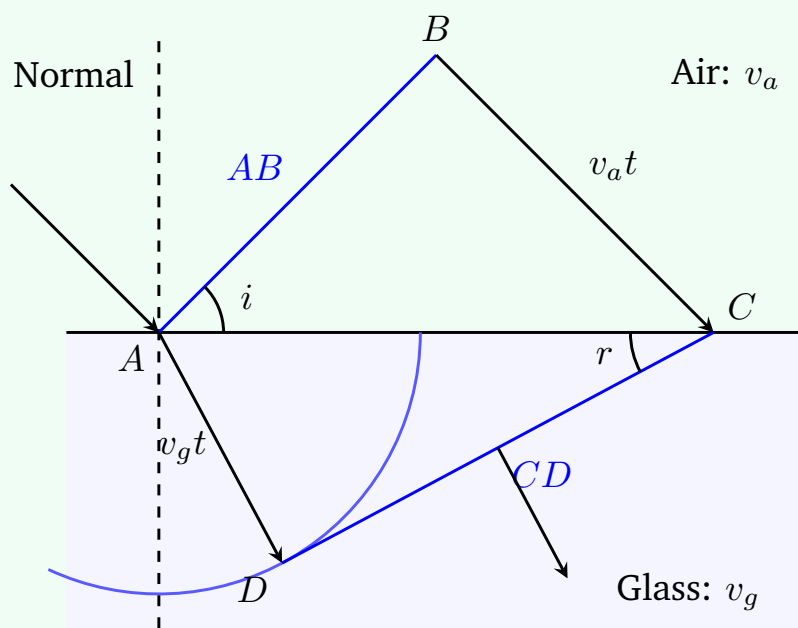
(ii) Use mirror formula to deduce that a convex mirror always produces a virtual image of an object kept in front of it. [5 marks]

**Solution:**

**Concept:**

- Huygens' principle: every point on a wavefront acts as a source of secondary wavelets. Their forward envelope gives the wavefront at a later time; rays are normal to wavefronts.
- If light has speeds  $v_a$  in air and  $v_g$  in glass, the absolute refractive indices are  $n_a = c/v_a$  and  $n_g = c/v_g$ , where  $c$  is its vacuum speed.
- The mirror formula is  $1/f = 1/v + 1/u$ , with object distance  $u$ , image distance  $v$  and focal length  $f$  measured using the Cartesian sign convention.

**Step 1: (i) Construct the refracted wavefront** Let  $AB$  be a plane incident wavefront in air, with end  $A$  just reaching the plane air–glass interface. The ray through  $B$ , perpendicular to  $AB$ , reaches the interface at  $C$  after a time  $t$ . Thus  $BC = v_a t$ . During the same interval, the secondary wavelet starting from  $A$  spreads into glass with radius  $AD = v_g t$ . Draw the tangent  $CD$  from  $C$  to this wavelet. Hence  $AD \perp CD$ . Secondary wavelets from the intervening points of the interface also have  $CD$  as their common forward tangent:  $CD$  is the refracted plane wavefront. The refracted rays are perpendicular to  $CD$ , along the direction  $AD$ .



Huygens construction:  $AB$  is incident and  $CD$  is refracted;  $BC = v_a t$  and  $AD = v_g t$ .

**Step 2: (i) Use the two right triangles** Let  $i$  and  $r$  be the angles the incident and refracted rays make with the normal to the interface. Since each ray is perpendicular to its wavefront,  $\angle BAC = i$  and  $\angle ACD = r$ . The triangles  $ABC$  and  $ADC$  are right-angled at  $B$  and  $D$ , respectively, and share hypotenuse  $AC$ . Therefore,

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

Dividing the expressions eliminates both  $t$  and  $AC$ :

$$\frac{\sin i}{\sin r} = \frac{v_a}{v_g} = \frac{c/n_a}{c/n_g} = \frac{n_g}{n_a}.$$

Thus  $n_a \sin i = n_g \sin r$ , verifying Snell's law. For air to glass,  $v_g < v_a$ , so  $r < i$ : the ray bends towards the normal. The construction lies in the plane of incidence. At normal incidence, symmetry gives  $i = r = 0$ , also satisfying Snell's law.

**Step 3: (ii) Apply the convex-mirror sign convention** Place a real object anywhere in front of a convex mirror. With incident light travelling towards the mirror, distances measured behind the mirror are positive. Thus  $u < 0$ , while the principal focus of a convex mirror lies behind it, giving  $f > 0$ . Write  $u = -a$ , where  $a > 0$  is the magnitude of the object distance. Substitution in the mirror formula gives

$$\begin{aligned} \frac{1}{f} &= \frac{1}{v} - \frac{1}{a}, \\ \frac{1}{v} &= \frac{1}{f} + \frac{1}{a} = \frac{a+f}{af}, \\ v &= \frac{af}{a+f}. \end{aligned}$$

Both numerator and denominator are positive for every real object position, so  $v > 0$ . Also  $a/(a+f) < 1$ , giving  $0 < v < f$  for a finite object distance. The image lies behind the mirror, between its pole and focus. The reflected rays diverge, and only their backward extensions meet there; such an image is virtual. For an object at infinity,  $v$  tends to  $f$ , still behind the mirror.

**Step 4: Conclusion** Huygens' construction gives  $n_a \sin i = n_g \sin r$ . For a real object in front of a convex mirror,  $v = af/(a + f) > 0$ , where  $a = -u > 0$  and  $f > 0$ ; hence its image is always virtual.

**Quick Tip to Solve:** In the Huygens construction, divide the two sine ratios that share hypotenuse  $AC$ . For a convex mirror, put  $u = -a$  and  $f > 0$  before deciding the sign of  $v$ .