

# CBSE Class 12 Physics Question Paper 2025 with Solution PDF-Set 55/2/3



## 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** : Question numbers **1** to **16** are Multiple Choice type questions. Each question carries **1** mark.
- (iv) In **Section B** : Question numbers **17** to **21** are Very Short Answer type questions. Each question carries **2** marks.
- (v) In **Section C** : Question numbers **22** to **28** are Short Answer type questions. Each question carries **3** marks.
- (vi) In **Section D** : Question numbers **29** & **30** are case study-based questions. Each question carries **4** marks.
- (vii) In **Section E** : Question numbers **31** to **33** are Long Answer 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 :

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

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

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

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

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

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

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

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

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

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

$$\text{Boltzman's constant} = 1.38 \times 10^{-23} \text{ JK}^{-1}$$

### Section A (16 marks)

1. Consider two identical dipoles  $D_1$  and  $D_2$ . Charges  $-q$  and  $q$  of dipole  $D_1$  are located at  $(0, 0)$  and  $(a, 0)$  and that of dipole  $D_2$  at  $(0, a)$  and  $(0, 2a)$  in  $x$ - $y$  plane, respectively. The net dipole moment of the system is [1 mark]

- (A)  $qa(\hat{i} + \hat{j})$
- (B)  $-qa(\hat{i} + \hat{j})$
- (C)  $qa(\hat{i} - \hat{j})$
- (D)  $-qa(\hat{i} - \hat{j})$

**Correct Answer:** (A)  $qa(\hat{i} + \hat{j})$

#### Solution:

##### Concept:

- The electric dipole moment is  $\vec{p} = q(\vec{r}_+ - \vec{r}_-)$ , directed from negative to positive charge.
- Dipole moments add vectorially; translating a neutral dipole does not change its moment.

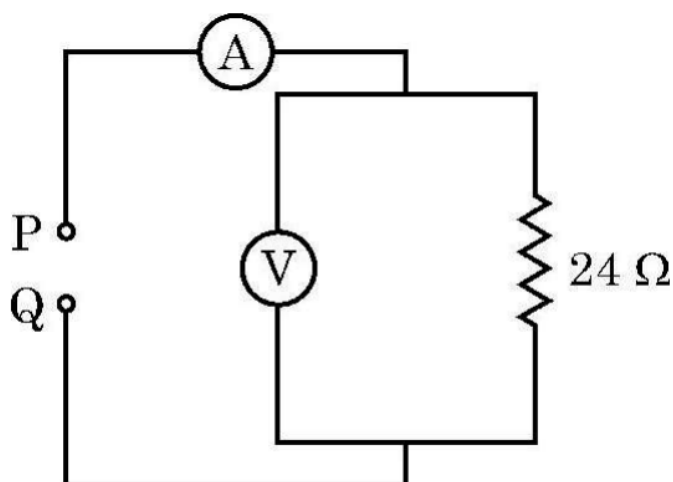
**Step 1: Find the two displacement vectors** In  $D_1$ , the positive charge lies a distance  $a$  to the right of the negative charge, so  $\vec{p}_1 = qa\hat{i}$ . In  $D_2$ , the displacement is  $(0, 2a) - (0, a) = (0, a)$ , so  $\vec{p}_2 = qa\hat{j}$ . The coordinate  $2a$  is a position, not the separation of the second dipole.

**Step 2: Add components and check the signs** The net moment is  $\vec{p}_1 + \vec{p}_2 = qa\hat{i} + qa\hat{j}$ . Both components must be positive. Option (B) reverses both; (C) reverses the second; (D) reverses the first. None agrees with the negative-to-positive directions of both dipoles.

**Step 3: Conclusion** The net dipole moment is  $qa(\hat{i} + \hat{j})$ . Hence, the correct option is (A).

**Quick Tip to Solve:** Subtract the negative charge's position from the positive charge's position for each dipole before adding moments.

2. Which pair of readings of ideal voltmeter and ideal ammeter in the given circuit is possible when a suitable power source of  $3\ \Omega$  internal resistance is connected between P and Q? [1 mark]



(A) 12.0 V, 2.0 A

(B) 2.0 V, 0.5 A

(C) 6.0 V, 2.0 A

(D) 12 V, 0.5 A

**Correct Answer:** (D) 12 V, 0.5 A

**Solution:**

**Concept:**

- An ideal voltmeter has infinite resistance and draws no current. An ideal ammeter has zero resistance.
- For a resistor,  $V = IR$ , where  $V$  is the potential difference across it and  $I$  is its current.

**Step 1: Identify what each meter measures** The voltmeter is connected across the  $24\ \Omega$  resistor. Since it draws no current, the ammeter reads exactly the current through this resistor. Consequently the readings must satisfy  $V/I = 24\ \Omega$ . The source's internal resistance is outside the voltmeter connection.

**Step 2: Test the offered pairs** The ratios  $V/I$  for (A), (B), (C) and (D) are respectively  $6\ \Omega$ ,  $4\ \Omega$ ,  $3\ \Omega$  and  $24\ \Omega$ . Only the last matches the circuit. It is feasible: a source of emf  $E = I(R+r) = 0.5(24+3) = 13.5\text{ V}$  gives these readings. Using  $3\ \Omega$  as the measured resistance in (C) confuses internal and external resistances.

**Step 3: Conclusion** The possible readings are 12 V and 0.5 A. Hence, the correct option is (D).

**Quick Tip to Solve:** Divide the voltmeter reading by the ammeter reading and compare it with the resistor across the voltmeter.

3. Which one of the following statements is correct? Electric field due to static charges is [1 mark]

- (A) conservative and field lines do not form closed loops.
- (B) conservative and field lines form closed loops.
- (C) non-conservative and field lines do not form closed loops.
- (D) non-conservative and field lines form closed loops.

**Correct Answer:** (A) conservative and field lines do not form closed loops.

**Solution:**

**Concept:**

- An electrostatic field is conservative: its work between two points depends only on their potentials.
- Around a closed path,  $\oint \vec{E} \cdot d\vec{l} = 0$ ; field lines point in the direction of decreasing potential.

**Step 1: Establish the conservative nature** Static charges produce an electric field expressible as  $\vec{E} = -\nabla V$ . The work done on charge  $q$  moving from A to B is  $q(V_A - V_B)$ , independent of path. Returning to the starting point gives zero net work, so the field is conservative.

**Step 2: Examine whether a field line can close** Along a field line the potential decreases continuously in its direction. A closed field line would return to the initial potential after continuously decreasing, which is impossible. Electrostatic lines begin on positive charges and end on negative charges, or extend to infinity. Thus (B) incorrectly allows closed loops, while (C) and (D) incorrectly call the field non-conservative.

**Step 3: Conclusion** The electric field is conservative and its field lines do not form closed loops. Hence, the correct option is (A).

**Quick Tip to Solve:** Use the decrease of potential along an electrostatic field line to rule out closed loops immediately.

4. A material is pushed out when placed in a uniform magnetic field. The material is [1 mark]

- (A) non-magnetic
- (B) diamagnetic
- (C) paramagnetic
- (D) ferromagnetic

**Correct Answer:** (B) diamagnetic

**Solution:**

**Concept:**

- A diamagnetic material has negative magnetic susceptibility,  $\chi_m < 0$ , and develops magnetisation opposite to the applied magnetic field.
- In a non-uniform field, diamagnetic matter tends to move towards weaker field; paramagnetic and ferromagnetic matter tend towards stronger field.

**Step 1: Interpret the stated repulsion** The stated behaviour, being pushed out of a magnetic-field region, identifies diamagnetic response in the usual classification of magnetic materials. Its induced magnetic moment opposes the applied field, so it is repelled from the stronger-field region near a magnet.

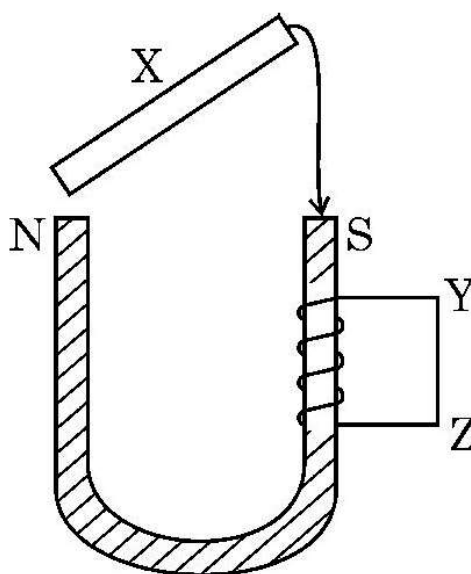
**Step 2: Compare the alternatives and the field wording** Paramagnetic and ferromagnetic materials are

attracted into a stronger-field region; an ideal non-magnetic material has no such response. Strictly, a perfectly uniform field throughout a sample produces no net translational force. The printed wording is understood as expulsion from a field region, with a field gradient at its boundary; diamagnetism is the intended material property.

**Step 3: Conclusion** The material is diamagnetic under the stated repulsion interpretation. Hence, the correct option is (B).

**Quick Tip to Solve:** Associate expulsion towards weaker magnetic field with negative susceptibility; a force requires a field gradient.

5. A soft iron rod X is allowed to fall on the two poles of a U shaped permanent magnet as shown in figure. A coil is wrapped over one arm of the U shaped magnet. During fall of the rod, the current in the coil will be [1 mark]



- (A) clockwise current
- (B) anticlockwise current
- (C) alternating current
- (D) zero

**Correct Answer:** (B) anticlockwise current

**Solution:**

**Concept:**

- Faraday's law gives induced emf  $\mathcal{E} = -d\Phi/dt$ , where  $\Phi$  is the magnetic flux linkage.
- Lenz's law makes the induced current oppose the change of flux. An anticlockwise current, viewed from an end of a coil, makes that end a north pole.

**Step 1: Identify the changing flux** As the soft iron rod approaches and bridges the poles, it provides an easier path for magnetic flux and increases the flux through the magnet and coil. At the arm marked S, the permanent magnet's flux is directed downwards into that pole. Its downward flux therefore increases during the fall.

**Step 2: Apply Lenz's law at the wound arm** The induced current must create an upward field in

the wound arm to oppose that increase. The top of the coil consequently behaves as a north pole. Viewed from the top of this arm, the current is anticlockwise. Clockwise current would reinforce the increasing downward flux. The change is in one direction during approach, so the current is not alternating; changing flux also rules out zero current.

**Step 3: Conclusion** The induced current is anticlockwise, viewed from the top of the wound arm. Hence, the correct option is (B).

**Quick Tip to Solve:** First find whether flux increases, then make the induced pole oppose that increase before applying the clock-face rule.

**6. A 1 cm straight segment of a conductor carrying 1 A current in x direction lies symmetrically at origin of Cartesian coordinate system. The magnetic field due to this segment at point (1 m, 1 m, 0) is** [1 mark]

- (A)  $1.0 \times 10^{-9} \hat{k}$  T
- (B)  $-1.0 \times 10^{-9} \hat{k}$  T
- (C)  $\frac{5.0}{\sqrt{2}} \times 10^{-10} \hat{k}$  T
- (D)  $-\frac{5.0}{\sqrt{2}} \times 10^{-10} \hat{k}$  T

**Correct Answer:** (C)  $\frac{5.0}{\sqrt{2}} \times 10^{-10} \hat{k}$  T

**Solution:**

**Concept:**

- A short current element produces  $\vec{B} = \frac{\mu_0}{4\pi} \frac{I \Delta \vec{l} \times \vec{r}}{r^3}$ , where  $\vec{r}$  points from the element to the observation point.
- The current-element approximation applies because the segment length is much smaller than its distance from the observation point;  $\mu_0/(4\pi) = 10^{-7}$  T m A<sup>-1</sup>.

**Step 1: Determine the geometry and direction** Here  $\Delta \vec{l} = 0.01 \hat{i}$  m,  $I = 1$  A, and  $\vec{r} = (\hat{i} + \hat{j})$  m, giving  $r = \sqrt{2}$  m. The cross product is  $\Delta \vec{l} \times \vec{r} = 0.01 \hat{k}$  m<sup>2</sup>, since  $\hat{i} \times \hat{j} = \hat{k}$ . Thus the field points along positive  $z$ .

**Step 2: Substitute and compare magnitudes**

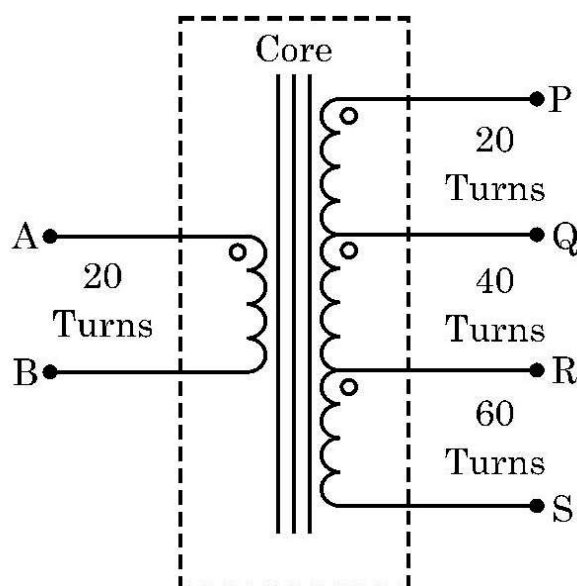
$$\vec{B} = 10^{-7} \frac{1 \times 0.01}{(\sqrt{2})^3} \hat{k} = \frac{5.0}{\sqrt{2}} \times 10^{-10} \hat{k} \text{ T.}$$

Options (B) and (D) have the wrong direction. Option (A) neglects the actual distance and angular factors. The short-segment approximation matches the precision of the printed choices.

**Step 3: Conclusion** The magnetic field is  $\frac{5.0}{\sqrt{2}} \times 10^{-10} \hat{k}$  T. Hence, the correct option is (C).

**Quick Tip to Solve:** Convert centimetres to metres first, then use the cross product to settle the sign before calculating the magnitude.

7. The number of turns between different pairs of output terminals are shown for a step-up transformer. Input voltage of 20 V is applied between A and B. Between which two terminals will the output be 120 V? [1 mark]



- (A) P and Q
- (B) Q and S
- (C) P and R
- (D) P and S

**Correct Answer:** (D) P and S

#### Solution:

##### Concept:

- For an ideal transformer,  $V_s/V_p = N_s/N_p$ , where  $N$  is the number of turns across the corresponding terminals.
- Successive sections of the same secondary winding add their turns, and therefore their induced voltages.

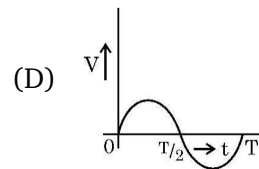
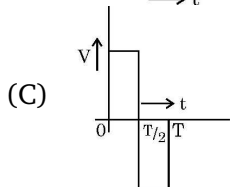
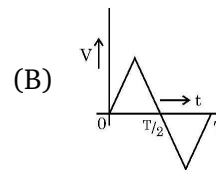
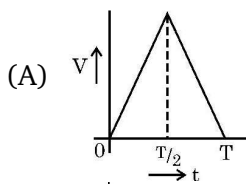
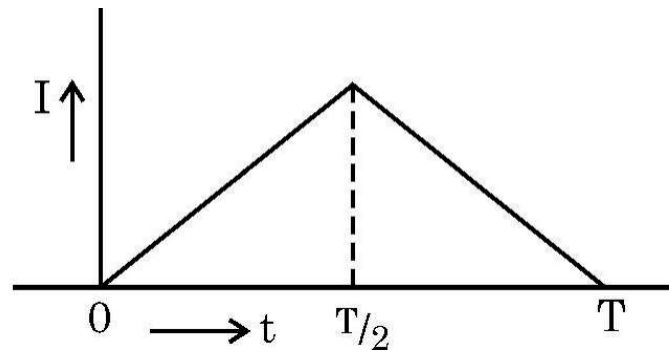
**Step 1: Calculate the voltage per turn** The input winding AB has 20 turns and receives 20 V. Therefore the voltage per turn is  $V_p/N_p = 1$  V. An output of 120 V requires 120 turns between the selected output terminals.

**Step 2: Add the secondary sections** The diagram gives  $N_{PQ} = 20$ ,  $N_{QR} = 40$  and  $N_{RS} = 60$ . Hence PQ gives 20 V, QS gives  $(40+60) = 100$  V, PR gives  $(20+40) = 60$  V, and PS gives  $(20+40+60) = 120$  V. The labels refer to individual winding sections, so they must be added for terminals spanning more than one section.

**Step 3: Conclusion** The output is 120 V between P and S. Hence, the correct option is (D).

**Quick Tip to Solve:** Find volts per turn from AB, then add all section turns lying between the proposed secondary terminals.

8. The alternating current  $I$  in an inductor is observed to vary with time  $t$  as shown in the graph for a cycle. Which one of the following graphs is the correct representation of wave form of voltage  $V$  with time  $t$ ? [1 mark]



**Correct Answer:** (C)

### Solution:

#### Concept:

- For an ideal inductor, the applied voltage is  $V = L \frac{dI}{dt}$ , where  $L$  is inductance and  $\frac{dI}{dt}$  is the slope of the current-time graph.
- A straight rising current gives a constant positive voltage; a straight falling current gives a constant negative voltage.

**Step 1: Differentiate the two straight segments** Let the maximum current be  $I_0$ . During  $0 < t < T/2$ , the slope is  $2I_0/T$ . During  $T/2 < t < T$ , the slope is  $-2I_0/T$ . Hence the applied voltage takes the constant values  $+2LI_0/T$  and  $-2LI_0/T$  in the two halves.

**Step 2: Compare all four waveforms** The voltage must change abruptly from a positive plateau to an equally large negative plateau at  $T/2$ . Option (A) incorrectly copies the current waveform. Options (B) and (D) have continuously changing slopes or curved voltage values instead of constant plateaus. The induced back emf has the opposite sign to the applied voltage; the graphs here represent the applied voltage.

**Step 3: Conclusion** The required voltage waveform is the rectangular waveform shown in (C). Hence, the correct option is (C).

**Quick Tip to Solve:** Read the slope of the current graph, not its height: each straight segment produces one constant-voltage plateau.

9. The plane face of a planoconvex lens is silvered. The refractive index of material and radius of curvature of the curved surface of the lens are  $n$  and  $R$  respectively. This lens will behave as a concave mirror of focal length

[1 mark]

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

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

**Solution:**

**Concept:**

- For a thin plano-convex lens in air, lens power is  $P_L = (n-1)/R$ , where  $n$  is refractive index and  $R$  is the magnitude of the curved surface radius.
- A ray traverses the lens twice after reflection at its silvered plane face. The plane mirror has zero optical power.

**Step 1: Count the two refractions through the lens** The light first passes through the converging lens, reflects at the plane silvered face, and then returns through the lens. The two lens powers add, while the plane reflecting surface adds no focusing power. Thus the effective converging power is  $P_{\text{eff}} = 2P_L = 2(n-1)/R$ .

**Step 2: Convert effective power to focal length** The focal-length magnitude is the reciprocal of effective power:

$$f_{\text{eff}} = \frac{1}{P_{\text{eff}}} = \frac{R}{2(n-1)}.$$

Option (B) is only the single-pass lens focal length. Options (A) and (C) omit the correct refractive-index dependence and do not represent the double traversal.

**Step 3: Conclusion** The combination behaves as a concave mirror with focal-length magnitude  $R/[2(n-1)]$ . Hence, the correct option is (D).

**Quick Tip to Solve:** For a plane-silvered thin lens, double the lens power; its effective focal-length magnitude is half the lens focal length.

**10. When the resistance measured between p and n ends of a p-n junction diode is high, it can act as a/an** [1 mark]

- (A) resistor
- (B) inductor
- (C) capacitor
- (D) switch

**Correct Answer:** (D) switch

**Solution:**

**Concept:**

- A p-n junction has a very high resistance in reverse bias because its depletion layer widens and only a very small leakage current flows.
- An electronic switch is open in its high-resistance state and closed in its low-resistance state.

**Step 1: Interpret the high measured resistance** High resistance means that the diode substantially blocks conduction between its p and n terminals. In the ideal-diode approximation, the reverse current is taken as zero. The circuit path is therefore effectively interrupted, as it is when an ordinary switch is open.

**Step 2: Identify the corresponding circuit function** The high-resistance condition is the OFF state of a diode switch. An inductor is identified by magnetic energy storage, and a capacitor by charge storage; neither function follows merely from a high resistance measurement. A reverse-biased junction does have capacitance, but that additional property is not what the stated resistance test establishes. A diode also differs from an ordinary resistor because its resistance depends strongly on bias direction.

**Step 3: Conclusion** The diode can act as a switch in the open or OFF state. Hence, the correct option is (D).

**Quick Tip to Solve:** Translate a diode resistance test into switch states: high resistance means OFF; low forward resistance means ON.

**11. Atomic spectral emission lines of hydrogen atom are incident on a zinc surface. The lines which can emit photoelectrons from the surface are members of** [1 mark]

- (A) Balmer series
- (B) Paschen series
- (C) Lyman series
- (D) Neither Balmer, nor Paschen nor Lyman series

**Correct Answer:** (C) Lyman series

**Solution:**

**Concept:**

- Photoelectric emission requires photon energy  $h\nu$  to be at least the work function  $\phi$  of the metal.
- Hydrogen Lyman transitions terminate at  $n = 1$ , Balmer at  $n = 2$ , and Paschen at  $n = 3$ . Lyman photons are ultraviolet and have the highest energies among these series.

**Step 1: Compare the photon-energy ranges** Lyman photons range from  $13.6(1 - 1/4) = 10.2$  eV to the series limit 13.6 eV. Even the Balmer series limit is only  $13.6/4 = 3.4$  eV, while the Paschen limit is

$$13.6/9 \approx 1.51 \text{ eV.}$$

**Step 2: Apply the zinc threshold** Zinc requires ultraviolet radiation for ordinary photoelectric emission; its work function is approximately 4.3 eV. Lyman photons exceed this threshold. All Balmer and Paschen photons fall below it, so (A) and (B) fail. Since Lyman photons do produce emission, the statement in (D) also fails.

**Step 3: Conclusion** The photoemitting lines belong to the Lyman series. Hence, the correct option is (C).

**Quick Tip to Solve:** Compare each series limit with the work function: if the limit is too low, every photon in that series is insufficient.

**12. The energy of an electron in a hydrogen atom in ground state is  $-13.6 \text{ eV}$ . Its energy in an orbit corresponding to quantum number  $n$  is  $-0.544 \text{ eV}$ . The value of  $n$  is** [1 mark]

- (A) 2
- (B) 3
- (C) 4
- (D) 5

**Correct Answer:** (D) 5

**Solution:**

**Concept:**

- The hydrogen energy levels obey  $E_n = E_1/n^2$ , where  $E_1$  is the ground-state energy and  $n$  is a positive integer.
- The negative energy indicates a bound electron. Use the ratio of the two signed energies so that  $n^2$  remains positive.

**Step 1: Form the energy ratio** Substitute  $E_1 = -13.6 \text{ eV}$  and  $E_n = -0.544 \text{ eV}$ :

$$n^2 = \frac{E_1}{E_n} = \frac{-13.6}{-0.544} = 25.$$

The electron-volt units cancel, leaving a dimensionless number.

**Step 2: Select the allowed quantum number** The principal quantum number must be positive, so the positive square root is used. As a check,  $-13.6/25 = -0.544 \text{ eV}$ . The alternatives  $n = 2, 3, 4$  would give approximately  $-3.40, -1.51, -0.850 \text{ eV}$ , respectively, and therefore do not match the stated energy.

**Step 3: Conclusion** The principal quantum number is  $n = 5$ . Hence, the correct option is (D).

**Quick Tip to Solve:** For hydrogen, divide the ground-state energy by the given bound-state energy, then take the positive square root.

**13. Assertion (A):** In an ideal step-down transformer, the electrical energy is not lost.

**Reason (R):** In a step-down transformer, voltage decreases but the current increases.

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

**Solution:**

**Concept:**

- An ideal transformer has no energy losses, so  $P_p = P_s$ , or  $V_p I_p = V_s I_s$ , for the usual ideal-transformer relation.
- The voltage ratio is  $V_s/V_p = N_s/N_p$ , while the current ratio is reciprocal:  $I_s/I_p = N_p/N_s$ .

**Step 1: Evaluate the assertion** The transformer is explicitly ideal. Winding heating, eddy-current loss, hysteresis loss and flux leakage are neglected. Input electrical energy is therefore transferred to the output without loss, so Assertion (A) is true.

**Step 2: Evaluate the reason** In a step-down transformer,  $N_s < N_p$ , and hence  $V_s < V_p$ . The output current is correspondingly larger:  $I_s/I_p = V_p/V_s > 1$ . Reason (R) is therefore true in the stated ideal-transformer context.

**Step 3: Connect the reason to energy transfer** The reason gives only qualitative trends: voltage decreases and current increases. These trends can also occur in a transformer with losses, so they do not establish equal input and output powers. Exact reciprocal compensation follows only after imposing ideal losslessness; using it to prove losslessness would be circular. Assertion (A) instead follows from the absence of dissipative losses in the ideal transformer. Thus (A) incorrectly claims an explanatory link, while (C) and (D) incorrectly classify true statements as false.

**Step 4: Conclusion** Both A and R are true, but R does not correctly explain A. Hence, the correct option is (B).

**Quick Tip to Solve:** For an assertion about zero energy loss, look for a reason that excludes losses; qualitative voltage and current trends alone do not establish equal powers.

**14. Assertion (A): Out of Infrared and radio waves, the radio waves show more diffraction effect.**

**Reason (R): Radio waves have greater frequency than infrared waves.**

[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:**

- Diffraction becomes more pronounced when wavelength  $\lambda$  is larger relative to the same aperture or obstacle size.
- For electromagnetic waves in vacuum,  $c = \nu\lambda$ ; frequency  $\nu$  and wavelength are inversely related.

**Step 1: Evaluate the assertion** Radio waves have longer wavelengths than infrared waves. For the same opening or obstacle, their larger wavelength-to-size ratio produces a more noticeable bending and spreading. Assertion (A) is therefore true.

**Step 2: Evaluate the reason** Since both are electromagnetic waves, their speeds in vacuum are equal. Their frequency ratio is the inverse of their wavelength ratio. Radio waves have lower, not greater, frequencies than infrared waves, so Reason (R) is false.

**Step 3: Apply the assertion-reason code** The physical explanation for greater radio-wave diffraction is the greater wavelength. The printed reason reverses the frequency ordering and cannot explain the true assertion. Options (A) and (B) require a true reason, while (D) incorrectly declares the assertion false.

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

**Quick Tip to Solve:** For diffraction comparisons at a fixed opening, rank wavelengths first; a larger wavelength also means a lower frequency.

**15. Assertion (A): In a semiconductor diode the thickness of depletion layer is not fixed.**

**Reason (R): Thickness of depletion layer in a semiconductor device depends upon many factors such as biasing of the semiconductor.** [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:**

- The depletion region of a p-n junction contains immobile ionised donors and acceptors, with very few mobile charge carriers.
- Applied bias changes the junction barrier and therefore the depletion-layer width: forward bias narrows it and reverse bias widens it.

**Step 1: Judge the assertion** The depletion-layer thickness is not a fixed geometrical dimension of a diode. Its boundaries move when the balance between the junction electric field and carrier diffusion changes. Thus Assertion (A) is true.

**Step 2: Judge the reason** Biasing is one factor controlling the depletion width. Forward bias opposes the built-in barrier and allows majority carriers to approach the junction, reducing its width. Reverse bias reinforces the barrier and draws majority carriers away, increasing the width. Reason (R) is therefore true.

**Step 3: Check the explanatory link** Since changing the applied bias changes the depletion thickness, the reason directly explains why the thickness is not fixed. Option (B) incorrectly denies this link, while (C) and (D) incorrectly classify a true statement as false.

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

**Quick Tip to Solve:** For a depletion-width question, remember: forward bias narrows the layer; reverse bias widens it.

**16. Assertion (A):** In Bohr model of hydrogen atom, the angular momentum of an electron in  $n^{\text{th}}$  orbit is proportional to the square root of its orbit radius  $r_n$ .

**Reason (R):** According to Bohr model, electron can jump to its nearest orbits only.

[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:**

- For the hydrogen atom, Coulomb attraction supplies centripetal force:  $m_e v_n^2 / r_n = k e^2 / r_n^2$ , where  $k = 1 / (4\pi\epsilon_0)$ .
- Angular momentum is  $L_n = m_e v_n r_n$ . A radiative transition between permitted levels satisfies  $h\nu = |E_i - E_f|$ .

**Step 1: Judge the assertion** Multiply the centripetal-force equation by  $m_e r_n^3$  to obtain

$$m_e^2 v_n^2 r_n^2 = m_e k e^2 r_n.$$

Therefore  $L_n^2 = m_e k e^2 r_n$ , so  $L_n \propto \sqrt{r_n}$ . The constants are the same in every hydrogen orbit. Assertion (A) is true.

**Step 2: Judge the reason** The Bohr model does not restrict an electron to transitions between neighbouring orbits. A transition may connect non-adjacent permitted energy levels; for example,  $n = 3$  to  $n = 1$  emits a photon whose energy equals their energy difference. Reason (R) is false.

**Step 3: Check the explanatory link** The asserted radius dependence follows from Coulomb attraction and circular motion, not from any nearest-orbit transition rule. Options (A) and (B) require a true reason, and (D) requires a false assertion; each is inconsistent with the analysis.

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

**Quick Tip to Solve:** You can also use  $L_n \propto n$  and  $r_n \propto n^2$ : eliminating  $n$  immediately gives  $L_n \propto \sqrt{r_n}$ .

## Section B (10 marks)

**17. The threshold voltage of a silicon diode is 0.7V. It is operated at this point by connecting the diode in series with a battery of  $V$  volt and a resistor of  $1000\ \Omega$ . Find the value of  $V$  when the current drawn is 15 mA.**

[2 marks]

**Solution:**

**Concept:**

- In a series circuit, the same current  $I$  flows through the resistor and the diode. Ohm's law gives the resistor's voltage drop as  $V_R = IR$ .
- Kirchhoff's loop law gives  $V = V_R + V_D$ , where  $V$  is the battery voltage and  $V_D$  is the forward voltage across the diode.

**Step 1: Use the specified diode voltage** The diode is operated at the stated threshold voltage, so use  $V_D = 0.7\text{ V}$  for its voltage drop. The series current is

$$I = 15\text{ mA} = 15 \times 10^{-3}\text{ A}.$$

This current flows through the  $1000\ \Omega$  resistor as well. The battery must supply both the resistor drop and the diode drop.

**Step 2: Calculate and add the series voltage drops** The potential difference across the resistor is

$$V_R = IR = (15 \times 10^{-3})(1000) = 15\text{ V}.$$

Applying the loop law to the forward-biased diode and resistor gives

$$V - 15 - 0.7 = 0, \quad V = 15 + 0.7\text{ V}.$$

Using only  $IR$  would omit the potential difference needed across the silicon junction.

**Step 3: Conclusion** The required battery voltage is  $V = 15.7\text{ V}$ , connected with the diode forward biased.

**Quick Tip to Solve:** Convert milliamperes to amperes before using  $IR$ , then add the diode's stated  $0.7\text{ V}$  drop to the resistor drop.

**18. In a double slit experiment, it is observed that the angular width of one fringe formed on the screen is  $0.2^\circ$ . The wavelength of light used in the experiment is  $500\text{ nm}$ . Calculate the separation of the two slits.** [2 marks]

**Solution:**

**Concept:**

- In Young's double-slit experiment, the linear fringe width is  $\beta = \lambda D/d$ , where  $D$  is the screen distance and  $d$  is the slit separation.
- For small angles, the angular fringe width in radians is  $\Delta\theta = \beta/D = \lambda/d$ . It is the angular separation of successive bright fringes or successive dark fringes.

**Step 1: Convert the data to compatible units** The angle must be in radians when using  $\Delta\theta = \lambda/d$ . Thus

$$\Delta\theta = 0.2 \times \frac{\pi}{180} = 3.49 \times 10^{-3}\text{ rad}.$$

The wavelength in metres is

$$\lambda = 500\text{ nm} = 500 \times 10^{-9}\text{ m}.$$

Since the angle is much smaller than one radian, the small-angle fringe-width formula applies.

**Step 2: Find the slit separation** Rearrange the angular fringe-width relation and substitute the

converted values:

$$d = \frac{\lambda}{\Delta\theta} = \frac{500 \times 10^{-9}}{3.49 \times 10^{-3}} = 1.43 \times 10^{-4} \text{ m.}$$

The screen distance is not needed because it cancels when linear fringe width is divided by  $D$ . The angle describes one complete fringe spacing, so no extra factor of two is required.

**Step 3: Conclusion** The separation of the two slits is  $d \approx 1.43 \times 10^{-4} \text{ m} = 0.143 \text{ mm}$ .

**Quick Tip to Solve:** For angular fringe width use  $d = \lambda/\Delta\theta$ , but first multiply the angle in degrees by  $\pi/180$ .

**19. A light beam converges at a point O. In the path of this beam, a concave lens of focal length 15 cm is placed at a distance of 10 cm before point O. The beam now converges at a point O'. Find the magnitude and the direction of shift OO'. [2 marks]**

**Solution:**

**Concept:**

- The thin-lens formula in the Cartesian convention is  $1/f = 1/v - 1/u$ . Distances measured in the direction of incident light are positive.
- Rays already converging to a point beyond a lens have a virtual object for that lens. A concave lens has negative focal length and reduces the convergence of the incident beam.

**Step 1: Assign the object distance and focal length** Take the incident light to travel from left to right, with the lens at the origin. Without the lens the rays would meet at  $O$ , which is 10 cm to its right. Thus  $O$  is a virtual object and  $u = +10$  cm. For the concave lens,  $f = -15$  cm. The positive object distance is essential here because the incident rays are converging rather than diverging.

**Step 2: Locate the new point of convergence** Substitute in the lens formula:

$$\begin{aligned} \frac{1}{v} &= \frac{1}{f} + \frac{1}{u} = -\frac{1}{15} + \frac{1}{10} \\ &= \frac{1}{30} \text{ cm}^{-1}, \quad v = +30 \text{ cm.} \end{aligned}$$

The positive value of  $v$  places  $O'$  to the right of the lens. The shift from the original convergence point is  $OO' = 30 - 10 = 20$  cm. This agrees with the reduced convergence produced by the concave lens: the rays meet farther away.

**Step 3: Conclusion** The point of convergence shifts by  $20 \text{ cm}$  in the direction of propagation of light, away from the lens, from  $O$  towards  $O'$ .

**Quick Tip to Solve:** For an incident converging beam, the intended convergence point beyond the lens is a virtual object: use positive  $u$ , then subtract the old position from the new one.

**20.** The threshold wavelength of a metal is 450 nm. Calculate (i) the work function of the metal in eV and (ii) the maximum energy of the ejected photoelectrons in eV by incident radiation of 250 nm. [2 marks]

**Solution:**

**Concept:**

- The work function  $\phi$  is the minimum energy needed to liberate an electron. At the threshold wavelength  $\lambda_0$ ,  $\phi = hc/\lambda_0$ .
- Einstein's photoelectric equation is  $K_{\max} = hc/\lambda - \phi$ . Here  $h$  is Planck's constant,  $c$  is the speed of light and  $\lambda$  is the incident wavelength;  $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$ .

**Step 1: Calculate the work function** At threshold, the emitted electron has zero maximum kinetic energy, so the whole photon energy supplies the work function. Convert the wavelength to metres before substitution:

$$\phi = \frac{(6.63 \times 10^{-34})(3 \times 10^8)}{450 \times 10^{-9}} = 4.42 \times 10^{-19} \text{ J}.$$

Dividing by the joule value of one electron-volt gives  $\phi = 4.42/1.6 = 2.7625 \text{ eV}$ .

**Step 2: Subtract the work function from the incident photon energy** The incident wavelength 250 nm is shorter than the threshold wavelength, so photoemission occurs. Its photon energy is

$$E = \frac{(6.63 \times 10^{-34})(3 \times 10^8)}{(250 \times 10^{-9})(1.6 \times 10^{-19})} = 4.9725 \text{ eV}.$$

The remaining energy is the largest possible kinetic energy of an emitted electron:

$$K_{\max} = 4.9725 - 2.7625 = 2.21 \text{ eV}.$$

**Step 3: Conclusion** (i) The work function is  $2.76 \text{ eV}$ . (ii) The maximum kinetic energy is  $2.21 \text{ eV}$ .

**Quick Tip to Solve:** Compute both photon energies in the same unit, then subtract:  $K_{\max} = hc(1/\lambda - 1/\lambda_0)$ . A shorter incident wavelength must give a positive result.

**21(a).** Two wires of the same material and the same radius have their lengths in the ratio 2 : 3. They are connected in parallel to a battery which supplies a current of 15 A. Find the current through the wires. [2 marks]

**Solution:**

**Concept:**

- A uniform wire has resistance  $R = \rho L/A$ , where  $\rho$  is resistivity,  $L$  is length and  $A$  is cross-sectional area.
- Parallel branches have the same potential difference. Thus  $I = U/R$  makes current inversely proportional to resistance, and the total current is the sum of the branch currents.

**Step 1: Obtain the resistance ratio** Call the currents in the wires of lengths  $2\ell$  and  $3\ell$  respectively  $I_1$

and  $I_2$ . Both wires have the same material and radius, so their resistivity and area  $A = \pi r^2$  are equal. Therefore

$$\frac{R_1}{R_2} = \frac{\rho(2\ell)/A}{\rho(3\ell)/A} = \frac{2}{3}.$$

The longer wire has the larger resistance; equal radii do not imply equal resistances when the lengths differ.

**Step 2: Divide the supplied current between the wires** Let the common voltage across the parallel combination be  $U$ . Ohm's law gives

$$\frac{I_1}{I_2} = \frac{U/R_1}{U/R_2} = \frac{R_2}{R_1} = \frac{3}{2}.$$

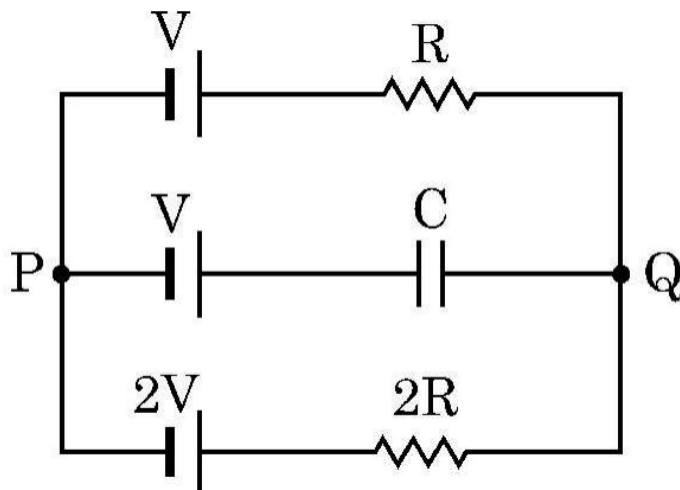
Write  $I_1 = 3k$  and  $I_2 = 2k$ . Conservation of charge at the junction requires  $3k + 2k = 15$  A, so  $k = 3$  A. Consequently, the shorter wire carries  $3k = 9$  A and the longer wire carries  $2k = 6$  A.

**Step 3: Conclusion** The current in the wire of length  $2\ell$  is  $\boxed{9 \text{ A}}$ , and that in the wire of length  $3\ell$  is  $\boxed{6 \text{ A}}$ . Their sum is the supplied 15 A.

**Quick Tip to Solve:** For parallel wires of equal material and radius, invert the length ratio to obtain the current ratio: 2 : 3 in length gives 3 : 2 in current.

OR

**21(b).** In the circuit three ideal cells of e.m.f.  $V$ ,  $V$  and  $2V$  are connected to a resistor of resistance  $R$ , a capacitor of capacitance  $C$  and another resistor of resistance  $2R$  as shown in figure. In the steady state find (i) the potential difference between P and Q and (ii) potential difference across capacitor C. [2 marks]



### Solution:

#### Concept:

- An ideal capacitor carries no steady d.c. current; only the two resistor branches form the conducting loop.
- Kirchhoff's loop rule gives zero net potential change around a loop. A cell raises potential from its short plate to its long plate.

**Step 1: Find the potential difference between the common nodes** All cells have their positive terminals towards the right. The current  $I$  flows from P to Q in the lower branch and returns through the upper branch. Their opposing emfs give  $2V - V = V$ , across resistance  $2R + R = 3R$ , so  $I = V/(3R)$ . Along the lower branch, the potential rises by  $2V$  and falls by  $2RI$ . Thus, defining  $U = V_Q - V_P$ ,

$$U = 2V - 2RI = 2V - \frac{2V}{3} = \frac{4V}{3}.$$

**Step 2: Find the voltage across the capacitor** Let X be the junction between the middle cell and the left capacitor plate. This cell gives  $V_X = V_P + V$ ; the right capacitor plate is connected to Q. Therefore

$$V_Q - V_X = (V_Q - V_P) - V = \frac{4V}{3} - V = \frac{V}{3}.$$

**Step 3: Conclusion** (i)  $V_Q - V_P = 4V/3$ , or  $V_P - V_Q = -4V/3$ . (ii) The capacitor voltage has magnitude  $V/3$ , with its Q-side plate at higher potential.

**Quick Tip to Solve:** Open only the capacitor branch in the steady state; retain its series cell when comparing the two capacitor-plate potentials.

## Section C (21 marks)

**22. (a) Define Electrical conductivity. Obtain the expression of electrical conductivity of a conductor in terms of number density and relaxation time of free electrons.**

**(b) Explain qualitative change in resistivity of a conductor with temperature using expression obtained in (a).** [3 marks]

### Solution:

#### Concept:

- Electrical conductivity  $\sigma$  measures how readily a material conducts current. It is the reciprocal of resistivity  $\rho$ :  $\sigma = 1/\rho$ , and relates current density to electric field through  $\mathbf{J} = \sigma\mathbf{E}$ . Its SI unit is  $\text{S m}^{-1}$ .
- Relaxation time  $\tau$  is the mean time between successive collisions of a conduction electron. Let  $n$  be the number of free electrons per unit volume,  $e$  the magnitude of their charge, and  $m$  their mass.

**Step 1: Relate drift velocity to the applied electric field** For part (a), an electron in an electric field  $\mathbf{E}$

experiences force  $-e\mathbf{E}$ . Its acceleration between collisions is consequently  $-e\mathbf{E}/m$ . Random thermal velocities have zero vector average; the field produces an additional average drift velocity

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

Thus electron drift is opposite to the field, with magnitude  $v_d = eE\tau/m$ . The mean interval  $\tau$  determines how much directed velocity the electron acquires before its motion is randomized by scattering.

**Step 2: Obtain the conductivity expression** The charge density associated with the free electrons is  $-ne$ . Multiplying by their drift velocity gives the conventional current density:

$$\mathbf{J} = -ne\mathbf{v}_d = \frac{ne^2\tau}{m}\mathbf{E}.$$

Comparing this with  $\mathbf{J} = \sigma\mathbf{E}$ , the conductivity is

$$\sigma = \frac{ne^2\tau}{m}, \quad \rho = \frac{1}{\sigma} = \frac{m}{ne^2\tau}.$$

Both  $\sigma$  and  $\rho$  are positive because the two negative signs from electron charge and drift direction cancel.

**Step 3: Explain the temperature dependence** For part (b), in a metallic conductor the number density  $n$  remains approximately constant over an ordinary temperature range. Heating increases lattice vibrations, causing more frequent scattering of conduction electrons. The relaxation time  $\tau$  decreases. Since  $\rho = m/(ne^2\tau)$ , the resistivity increases and the conductivity decreases as temperature rises. Over a moderate temperature interval this rise is approximately linear, commonly expressed as  $\rho(T) = \rho(T_0)[1 + \alpha(T - T_0)]$  with positive temperature coefficient  $\alpha$ .

**Step 4: Conclusion** Electrical conductivity is  $\sigma = 1/\rho = ne^2\tau/m$ . A metallic conductor becomes more resistive on heating because increased lattice scattering reduces  $\tau$ , so  $\rho \propto 1/\tau$  increases.

**Quick Tip to Solve:** For a heated metal, follow the chain: stronger lattice vibrations, shorter relaxation time, lower conductivity and higher resistivity; do not assume the free-electron density rises substantially.

**23. (a)** Show the variation of binding energy per nucleon with mass number. Write the significance of the binding energy curve.

**(b)** Two nuclei with lower binding energy per nucleon form a nuclei with more binding energy per nucleon.

**(i)** What type of nuclear reaction is it?

**(ii)** Whether the total mass of nuclei increases, decreases or remains unchanged?

**(iii)** Does the process require energy or produce energy?

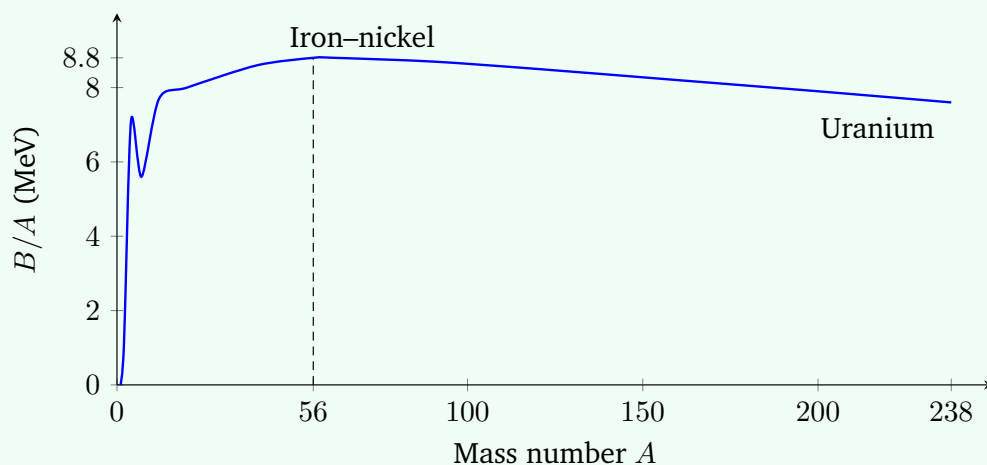
[3 marks]

**Solution:**

**Concept:**

- Binding energy  $B = \Delta mc^2$  is the energy needed to separate a nucleus into its free nucleons;  $B/A$  measures the average binding of each nucleon.
- A greater binding energy per nucleon generally means greater nuclear stability. Energy is released when the total binding energy of the products exceeds that of the reactants.

**Step 1: (a) Sketch the binding-energy curve** Plot mass number  $A$  horizontally and binding energy per nucleon  $B/A$ , in MeV, vertically. For very light nuclei the curve rises rapidly, with local irregularities. It reaches a broad maximum of approximately 8.8 MeV near the iron–nickel region,  $A \simeq 56$ –62. For heavier nuclei it decreases slowly, reaching about 7.6 MeV near uranium. The graph below shows the schematic trend.



*Schematic binding energy per nucleon versus mass number*

**Step 2: (a) Explain the significance** Nuclei near the maximum are tightly bound and particularly stable. Light nuclei can release energy by combining into a more tightly bound nucleus (fusion). Very heavy nuclei can release energy by splitting into medium-mass nuclei (fission). In both cases the products move towards the higher part of the binding-energy-per-nucleon curve. The nearly constant value for medium nuclei also reflects the short range and saturation of nuclear forces.

**Step 3: (b) Identify the reaction and account for mass and energy** (i) Two nuclei combining into one is **nuclear fusion**. (ii) Since the nucleon number is conserved while binding energy per nucleon increases, total binding energy increases. The final nucleus therefore has less rest mass than the two initial nuclei together. (iii) The lost rest mass appears as released energy:

$$Q = (M_{\text{initial}} - M_{\text{final}})c^2 = B_{\text{final}} - B_{\text{initial}} > 0.$$

Thus the process produces energy overall. Energy may initially be needed to overcome electrostatic repulsion, but the stated reaction has a positive net energy yield.

**Step 4: Conclusion** The binding-energy curve peaks near iron–nickel and explains energy release by light-nucleus fusion and heavy-nucleus fission. In (b): (i) fusion, (ii) total nuclear rest mass decreases, and (iii) energy is produced.

**Quick Tip to Solve:** Compare total binding energies: an increase means a decrease of nuclear rest mass and a positive energy release.

24. (a) ac voltage of frequency  $\omega$  is applied across a series LCR circuit. Draw the phasor diagram and obtain the impedance of the circuit.

(b) Discuss 'resonance' in a series LCR circuit and write the expression for resonant frequency.

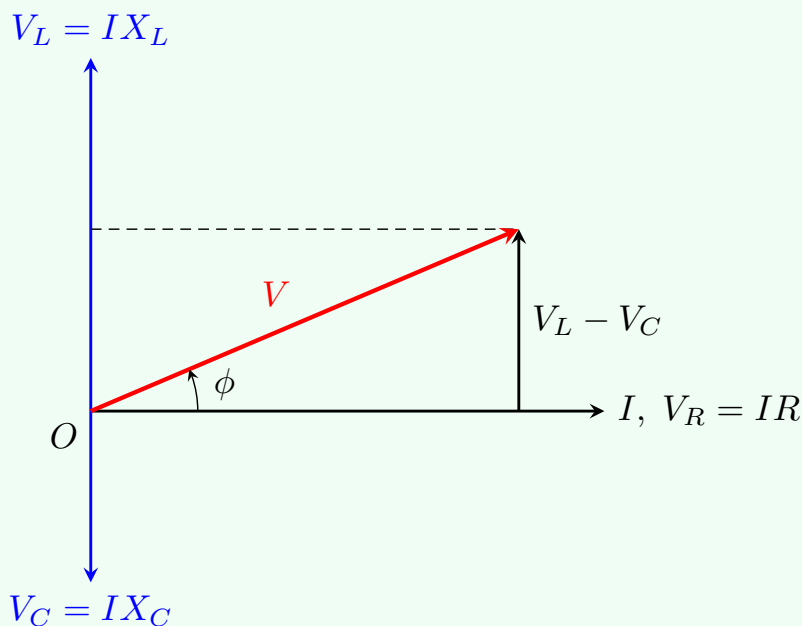
[3 marks]

### Solution:

#### Concept:

- In a series LCR circuit the same current flows through all three elements. Take its phasor as the reference; resistor voltage is in phase, inductor voltage leads by  $90^\circ$ , and capacitor voltage lags by  $90^\circ$ .
- At angular frequency  $\omega$ , the reactances are  $X_L = \omega L$  and  $X_C = 1/(\omega C)$ . The impedance  $Z$  relates rms voltage and rms current by  $V = IZ$ .

**Step 1: (a) Add the voltage phasors** Choose current  $I$  along the positive horizontal axis. Draw  $V_R = IR$  along it,  $V_L = IX_L$  vertically upwards and  $V_C = IX_C$  vertically downwards. Since the reactive voltages oppose one another, their resultant is  $V_L - V_C$ . The supply voltage is the vector sum of  $V_R$  and this perpendicular resultant. The diagram illustrates  $X_L > X_C$ ; if  $X_C > X_L$ , the reactive resultant points downwards.



Series LCR voltage phasors for an inductive circuit

**Step 2: (a) Obtain the impedance** Apply Pythagoras to the right-angled voltage triangle:

$$\begin{aligned} V^2 &= V_R^2 + (V_L - V_C)^2 \\ &= I^2 R^2 + I^2 (X_L - X_C)^2, \\ Z = \frac{V}{I} &= \sqrt{R^2 + \left( \omega L - \frac{1}{\omega C} \right)^2}. \end{aligned}$$

Also,  $\tan \phi = (X_L - X_C)/R$ , where  $\phi$  is the supply-voltage phase relative to current. A positive  $\phi$  means current lags voltage; a negative value means current leads it.

**Step 3: (b) State and derive the resonance condition** Series resonance occurs when the inductive and capacitive reactances are equal. Their voltage phasors cancel, leaving the supply voltage in phase

with the current:

$$\omega_0 L = \frac{1}{\omega_0 C} \Rightarrow \omega_0 = \frac{1}{\sqrt{LC}}, \quad f_0 = \frac{1}{2\pi\sqrt{LC}}.$$

At resonance the impedance is minimum,  $Z = R$ ; for fixed applied rms voltage the current is maximum,  $I = V/R$ , and the power factor is unity. Here  $\omega_0$  is angular frequency in radians per second and  $f_0$  is frequency in hertz.

**Step 4: Conclusion**  $Z = \sqrt{R^2 + (\omega L - 1/\omega C)^2}$ . Resonance occurs at  $X_L = X_C$ , with  $\omega_0 = 1/\sqrt{LC}$ , or  $f_0 = 1/(2\pi\sqrt{LC})$ , when  $Z = R$  and current is maximum.

**Quick Tip to Solve:** Add inductor and capacitor voltages with opposite signs before using Pythagoras; at resonance they cancel, even though each can be large.

**25. (a)** The amplitude of a light wave becomes  $n$  times. This results in intensity of the wave becoming  $m$  times. What is the relation between  $n$  and  $m$ ?

**(b)** White light is incident on three identical surfaces - a black surface, a yellow surface and a white surface, one by one. For which surface, the pressure exerted on the surface by the incident light will be (i) maximum (ii) minimum? Justify your answer. [3 marks]

**Solution:**

**Concept:**

- The intensity of a sinusoidal electromagnetic wave is proportional to the square of its field amplitude:  $I = \frac{1}{2}\epsilon_0 c E_0^2$ , where  $E_0$  is the electric-field amplitude.
- Light carries momentum. Radiation pressure is the normal momentum transferred per unit area per unit time; reflection transfers more momentum than absorption for the same incident light.

**Step 1: (a) Relate the amplitude and intensity multipliers** Let the initial electric-field amplitude and intensity be  $E_0$  and  $I$ . After the change, the amplitude is  $E'_0 = nE_0$  and the intensity is  $I' = mI$ . The medium is unchanged, so the proportionality constant in the intensity relation is unchanged:

$$\frac{I'}{I} = \frac{(E'_0)^2}{E_0^2} = \frac{(nE_0)^2}{E_0^2} = n^2.$$

Therefore  $m = n^2$ . The same result follows if amplitude means magnetic-field amplitude, since  $E_0 = cB_0$  for light in vacuum.

**Step 2: (b) Compare the momentum transfer** An absorbed light quantum transfers its incident momentum to the surface. Reflection reverses the normal component of its momentum, producing a larger change and hence a larger force on the surface. For normal incidence the ideal limiting pressures are

$$p_{\text{abs}} = \frac{I}{c}, \quad p_{\text{refl}} = \frac{2I}{c}.$$

These limits illustrate why reflecting more of the incident light increases the pressure. For opaque surfaces under the same illumination and reflection geometry, greater reflectance gives greater momentum transfer.

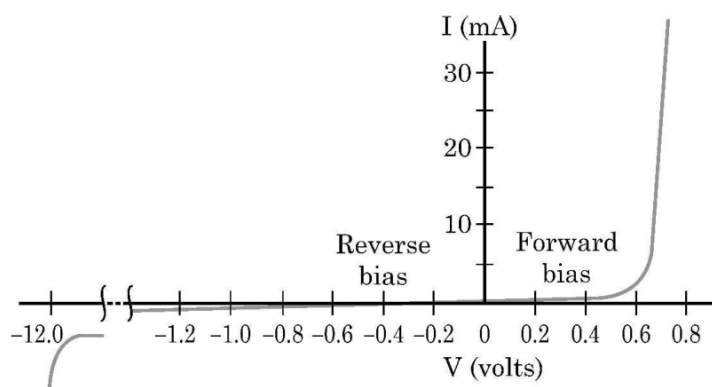
**Step 3: (b) Apply the comparison to the three colours** The white surface reflects most of the incident white light and therefore experiences the **maximum** radiation pressure. The black surface absorbs almost all the incident light and reflects the least, so it experiences the **minimum** pressure. The yellow surface reflects selected wavelengths while absorbing the others, giving an intermediate pressure in

the usual idealised comparison. The minimum is not zero: absorbed light also transfers momentum, although less than reflected light.

**Step 4: Conclusion** (a)  $m = n^2$ . (b) Radiation pressure is maximum on the white surface and minimum on the black surface, because reflection transfers more momentum than absorption under the same illumination.

**Quick Tip to Solve:** Square the amplitude multiplier to obtain the intensity multiplier. For radiation pressure, compare momentum change, not merely the energy absorbed.

26. (a) What are majority and minority charge carriers in an extrinsic semiconductor?  
 (b) A p-n junction is forward biased. Describe the movement of the charge carriers which produce current in it.  
 (c) The graph shows the variation of current with voltage for a p-n junction diode. Estimate the dynamic resistance of diode at  $V = -0.6$  volt. [3 marks]



### Solution:

#### Concept:

- Doping creates unequal electron and hole concentrations. The more numerous mobile carriers are majority carriers; the less numerous mobile carriers are minority carriers.
- Forward bias lowers the junction potential barrier and narrows the depletion region, allowing majority carriers to cross the junction by diffusion.
- Dynamic resistance at an operating point is  $r_d = dV/dI$ , the reciprocal of the local slope of the current-voltage graph.

**Step 1: Identify both types of charge carrier** (a) In an n-type semiconductor, donor impurities supply many free electrons: electrons are the majority carriers and holes are the minority carriers. In a p-type semiconductor, acceptor impurities create many holes: holes are the majority carriers and electrons are the minority carriers. Both kinds of mobile carrier are present in either material; majority and minority refer to their relative concentrations, not to their charges.

**Step 2: Describe the forward current** (b) The p-side is connected to the positive terminal and the n-side to the negative terminal. The applied voltage opposes the built-in barrier, so holes move from the p-region into the n-region and electrons move from the n-region into the p-region. After crossing, these injected carriers recombine with opposite carriers. The external source replenishes them, maintaining a steady current. Electron motion from n to p and hole motion from p to n both contribute conventional current from p to n through the junction.

**Step 3: Read the reverse-bias slope** (c) The specified voltage is  $-0.6\text{ V}$ , which lies on the nearly horizontal reverse-bias portion of the graph, well before breakdown. A small change in reverse voltage causes practically no change in reverse saturation current. Thus,

$$\frac{\Delta I}{\Delta V} \simeq 0, \quad r_d = \frac{\Delta V}{\Delta I} \rightarrow \infty.$$

This is a slope resistance, so the ratio of the coordinates  $V/I$  is not the quantity requested. The graph provides no resolvable nonzero slope from which to quote a finite numerical value.

**Step 4: Conclusion** Electrons are majority carriers in n-type material and holes in p-type material; the other type is the minority carrier. Forward current is due to holes crossing p to n and electrons crossing n to p. At  $-0.6\text{ V}$ , the diode has extremely large dynamic resistance, ideally  $r_d \rightarrow \infty$ .

**Quick Tip to Solve:** First locate the sign of the stated voltage on the graph; use the local slope, not  $V/I$ , to find dynamic resistance.

**27(a).** In a region of a uniform electric field  $\vec{E}$ , a negatively charged particle is moving with a constant velocity  $\vec{v} = -v_0\hat{i}$  near a long straight conductor coinciding with  $XX'$  axis and carrying current  $I$  towards  $-X$  axis. The particle remains at a distance  $d$  from the conductor.

(i) Draw diagram showing direction of electric and magnetic fields.

(ii) What are the various forces acting on the charged particle?

(iii) Find the value of  $v_0$  in terms of  $E$ ,  $d$  and  $I$ .

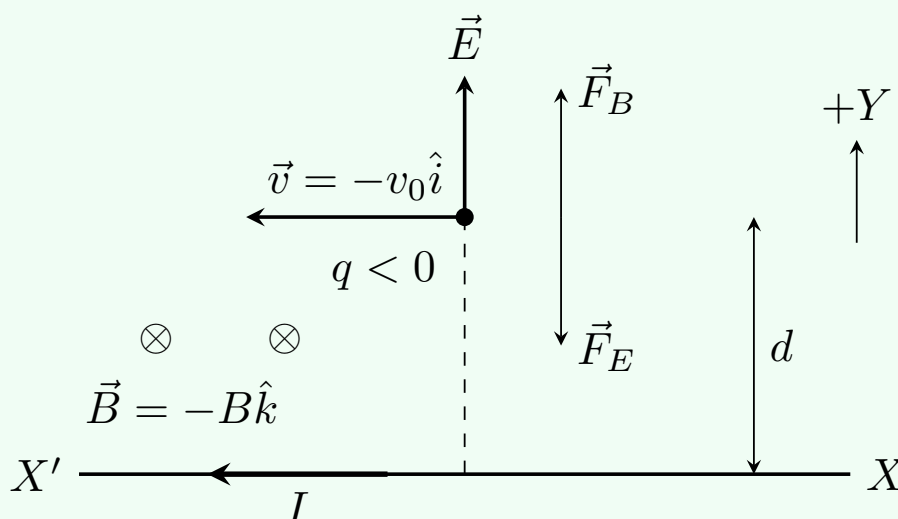
[3 marks]

**Solution:**

**Concept:**

- A long straight conductor produces magnetic field  $B = \mu_0 I / (2\pi d)$  at perpendicular distance  $d$ ; its direction follows the right-hand thumb rule.
- The electromagnetic force on charge  $q$  is  $\vec{F} = q\vec{E} + q(\vec{v} \times \vec{B})$ . Constant velocity requires the net force to vanish.

**Step 1: Draw the field directions** (i) Place the particle above the conductor, at  $y = d$ , with  $+X$  to the right and  $+Y$  upward. The current and particle velocity are both towards  $-X$ . The right-hand rule gives  $\vec{B} = -B\hat{k}$ , into the page at the particle. For the electric force to balance the magnetic force, the electric field must point upward, away from the conductor. If the particle is drawn below the wire instead, both field directions reverse relative to this sketch.



Field and force directions for a negative charge above the wire; crosses denote magnetic field into the page.

**Step 2: Identify and balance the two forces** (ii) Write the negative charge as  $q = -|q|$ . The electric force  $q\vec{E}$  is opposite to  $\vec{E}$ , hence downward towards the conductor. Since

$$\vec{v} \times \vec{B} = (-v_0 \hat{i}) \times (-B \hat{k}) = -v_0 B \hat{j},$$

the magnetic force on the negative charge is upward, away from the conductor:

$$\vec{F}_E = -|q|E\hat{j}, \quad \vec{F}_B = +|q|v_0 B\hat{j}.$$

These are the electric and magnetic forces relevant to the stated motion. Their equal magnitudes and opposite directions keep the particle moving uniformly parallel to the wire, at fixed distance  $d$ .

**Step 3: Determine the speed** (iii) The velocity is perpendicular to the magnetic field, so the magnetic force magnitude is  $|q|v_0 B$ . Setting the net transverse force equal to zero gives

$$|q|E = |q|v_0 B, \quad v_0 = \frac{E}{B}.$$

At the specified distance from an infinitely long straight conductor,

$$B = \frac{\mu_0 I}{2\pi d}, \quad v_0 = \frac{2\pi d E}{\mu_0 I}.$$

The charge magnitude cancels because both forces are proportional to it. The result has units of speed since  $E/B$  is measured in  $\text{m s}^{-1}$ .

**Step 4: Conclusion** With the particle above the wire,  $\vec{B}$  is into the page and  $\vec{E}$  is upward. The magnetic force is away from the wire and the electric force is towards it. Their balance gives  $v_0 = 2\pi d E / (\mu_0 I)$ .

**Quick Tip to Solve:** Apply the right-hand rule to  $\vec{v} \times \vec{B}$ , then reverse that force for a negative charge before choosing the electric-field direction.

**27(b).** Two infinitely long conductors kept along  $XX'$  and  $YY'$  axes are carrying current  $I_1$  and  $I_2$  along  $-X$  axis and  $-Y$  axis respectively. Find the magnitude and direction of the net magnetic field produced at point  $P(X, Y)$ . [3 marks]

**Solution:**

**Concept:**

- At perpendicular distance  $r$  from an infinitely long straight conductor carrying current  $I$ , the magnetic field magnitude is  $B = \mu_0 I / (2\pi r)$ .
- Magnetic fields obey vector superposition:  $\vec{B}_{\text{net}} = \vec{B}_1 + \vec{B}_2$ . Determine each direction with the right-hand thumb rule before adding magnitudes.

**Step 1: Find the contribution from the horizontal conductor** Take the coordinate axes in the plane of the page, with  $+X$  rightward,  $+Y$  upward and  $+\hat{k}$  out of the page. First consider  $P(X, Y)$  in the first quadrant, so  $X, Y > 0$ . Its perpendicular distance from the  $XX'$  conductor is  $Y$ , not its distance from the origin. With current  $I_1$  towards  $-X$ , the right-hand thumb rule gives a field into the page at P:

$$\vec{B}_1 = -\frac{\mu_0 I_1}{2\pi Y} \hat{k}.$$

**Step 2: Find the contribution from the vertical conductor** The perpendicular distance from the  $YY'$  conductor is  $X$ . The current  $I_2$  flows towards  $-Y$ . At a point to the right of this wire, its field points out of the page, since  $(-\hat{j}) \times \hat{i} = +\hat{k}$ . Therefore,

$$\vec{B}_2 = +\frac{\mu_0 I_2}{2\pi X} \hat{k}.$$

The two fields are perpendicular to the plane of the wires and oppose one another in the first quadrant; the perpendicular wires do not imply perpendicular magnetic fields at P.

**Step 3: Superpose the fields and state the direction** Adding the signed components gives

$$\vec{B}_{\text{net}} = \frac{\mu_0}{2\pi} \left( \frac{I_2}{X} - \frac{I_1}{Y} \right) \hat{k}, \quad B_{\text{net}} = \frac{\mu_0}{2\pi} \left| \frac{I_2}{X} - \frac{I_1}{Y} \right|.$$

The field is out of the page when  $I_2/X > I_1/Y$ , into the page when  $I_2/X < I_1/Y$ , and zero when the ratios are equal. For a point in another quadrant, the same vector expression holds when  $X$  and  $Y$  are treated as signed coordinates; the positive magnitude is always the absolute value. The formula excludes points on the ideal wires, where a perpendicular distance is zero.

**Step 4: Conclusion**  $B_{\text{net}} = \frac{\mu_0}{2\pi} \left| \frac{I_2}{X} - \frac{I_1}{Y} \right|$ . It is normal to the plane of the conductors, along  $+\hat{k}$  if  $I_2/X - I_1/Y > 0$  and along  $-\hat{k}$  if this difference is negative; it vanishes when the contributions cancel.

**Quick Tip to Solve:** Pair the horizontal wire with distance  $|Y|$  and the vertical wire with  $|X|$ ; assign into-page and out-of-page signs before adding.

28. (a) When a parallel beam of light enters water surface obliquely at some angle, what is the effect on the width of the beam?
- (b) With the help of a ray diagram, show that a straw appears bent when it is partly dipped in water and explain it.
- (c) Explain the transmission of optical signal through an optical fibre by a diagram. [3 marks]

### Solution:

#### Concept:

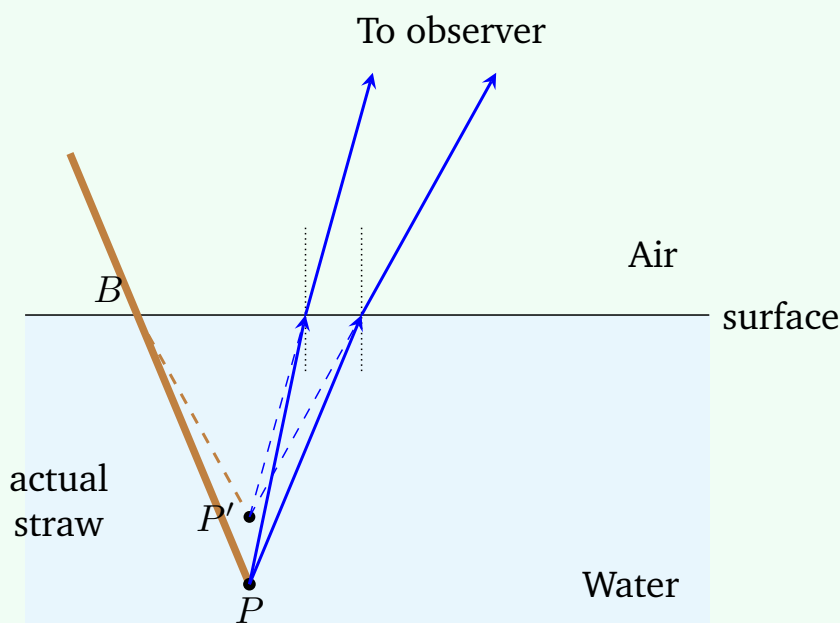
- Snell's law is  $n_1 \sin i = n_2 \sin r$ , where  $i, r$  are angles from the normal. Light bends towards the normal on entering water from air.
- Rays emerging from water bend away from the normal; their backward extensions locate the virtual image of a submerged point.
- Total internal reflection occurs from a denser core to rarer cladding when  $i > C$ , where  $\sin C = n_{\text{clad}}/n_{\text{core}}$ .

**Step 1: (a) Compare the incident and refracted widths** Let the two extreme rays meet the surface at points separated by  $L$ . The beam width is the perpendicular separation of these rays, so  $w_{\text{air}} = L \cos i$  and  $w_{\text{water}} = L \cos r$ . Since water is optically denser,  $r < i$ , giving  $\cos r > \cos i$ . Therefore

$$\frac{w_{\text{water}}}{w_{\text{air}}} = \frac{\cos r}{\cos i} > 1.$$

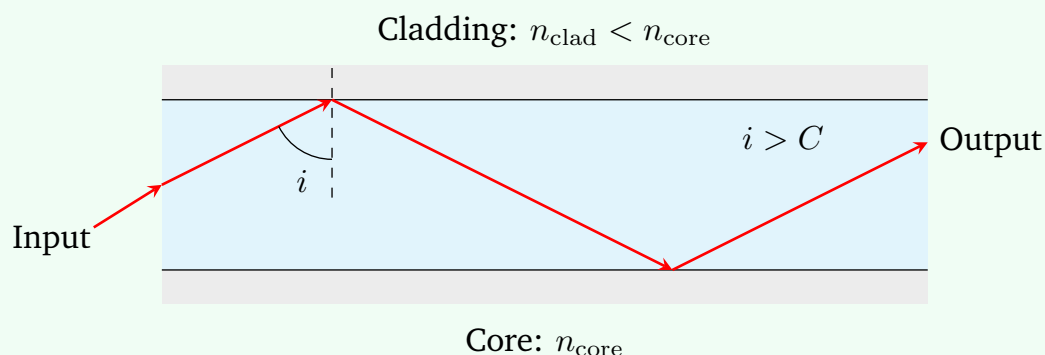
The parallel beam becomes wider in water; the same surface separation must be projected perpendicular to the new direction.

**Step 2: (b) Locate the apparent submerged end** Consider light from the submerged end  $P$  reaching the water surface. The rays refract away from their local normals as they enter air. An observer traces the emergent rays backwards in straight lines to  $P'$ , which is a virtual image above  $P$ . Thus the submerged part appears raised, while the part above water is seen directly. The apparent segment  $BP'$  and the actual upper segment have different directions, so the straw appears bent at the surface  $B$ . The dashed lines in the ray diagram are backward extensions, not actual light paths.



*Refraction at the water surface forms a raised virtual image of the submerged straw end.*

**Step 3: (c) Apply repeated total internal reflection** An optical fibre has a transparent core of refractive index  $n_{\text{core}}$ , surrounded by cladding with  $n_{\text{clad}} < n_{\text{core}}$ . A light signal entering within the acceptance range strikes the core–cladding boundary at an incidence angle greater than the critical angle. It undergoes repeated total internal reflection and travels along the core to the other end with very little loss. Incidence is measured from the normal to the reflecting boundary, not from the fibre axis.



*A guided ray undergoes repeated total internal reflection in a core with  $n_{\text{core}} > n_{\text{clad}}$ .*

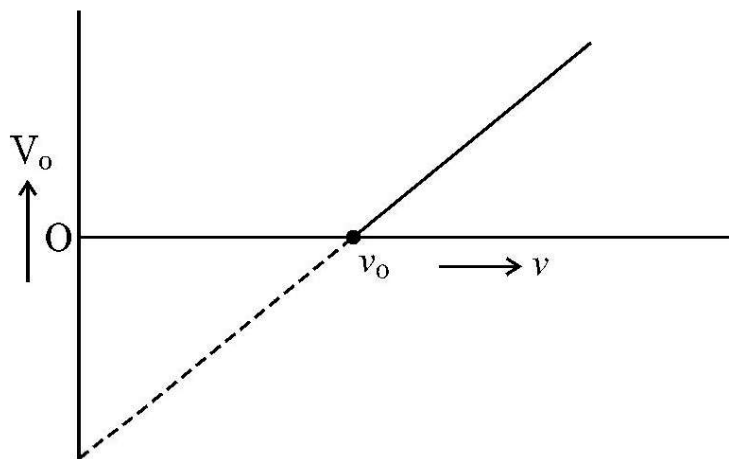
**Step 4: Conclusion** (a) The beam width increases. (b) Refraction makes the submerged portion appear raised and the straw appear bent. (c) Repeated total internal reflection guides the optical signal through the higher-index core.

**Quick Tip to Solve:** For beam width use the perpendicular projection  $L \cos \theta$ ; for fibres compare the ray angle with the normal to the core boundary.

### Section D (8 marks)

Question numbers 29 and 30 are case study based questions. Read the following paragraphs and answer the questions that follow.

29. When a photon of suitable frequency is incident on a metal surface, photoelectron is emitted from it. If the frequency is below a threshold frequency  $\nu_0$  for the surface, no photoelectron is emitted. For a photon of frequency  $\nu$  ( $\nu > \nu_0$ ), the kinetic energy of the emitted photoelectrons is  $h(\nu - \nu_0)$ . The photocurrent can be stopped by applying a potential  $V_0$ , called 'stopping potential' on the anode. Thus maximum kinetic energy of photoelectrons  $K_m = eV_0 = h(\nu - \nu_0)$ . The experimental graph between  $V_0$  and  $\nu$  for a metal is shown in figure. This is a straight line of slope  $m$ . [4 marks]



29(i). The straight line graphs obtained for two metals

[1 mark]

- (A) coincide each other.
- (B) are parallel to each other.
- (C) are not parallel to each other and cross at a point on  $\nu$ -axis.
- (D) are not parallel to each other and do not cross at a point on  $\nu$ -axis.

**Correct Answer:** (B) are parallel to each other.

#### Solution:

##### Concept:

- Einstein's equation gives  $eV_0 = h\nu - \phi$ , where  $\phi$  is the metal work function.
- The straight-line form is  $V_0 = (h/e)\nu - \phi/e$ ; its slope is the universal ratio  $h/e$ .

**Step 1: Compare the slopes** Both metals have the same values of Planck's constant  $h$  and electronic charge magnitude  $e$ . Consequently both stopping-potential graphs have slope  $h/e$ , independent of the metal.

**Step 2: Compare the intercepts** The work function, and hence the threshold frequency  $\nu_0 = \phi/h$ , depends on the metal. Different work functions shift the lines horizontally without changing the slope. Thus the usual graphs for two metals are parallel. Coincidence would require equal work functions;

neither non-parallel option can agree with the common slope.

**Step 3: Conclusion** The graphs have the same slope and are parallel to each other. Hence, the correct option is (B).

**Quick Tip to Solve:** Write the graph as  $y = mx + c$ : the metal changes  $c$ , while  $m = h/e$  stays universal.

**29(ii). The value of Planck's constant for this metal is**

[1 mark]

- (A)  $\frac{e}{m}$
- (B)  $\frac{1}{me}$
- (C)  $me$
- (D)  $\frac{m}{e}$

**Correct Answer:** (C)  $me$

**Solution:**

**Concept:**

- The stopping-potential relation is  $V_0 = (h/e)\nu - h\nu_0/e$ .
- For a plot with  $V_0$  on the vertical axis and  $\nu$  on the horizontal axis, slope  $m = \Delta V_0/\Delta \nu$ .

**Step 1: Identify the coefficient of frequency** Comparison with  $y = mx + c$  shows that the slope is  $m = h/e$ . The work-function term affects the intercept only, so it cannot change the slope for the given metal.

**Step 2: Isolate Planck's constant** Multiplying the slope relation by the charge magnitude gives

$$h = em.$$

This also has the correct units:  $m$  has units V s, so  $em$  has units C V s = J s. The quotient and inverse-product options do not follow from the slope equation.

**Step 3: Conclusion** Planck's constant is  $h = me$ . Hence, the correct option is (C).

**Quick Tip to Solve:** Check which variable is vertical: a  $V_0$ -versus- $\nu$  slope equals  $h/e$ , so multiply it by  $e$ .

**29(iii). The intercepts on  $\nu$ -axis and  $V_0$ -axis of the graph are respectively:**

[1 mark]

- (A)  $\nu_0, \frac{h\nu_0}{e}$
- (B)  $\nu_0, h\nu_0$
- (C)  $\frac{h\nu_0}{e}, \nu_0$
- (D)  $h\nu_0, \nu_0$

**Correct Answer:** (A)  $\nu_0, \frac{h\nu_0}{e}$

**Solution:**

**Concept:**

- The line obeys  $V_0 = (h/e)(\nu - \nu_0)$ . Its intercept on either axis is found by setting the other variable to zero.

- The signed vertical intercept is negative; an intercept length is quoted as its positive magnitude.

**Step 1: Find the frequency-axis intercept** Set  $V_0 = 0$ . Then  $0 = (h/e)(\nu - \nu_0)$ , so the line meets the frequency axis at  $\nu = \nu_0$ . This eliminates options (C) and (D), whose first entries are not the threshold frequency.

**Step 2: Find the vertical intercept and interpret the choices** Extrapolating to  $\nu = 0$  gives

$$V_0 = -\frac{h\nu_0}{e}.$$

The graph indeed extends below the origin. Its vertical intercept length is therefore  $h\nu_0/e$ , as in (A); (B) incorrectly gives an energy instead of a potential. The printed choices use the magnitude of the vertical intercept. If signed coordinates are requested, none includes the required minus sign.

**Step 3: Conclusion** The intercept lengths are  $\nu_0$  and  $h\nu_0/e$ , respectively. Hence, the correct option is (A). The signed vertical intercept is  $-h\nu_0/e$ .

**Quick Tip to Solve:** Set each axis variable to zero in turn, and distinguish a negative intercept coordinate from its positive length.

OR

**29(iii).** When the wavelength of a photon is doubled, how many times its wave number and frequency become, respectively? [1 mark]

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

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

**Solution:**

**Concept:**

- Frequency and wavelength satisfy  $\nu = c/\lambda$ , with  $c$  the speed of light.
- Wave number is  $\bar{\nu} = 1/\lambda$ ; if angular wave number  $k = 2\pi/\lambda$  is used, its scaling is the same.

**Step 1: Scale the wave number** For  $\lambda' = 2\lambda$ ,

$$\bar{\nu}' = \frac{1}{2\lambda} = \frac{1}{2}\bar{\nu}.$$

Wave number counts waves per unit length, so increasing the wavelength decreases that count.

**Step 2: Scale the frequency** At the same light speed,

$$\nu' = \frac{c}{2\lambda} = \frac{1}{2}\nu.$$

Both quantities are inversely proportional to wavelength. Options containing a factor of 2 for either quantity therefore reverse the required dependence.

**Step 3: Conclusion** The wave number and frequency each become half their initial values. Hence, the correct option is (B).

**Quick Tip to Solve:** For any quantity proportional to  $1/\lambda$ , multiply its value by the reciprocal of the wavelength change factor.

**29(iv).** The momentum of a photon is  $5.0 \times 10^{-29} \text{ kg m/s}$ . Ignoring relativistic effects (if any), the wavelength of the photon is [1 mark]

- (A)  $1.33 \mu\text{m}$
- (B)  $3.3 \mu\text{m}$
- (C)  $16.6 \mu\text{m}$
- (D)  $13.3 \mu\text{m}$

**Correct Answer:** (D)  $13.3 \mu\text{m}$

**Solution:**

**Concept:**

- A photon has momentum  $p = h/\lambda$ , so  $\lambda = h/p$ .
- Use  $h = 6.63 \times 10^{-34} \text{ J s}$  and  $1 \mu\text{m} = 10^{-6} \text{ m}$ .

**Step 1: Substitute the photon momentum** With  $p = 5.0 \times 10^{-29} \text{ kg m s}^{-1}$ ,

$$\lambda = \frac{6.63 \times 10^{-34}}{5.0 \times 10^{-29}} = 1.326 \times 10^{-5} \text{ m}.$$

The units reduce to metres because  $\text{J s} = \text{kg m}^2 \text{s}^{-1}$ .

**Step 2: Convert to the units in the choices** Multiplying the metre value by  $10^6$  gives

$$\lambda = 13.26 \mu\text{m} \simeq 13.3 \mu\text{m}.$$

Option (A) is smaller by a factor of ten, while (B) and (C) do not match the substitution. The photon relation  $p = h/\lambda$  applies directly; no massive-particle speed correction is required by the printed qualification.

**Step 3: Conclusion** The wavelength is approximately  $13.3 \mu\text{m}$ . Hence, the correct option is (D).

**Quick Tip to Solve:** Subtract exponents before converting metres to micrometres:  $10^{-34}/10^{-29} = 10^{-5}$ .

**30. Case study:** A parallel plate capacitor has two parallel plates which are separated by an insulating medium like air, mica, etc. When the plates are connected to the terminals of a battery, they get equal and opposite charges and an electric field is set up in between them. This electric field between the two plates depends upon the potential difference applied, the separation of the plates and nature of the medium between the plates. [4 marks]

**30(i).** The electric field between the plates of a parallel plate capacitor is  $E$ . Now the separation between the plates is doubled and simultaneously the applied potential difference between the plates is reduced to half of its initial value. The new value of the electric field between the plates will be: [1 mark]

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

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

**Solution:**

**Concept:**

- For uniform field between parallel plates,  $E = V/d$ , where  $V$  is the potential difference and  $d$  is the plate separation.
- When both quantities change, use the ratio  $E'/E = (V'/V)/(d'/d)$ .

**Step 1: Apply both changes** The new potential difference is  $V' = V/2$ , whereas the new separation is  $d' = 2d$ . Substituting both changes together gives

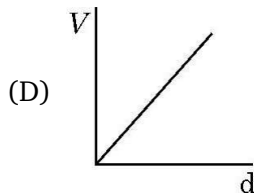
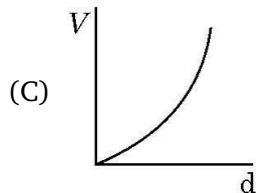
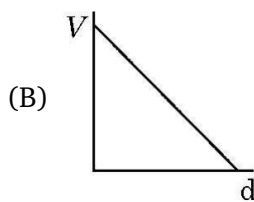
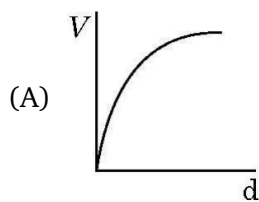
$$E' = \frac{V/2}{2d} = \frac{V}{4d}.$$

**Step 2: Compare with the initial field** Since  $E = V/d$ , the ratio is  $E'/E = 1/4$ . Halving the voltage alone would give  $E/2$ , but doubling the distance produces a second factor of one-half. Thus neither the unchanged field  $E$  nor the increased field  $2E$  is consistent with the two changes.

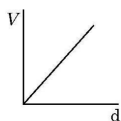
**Step 3: Conclusion** The new electric field is  $E' = E/4$ . Hence, the correct option is (C).

**Quick Tip to Solve:** For simultaneous voltage and separation changes, divide the voltage factor by the distance factor: here  $(1/2)/2 = 1/4$ .

**30(ii).** A constant electric field is to be maintained between the two plates of a capacitor whose separation  $d$  changes with time. Which of the graphs correctly depict the potential difference ( $V$ ) to be applied between the plates as a function of separation between the plates ( $d$ ) to maintain the constant electric field? [1 mark]



**Correct Answer:** (D)



### Solution:

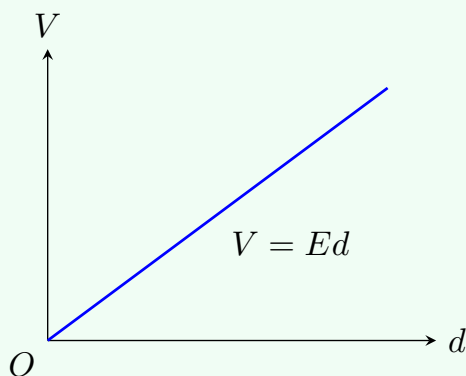
#### Concept:

- The uniform electric field of a parallel plate capacitor obeys  $E = V/d$ , where  $V$  is the potential difference and  $d$  is the separation.
- Keeping  $E$  constant requires  $V = Ed$ ; therefore  $V$  is directly proportional to  $d$ .

**Step 1: Identify the graph equation** Rearrange the field relation to

$$V = Ed.$$

In a graph with  $V$  on the vertical axis and  $d$  on the horizontal axis, the slope is the constant positive field magnitude  $E$ . The line extrapolates to the origin.



*Potential difference increases linearly with plate separation at constant  $E$ .*

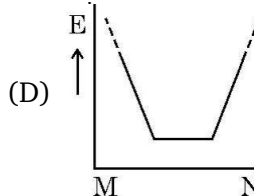
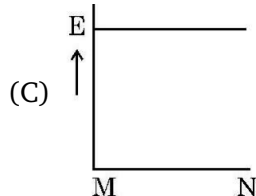
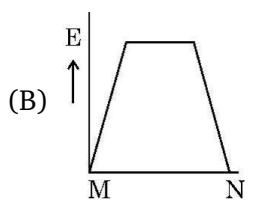
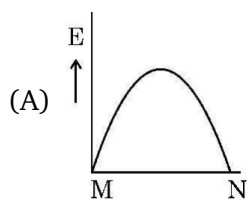
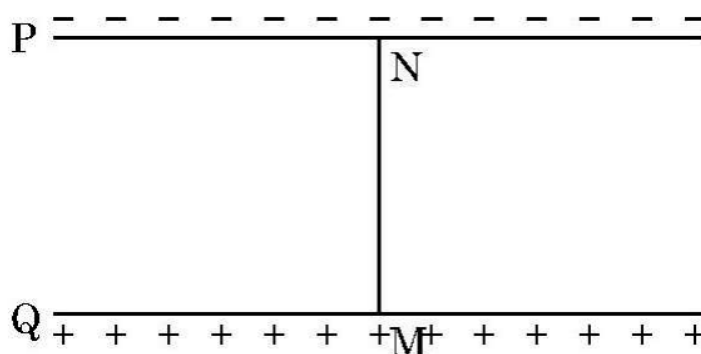
**Step 2: Compare all four graphs** Graph (D) is a rising straight line through the origin. Graphs (A) and (C) are curved, so  $V/d$  changes as the separation changes. Graph (B) decreases with increasing

separation, whereas the voltage must increase to maintain the field.

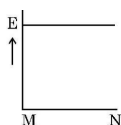
**Step 3: Conclusion** The required graph is the straight line through the origin with positive slope. Hence, the correct option is (D).

**Quick Tip to Solve:** For a constant field, doubling the plate separation must double the voltage: select the straight  $V$ -versus- $d$  line through the origin.

**30(iii).** In the above figure P, Q are the two parallel plates of a capacitor. Plate Q is at positive potential with respect to plate P. MN is an imaginary line drawn perpendicular to the plates. Which of the graphs shows correctly the variations of the magnitude of electric field strength  $E$  along the line MN? [1 mark]



**Correct Answer:** (C)



**Solution:**

**Concept:**

- Neglecting edge effects, two large oppositely charged parallel plates produce a uniform electric field between them.
- The electric field points from positive plate Q towards negative plate P; its magnitude is  $E = V/d$ , where  $d$  is their separation.

**Step 1: Locate the path in the field** The segment  $MN$  runs perpendicular to the plates from the vicinity of plate  $Q$  to plate  $P$ , within the gap. The superposed fields of the plates add in this gap, producing the same nonzero field strength throughout the segment.

**Step 2: Compare the magnitude graphs** The requested quantity is the magnitude, so it remains a positive constant as one moves from  $M$  to  $N$ . Graph (C) is horizontal at a nonzero value. Graph (A) rises and falls, graph (B) varies near the ends, and graph (D) has a lower central value; these variations do not describe the ideal uniform field.

**Step 3: Conclusion** The electric field magnitude stays constant along  $MN$ . Hence, the correct option is (C).

**Quick Tip to Solve:** First check whether the plotted path lies inside the plate gap. Within an ideal parallel plate capacitor, the field-magnitude graph is horizontal.

**30(iv).** Three parallel plates are placed above each other with equal displacement  $\vec{d}$  between neighbouring plates. The electric field between the first pair of the plates is  $\vec{E}_1$  and the electric field between the second pair of the plates is  $\vec{E}_2$ . The potential difference between the third and the first plate is [1 mark]

(A)  $(\vec{E}_1 + \vec{E}_2) \cdot \vec{d}$

(B)  $(\vec{E}_1 - \vec{E}_2) \cdot \vec{d}$

(C)  $(\vec{E}_2 - \vec{E}_1) \cdot \vec{d}$

(D)  $\frac{d(E_1 + E_2)}{2}$

**Correct Answer:** (A)  $(\vec{E}_1 + \vec{E}_2) \cdot \vec{d}$

**Solution:**

**Concept:**

- Potential difference across a uniform field region follows  $V_b - V_a = -\vec{E} \cdot \Delta\vec{r}$ . Equivalently, the potential drop along a displacement is  $V_a - V_b = \vec{E} \cdot \Delta\vec{r}$ .
- Potential differences across successive gaps add; the displacement across each neighbouring pair here is the same vector  $\vec{d}$ .

**Step 1: Write the contributions of the gaps** Denote the plate potentials by  $V_1, V_2, V_3$ . Taking  $\vec{d}$  along the successive path from plate 1 to plate 2 and then from plate 2 to plate 3, the potential drops are

$$V_1 - V_2 = \vec{E}_1 \cdot \vec{d}, \quad V_2 - V_3 = \vec{E}_2 \cdot \vec{d}.$$

**Step 2: Add the two potential drops** Adding eliminates the intermediate potential:

$$V_1 - V_3 = (\vec{E}_1 + \vec{E}_2) \cdot \vec{d}.$$

The printed options use this total potential-drop convention. Reversing the order of the potentials

would reverse the overall sign. Options (B) and (C) incorrectly subtract the two gap contributions, while (D) incorrectly averages them.

**Step 3: Conclusion** The total potential difference, expressed as the drop across the two gaps, is  $(\vec{E}_1 + \vec{E}_2) \cdot \vec{d}$ . Hence, the correct option is (A).

**Quick Tip to Solve:** Add potential drops across successive gaps; do not average the fields unless you also multiply by the full distance  $2d$ . Keep the chosen potential order explicit.

OR

**30(iv).** A material of dielectric constant  $K$  is filled in a parallel plate capacitor of capacitance  $C$ . The new value of its capacitance becomes [1 mark]

- (A)  $C$
- (B)  $\frac{C}{K}$
- (C)  $CK$
- (D)  $C \left(1 + \frac{1}{K}\right)$

**Correct Answer:** (C)  $CK$

**Solution:**

**Concept:**

- For a parallel plate capacitor without a dielectric,  $C = \epsilon_0 A/d$ , where  $A$  is plate area and  $d$  is plate separation.
- A dielectric completely filling the gap replaces the permittivity  $\epsilon_0$  by  $K\epsilon_0$ , where  $K$  is the relative permittivity.

**Step 1: Write the new capacitance** The plate geometry remains unchanged when the dielectric is inserted. Thus

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

Comparing this with the original expression directly gives a multiplication factor  $K$ .

**Step 2: Compare the proposed changes** The dielectric increases the capacitance to  $K$  times its original value. Option (A) ignores the dielectric, and option (B) reverses its effect. Option (D) does not follow the capacitance formula for a single material filling the entire gap; no partial filling or additional capacitor is specified.

**Step 3: Conclusion** The new capacitance is  $C' = KC$ . Hence, the correct option is (C).

**Quick Tip to Solve:** For complete dielectric filling at unchanged geometry, multiply the original capacitance by  $K$ ; the battery connection does not change this capacitance formula.

## Section E (15 marks)

**31(a).** (i) What is the source of force acting on a current-carrying conductor placed in a magnetic field? Obtain the expression for force acting between two long straight parallel conductors carrying steady currents and hence define 'ampere'.

(ii) A point charge  $q$  is moving with velocity  $\vec{v}$  in a uniform magnetic field  $\vec{B}$ . Find the work done by the magnetic force on the charge.

(iii) Explain the necessary conditions in which the trajectory of a charged particle is helical in a uniform magnetic field.

[5 marks]

### Solution:

#### Concept:

- The magnetic Lorentz force on a moving charge is  $\vec{F} = q\vec{v} \times \vec{B}$ ; for a straight current element,  $\vec{F} = I\vec{l} \times \vec{B}$ .
- A long straight wire carrying current  $I$  produces  $B = \mu_0 I / (2\pi d)$  at perpendicular distance  $d$ , with direction given by the right-hand thumb rule.
- Magnetic force is perpendicular to velocity, so it does no work. Resolve an oblique velocity into components parallel and perpendicular to the uniform field.

**Step 1: (i) Identify the source of the conductor's force** The current consists of moving charge carriers. The external magnetic field exerts Lorentz forces on these carriers; their interaction with the lattice transmits the force to the conductor. If there are  $n$  carriers per unit volume, each of charge  $q$ , in a wire of cross-sectional area  $A$  and length  $l$ , then

$$\vec{F} = nAlq\vec{v}_d \times \vec{B} = I\vec{l} \times \vec{B}.$$

Here  $\vec{v}_d$  is the drift velocity and  $\vec{l}$  points along conventional current. Thus moving charges in the applied field are the microscopic source of the force.

**Step 2: (i) Derive the force between the two wires** Consider two very long straight parallel wires in vacuum, separated by  $d$ , carrying steady currents  $I_1$  and  $I_2$ . At wire 2, the field due to wire 1 is  $B_1 = \mu_0 I_1 / (2\pi d)$ . This field is perpendicular to the current in wire 2. Therefore the force on length  $l$  of wire 2 is

$$F_{21} = I_2 l B_1 = \frac{\mu_0 I_1 I_2 l}{2\pi d}, \quad \frac{F}{l} = \frac{\mu_0 I_1 I_2}{2\pi d}.$$

Interchanging the wire labels gives an equal and opposite force on wire 1. The right-hand rule shows attraction for currents in the same direction and repulsion for currents in opposite directions. End effects are negligible for the long wires considered here.

**Step 3: (i) State the force-based definition of ampere** Put  $I_1 = I_2 = 1$  A and  $d = 1$  m in the force-per-unit-length expression, using the textbook value  $\mu_0 = 4\pi \times 10^{-7}$  N A<sup>-2</sup>:

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

Hence the classical force-based definition requested here is: one ampere is that constant current which, maintained in each of two straight parallel conductors of infinite length and negligible circular cross-section placed one metre apart in vacuum, produces a force of  $2 \times 10^{-7}$  N per metre between them.

**Step 4: (ii) Evaluate the work done on the point charge** During time  $dt$ , the displacement is  $d\vec{r} = \vec{v} dt$ .

Thus

$$dW = \vec{F} \cdot d\vec{r} = q(\vec{v} \times \vec{B}) \cdot \vec{v} dt = 0, \quad W = 0.$$

This remains true as the velocity changes direction, because the instantaneous magnetic force is always perpendicular to it. Magnetic force alone changes neither the speed nor the kinetic energy.

**Step 5: (iii) Establish the conditions for a helix** Let  $\theta$  be the angle between the initial velocity and  $\vec{B}$ . A helix requires both  $v_{\parallel} = v \cos \theta \neq 0$  and  $v_{\perp} = v \sin \theta \neq 0$ , with nonzero charge and field, and no additional force affecting the motion. The perpendicular component produces uniform circular motion, while the parallel component remains constant and carries the particle along the field axis. In the nonrelativistic case,

$$r = \frac{mv_{\perp}}{|q|B}, \quad T = \frac{2\pi m}{|q|B}, \quad p = |v_{\parallel}|T.$$

The superposition is a helix of radius  $r$  and pitch  $p$ . Exactly perpendicular entry gives a circle; exactly parallel or antiparallel entry gives a straight line.

**Step 6: Conclusion** The conductor force originates in magnetic forces on moving carriers. Parallel wires experience  $F/l = \mu_0 I_1 I_2 / (2\pi d)$ , attractive for like current directions and repulsive for opposite directions. Magnetic work on the charge is zero. A helical path requires nonzero velocity components both along and across the uniform field.

**Quick Tip to Solve:** Use the field of one wire to find the force on the other. For particle motion, split velocity along and across the field before deciding between a line, circle and helix.

OR

**31(b). (i)** A current carrying loop can be considered as a magnetic dipole placed along its axis. Explain.

**(ii)** Obtain the relation for magnetic dipole moment  $\vec{M}$  of current carrying coil. Give the direction of  $\vec{M}$ .

**(iii)** A current carrying coil is placed in an external uniform magnetic field. The coil is free to turn in the magnetic field. What is the net force acting on the coil? Obtain the orientation of the coil in stable equilibrium. Show that in this orientation the flux of the total field (field produced by the loop + external field) through the coil is maximum. [5 marks]

**Solution:**

**Concept:**

- A current loop behaves as a magnetic dipole whose moment is along its area vector. For  $N$  turns of area  $A$  carrying current  $I$ ,  $\vec{M} = NIA\hat{n}$ .
- In an external uniform field, the net force on a closed current loop is zero, but the torque is  $\vec{\tau} = \vec{M} \times \vec{B}_{\text{ext}}$  and the potential energy is  $U = -\vec{M} \cdot \vec{B}_{\text{ext}}$ .
- The external magnetic flux through one turn is  $\Phi_{\text{ext}} = B_{\text{ext}}A \cos \theta$ , where  $\theta$  is the angle between the area normal and the external field.

**Step 1: (i) Compare a current loop with a magnetic dipole** The magnetic field lines of a current loop have the same qualitative pattern as those of a short bar magnet. Viewed from one face, anticlockwise current makes that face a north face; the opposite face is a south face. Thus the dipole axis is the line through the centre perpendicular to the loop's plane. For a circular loop of radius  $R$ , the field on its

axis at distance  $x$  is

$$B_{\text{loop}} = \frac{\mu_0 I R^2}{2(R^2 + x^2)^{3/2}}.$$

At  $x \gg R$ , this becomes

$$B_{\text{loop}} \simeq \frac{\mu_0}{4\pi} \frac{2(I\pi R^2)}{x^3}.$$

The axial field of a magnetic dipole of moment  $M$  is  $B_{\text{dipole}} = (\mu_0/4\pi)(2M/x^3)$ . Their identical distant-field form demonstrates that the loop is equivalent to a dipole directed along its axis, with  $M = I\pi R^2 = IA$ .

**Step 2: (ii) Obtain the coil's dipole moment and direction** For  $N$  closely wound turns carrying the same current, the moments of the turns add. Hence

$$\vec{M} = NI\vec{A} = NIA\hat{n}.$$

Here  $\vec{A} = A\hat{n}$  is the area vector of one turn. The direction is perpendicular to the coil's plane, given by the right-hand rule: curl the fingers along conventional current, and the extended thumb points along  $\vec{M}$ . It points from the loop's south face towards its north face. The SI unit of magnetic moment is  $\text{A m}^2$ ; a single turn has  $M = IA$ .

**Step 3: (iii) Find the net force and the turning effect** For a uniform external field, the force on each current element is  $d\vec{F} = I d\vec{l} \times \vec{B}_{\text{ext}}$ . On summing round a closed turn,

$$\vec{F}_{\text{net}} = NI \left( \oint d\vec{l} \right) \times \vec{B}_{\text{ext}} = 0,$$

because the vector sum of displacements around a closed path is zero. Forces at different positions can nevertheless form a couple. For a rectangular coil with sides  $a, b$ , choose the sides of length  $a$  perpendicular to the field. Each has force magnitude  $N Ia B_{\text{ext}}$ , and the couple arm is  $b \sin \theta$ . Thus

$$\tau = NIab B_{\text{ext}} \sin \theta = NIAB_{\text{ext}} \sin \theta = MB_{\text{ext}} \sin \theta.$$

The vector relation is  $\vec{\tau} = \vec{M} \times \vec{B}_{\text{ext}}$ , valid for a planar coil of any shape.

**Step 4: (iii) Identify the stable equilibrium orientation** Zero torque requires  $\theta = 0$  or  $\pi$ . Since

$$U = -MB_{\text{ext}} \cos \theta, \quad \frac{d^2U}{d\theta^2} = MB_{\text{ext}} \cos \theta,$$

the energy has a minimum at  $\theta = 0$ . A small angular displacement there produces a restoring torque. The stable orientation therefore has  $\vec{M}$  parallel to  $\vec{B}_{\text{ext}}$ , so the plane of the coil is perpendicular to the field. The antiparallel orientation is unstable because its energy is a maximum.

**Step 5: (iii) Show that the total flux is maximum** Choose the positive area normal along  $\vec{M}$ . For a rigid coil carrying a steady current, its own flux through the coil is constant as the whole coil rotates: the coil and its self-field rotate together. Denote this flux through one turn by  $\Phi_{\text{self}}$ . Superposition gives

$$\Phi_{\text{total}} = \Phi_{\text{self}} + B_{\text{ext}}A \cos \theta.$$

Since  $\cos \theta \leq 1$ , the maximum occurs at  $\theta = 0$ , precisely the stable equilibrium orientation:

$$\Phi_{\text{total,max}} = \Phi_{\text{self}} + B_{\text{ext}}A.$$

For  $N$  equivalent turns, multiplying by  $N$  gives the total flux linkage and leaves the maximizing orientation unchanged.

**Step 6: Conclusion** A current coil behaves as an axial magnetic dipole with  $\vec{M} = NIA\hat{n}$ , directed by the right-hand rule. In a uniform external field its net force is zero. Stable equilibrium has  $\vec{M} \parallel \vec{B}_{\text{ext}}$ , with the coil plane perpendicular to the field; the total magnetic flux through the coil is then maximum.

**Quick Tip to Solve:** Measure the angle from the coil's normal, not its plane. Alignment of the moment with the field simultaneously minimizes  $-MB \cos \theta$  and maximizes the external flux  $BA \cos \theta$ .

**32(a). (i)** A thin pencil of length  $f/4$  is placed coinciding with the principal axis of a mirror of focal length  $f$ . The image of the pencil is real and enlarged, just touches the pencil. Calculate the magnification produced by the mirror.

**(ii)** A ray of light is incident on a refracting face AB of a prism ABC at an angle of  $45^\circ$ . The ray emerges from face AC and the angle of deviation is  $15^\circ$ . The angle of prism is  $30^\circ$ . Show that the emergent ray is normal to the face AC from which it emerges out. Find the refraction index of the material of the prism. [5 marks]

**Solution:**

**Concept:**

- Only a concave mirror can form a real enlarged image of a real object. With  $f > 0$  denoting the focal-length magnitude and  $x, y > 0$  the distances of a real object point and its image from the pole, the mirror equation is  $1/f = 1/x + 1/y$ .
- For a finite pencil along the principal axis, longitudinal magnification is the ratio of image length to pencil length. Find the images of both endpoints; the transverse formula  $-v/u$  at one point does not give this finite length ratio.
- For a prism,  $\delta = i + e - A$  and  $r_1 + r_2 = A$ , where  $i, e$  are the external incidence and emergence angles and  $r_1, r_2$  are the internal refraction angles, all measured from the appropriate normals. Snell's law at the first face gives  $\mu = \sin i / \sin r_1$  for incidence from air.

**Step 1: (i) Locate the touching endpoint** Let the pencil occupy distances  $a$  to  $b$  from the pole, with  $b - a = f/4$ . A real enlarged image lies on the same side of the mirror as the pencil. The relation  $y = fx/(x - f)$  decreases as  $x$  increases, so the endpoint nearer the mirror forms the farther image endpoint. For the enlarged image to just touch the pencil without overlapping it, the pencil's farther endpoint must coincide with its own image. Its distance  $b$  therefore obeys

$$\frac{1}{f} = \frac{1}{b} + \frac{1}{b}, \quad b = 2f.$$

This endpoint is at the centre of curvature. Thus the nearer endpoint lies at

$$a = 2f - \frac{f}{4} = \frac{7f}{4}.$$

The alternative placement beyond the centre would form a diminished image and is excluded by the question.

**Step 2: Calculate the image length from the endpoint images** The endpoint at  $2f$  has its image at  $2f$ .

Let  $y_a$  be the image distance for the endpoint at  $7f/4$ . Substituting into the mirror equation,

$$\begin{aligned}\frac{1}{y_a} &= \frac{1}{f} - \frac{4}{7f} = \frac{3}{7f}, \\ y_a &= \frac{7f}{3}, \\ L_{\text{image}} &= \frac{7f}{3} - 2f = \frac{f}{3}.\end{aligned}$$

The required ratio of finite axial lengths is

$$M = \frac{L_{\text{image}}}{L_{\text{pencil}}} = \frac{f/3}{f/4} = \frac{4}{3}.$$

The endpoints reverse their axial order, so a signed axial mapping would have ratio  $-4/3$ ; the enlargement factor requested here is the positive length ratio.

**Step 3: (ii) Determine the angle of emergence** Substitute the given  $i = 45^\circ$ ,  $A = 30^\circ$  and  $\delta = 15^\circ$  into the prism deviation relation:

$$e = \delta + A - i = 15^\circ + 30^\circ - 45^\circ = 0^\circ.$$

Since the angle of emergence is measured from the normal to AC, zero emergence angle proves that the emerging ray is perpendicular to face AC.

**Step 4: Apply Snell's law to find the prism index** At the second face, Snell's law is  $\mu \sin r_2 = \sin e$ . Since  $e = 0^\circ$ , the internal angle  $r_2$  is also zero. The prism-angle relation then gives

$$r_1 = A - r_2 = 30^\circ.$$

Applying Snell's law at the first face AB,

$$\mu = \frac{\sin 45^\circ}{\sin 30^\circ} = \frac{1/\sqrt{2}}{1/2} = \sqrt{2} \simeq 1.414.$$

No minimum-deviation assumption is used: the ray is normal only at the exit face, and the internal angles are unequal.

**Step 5: Conclusion** (i) The pencil's image has length  $f/3$ , so its longitudinal enlargement factor is  $\boxed{4/3}$ . (ii) The emergence angle is  $\boxed{e = 0^\circ}$ , proving normal emergence from AC, and the prism's refractive index is  $\boxed{\mu = \sqrt{2} \simeq 1.414}$ .

**Quick Tip to Solve:** For a finite axial pencil, image both endpoints and subtract their image distances. For this prism, calculate the emergence angle from the deviation equation before applying Snell's law.

**32(b).** (i) Light consisting of two wavelengths 600 nm and 480 nm is used to obtain interference fringes in a double slit experiment. The screen is placed 1.0 m away from slits which are 1.0 nm apart.

(1) Calculate the distance of the third bright fringe on the screen from the central maximum for wavelength 600 nm.

(2) Find the least distance from the central maximum where the bright fringes due to both the wavelengths coincide.

(ii) (1) Draw the variation of intensity with angle of diffraction in single slit diffraction pattern. Write the expression for value of angle corresponding to zero intensity locations.

(2) In what way diffraction of light waves differs from diffraction of sound waves?

[5 marks]

### Solution:

#### Concept:

- Double-slit bright fringes require path difference  $d \sin \theta = n\lambda$ , where  $d$  is the slit separation and  $n$  is an integer. The screen formula  $y_n = n\lambda D/d$  additionally assumes a small angle,  $y_n \ll D$ .
- Coincidence of bright fringes requires  $n_1\lambda_1 = n_2\lambda_2$ , as well as a physically possible diffraction angle,  $|\sin \theta| \leq 1$ .
- For a single slit of width  $a$ ,  $I = I_0(\sin \beta / \beta)^2$ , with  $\beta = \pi a \sin \theta / \lambda$ . Diffraction is appreciable when the aperture or obstacle size is comparable to the wavelength.

**Step 1: (i)(1) Check the printed slit separation** The paper prints  $d = 1.0 \text{ nm} = 10^{-9} \text{ m}$ , with  $D = 1.0 \text{ m}$  and  $\lambda_1 = 600 \text{ nm}$ . Formally substituting in the usual small-angle formula gives

$$y_3 = \frac{3(600 \times 10^{-9})(1.0)}{1.0 \times 10^{-9}} = 1800 \text{ m}.$$

This is an algebraic extrapolation, not a physically valid fringe position: it violates  $y \ll D$ . More decisively, the exact constructive-interference condition would require

$$\sin \theta = \frac{3\lambda_1}{d} = 1800 > 1.$$

The path difference cannot exceed the slit separation, so even the first off-axis maximum is impossible. The printed data therefore admit no third bright fringe.

**Step 2: (i)(2) Find the first possible order coincidence** Equating the two bright-fringe path differences gives

$$600n_1 = 480n_2 \Rightarrow 5n_1 = 4n_2.$$

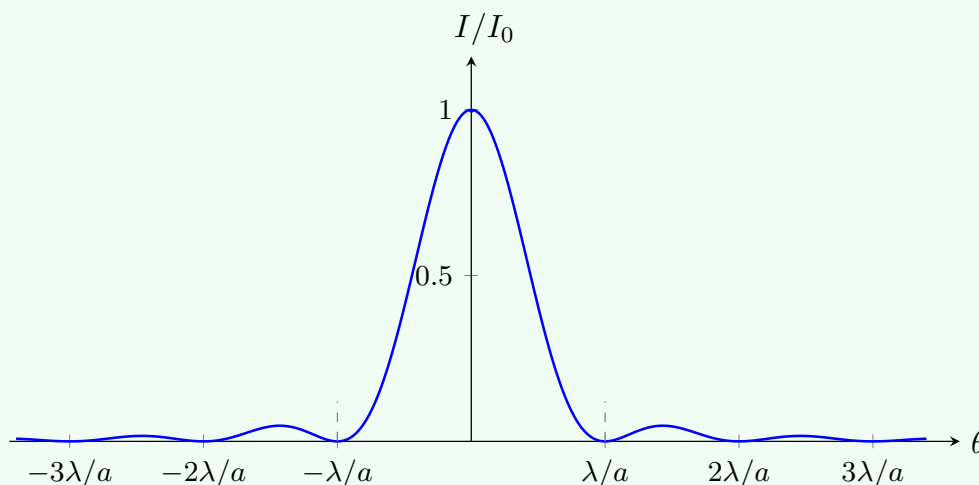
The smallest positive order pair is  $n_1 = 4$ ,  $n_2 = 5$ , corresponding to path difference 2400 nm. A formal application of the screen formula would give

$$y = \frac{4(600 \times 10^{-9})(1.0)}{10^{-9}} = 2400 \text{ m}.$$

However, this requires  $\sin \theta = 2400$ , so it too is physically impossible with the printed separation. There is no positive distance at which two off-axis bright fringes coincide. The common central maximum, with  $n_1 = n_2 = 0$ , lies at  $y = 0$ .

**Step 3: (ii)(1) Sketch the single-slit intensity distribution** The graph is symmetric about  $\theta = 0$ , where

the limiting value of  $\sin \beta / \beta$  is unity, giving intensity  $I_0$ . The central maximum is the brightest and has twice the angular width of each adjacent secondary maximum in the small-angle approximation. Secondary maxima become progressively weaker away from the centre. The horizontal tick labels in the sketch use  $\sin \theta \simeq \theta$ .



Single-slit intensity against diffraction angle; tick positions use the small-angle approximation.

**Step 4: Locate the zero-intensity directions** Noncentral minima occur when  $\sin \beta = 0$ , with  $\beta \neq 0$ . Hence

$$a \sin \theta_m = m\lambda, \quad m = \pm 1, \pm 2, \pm 3, \dots$$

Therefore  $\theta_m = \sin^{-1}(m\lambda/a)$  for orders satisfying  $|m\lambda/a| \leq 1$ . For small angles,

$$\theta_m \simeq \frac{m\lambda}{a}.$$

The first minima are at approximately  $\pm \lambda/a$ , so the central maximum has angular width  $2\lambda/a$ . The value  $m = 0$  must be excluded from the minima condition because it gives the central maximum, not zero intensity.

**Step 5: (ii)(2) Compare diffraction of light and sound** Both spread into the geometrical shadow of an aperture or obstacle. Audible sound has wavelengths comparable to ordinary doors and obstacles, so it diffracts appreciably and can be heard around a corner. Visible wavelengths are only a few hundred nanometres, far smaller than ordinary openings, so the diffraction angles there are very small. Pronounced light diffraction requires a sufficiently narrow slit or small obstacle. The difference is the relative scale of wavelength and aperture; the underlying principle is the same.

**Step 6: Conclusion** For the printed 1.0 nm separation, no third bright fringe or positive-distance bright-fringe coincidence exists; only the central maxima coincide at  $y = 0$ . Formal small-angle substitutions give 1800 m and 2400 m, but are invalid here. Single-slit minima satisfy  $a \sin \theta = m\lambda$ ,  $m \neq 0$ ; sound diffracts much more noticeably around everyday obstacles because of its much longer wavelength.

**Quick Tip to Solve:** Before using  $y = n\lambda D/d$ , check that  $n\lambda/d \ll 1$ . For coincident fringes, reduce the wavelength ratio to the smallest integer order pair first.

**33(a).** (i) A small conducting sphere A of radius  $r$  charged to a potential  $V$ , is enclosed by a spherical conducting shell B of radius  $R$ . If A and B are connected by a thin wire, calculate the final potential on sphere A and shell B.

(ii) Write two characteristics of equipotential surfaces. A uniform electric field of  $50 \text{ N C}^{-1}$  is set up in a region along  $+x$  axis. If the potential at the origin  $(0, 0)$  is  $220 \text{ V}$ , find the potential at a point  $(4 \text{ m}, 3 \text{ m})$ . [5 marks]

### Solution:

#### Concept:

- An isolated conducting sphere of radius  $a$  carrying charge  $Q$  has surface potential  $V_s = Q/(4\pi\epsilon_0 a)$ , taking the potential at infinity as zero.
- Conductors joined by a wire reach a common potential. In electrostatic equilibrium, excess charge resides on the outer surface of a connected conductor when its cavity contains no isolated charge.
- Potential difference obeys  $V_P - V_O = -\int_O^P \vec{E} \cdot d\vec{l}$ . For a uniform field along  $+x$ , this becomes  $V_P - V_O = -E(x_P - x_O)$ .

**Step 1: (i) Find the initial charge on sphere A** The small sphere has radius  $r$  and is initially charged to potential  $V$ , before it is enclosed by the shell. With the shell initially uncharged, the total charge available to the two-conductor system is the charge originally placed on A. Therefore,

$$V = \frac{Q}{4\pi\epsilon_0 r} \Rightarrow Q = 4\pi\epsilon_0 r V.$$

Enclosing A induces opposite charges on the two surfaces of B, but does not change the total charge of the isolated system.

**Step 2: (i) Apply charge conservation after joining A and B** The wire makes A and B a single equipotential conductor. Charge moves until the field in the empty region between the joined conductors vanishes. Sphere A then carries no net excess charge; the conserved charge  $Q$  resides on the outer surface of shell B. Since its outer radius is  $R$ , the common potential is

$$V_f = \frac{Q}{4\pi\epsilon_0 R} = \frac{4\pi\epsilon_0 r V}{4\pi\epsilon_0 R}.$$

The potential is constant throughout the shell and its charge-free cavity, so this same value applies to A as well as B. The larger final outer radius increases the system's capacitance and reduces the potential for fixed total charge.

**Step 3: (ii) State two characteristics of equipotential surfaces** First, moving a test charge between any two points of an equipotential surface requires no electrostatic work: the potential difference is zero, so  $W = q\Delta V = 0$ . Second, wherever the electric field is nonzero, it is perpendicular to the equipotential surface. A tangential field component would perform work along the surface and contradict the constant potential there.

**Step 4: (ii) Calculate the potential difference along the field** Here  $\vec{E} = 50\hat{x} \text{ N C}^{-1}$ . Only the displacement along the  $x$ -axis contributes to the scalar product; the displacement of  $3 \text{ m}$  along  $y$  contributes zero. Thus,

$$\begin{aligned} V(4, 3) - V(0, 0) &= -E(4 - 0) \\ &= -(50 \text{ V m}^{-1})(4 \text{ m}) \\ &= -200 \text{ V}. \end{aligned}$$

Since  $V(0, 0) = 220 \text{ V}$ , add this potential difference to the given reference potential. The negative sign

agrees with the decrease of potential in the direction of the electric field.

**Step 5: Conclusion** (i) The final potentials are  $V_A = V_B = (r/R)V$ . (ii) Equipotential surfaces require no work for motion along them and are perpendicular to a nonzero electric field. The required point has potential  $V(4\text{ m}, 3\text{ m}) = 220 - 200 = 20\text{ V}$ .

**Quick Tip to Solve:** For nested conductors joined by a wire, use the outermost radius for the final potential. In a uniform field, use only displacement parallel to the field, not the full distance.

OR

**33(b).** (i) What is difference between an open surface and a closed surface? Draw elementary surface vector  $d\vec{S}$  for a spherical surface  $S$ .

(ii) Define electric flux through a surface. Give the significance of a Gaussian surface. A charge outside a Gaussian surface does not contribute to total electric flux through the surface. Why?

(iii) A small spherical shell  $S_1$  has point charges  $q_1 = -3\mu\text{C}$ ,  $q_2 = -2\mu\text{C}$  and  $q_3 = 9\mu\text{C}$  inside it. This shell is enclosed by another big spherical shell  $S_2$ . A point charge  $Q$  is placed in between the two surfaces  $S_1$  and  $S_2$ . If the electric flux through the surface  $S_2$  is four times the flux through surface  $S_1$ , find charge  $Q$ . [5 marks]

**Solution:**

**Concept:**

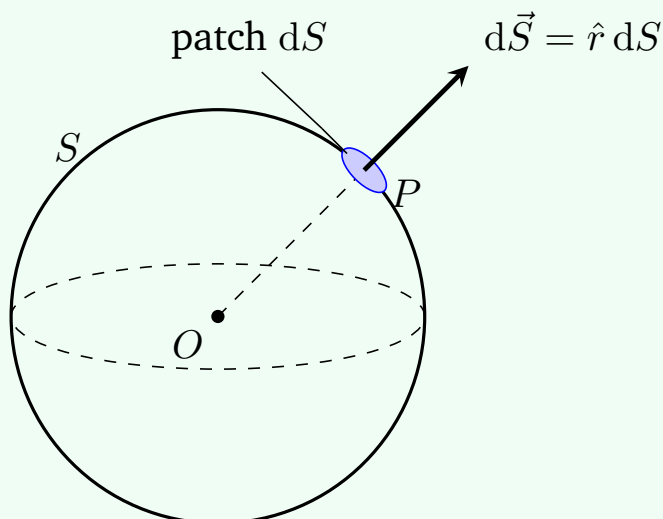
- A surface element has area vector  $d\vec{S} = \hat{n} dS$ , where  $\hat{n}$  is the local unit normal. For a closed surface the normal is chosen outward.
- Electric flux is  $\Phi_E = \int_S \vec{E} \cdot d\vec{S}$ , the surface integral of the normal component of the electric field.
- Gauss's law gives  $\oint_S \vec{E} \cdot d\vec{S} = q_{\text{enclosed}}/\epsilon_0$ , where  $\epsilon_0$  is the permittivity of free space. The enclosed charge is an algebraic sum.

**Step 1: (i) Distinguish the surfaces and draw the area vector** An open surface has a boundary and does not completely enclose a volume; a plane circular disc or a hemispherical surface without its base is an example. A closed surface has no boundary edge and completely encloses a volume; the complete surface of a sphere is an example. For an open surface either normal orientation can be chosen consistently. For a closed surface the conventional positive normal points outward.

On a spherical surface  $S$ , take a small patch of area  $dS$  at  $P$ . Its elementary area vector is perpendicular to the local tangent plane and directed radially outward from the centre  $O$ :

$$d\vec{S} = \hat{r} dS.$$

The arrow starts at the small surface patch and points away from the centre, as shown.



The elementary area vector is normal to the spherical surface and points radially outward.

**Step 2: (ii) Define flux and explain a Gaussian surface** Electric flux through a surface measures the electric field passing normally through it. For an infinitesimal element,

$$d\Phi_E = \vec{E} \cdot d\vec{S} = E \cos \theta dS, \quad \Phi_E = \int_S E \cos \theta dS,$$

where  $\theta$  is the angle between the field and the chosen surface normal. Its SI unit is  $\text{N m}^2\text{C}^{-1}$ .

A Gaussian surface is an imaginary closed surface used to apply Gauss's law. Its significance is that it connects the total outward electric flux with the net enclosed charge. When charge symmetry permits a suitable choice, such as a sphere for spherical symmetry, it also makes the calculation of the electric field simple by making the field magnitude constant on relevant portions of the surface.

**Step 3: (ii) Explain why an external charge gives zero net flux** Consider the field due to the external charge alone. It has no charge enclosed by the Gaussian surface, so Gauss's law gives

$$\oint_S \vec{E}_{\text{external}} \cdot d\vec{S} = 0.$$

Field lines due to that charge which enter the closed surface leave it again: the inward flux is negative and the outward flux is positive, with equal magnitudes. Thus the external charge can produce a nonzero field and nonzero local flux at individual patches, but its contribution to the total flux through the complete closed surface is zero.

**Step 4: (iii) Relate the two fluxes to enclosed charge** The inner shell encloses the three stated charges. Their algebraic sum is

$$q_{\text{in}} = q_1 + q_2 + q_3 = (-3 - 2 + 9) \mu\text{C} = 4 \mu\text{C}.$$

Hence  $\Phi_1 = (4 \times 10^{-6} \text{ C})/\epsilon_0$ . The outer shell encloses these same charges and also  $Q$ , so

$$\Phi_2 = \frac{4 \times 10^{-6} \text{ C} + Q}{\epsilon_0}.$$

Using the given signed flux relation  $\Phi_2 = 4\Phi_1$ , and cancelling the common permittivity, gives

$$4 \times 10^{-6} \text{ C} + Q = 4(4 \times 10^{-6} \text{ C}), \quad Q = (16 - 4) \times 10^{-6} \text{ C}.$$

**Step 5: Conclusion** An open surface has a boundary, while a closed surface encloses a volume. For a sphere,  $d\vec{S}$  is radially outward. Electric flux is  $\int_S \vec{E} \cdot d\vec{S}$ , and an external charge gives zero net flux through a closed surface. The required charge between the shells is  $Q = +12 \mu\text{C}$ .

**Quick Tip to Solve:** Compare enclosed algebraic charges directly when comparing fluxes: if  $\Phi_2 = k\Phi_1$ , then the additional charge is  $Q = (k - 1)q_{\text{in}}$ . Radii do not enter this flux ratio.