

CBSE Class 12 Physics Question Paper 2023 with Solution PDF-Set 55/1/3



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 **35** questions. **All** questions are **compulsory**.
- (ii) This question paper is divided into **five** Sections – **A, B, C, D** and **E**.
- (iii) In **Section A** – Questions no. **1** to **18** are Multiple Choice (MCQ) type questions, carrying **1** mark each.
- (iv) In **Section B** – Questions no. **19** to **25** are Very Short Answer (VSA) type questions, carrying **2** marks each.
- (v) In **Section C** – Questions no. **26** to **30** are Short Answer (SA) type questions, carrying **3** marks each.
- (vi) In **Section D** – Questions no. **31** to **33** are Long Answer (LA) type questions carrying **5** marks each.
- (vii) In **Section E** – Questions no. **34** and **35** are case-based questions carrying **4** marks each.
- (viii) There is no overall choice. However, an internal choice has been provided in 2 questions in Section B, 2 questions in Section C, 3 questions in Section D and 2 questions in Section E.
- (ix) Use of calculators is **not** allowed.

Use the following values of physical constants, if required :

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

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

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

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

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

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

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

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

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

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

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

Section A (18 marks)

1. In the energy-band diagram of n-type Si, the gap between the bottom of the conduction band E_C and the donor energy level E_D is of the order of: [1 mark]

- (A) 10 eV
- (B) 1 eV
- (C) 0.1 eV
- (D) 0.01 eV

Correct Answer: (D) 0.01 eV

Solution:

Concept:

- In n-type silicon, pentavalent dopants introduce donor levels E_D just below the conduction-band edge E_C .
- The donor ionisation energy $E_C - E_D$ is much smaller than the energy gap between the valence and conduction bands.

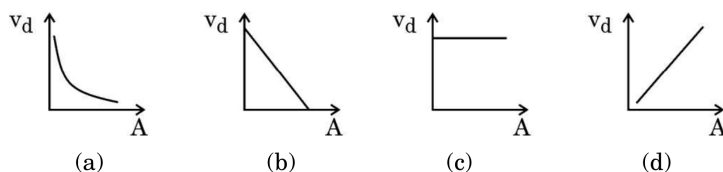
Step 1: Identify the energy separation The question asks for the energy needed to lift a donor electron into the conduction band. Since the extra donor electron is weakly bound, this energy is only a few hundredths of an electronvolt, of order 10^{-2} eV.

Step 2: Compare the proposed scales An energy near 1 eV describes the full silicon band-gap scale, not the donor separation. The values 10 eV and 0.1 eV are also too large for the expected shallow donor energy scale in this textbook model.

Step 3: Conclusion The separation $E_C - E_D$ is of order 0.01 eV. Hence, the correct option is (D).

Quick Tip to Solve: Distinguish the small donor-to-conduction separation from the much larger valence-to-conduction band gap.

2. A steady current flows through a metallic wire whose area of cross-section (A) increases continuously from one end of the wire to the other. The magnitude of drift velocity (v_d) of the free electrons as a function of ' A ' can be shown by: [1 mark]



- (A) Graph (a)
 (B) Graph (b)
 (C) Graph (c)
 (D) Graph (d)

Correct Answer: (A) Graph (a)

Solution:

Concept:

- The magnitude of current in a metal is $I = neAv_d$, where n is free-electron number density, e is elementary charge and A is the cross-sectional area.
- Steady current has the same value through every cross-section of a single wire, by conservation of charge.

Step 1: Express the drift speed in terms of area For the same metallic wire, n is constant. Since I and e are also constant, rearranging the current relation gives

$$v_d = \frac{I}{neA}, \quad v_d \propto \frac{1}{A}.$$

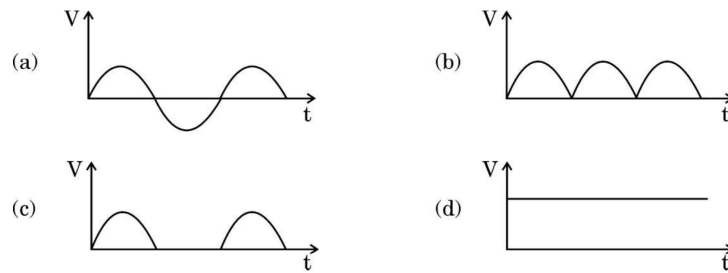
Thus, doubling the area halves the drift speed.

Step 2: Identify the curve An inverse relation gives a decreasing rectangular hyperbola in the positive quadrant. Graph (a) has this form. Graph (b) shows a linear decrease, (c) a constant speed, and (d) an increasing speed; none satisfies $Av_d = \text{constant}$.

Step 3: Conclusion The required variation is graph (a). Hence, the correct option is (A).

Quick Tip to Solve: Use constant current to write $Av_d = \text{constant}$; an inverse relation produces a curve, not a straight line.

3. An ac source of voltage is connected in series with a p-n junction diode and a load resistor. The correct option for output voltage across load resistance will be: [1 mark]



(A) Graph (a)

(B) Graph (b)

(C) Graph (c)

(D) Graph (d)

Correct Answer: (C) Graph (c)

Solution:

Concept:

- A p-n junction diode conducts appreciably when forward biased and blocks current when reverse biased.
- A single diode in series with an ac source and a load resistor forms a half-wave rectifier; the load voltage is $V_R = IR$.

Step 1: Examine the two half-cycles During the forward-bias half-cycle, current passes through the resistor and the load voltage follows that half of the sinusoidal input. During the reverse-bias half-cycle, the current is approximately zero, so the load voltage is approximately zero as well.

Step 2: Compare the output waveforms Graph (c) shows pulses separated by intervals of zero voltage, as required for half-wave rectification. Graph (a) leaves both signs of the input unchanged. Graph (b) is full-wave rectification, requiring additional diodes. Graph (d) is constant dc, which this unfiltered single-diode circuit cannot produce.

Step 3: Conclusion The output is the half-wave rectified waveform in graph (c). Hence, the correct option is (C).

Quick Tip to Solve: Count the diodes: one series diode transmits alternate half-cycles, leaving a zero-output gap after each pulse.

4. Hydrogen atom initially in the ground state, absorbs a photon which excites it to $n = 5$ level. The wavelength of the photon is: [1 mark]

- (A) 975 nm
- (B) 740 nm
- (C) 523 nm
- (D) 95 nm

Correct Answer: (D) 95 nm

Solution:

Concept:

- The hydrogen energy levels are $E_n = -13.6/n^2$ eV, with n the principal quantum number.
- In absorption, the photon supplies the positive energy difference: $hc/\lambda = E_f - E_i$, with $hc \simeq 1240$ eV nm.

Step 1: Calculate the excitation energy The ground state has $n_i = 1$, and the final state has $n_f = 5$. Thus,

$$\Delta E = 13.6 \left(1 - \frac{1}{25} \right) = 13.056 \text{ eV.}$$

The absorbed energy is positive even though both bound-state energies are negative.

Step 2: Convert energy to wavelength Using the energy difference rather than the final level energy,

$$\lambda = \frac{1240}{13.056} \text{ nm} \simeq 94.98 \text{ nm.}$$

The wavelengths 975, 740 and 523 nm correspond to much smaller photon energies and cannot excite a ground-state hydrogen atom to this level.

Step 3: Conclusion The wavelength is approximately 95 nm. Hence, the correct option is (D).

Quick Tip to Solve: A hydrogen transition from the ground state belongs to the ultraviolet Lyman series; expect a wavelength near 100 nm.

5. In the process of charging of a capacitor, the current produced between the plates of the capacitor is (where symbols have their usual meanings): [1 mark]

- (A) $\mu_0 \frac{d\phi_E}{dt}$
- (B) $\frac{1}{\mu_0} \frac{d\phi_E}{dt}$
- (C) $\varepsilon_0 \frac{d\phi_E}{dt}$
- (D) $\frac{1}{\varepsilon_0} \frac{d\phi_E}{dt}$

Correct Answer: (C) $\varepsilon_0 \frac{d\phi_E}{dt}$

Solution:

Concept:

- A changing electric flux produces displacement current, defined as $I_d = \varepsilon_0 d\phi_E/dt$, where ϕ_E is electric flux.

- In an ideal charging capacitor, no conduction current crosses the gap between the plates, but displacement current ensures current continuity.

Step 1: Relate charge to electric flux For parallel plates of area A carrying charges of magnitude Q , neglect fringing. The field between the plates is $E = Q/(\epsilon_0 A)$, so the electric flux is

$$\phi_E = EA = \frac{Q}{\epsilon_0}.$$

Step 2: Differentiate during charging Multiplying the rate of change of flux by ϵ_0 gives

$$\epsilon_0 \frac{d\phi_E}{dt} = \frac{dQ}{dt} = I_d.$$

Thus the multiplier is the permittivity, not the permeability μ_0 or either reciprocal. The other three options do not reproduce the charging current.

Step 3: Conclusion The current between the plates is $I_d = \epsilon_0 \frac{d\phi_E}{dt}$. Hence, the correct option is (C).

Quick Tip to Solve: Recall $\phi_E = Q/\epsilon_0$; differentiating immediately fixes the correct coefficient of displacement current.

6. In an experiment, photons of energy 7.5 eV are incident on a metal surface. Electrons emitted from the metal surface are stopped by an electrode at a potential of -4.5 V w.r.t. the metal. The work function of the metal is: [1 mark]

- (A) 3.0 eV
- (B) 4.5 eV
- (C) 7.5 eV
- (D) 12.0 eV

Correct Answer: (A) 3.0 eV

Solution:

Concept:

- Einstein's photoelectric equation is $E_\gamma = \phi + K_{\max}$, where ϕ is the work function and $K_{\max}$ the maximum emitted-electron kinetic energy.
- A retarding stopping potential of magnitude V_s corresponds to $K_{\max} = eV_s$.

Step 1: Obtain the maximum kinetic energy The collector is at -4.5 V relative to the metal, so it repels emitted electrons. The stopping-potential magnitude is 4.5 V, giving

$$K_{\max} = e(4.5 \text{ V}) = 4.5 \text{ eV}.$$

The kinetic energy is positive; the negative electrode voltage only specifies its retarding polarity.

Step 2: Apply energy conservation The incident photon supplies both the escape energy and kinetic energy. Therefore,

$$\phi = E_\gamma - K_{\max} = 7.5 - 4.5 = 3.0 \text{ eV}.$$

The values 4.5 and 7.5 eV are the kinetic and incident energies. Adding them to obtain 12.0 eV would violate the photoelectric energy balance.

Step 3: Conclusion The work function is 3.0 eV. Hence, the correct option is (A).

Quick Tip to Solve: Use the magnitude of a negative stopping voltage: subtract its numerical value in volts from photon energy in electronvolts.

7. A circular coil of radius 8.0 cm and 40 turns is rotated about its vertical diameter with an angular speed of $\frac{25}{\pi}$ rad s⁻¹ in a uniform horizontal magnetic field of magnitude 3.0×10^{-2} T. The maximum emf induced in the coil is: [1 mark]

- (A) 0.12 V
- (B) 0.15 V
- (C) 0.19 V
- (D) 0.22 V

Correct Answer: (C) 0.19 V

Solution:

Concept:

- For a coil rotating in a uniform field, the flux linkage is $N\Phi = NBA \cos \omega t$, where N is turns, A is coil area and ω is angular speed.
- Faraday's law gives $\varepsilon = NBA\omega \sin \omega t$, so the peak induced emf is $\varepsilon_{\max} = NBA\omega$.

Step 1: Convert the radius and find the area The radius is $r = 8.0 \text{ cm} = 0.080 \text{ m}$, giving

$$A = \pi r^2 = \pi(0.080)^2 = 0.0064\pi \text{ m}^2.$$

The vertical axis of rotation is perpendicular to the horizontal field, allowing the flux to vary sinusoidally through its full range.

Step 2: Substitute the printed angular speed Using $N = 40$, $B = 3.0 \times 10^{-2} \text{ T}$ and the printed $\omega = 25/\pi \text{ rad s}^{-1}$,

$$\varepsilon_{\max} = 40(3.0 \times 10^{-2})(0.0064\pi)\frac{25}{\pi} = 0.192 \text{ V}.$$

The factors of π cancel. The other listed values, 0.12, 0.15 and 0.22 V, do not agree with this product to two significant figures.

Step 3: Conclusion The maximum induced emf is approximately 0.19 V. Hence, the correct option is (C).

Quick Tip to Solve: Keep the area as πr^2 until substituting $25/\pi$; cancel π before multiplying the numbers.

8. Two nuclei have their mass numbers in the ratio of 8 : 1. The ratio of their nuclear densities is: [1 mark]

- (A) 8 : 1
- (B) 4 : 1
- (C) 2 : 1
- (D) 1 : 1

Correct Answer: (D) 1 : 1

Solution:

Concept:

- A nucleus of mass number A has radius $R = R_0 A^{1/3}$, where R_0 is approximately constant for different nuclei.
- Nuclear mass is approximately $A m_N$, where m_N is the nucleon mass, and density is mass divided by volume.

Step 1: Express density using the mass number Model the nucleus as a sphere. Its volume is proportional to R^3 , hence to A . Therefore,

$$\rho = \frac{A m_N}{\frac{4}{3} \pi R^3} = \frac{A m_N}{\frac{4}{3} \pi R_0^3 A} = \frac{3 m_N}{4 \pi R_0^3}.$$

The mass number cancels, so nuclear density is approximately independent of nuclear size.

Step 2: Compare the two nuclei With mass numbers in the ratio 8 : 1, their masses and volumes both have ratio 8 : 1. Their radii have ratio 2 : 1. Dividing the mass ratio by the volume ratio gives equal densities. Thus 8 : 1, 4 : 1 and 2 : 1 cannot be the density ratio.

Step 3: Conclusion The ratio of nuclear densities is 1 : 1. Hence, the correct option is (D).

Quick Tip to Solve: Since nuclear mass and nuclear volume both scale as A , their ratio is approximately the same for all nuclei.

9. A point charge situated at a distance 'r' from a short electric dipole on its axis, experiences a force $\vec{F}$. If the distance of the charge is '2r', the force on the charge will be: [1 mark]

- (A) $\vec{F}/16$
- (B) $\vec{F}/8$
- (C) $\vec{F}/4$
- (D) $\vec{F}/2$

Correct Answer: (B) $\vec{F}/8$

Solution:

Concept:

- On the axis of a short electric dipole, the electric field is $\vec{E} = \frac{1}{4\pi\epsilon_0} \frac{2\vec{p}}{r^3}$, where $\vec{p}$ is the dipole moment and r is the distance from its centre.
- The force on a fixed point charge q is $\vec{F} = q\vec{E}$; therefore its magnitude varies as r^{-3} .

Step 1: Compare the two distances The same charge remains on the same side of the dipole axis, so

neither the charge nor the dipole moment changes. Only the factor involving distance changes:

$$\frac{F(2r)}{F(r)} = \frac{r^3}{(2r)^3} = \frac{1}{8}.$$

Step 2: Check the direction and alternatives The field, and hence the force, keeps its original direction at the new axial position. The factor $1/4$ would apply to the inverse-square field of an isolated point charge, not a short dipole. The factors $1/2$ and $1/16$ correspond to other distance dependences and do not follow the dipole law.

Step 3: Conclusion The new force is $\vec{F}/8$, in the original direction. Hence, the correct option is (B).

Quick Tip to Solve: First identify the source: a short dipole gives an inverse-cube field, so doubling distance divides its force on a fixed charge by eight.

10. The number of electrons flowing through a conductor per second is 3.3×10^{19} . The current flowing through the conductor is: [1 mark]

- (A) 2.0 A
- (B) 3.4 A
- (C) 4.8 A
- (D) 5.3 A

Correct Answer: (D) 5.3 A

Solution:

Concept:

- Electric current is the charge crossing a conductor's cross-section per unit time: $I = \Delta Q / \Delta t$.
- If N electrons cross in time t , the magnitude of transferred charge is Ne , with $e = 1.6 \times 10^{-19}$ C.

Step 1: Convert electron flow into charge flow The stated electron flow rate is $N/t = 3.3 \times 10^{19} \text{ s}^{-1}$. Each electron carries one elementary charge in magnitude, so

$$I = \frac{N}{t}e = (3.3 \times 10^{19})(1.6 \times 10^{-19}) \text{ C s}^{-1}.$$

Step 2: Evaluate and compare the options The powers of ten cancel and the numerical product is $3.3 \times 1.6 = 5.28$. Thus the result rounds to 5.3 A at two significant figures. None of 2.0, 3.4, or 4.8 A agrees with the stated electron rate. The negative electron charge determines the direction of conventional current, not a negative value for the requested magnitude.

Step 3: Conclusion The current magnitude is 5.3 A. Hence, the correct option is (D).

Quick Tip to Solve: For an electron rate containing 10^{19} , multiply its coefficient by 1.6: the elementary charge cancels that power of ten.

11. When an intrinsic semiconductor is doped with a small amount of trivalent impurity, then:

[1 mark]

- (A) its resistance increases.
- (B) it becomes a p-type semiconductor.
- (C) there will be more free electrons than holes in the semiconductor.
- (D) dopant atoms become donor atoms.

Correct Answer: (B) it becomes a p-type semiconductor.

Solution:

Concept:

- A trivalent dopant has three valence electrons, whereas a silicon or germanium atom forms four covalent bonds.
- Such an impurity accepts an electron to complete a bond, leaving a mobile hole; it is an acceptor impurity.

Step 1: Identify the majority charge carriers Replacing a tetravalent host atom by a trivalent dopant leaves one bond deficient in an electron. The resulting holes greatly outnumber the thermally generated free electrons. A semiconductor whose majority carriers are holes is called p-type; the material as a whole remains electrically neutral.

Step 2: Eliminate the other descriptions Doping increases the mobile carrier concentration, so the conductivity increases and the resistance of the same specimen decreases under ordinary conditions; option (A) is incorrect. More electrons than holes describes n-type material, ruling out (C). Trivalent impurities accept electrons rather than donate an extra valence electron, ruling out (D).

Step 3: Conclusion The doped material becomes a p-type semiconductor. Hence, the correct option is (B).

Quick Tip to Solve: Count the dopant's valence electrons: three leaves a hole and gives p-type; five supplies an extra electron and gives n-type.

12. A diamagnetic substance is brought near the north or south pole of a bar magnet. It will be:

[1 mark]

- (A) repelled by both the poles.
- (B) attracted by both the poles.
- (C) repelled by the north pole and attracted by the south pole.
- (D) attracted by the north pole and repelled by the south pole.

Correct Answer: (A) repelled by both the poles.

Solution:

Concept:

- Diamagnetic substances have negative magnetic susceptibility: their induced magnetisation opposes the applied magnetic field.
- In a non-uniform field, a diamagnetic specimen tends to move from stronger-field regions towards weaker-field regions.

Step 1: Examine the field near either pole The magnetic field becomes stronger as a small specimen

approaches either end of a bar magnet. The induced magnetic response therefore tends to push the diamagnetic specimen away from the nearby pole towards a weaker field.

Step 2: Reverse the pole and compare Changing the nearby pole reverses the local field direction, but also reverses the induced magnetisation. The magnetisation still opposes that field, so the force remains repulsive. Attraction by both poles describes the usual response of paramagnetic or ferromagnetic substances. Opposite responses to the two poles would incorrectly treat the specimen as a fixed permanent magnetic pole.

Step 3: Conclusion The diamagnetic substance is repelled by both poles. Hence, the correct option is (A).

Quick Tip to Solve: For diamagnetism, track field strength rather than the pole's name: the specimen always prefers the weaker-field region.

13. Which of the following pairs of media has the least value of critical angle?

[1 mark]

- (A) Glass to air
- (B) Glass to water
- (C) Diamond to water
- (D) Diamond to air

Correct Answer: (D) Diamond to air

Solution:

Concept:

- For light travelling from refractive index n_1 to a smaller index n_2 , the critical angle C satisfies $\sin C = n_2/n_1$.
- A smaller ratio n_2/n_1 gives a smaller critical angle, since sine increases between 0° and 90° .

Step 1: Compare the refractive-index ratios Air has a lower refractive index than water, and diamond has a higher refractive index than glass. For either starting material, choosing air as the second medium reduces the numerator and therefore reduces the critical angle. This eliminates glass-to-water and diamond-to-water as the smallest possible pair.

Step 2: Compare glass and diamond with air For the two remaining pairs the numerator is the same, n_{air} . The larger denominator n_{diamond} gives a smaller ratio than n_{glass} :

$$\frac{n_{\text{air}}}{n_{\text{diamond}}} < \frac{n_{\text{air}}}{n_{\text{glass}}}.$$

Thus the largest refractive index in the first medium combined with the smallest in the second gives the required minimum.

Step 3: Conclusion Diamond to air has the least critical angle. Hence, the correct option is (D).

Quick Tip to Solve: Minimise $\sin C = n_2/n_1$: choose the highest-index starting medium and the lowest-index final medium.

14. A bar magnet is dropped in a hollow metallic cylinder along its vertical axis. The acceleration of the falling magnet will be: [1 mark]

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

Correct Answer: (C) less than g

Solution:

Concept:

- A moving magnet changes the magnetic flux through loops within a conducting cylinder, producing eddy currents by Faraday's law.
- Lenz's law makes the magnetic effect of these currents oppose the flux change that produces them, thereby opposing the magnet's motion.

Step 1: Determine the induced force As the magnet falls, its flux through each part of the metallic wall changes. The induced currents create a magnetic force opposing the downward motion. The resulting magnetic drag acts upward, irrespective of which pole of the falling magnet points downward.

Step 2: Apply Newton's second law Taking downward as positive and writing the upward drag magnitude as F_m ,

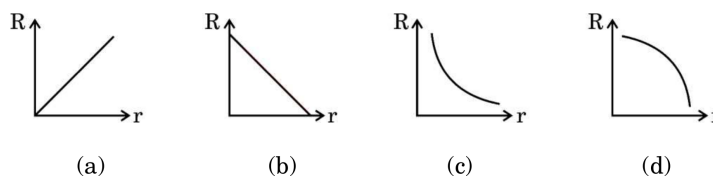
$$ma = mg - F_m, \quad a = g - \frac{F_m}{m}.$$

Once the magnet is moving and currents are induced, the downward acceleration is reduced below g . It is not greater than g , since the force is retarding. Zero acceleration is only a possible terminal-speed condition, not the general acceleration throughout the fall; exactly at release the speed and drag initially vanish.

Step 3: Conclusion During its fall with induced magnetic drag, the magnet's acceleration is less than g . Hence, the correct option is (C).

Quick Tip to Solve: In a conducting tube, draw eddy-current drag opposite the magnet's velocity, then subtract that force from its weight.

15. The correct graph showing the variation of the resistance (R) of a cylindrical metal wire as a function of its radius (r), keeping its length and temperature constant, is: [1 mark]



- (A) Graph (a)
(B) Graph (b)
(C) Graph (c)
(D) Graph (d)

Correct Answer: (C) Graph (c)

Solution:

Concept:

- The resistance of a uniform wire is $R = \rho L/A$, where ρ is resistivity, L is length and A is cross-sectional area.
- For a circular wire $A = \pi r^2$. Fixed temperature and length keep ρ and L constant, giving $R = (\rho L/\pi)r^{-2}$.

Step 1: Identify the shape of the variation Increasing radius reduces resistance as the inverse square. In particular, doubling the radius reduces the resistance to one quarter. For positive radius, resistance stays positive, is very large near zero radius and approaches zero as radius becomes large.

Step 2: Compare the four printed graphs The required curve falls steeply at small radius and then becomes progressively flatter, as in graph (c). Graph (a) incorrectly increases. Graph (b) is a straight line and reaches zero at finite radius. Graph (d) becomes steeper as radius increases, whereas the magnitude of the slope of $R = k/r^2$ is $2k/r^3$, which decreases with radius.

Step 3: Conclusion Graph (c) represents $R \propto 1/r^2$. Hence, the correct option is (C).

Quick Tip to Solve: Use both tests for an inverse-square graph: it must decrease and flatten as radius increases; doubling radius quarters the resistance.

16. Assertion (A): Photoelectric effect demonstrates the particle nature of light.

Reason (R): Photoelectric current is proportional to intensity of incident radiation for frequencies more than the threshold frequency. [1 mark]

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

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

Solution:

Concept:

- In the photon model, an electron absorbs energy $h\nu$ from one photon. Einstein's equation is $K_{\max} = h\nu - \phi$, with work function ϕ .
- At fixed frequency above threshold, increasing light intensity increases the photon arrival rate and hence the number of emitted electrons per second under the same collection conditions.

Step 1: Judge the assertion The assertion is true. The threshold frequency and the dependence of maximum kinetic energy on frequency are explained by discrete photon energy transfers, demonstrating the particle nature of light.

Step 2: Judge the reason The reason is also true. For incident frequency greater than the threshold and fixed experimental conditions, greater intensity produces more photoelectrons per second. The photoelectric current is therefore proportional to intensity; the maximum kinetic energy does not increase for that reason.

Step 3: Test the explanatory connection Current proportional to intensity alone is not distinctive evidence for the particle nature of light: increasing the energy delivered per second also accords with a classical intensity description. The decisive evidence concerns threshold frequency and electron energy depending on frequency. Thus the stated reason is a valid observation but does not explain the assertion; the options labelling either statement false are excluded.

Step 4: Conclusion Both statements are true, but the Reason does not correctly explain the Assertion. Hence, the correct option is (B).

Quick Tip to Solve: Distinguish photon count from photon energy: intensity controls photoelectric current, while frequency controls the maximum electron energy.

17. Assertion (A): When a bar of copper is placed in an external magnetic field, the field lines get concentrated inside the bar.

Reason (R): Copper is a paramagnetic substance.

[1 mark]

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

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

Solution:

Concept:

- A diamagnetic material has negative magnetic susceptibility, $\chi_m < 0$, so its induced magnetisation opposes the applied magnetic field.
- Copper is diamagnetic; its relative permeability $\mu_r = 1 + \chi_m$ is slightly less than one.

Step 1: Evaluate the assertion In copper the induced magnetic field opposes the external field. The magnetic field inside the bar is slightly weaker than the applied field, and field lines are less dense inside it. Thus the claim that the lines get concentrated inside copper is false.

Step 2: Evaluate the reason Copper is a diamagnetic substance, not a paramagnetic one. A paramagnetic substance would weakly reinforce the applied field, but this is not copper's behaviour. Therefore the reason is also false.

Step 3: Check the explanation and options Since both statements are false, the reason cannot explain the assertion. Options (A) and (B) require both statements to be true, while option (C) requires a true assertion; all three are excluded.

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

Quick Tip to Solve: For copper, remember $\chi_m < 0$: field lines become less dense inside the sample, not more dense.

18. Assertion (A): The phase difference between any two points on a wavefront is zero.

Reason (R): All points on a wavefront are at the same distance from the source and thus oscillate in the same phase. [1 mark]

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

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

Solution:

Concept:

- A wavefront is a surface joining points of a wave that oscillate in the same phase at a given instant.
- In a homogeneous medium, the phase difference associated with a path difference Δr is $\Delta\phi = 2\pi\Delta r/\lambda$, where λ is the wavelength.

Step 1: Evaluate the assertion Every point on a wavefront has the same phase by the definition of a wavefront. Consequently, the phase difference between any two points on it is zero. The assertion is true.

Step 2: Evaluate the reason In the usual homogeneous-medium description of propagation from a source, points on the same advancing wavefront have travelled equal distances from the source. They therefore have equal propagation times and oscillate in the same phase. In this standard context the reason is true.

Step 3: Relate the reason to the assertion Equal propagation distances give $\Delta r = 0$, hence $\Delta\phi = 0$. The reason thus explains the asserted zero phase difference. Option (B) denies this explanation, while (C) and (D) incorrectly make one or both statements false.

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

Quick Tip to Solve: Use the defining property of a wavefront first: it is an equal-phase surface, so any two of its points have zero phase difference.

Section B (14 marks)

19. The radii of curvature of the faces of a double-convex lens are 20 cm and 30 cm. Its power is $\frac{25}{6}$ D. What is the refractive index of the glass of the lens? [2 marks]

Solution:

Concept:

- For a thin lens in air, the lens-maker's formula is $P = (\mu - 1)(1/R_1 - 1/R_2)$, where P is power and μ is the refractive index of glass relative to air.
- With radii in metres, power is in dioptres. Under the Cartesian sign convention, a double-convex lens has $R_1 > 0$ and $R_2 < 0$ for light travelling from left to right.

Step 1: Assign signs and convert the radii The centre of curvature of the first surface is to its right, while that of the second surface is to its left. Thus the stated radii have the signed values

$$R_1 = +0.20 \text{ m}, \quad R_2 = -0.30 \text{ m}.$$

The printed power is $P = 25/6 \text{ D}$. The negative sign on R_2 means the two curvature contributions add for this converging lens.

Step 2: Apply the lens-maker's formula Substituting the power and radii gives

$$\begin{aligned} \frac{25}{6} &= (\mu - 1) \left(\frac{1}{0.20} - \frac{1}{-0.30} \right) \\ &= (\mu - 1) \left(5 + \frac{10}{3} \right) = (\mu - 1) \frac{25}{3}. \end{aligned}$$

Dividing by the curvature factor yields $\mu - 1 = (25/6)(3/25) = 1/2$. Refractive index is a ratio and therefore has no unit.

Step 3: Conclusion The refractive index of the glass is $\boxed{\mu = 1.50}$.

Quick Tip to Solve: For a double-convex lens in air, use opposite signs for its two radii; the lens-maker curvature terms then add.

20. Briefly explain how the diffusion and drift currents contribute to the formation of potential barrier in a p-n junction diode. [2 marks]

Solution:

Concept:

- Diffusion is the motion of charge carriers from a region of higher concentration to one of lower concentration; drift is their motion due to an electric field.
- In an unbiased p-n junction at thermal equilibrium, diffusion and drift currents are equal in magnitude and opposite in direction, so the net current is zero.

Step 1: Explain how diffusion creates the barrier When p-type and n-type regions are joined, majority electrons diffuse from the n side to the p side, while majority holes diffuse from p to n. Near the junction they recombine, leaving behind immobile positive donor ions on the n side and immobile negative acceptor ions on the p side. This region is depleted of mobile majority carriers and is called the depletion layer. Its separated fixed charges establish an electric field from n to p and a built-in potential barrier opposing further majority-carrier diffusion.

Step 2: Explain the opposing drift current and equilibrium The junction electric field drives minority electrons from p to n and minority holes from n to p. Their conventional drift current is from n to p, opposite to the conventional diffusion current from p to n. As the potential barrier develops, it suppresses further diffusion until the opposing currents balance:

$$I_{\text{diffusion}} + I_{\text{drift}} = 0.$$

The individual carrier processes continue at equilibrium even though there is no net current through the unbiased junction.

Step 3: Conclusion Diffusion and recombination establish the depletion layer and potential barrier.

The barrier's electric field produces an opposing drift current; equilibrium is reached when the two currents have equal magnitudes.

Quick Tip to Solve: Trace the sequence: diffusion leaves fixed ions, fixed ions create the barrier field, and that field drives the opposing drift current.

21. An alpha particle is projected with velocity $\vec{V} = (3.0 \times 10^5 \text{ m/s}) \hat{i}$ into a region in which magnetic field $\vec{B} = [(0.4 \text{ T}) \hat{i} + (0.3 \text{ T}) \hat{j}]$ exists. Calculate the acceleration of the particle in the region. $\hat{i}$, $\hat{j}$ and $\hat{k}$ are unit vectors along x , y and z axis respectively and charge to mass ratio for alpha particle is $4.8 \times 10^7 \text{ C/kg}$. [2 marks]

Solution:

Concept:

- The magnetic force on a charge q moving with velocity $\vec{v}$ is $\vec{F} = q(\vec{v} \times \vec{B})$. Therefore its acceleration is $\vec{a} = (q/m)(\vec{v} \times \vec{B})$.
- Only the component of magnetic field perpendicular to the velocity contributes to this force: $\hat{i} \times \hat{i} = 0$ and $\hat{i} \times \hat{j} = \hat{k}$. An alpha particle carries positive charge.

Step 1: Calculate the vector product The given velocity is along the positive x -axis. The 0.4 T component parallel to this velocity gives no force. At the instant of projection,

$$\begin{aligned}\vec{v} \times \vec{B} &= 3.0 \times 10^5 [0.4(\hat{i} \times \hat{i}) + 0.3(\hat{i} \times \hat{j})] \\ &= 9.0 \times 10^4 \hat{k} \text{ T m s}^{-1}.\end{aligned}$$

The positive $\hat{k}$ direction follows from the right-hand rule.

Step 2: Use the charge-to-mass ratio Multiplying by the given $q/m = 4.8 \times 10^7 \text{ C kg}^{-1}$ gives

$$\begin{aligned}\vec{a} &= (4.8 \times 10^7)(9.0 \times 10^4) \hat{k} \text{ m s}^{-2} \\ &= 4.32 \times 10^{12} \hat{k} \text{ m s}^{-2}.\end{aligned}$$

Since the charge is positive, acceleration has the same direction as $\vec{v} \times \vec{B}$. The result is the instantaneous acceleration for the stated velocity; its direction changes as the magnetic field bends the trajectory.

Step 3: Conclusion The acceleration is $\boxed{\vec{a} = 4.32 \times 10^{12} \hat{k} \text{ m s}^{-2}}$, along the positive z -axis at projection.

Quick Tip to Solve: With velocity along $\hat{i}$, discard the $\hat{i}$ component of the magnetic field before taking the cross product.

22. The ground state energy of hydrogen atom is -13.6 eV in Bohr model. An electron makes a transition from an energy level of -1.51 eV to that of -3.4 eV. Calculate the wavelength of the spectral line emitted. [2 marks]

Solution:

Concept:

- When an electron falls to a lower energy level, it emits a photon with energy $E_\gamma = E_i - E_f = h\nu = hc/\lambda$. Here h is Planck's constant, c is the speed of light and λ is the emitted wavelength.
- Hydrogen energy levels obey $E_n = -13.6/n^2$ eV. To use SI values of h and c , convert the photon energy using $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$.

Step 1: Find the emitted photon energy The initial level is -1.51 eV and the final level is -3.4 eV. The final level is more negative, so the atom loses energy and emits a photon. Its energy is the positive difference

$$\begin{aligned} E_\gamma &= (-1.51) - (-3.4) = 1.89 \text{ eV} \\ &= 1.89(1.6 \times 10^{-19}) = 3.024 \times 10^{-19} \text{ J}. \end{aligned}$$

These levels correspond approximately to $n = 3$ and $n = 2$, respectively, so the line belongs to the Balmer series.

Step 2: Convert photon energy into wavelength Using $h = 6.63 \times 10^{-34} \text{ J s}$ and $c = 3.0 \times 10^8 \text{ m s}^{-1}$,

$$\begin{aligned} \lambda &= \frac{hc}{E_\gamma} = \frac{(6.63 \times 10^{-34})(3.0 \times 10^8)}{3.024 \times 10^{-19}} \\ &\approx 6.58 \times 10^{-7} \text{ m} = 658 \text{ nm}. \end{aligned}$$

The small difference from the usual tabulated Balmer-alpha wavelength is due to the rounded energy levels and constants supplied in the question.

Step 3: Conclusion The emitted spectral line has wavelength $\lambda \approx 6.58 \times 10^{-7} \text{ m}$, or about 658 nm, in the red region of the visible spectrum.

Quick Tip to Solve: Subtract the two negative levels carefully: photon energy is the positive drop, $E_i - E_f$, before applying $\lambda = hc/E_\gamma$.

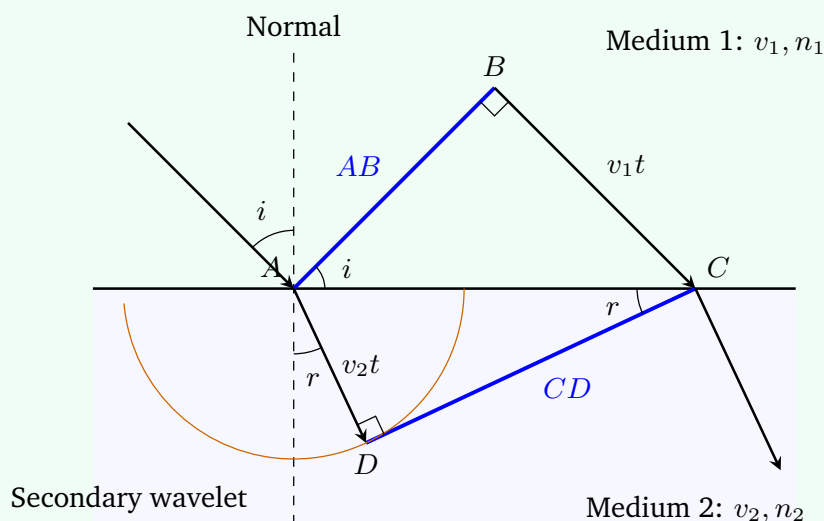
23(a). Using Huygens' principle, draw a ray diagram showing the propagation of a plane wave refracting at a plane surface separating two media. Also verify Snell's law of refraction. [2 marks]

Solution:

Concept:

- Huygens' principle states that every point of a wavefront emits secondary wavelets; their forward envelope is the new wavefront. Rays are perpendicular to wavefronts.
- In a medium of refractive index n , the speed of light is $v = c/n$, where c is its speed in vacuum. Angles of incidence i and refraction r are measured from the normal.

Step 1: Construct the refracted wavefront Let the plane wavefront AB be incident from medium 1 onto the plane boundary, with A reaching it first. In time t , point B travels along the incident ray to C , so $BC = v_1 t$. Meanwhile the secondary wavelet from A spreads into medium 2 with radius $AD = v_2 t$. Draw the tangent CD from C to this wavelet. Then CD is the refracted plane wavefront and AD , perpendicular to it, gives the refracted ray direction. The sketch shows $v_2 < v_1$.



Huygens construction: AB and CD are wavefronts; arrows show ray propagation.

Step 2: Use the two right triangles Since rays are normal to their wavefronts, $\angle BAC = i$ and $\angle ACD = r$. Also $AB \perp BC$ and $AD \perp CD$. Thus

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

Dividing eliminates the common time and boundary length:

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}.$$

Step 3: Conclusion The construction gives the refracted wavefront CD , and $n_1 \sin i = n_2 \sin r$, verifying Snell's law. For the illustrated slower second medium, $r < i$, so the ray bends towards the normal.

Quick Tip to Solve: Use the same time for both distances: $BC = v_1 t$ and $AD = v_2 t$; divide the sine ratios with common hypotenuse AC .

OR

23(b). Why is a reflecting telescope preferred over a refracting telescope? Justify your answer giving two reasons. [2 marks]

Solution:

Concept:

- A reflecting telescope uses a concave mirror as its objective; a refracting telescope uses a converging lens. The objective gathers light and forms the image viewed through the eyepiece.
- Chromatic aberration occurs when different wavelengths have different focal lengths. For a circular objective, light-gathering power grows as D^2 and angular resolution improves as its diameter D increases.

Step 1: Explain the absence of chromatic aberration in the objective Reflection obeys the same law for all colours, so a reflecting objective has the same focal length for different wavelengths. It

therefore forms an image without the colour fringes produced by a simple refracting objective. In a lens, refractive index depends on wavelength, so different colours are brought to different foci.

Step 2: Explain the advantage of a large aperture A large mirror can be supported over its back, whereas an objective lens is supported at its rim. This makes a large reflecting objective easier to construct and support without appreciable distortion. Its larger diameter collects more light from faint astronomical objects and gives better resolving power, allowing closely spaced objects to be distinguished.

Step 3: Conclusion A reflecting telescope is preferred because its objective is free from chromatic aberration and can readily have a large aperture, giving greater light-gathering and resolving powers.

Quick Tip to Solve: Link each advantage to its cause: reflection avoids colour dispersion, and support from the back permits a larger objective.

24. Identify the part of electromagnetic spectrum which is:

(a) next to the lowest frequency end of the visible part of electromagnetic spectrum, and

(b) produced by bombarding a metal target by high energy electrons.

Give one use of each of them.

[2 marks]

Solution:

Concept:

- Electromagnetic waves obey $c = \nu\lambda$ in vacuum, where ν is frequency and λ is wavelength. Red light is at the lowest-frequency end of the visible spectrum.
- Different regions of the electromagnetic spectrum can be identified by their position relative to visible light or by their characteristic production process.

Step 1: Identify the radiation beyond the red end (a) The region immediately beyond visible red on the lower-frequency side is infrared radiation. Infrared has a longer wavelength and lower frequency than visible red light; ultraviolet instead lies beyond the violet, higher-frequency end. One use of infrared radiation is in a television remote control, where an infrared emitter sends coded control signals to the receiver.

Step 2: Identify the radiation produced at the metal target (b) High-energy electrons striking a metal target undergo rapid deceleration and can also disturb inner-shell electrons of its atoms. These processes produce X-rays. One use is medical radiography, such as imaging bone fractures: bones absorb X-rays more strongly than surrounding soft tissue, producing contrast in the image.

Step 3: Conclusion (a) Infrared radiation: used in television remote controls. (b) X-rays: used in medical radiography to detect bone fractures.

Quick Tip to Solve: Remember the neighbouring regions: infrared is beyond red, ultraviolet is beyond violet; a fast electron beam hitting metal produces X-rays.

25(a). Differentiate between intrinsic and extrinsic semiconductors.

[2 marks]

Solution:

Concept:

- Semiconductor conduction involves electrons in the conduction band and holes in the valence band. Their number densities are denoted by n and p , respectively.
- Doping is the controlled addition of a small amount of suitable impurity to a pure semiconductor to increase its carrier concentration and conductivity.

Step 1: Compare composition and carrier concentrations An intrinsic semiconductor is a pure semiconductor, such as pure silicon or germanium, without intentional doping. Thermal excitation produces electrons and holes in pairs, so $n = p = n_i$, where n_i is the intrinsic carrier concentration. An extrinsic semiconductor is doped with a suitable impurity. Donor impurities produce an n-type semiconductor with $n > p$; acceptor impurities produce a p-type semiconductor with $p > n$.

Step 2: Compare conduction and conductivity In an intrinsic semiconductor both thermally generated electrons and holes contribute to conduction, and its conductivity is relatively low. In an extrinsic semiconductor, conduction is dominated by the majority carriers: electrons in n-type material and holes in p-type material. At the same ordinary operating temperature, doping generally gives higher conductivity than that of the corresponding pure semiconductor by increasing the available carrier concentration.

Step 3: Conclusion Intrinsic semiconductors are pure and have equal electron and hole concentrations. Extrinsic semiconductors are doped, have unequal carrier concentrations with a majority carrier type, and generally conduct better than the corresponding intrinsic material.

Quick Tip to Solve: Compare both materials under the same headings: purity, electron-hole concentrations, and majority carriers; n-type and p-type are both extrinsic.

OR

25(b). Draw the circuit arrangement for studying the V - I characteristics of a p-n junction diode in forward bias and reverse bias. Show the plot of V - I characteristic of a silicon diode.

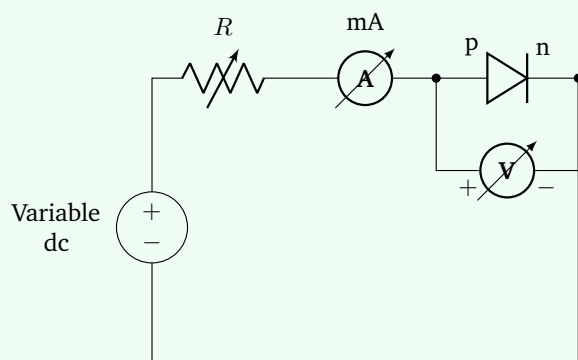
[2 marks]

Solution:

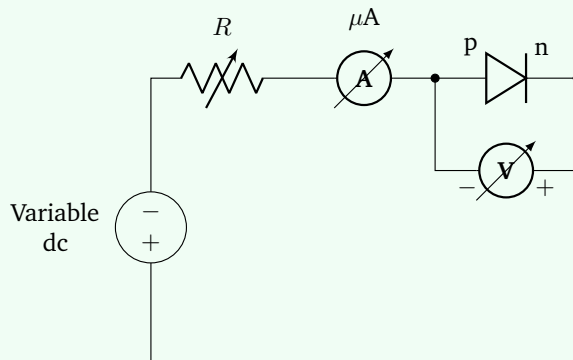
Concept:

- In forward bias the p-side connects to the positive supply terminal and the n-side to the negative terminal; reverse bias interchanges the supply polarity.
- Measure diode current with a series ammeter and diode voltage with a parallel voltmeter. A series variable resistance limits and varies the current.

Step 1: Arrange the forward- and reverse-bias circuits Connect the circuit as shown. Use a milliammeter for the appreciable forward current and a microammeter for the small reverse current. In each arrangement, vary the applied dc voltage gradually using the variable supply or rheostat, and record the corresponding diode voltage and current. The voltmeter is connected directly across the diode, so its reading excludes the drop across the series resistor and ammeter.



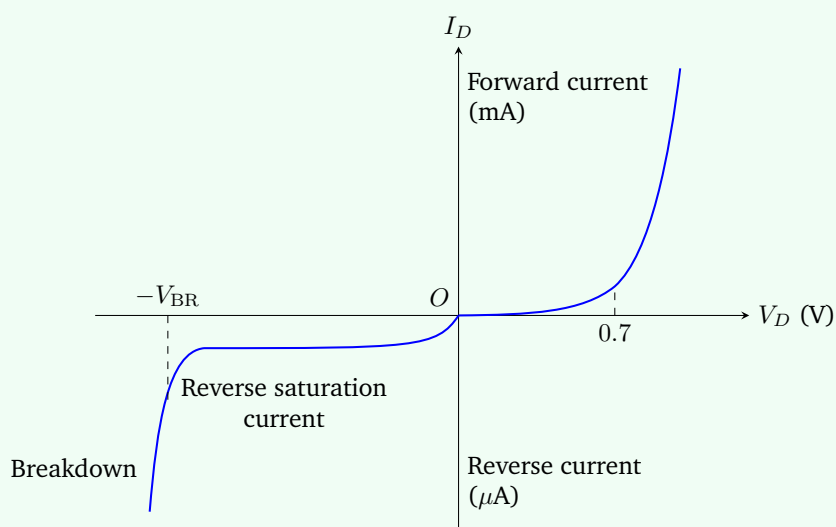
Forward bias



Reverse bias

Forward bias (left) and reverse bias (right); R is a variable current-limiting resistance.

Step 2: Plot the silicon diode characteristic Plot diode voltage $V_D = V_p - V_n$ horizontally and conventional diode current I_D , positive from p to n, vertically. Forward current rises slowly at first and then steeply beyond the knee, approximately 0.7 V for silicon. In reverse bias a very small, nearly constant reverse saturation current flows until breakdown, where its magnitude increases sharply. The reverse-current scale is enlarged in the sketch because it is normally in microamperes, whereas forward current is in milliamperes. Avoid breakdown during an ordinary characteristic measurement.



Silicon diode characteristic (schematic; different forward and reverse current scales).

Step 3: Conclusion The two arrangements measure forward and reverse characteristics; the silicon diode has a forward knee near 0.7 V and a very small reverse current before breakdown.

Quick Tip to Solve: Keep the diode orientation fixed and reverse the supply polarity; switch from a milliammeter to a microammeter when measuring reverse current.

Section C (15 marks)

26. An ac voltage $v = v_m \sin \omega t$ ($v_m = 310 \text{ V}$ and $f = 50 \text{ Hz}$) **is connected to a pure capacitor of capacitance** $15 \mu\text{F}$. **Calculate (i) the reactance of the capacitor, and (ii) the amplitude of the current. Write the expression of current through the capacitor as a function of time.** [3 marks]

Solution:

Concept:

- A capacitor offers capacitive reactance $X_C = 1/(\omega C)$, where C is the capacitance and $\omega = 2\pi f$ is the angular frequency of the supply.
- The instantaneous capacitor current is $i = dq/dt = C dv/dt$. Hence, in a purely capacitive circuit the current leads the applied voltage by $\pi/2$.

Step 1: Calculate the angular frequency and reactance Convert the capacitance to SI units: $C = 15 \times 10^{-6} \text{ F}$. The stated voltage $v_m = 310 \text{ V}$ is the peak value, not the rms value. Using $f = 50 \text{ Hz}$,

$$\omega = 2\pi(50) = 100\pi \text{ rad s}^{-1}, \quad X_C = \frac{1}{100\pi \times 15 \times 10^{-6}} = 212.2 \Omega.$$

This reactance is the ratio of the voltage amplitude to the current amplitude and decreases when either frequency or capacitance increases.

Step 2: Find the amplitude of the current Apply the ac amplitude relation $i_m = v_m/X_C$, using peak values on both sides:

$$i_m = \frac{310}{212.2} = 1.461 \text{ A}.$$

No factor of $\sqrt{2}$ is required because the question asks for amplitude rather than rms current.

Step 3: Obtain the current as a function of time Differentiate the given voltage to determine the phase, instead of assigning it by guesswork:

$$\begin{aligned} i(t) &= C \frac{d}{dt} (v_m \sin \omega t) \\ &= \omega C v_m \cos \omega t \\ &= 1.461 \cos(100\pi t) \text{ A}. \end{aligned}$$

Equivalently, $i(t) = 1.461 \sin(100\pi t + \pi/2) \text{ A}$, with t in seconds. The positive phase shift shows that current reaches its maximum a quarter-cycle before voltage does.

Step 4: Conclusion $X_C \approx 212 \Omega$, $i_m \approx 1.46 \text{ A}$, and $i(t) = 1.46 \sin(100\pi t + \pi/2) \text{ A}$.

Quick Tip to Solve: For a capacitor, differentiate the given sine voltage: its cosine derivative supplies both the current amplitude $\omega C v_m$ and the correct leading phase.

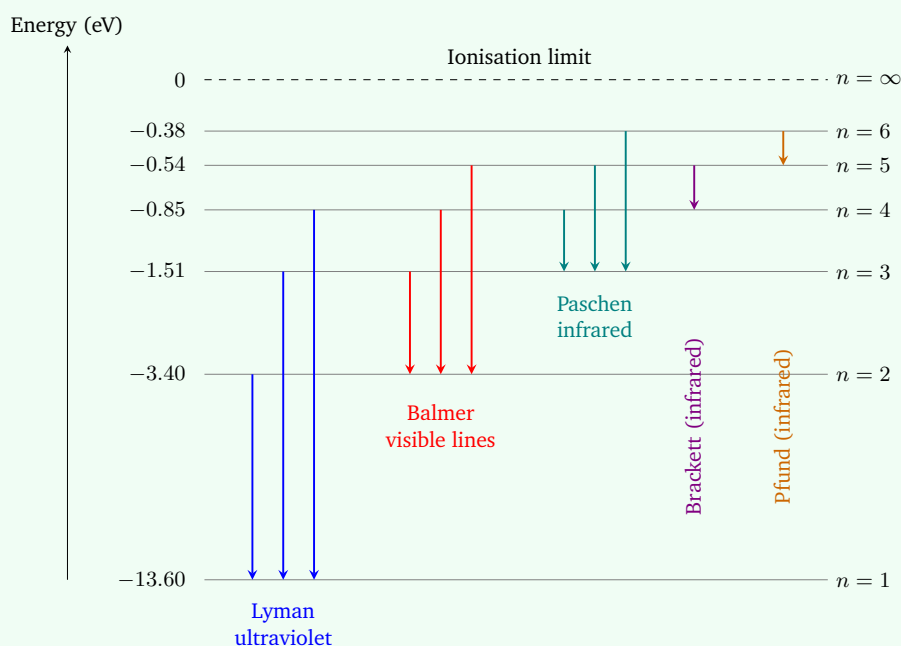
27(a). Draw the energy level diagram for hydrogen atom. Mark the transitions corresponding to the series lying in the ultraviolet region, visible region and infrared region. [3 marks]

Solution:

Concept:

- The allowed energies of hydrogen are $E_n = -13.6/n^2$ eV, where the positive integer n is the principal quantum number. The energy zero corresponds to an electron at rest infinitely far from the proton.
- An emission line results when an electron falls from a higher level n_i to a lower level n_f , emitting a photon with $h\nu = E_{n_i} - E_{n_f}$. A series has a common final level.

Step 1: Draw and label the allowed energy levels Draw horizontal lines for $n = 1, 2, 3, \dots$ and label their energies. The ground state is -13.6 eV, while the first excited state is -3.40 eV. Higher levels are closer together and approach the ionisation limit $E_\infty = 0$. The following diagram shows downward emission transitions; the vertical spacing is schematic to keep the series arrows legible.



Hydrogen energy levels and representative emission transitions (not to scale).

Step 2: Identify the series by their final levels For the **Lyman series**, all transitions $n_i = 2, 3, 4, \dots \rightarrow n_f = 1$ lie in the ultraviolet region. For the **Balmer series**, $n_i = 3, 4, 5, \dots \rightarrow n_f = 2$; its prominent lines lie in the visible region. The high-order Balmer lines approach a near-ultraviolet series limit.

For the **Paschen series**, $n_i = 4, 5, 6, \dots \rightarrow n_f = 3$, and the lines lie in the infrared region. Transitions ending at $n_f = 4$ (Brackett) and $n_f = 5$ (Pfund) are also infrared. Representative arrows for these series are marked in the diagram; each series includes all higher initial levels, not just the few drawn.

Step 3: Conclusion The standard series identification is Lyman ($n_f = 1$): ultraviolet; Balmer ($n_f = 2$): visible lines; Paschen ($n_f = 3$), Brackett ($n_f = 4$), and Pfund ($n_f = 5$): infrared.

Quick Tip to Solve: Identify an emission series from the level at the arrowhead: final levels 1, 2 and 3 give Lyman, Balmer and Paschen, respectively.

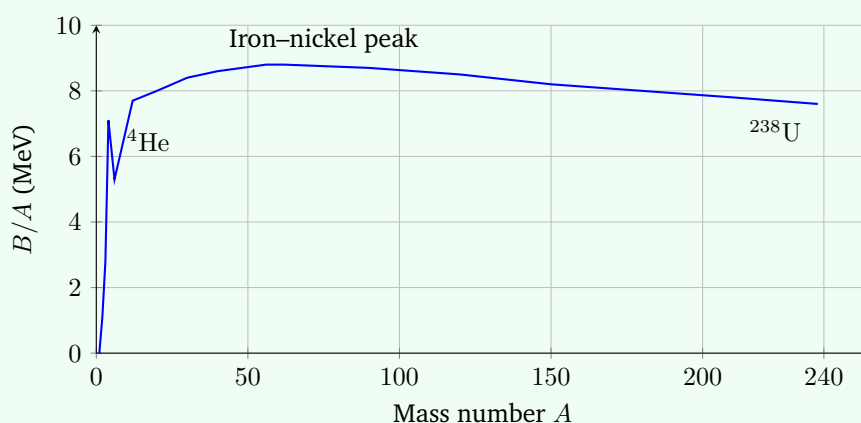
27(b). Draw a diagram to show the variation of binding energy per nucleon with mass number for different nuclei and mention its two features. Why do lighter nuclei usually undergo nuclear fusion? [3 marks]

Solution:

Concept:

- The binding energy B is the energy required to separate a nucleus into its constituent nucleons. The binding energy per nucleon is B/A , where A is the mass number.
- A larger binding energy per nucleon generally means a more tightly bound, more stable nucleus. An increase in total binding energy in a nuclear reaction releases energy, $Q = B_{\text{products}} - B_{\text{reactants}}$.

Step 1: Sketch the binding-energy curve Plot the mass number A on the horizontal axis and B/A , in MeV, on the vertical axis. The schematic curve rises rapidly for light nuclei, has a broad maximum near the iron–nickel region $A \simeq 56\text{--}62$, and then falls slowly towards heavy nuclei. Small irregularities among light nuclei are represented by the strongly bound helium nucleus.



Schematic variation of binding energy per nucleon with mass number.

Step 2: State two features First, binding energy per nucleon increases rapidly for light nuclei and reaches about 8.8 MeV in the iron–nickel region. These nuclei are among the most stable.

Second, it is nearly constant at about 8 MeV over much of the intermediate range $30 \lesssim A \lesssim 170$, then decreases gradually to about 7.6 MeV for uranium. The broad, nearly flat region reflects the short range and saturation of nuclear forces: each nucleon interacts strongly mainly with nearby nucleons.

Step 3: Explain why fusion releases energy for light nuclei When suitable light nuclei combine, the resulting nucleus usually lies higher on the rising part of the curve and has a greater binding energy per nucleon. Since the total number of nucleons is conserved, the products then have greater total binding energy. Their total rest mass is lower, and the mass difference appears as released energy, $Q = \Delta mc^2 > 0$. Very high temperature is still needed to overcome the electrostatic repulsion between the positive nuclei; energy release does not mean fusion occurs freely at ordinary temperatures.

Step 4: Conclusion The curve has a broad maximum near $A \simeq 56\text{--}62$ and a slow decline for heavier nuclei. Fusion of suitable light nuclei releases energy because the product is more tightly bound per nucleon.

Quick Tip to Solve: Compare the heights on the binding-energy-per-nucleon curve: motion towards the iron–nickel peak generally releases energy.

28. Three point charges Q_1 ($-15\ \mu\text{C}$), Q_2 ($10\ \mu\text{C}$) and Q_3 ($16\ \mu\text{C}$) are located at (0 cm, 0 cm), (0 cm, 3 cm) and (4 cm, 3 cm) respectively. Calculate the electrostatic potential energy of this system of charges. [3 marks]

Solution:

Concept:

- Taking the energy of infinitely separated charges as zero, the electrostatic potential energy is the sum of the energies of every distinct charge pair: $U = \sum_{i < j} kQ_iQ_j/r_{ij}$, where $k = 1/(4\pi\epsilon_0)$.
- The distance r_{ij} is always positive, whereas the product Q_iQ_j retains its sign. Unlike charges contribute negative energy and like charges contribute positive energy.

Step 1: Find the three pair separations The two charges on the vertical line are separated by 3 cm, while the two on the horizontal line are separated by 4 cm. The remaining separation is the hypotenuse of a right triangle:

$$r_{12} = 3\text{ cm} = 0.03\text{ m},$$

$$r_{23} = 4\text{ cm} = 0.04\text{ m},$$

$$r_{13} = \sqrt{4^2 + 3^2}\text{ cm} = 0.05\text{ m}.$$

Convert the charges to coulombs: $Q_1 = -15 \times 10^{-6}\text{ C}$, $Q_2 = 10 \times 10^{-6}\text{ C}$, and $Q_3 = 16 \times 10^{-6}\text{ C}$.

Step 2: Calculate each pair's potential energy Using $k = 9 \times 10^9\text{ N m}^2\text{C}^{-2}$, retain the signs of both attractive pairs:

$$U_{12} = \frac{9 \times 10^9(-15 \times 10^{-6})(10 \times 10^{-6})}{0.03} = -45\text{ J},$$

$$U_{23} = \frac{9 \times 10^9(10 \times 10^{-6})(16 \times 10^{-6})}{0.04} = 36\text{ J},$$

$$U_{13} = \frac{9 \times 10^9(-15 \times 10^{-6})(16 \times 10^{-6})}{0.05} = -43.2\text{ J}.$$

Step 3: Add the distinct pair contributions Each pair must be counted once; no extra factor of one-half is needed in this three-term sum.

$$U = U_{12} + U_{23} + U_{13} = -45 + 36 - 43.2 = -52.2\text{ J}.$$

The negative total means this configuration has less electrostatic energy than the charges at infinite separation. A net external work of 52.2 J would be required to separate them quasistatically to infinity.

Step 4: Conclusion The electrostatic potential energy of the three-charge system is $U = -52.2\text{ J}$, with zero energy defined at infinite separation.

Quick Tip to Solve: Identify the 3–4–5 triangle first, convert centimetres to metres, and retain charge signs in all three pair energies.

29(a). How does resistance differ from impedance? With the help of a suitable phasor diagram, obtain an expression for the impedance of a series LCR circuit, connected to a source $v = v_m \sin \omega t$. [3 marks]

Solution:

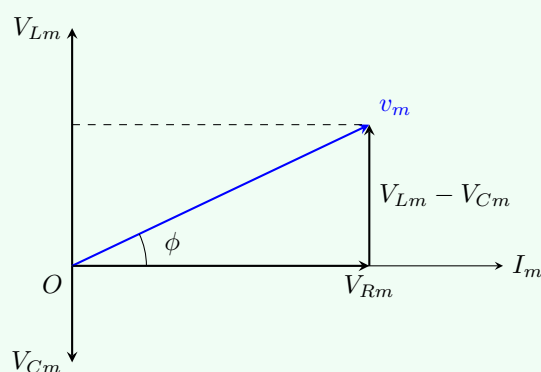
Concept:

- Resistance R dissipates energy; impedance Z is the total opposition to alternating current, including resistance and reactance. Both are measured in ohms.

- For ideal components at angular frequency ω , the inductive and capacitive reactances are $X_L = \omega L$ and $X_C = 1/(\omega C)$, where L is inductance and C is capacitance.

Step 1: Distinguish resistance from impedance Ideal resistance dissipates energy as heat and is independent of frequency. Impedance includes reactance from inductors and capacitors, which store and return energy. It depends on frequency and may cause a voltage–current phase difference. For a pure resistor, $Z = R$.

Step 2: Construct the voltage phasors The same current passes through all three elements. Choose its peak-value phasor I_m along the positive horizontal axis. Then $V_{Rm} = I_m R$ is in phase with current, $V_{Lm} = I_m X_L$ leads it by 90° , and $V_{Cm} = I_m X_C$ lags it by 90° . Hence the two reactive voltages oppose one another. The diagram illustrates $X_L > X_C$; the net vertical component points downward if $X_C > X_L$.



Peak voltage phasors for $X_L > X_C$, with current as the phase reference.

Step 3: Add the perpendicular voltage components The supply voltage phasor is the resultant of the horizontal resistive voltage and the net vertical reactive voltage. By Pythagoras,

$$\begin{aligned} v_m^2 &= V_{Rm}^2 + (V_{Lm} - V_{Cm})^2 \\ &= I_m^2 R^2 + I_m^2 (X_L - X_C)^2. \end{aligned}$$

Dividing by I_m^2 , and using $Z = v_m/I_m$, gives the impedance. The phase angle obeys $\tan \phi = (X_L - X_C)/R$.

Step 4: Conclusion For a series LCR circuit, the impedance magnitude is

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

Quick Tip to Solve: Draw the current first: V_R lies along it, V_L points up, and V_C points down. Subtract reactive voltages before applying Pythagoras.

29(b). Find the condition for resonance in a series LCR circuit connected to a source $v = v_m \sin \omega t$, where ω can be varied. Give the factors on which the resonant frequency of a series LCR circuit depends. Plot a graph showing the variation of electric current with frequency in a series LCR circuit. [3 marks]

Solution:

Concept:

- In a series LCR circuit, the impedance is $Z = \sqrt{R^2 + (X_L - X_C)^2}$, where R is resistance, $X_L = \omega L$ is inductive reactance and $X_C = 1/(\omega C)$ is capacitive reactance.
- For a source of fixed voltage amplitude v_m , the current amplitude is $I_m = v_m/Z$. Resonance means maximum current as the driving frequency is varied.

Step 1: Minimise the impedance The square $(X_L - X_C)^2$ is non-negative, so the smallest possible impedance is R . It occurs when the inductive and capacitive reactances cancel:

$$X_L = X_C, \quad \omega_0 L = \frac{1}{\omega_0 C}.$$

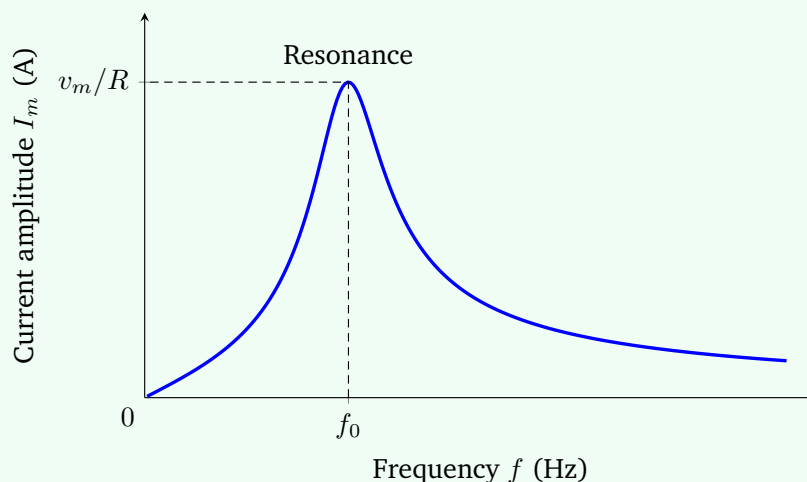
Multiplying by $\omega_0 C$ gives $\omega_0^2 LC = 1$. Thus

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

At resonance the net reactance is zero, the voltage and current are in phase, and $I_{m,\max} = v_m/R$.

Step 2: Identify the factors determining resonance The resonant frequency depends on the inductance L and capacitance C , varying inversely as the square root of their product. Increasing either L or C lowers f_0 . In the ideal series LCR model, R does not change this resonant frequency; it controls the peak current and the sharpness of the resonance curve.

Step 3: Plot current against driving frequency At low frequency, capacitive reactance is large and the current is small. As frequency rises towards f_0 , the difference of the reactances decreases and the current rises. Beyond f_0 , inductive reactance dominates, the impedance rises again, and the current falls. The graph below shows current amplitude for a fixed source amplitude; an rms-current graph has the same shape, with maximum V_{rms}/R .



Current amplitude versus frequency for a series LCR circuit.

Step 4: Conclusion Resonance occurs at $X_L = X_C$, with $f_0 = 1/(2\pi\sqrt{LC})$. It depends on L and C , and the current reaches a maximum at this frequency.

Quick Tip to Solve: Set the two reactances equal to find resonance; do not set the total impedance to zero, since the resistance remains.

30. A particle is associated with a de Broglie wave of wavelength 1.2 nm. The kinetic energy of the particle is made four times. Calculate the new value of the wavelength of the wave. [3 marks]

Solution:

Concept:

- The de Broglie wavelength of a particle is $\lambda = h/p$, where h is Planck's constant and p is the magnitude of its momentum.
- For non-relativistic motion, kinetic energy is $K = p^2/(2m)$. Hence $\lambda = h/\sqrt{2mK}$, where m is the particle's mass.

Step 1: Relate wavelength to kinetic energy The question changes the kinetic energy of the same particle, so its mass remains constant. Planck's constant also remains unchanged. Combining the two relations gives

$$p = \sqrt{2mK}, \quad \lambda = \frac{h}{\sqrt{2mK}}.$$

Thus wavelength varies inversely as the square root of kinetic energy, rather than inversely as the kinetic energy itself. This is the standard non-relativistic relation used for a material particle in this question.

Step 2: Compare the initial and final states Let K_1 and λ_1 describe the initial state, and K_2 and λ_2 the final state. Dividing the wavelength expressions cancels both h and m :

$$\frac{\lambda_2}{\lambda_1} = \sqrt{\frac{K_1}{K_2}}.$$

The kinetic energy is made four times its initial value, so $K_2 = 4K_1$. The momentum therefore doubles, since $p_2/p_1 = \sqrt{4} = 2$, and the wavelength must become half its original value.

Step 3: Substitute the given wavelength Using $\lambda_1 = 1.2$ nm,

$$\lambda_2 = (1.2 \text{ nm})\sqrt{\frac{1}{4}} = \frac{1.2}{2} \text{ nm} = 0.60 \text{ nm}.$$

Both wavelengths are expressed in nanometres, so no conversion is needed for the ratio. In SI units, the same result is 6.0×10^{-10} m. The decrease in wavelength is consistent with the increase in momentum.

Step 4: Conclusion The new de Broglie wavelength is 0.60 nm , or 6.0×10^{-10} m.

Quick Tip to Solve: For the same particle, multiply kinetic energy by n and divide its wavelength by $\sqrt{n}$; a fourfold energy gives half the wavelength.

Section D (15 marks)

- 31(a).** (i) (1) Write two points of difference between an interference pattern and a diffraction pattern.
(2) Name any two factors on which the fringe width in a Young's double-slit experiment depends.
(ii) In Young's double-slit experiment, the two slits are separated by a distance equal to 100 times the wavelength of light that passes through the slits. Calculate:
(1) the angular separation in radians between the central maximum and the adjacent maximum.
(2) the distance between these two maxima on a screen 50 cm from the slits. [5 marks]

Solution:

Concept:

- Interference is the superposition of light from two coherent sources; single-slit diffraction results from superposition of secondary wavelets from different parts of the same aperture.
- For slit separation d , wavelength λ and slit-to-screen distance D , the Young's double-slit fringe width is $\beta = \lambda D/d$, in the small-angle approximation.
- Bright fringes satisfy $d \sin \theta_m = m\lambda$, where m is the fringe order and θ_m is measured from the central axis.

Step 1: (i)(1) Compare the spacing of the patterns In the ideal interference pattern of two narrow slits, consecutive bright fringes have equal spacing; bright and dark fringes have the same width. In single-slit diffraction, the central bright maximum is twice as wide as the secondary bright maxima, when widths are measured between their bounding minima. Thus the diffraction pattern does not have the uniform bright-fringe widths of ideal interference.

Step 2: (i)(1) Compare the intensities of the maxima For interference of two coherent waves of equal intensity, all ideal bright maxima have the same intensity. For single-slit diffraction, the central maximum is the brightest and the secondary maxima become progressively weaker away from the centre. These comparisons describe the usual ideal interference pattern; finite slit width can impose a diffraction envelope on an actual double-slit pattern.

Step 3: (i)(2) Identify two factors controlling fringe width From $\beta = \lambda D/d$, two factors are the wavelength λ and the slit separation d . Keeping the other quantities fixed, fringe width increases with wavelength and decreases with slit separation. The screen distance D is a third possible factor: increasing it also increases fringe width.

Step 4: (ii)(1) Apply the bright-fringe condition The central maximum has order $m = 0$, whereas the adjacent maximum has order $m = 1$. The given slit separation is $d = 100\lambda$, so

$$\sin \theta_1 = \frac{\lambda}{d} = \frac{1}{100} = 0.010.$$

Since the angle is small, $\sin \theta_1 \simeq \theta_1$ in radians. Hence the angular separation is $\Delta\theta \simeq 0.010$ rad. Using $\arcsin(0.010)$ gives the same answer to the stated precision.

Step 5: (ii)(2) Convert angular separation into screen separation Convert the screen distance to SI units: $D = 50 \text{ cm} = 0.50 \text{ m}$. The separation between adjacent maxima is one fringe width:

$$\begin{aligned}\beta &= \frac{\lambda D}{d} = \frac{D}{100} \\ &= \frac{0.50}{100} \text{ m} = 5.0 \times 10^{-3} \text{ m}.\end{aligned}$$

Equivalently, $\beta \simeq D\Delta\theta$; the wavelength cancels because d is already specified as a multiple of λ .

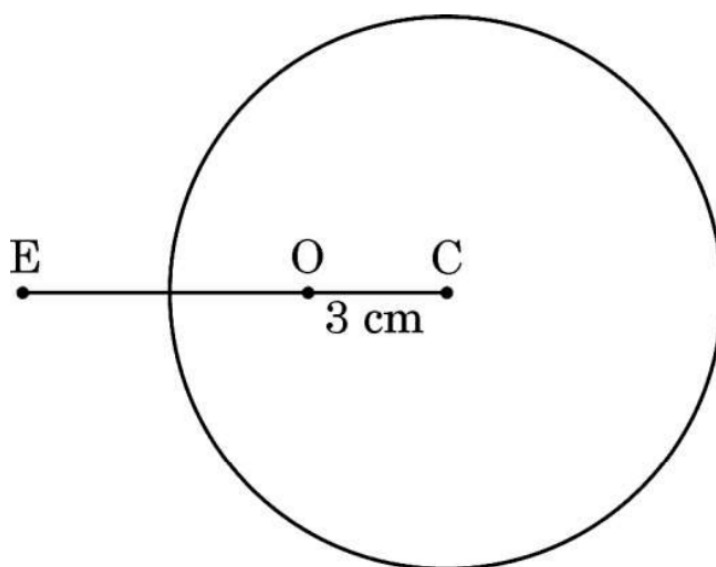
Step 6: Conclusion Ideal interference maxima have uniform spacing and equal intensity, whereas diffraction has a broader, stronger central maximum and weaker side maxima. Two fringe-width factors are wavelength and slit separation. The angular separation is 0.010 rad, and the screen separation is 5.0 mm.

Quick Tip to Solve: When $d = N\lambda$, cancel the wavelength immediately: the angular fringe width is $1/N$ radians and the linear fringe width is D/N .

OR

31(b). (i) A spherical surface of radius of curvature R separates two media of refractive indices n_1 and n_2 . A point object is placed in front of the surface at distance u in medium of refractive index n_1 and its image is formed by the surface at distance v , in the medium of refractive index n_2 . Derive a relation between u and v .

(ii) A solid glass sphere of radius 6.0 cm has a small air bubble trapped at a distance 3.0 cm from its centre C as shown in the figure. The refractive index of the material of the sphere is 1.5. Find the apparent position of this bubble when seen through the surface of the sphere from an outside point E in air. [5 marks]



Solution:

Concept:

- Snell's law is $n_1 \sin i = n_2 \sin r$. For paraxial rays, the angles are small and it reduces to $n_1 i = n_2 r$, with angles measured in radians.
- Distances for spherical refraction are measured from the pole P . In the Cartesian convention, the direction of incident light is positive; u , v and R are signed object, image and centre-of-curvature distances.

- The normal to a spherical surface at any point passes through its centre of curvature. A negative image distance corresponds to a virtual image on the incident side of the surface.

Step 1: (i) Set up the paraxial ray geometry To derive the relation, consider a convex surface with pole P and centre C to its right. A real object O lies on the principal axis to the left and a paraxial real image I lies to the right. Let an incident ray strike the surface at A , a small height h above the axis. The normal is AC . Denote the positive small inclinations of OA , AI and AC to the principal axis by α , β and γ , respectively. The incident ray slopes upward, while the refracted ray and normal slope downward. Hence

$$i = \alpha + \gamma, \quad r = \gamma - \beta.$$

Neglecting the small axial displacement of A from the pole for paraxial rays gives $\alpha \simeq h/|u|$, $\beta \simeq h/v$ and $\gamma \simeq h/R$.

Step 2: (i) Apply Snell's law and introduce signed distances Using the small-angle form of Snell's law,

$$\begin{aligned} n_1(\alpha + \gamma) &= n_2(\gamma - \beta), \\ n_1\alpha + n_2\beta &= (n_2 - n_1)\gamma. \end{aligned}$$

Substitute the paraxial inclinations and cancel h :

$$\frac{n_1}{|u|} + \frac{n_2}{v} = \frac{n_2 - n_1}{R}.$$

In this geometry $u < 0$, so $|u| = -u$. Therefore the signed relation is

$$\boxed{\frac{n_2}{v} - \frac{n_1}{u} = \frac{n_2 - n_1}{R}}.$$

With Cartesian signs consistently assigned, this relation also applies to a concave surface and to virtual images.

Step 3: (ii) Locate the bubble relative to the viewed surface The printed figure places the bubble O between the left surface and centre C , with $OC = 3.0$ cm. The observer E is to the left. Thus light travels leftward from the bubble through the near glass-air surface, and leftward is the positive direction for this calculation. If P is the left-hand pole, the actual bubble depth is

$$PO = PC - OC = 6.0 - 3.0 = 3.0 \text{ cm}.$$

Both the bubble and the centre lie to the right of P , opposite the incident-light direction. Consequently $u = -3.0$ cm, $R = -6.0$ cm, $n_1 = 1.5$ for glass and $n_2 = 1$ for air.

Step 4: (ii) Calculate and interpret the image position Substitute the signed distances into the

spherical-refraction formula, keeping all distances in centimetres:

$$\begin{aligned}\frac{1}{v} - \frac{1.5}{-3.0} &= \frac{1 - 1.5}{-6.0}, \\ \frac{1}{v} + \frac{1}{2} &= \frac{1}{12}, \\ \frac{1}{v} &= -\frac{5}{12} \text{ cm}^{-1}, \\ v &= -2.4 \text{ cm}.\end{aligned}$$

The negative sign places the apparent bubble inside the glass, on the same side of the viewed surface as the actual bubble. Its virtual image is 2.4 cm behind that surface, or $6.0 - 2.4 = 3.6$ cm from the centre towards E .

Step 5: Conclusion The paraxial refraction relation is $n_2/v - n_1/u = (n_2 - n_1)/R$. The bubble appears 2.4 cm inside the surface facing E , equivalently 3.6 cm from C towards E ; its image is virtual.

Quick Tip to Solve: First measure bubble depth from the viewed surface, then assign signs along the incident light. Do not use the plane-surface apparent-depth formula for a curved sphere.

32(a). (i) State Coulomb's law in electrostatics and write it in vector form, for two charges.

(ii) 'Gauss's law is based on the inverse-square dependence on distance contained in the Coulomb's law.' Explain.

(iii) Two charges A (charge q) and B (charge $2q$) are located at points $(0, 0)$ and (a, a) respectively. Let $\hat{i}$ and $\hat{j}$ be the unit vectors along x -axis and y -axis respectively. Find the force exerted by A on B , in terms of $\hat{i}$ and $\hat{j}$. [5 marks]

Solution:

Concept:

- Coulomb's law gives the electrostatic force between two stationary point charges. In vacuum, $k = 1/(4\pi\epsilon_0)$, where ϵ_0 is the permittivity of free space.
- Electric flux through a surface is $\Phi_E = \int \vec{E} \cdot d\vec{S}$. For a closed surface, Gauss's law states $\oint \vec{E} \cdot d\vec{S} = Q_{\text{enc}}/\epsilon_0$.
- A force vector contains both its magnitude and a unit vector along its direction; the displacement vector must therefore be divided by its length before being used as a direction factor.

Step 1: (i) State Coulomb's law and define its vector direction The magnitude of the electrostatic force between two stationary point charges is directly proportional to the product of the magnitudes of their charges and inversely proportional to the square of their separation. The force acts along the line joining the charges; it is repulsive for like charges and attractive for unlike charges. Thus, for separation r ,

$$F = \frac{1}{4\pi\epsilon_0} \frac{|q_1 q_2|}{r^2}.$$

Let q_1 and q_2 be at position vectors $\vec{r}_1$ and $\vec{r}_2$. Define $\vec{r}_{21} = \vec{r}_2 - \vec{r}_1$, $r_{21} = |\vec{r}_{21}|$, and $\hat{r}_{21} = \vec{r}_{21}/r_{21}$, directed from charge 1 towards charge 2. The force on charge 2 due to charge 1 is

$$\vec{F}_{2 \leftarrow 1} = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r_{21}^2} \hat{r}_{21} = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2 (\vec{r}_2 - \vec{r}_1)}{|\vec{r}_2 - \vec{r}_1|^3}.$$

The signed product $q_1 q_2$ automatically accounts for attraction or repulsion. The force on charge 1 is equal and opposite.

Step 2: (ii) Relate inverse-square dependence to Gauss's law Consider a point charge Q at the centre of a spherical Gaussian surface of radius r . Coulomb's law gives a radial field $E = kQ/r^2$, with its sign specifying outward or inward direction. Therefore,

$$\Phi_E = \frac{Q}{4\pi\epsilon_0 r^2} (4\pi r^2) = \frac{Q}{\epsilon_0}.$$

The r^{-2} factor in the field exactly cancels the r^2 factor in the area, so the total flux is independent of the size of the sphere. More generally, for a surface element making angle θ with the radial direction,

$$d\Phi_E = \frac{Q}{4\pi\epsilon_0} \frac{dS \cos \theta}{r^2} = \frac{Q}{4\pi\epsilon_0} d\Omega.$$

Here $d\Omega$ is the signed solid angle subtended at the charge. Its integral over a closed surface enclosing the charge is 4π ; a charge outside contributes zero net flux. Superposition then gives the enclosed-charge form of Gauss's law. A different power of r would leave a radius dependence even for a sphere and would not give this flux law.

Step 3: (iii) Use the displacement from A to B The charge at A is q and that at B is $2q$. Their displacement and separation are

$$\vec{r}_B - \vec{r}_A = a\hat{i} + a\hat{j}, \quad AB = \sqrt{a^2 + a^2} = \sqrt{2}a.$$

Taking $a > 0$, the unit vector from A to B is $(\hat{i} + \hat{j})/\sqrt{2}$. The force magnitude is

$$F_{B \leftarrow A} = k \frac{q(2q)}{(\sqrt{2}a)^2} = \frac{kq^2}{a^2}.$$

Both charges have the same sign, so the force on B points away from A , along the positive diagonal. Multiplying this magnitude by the unit vector gives equal positive x and y components.

Step 4: Conclusion Coulomb's vector law is $\vec{F}_{2 \leftarrow 1} = kq_1 q_2 \hat{r}_{21}/r_{21}^2$. Its inverse-square dependence makes the flux through an enclosing closed surface $Q_{\text{enc}}/\epsilon_0$. For the given charges,

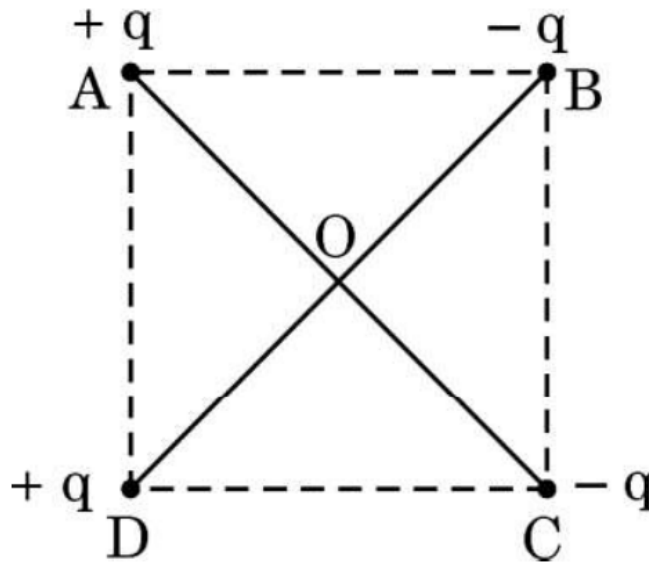
$$\boxed{\vec{F}_{B \leftarrow A} = \frac{q^2}{4\pi\epsilon_0 \sqrt{2} a^2} (\hat{i} + \hat{j})}.$$

Quick Tip to Solve: For charges separated by equal x and y displacements, first find the diagonal distance and then use the unit vector $(\hat{i} + \hat{j})/\sqrt{2}$; omitting its $\sqrt{2}$ gives incorrect force components.

32(b). (i) Derive an expression for the electric field at a point on the equatorial plane of an electric dipole consisting of charges q and $-q$ separated by a distance $2a$.

(ii) The distance of a far off point on the equatorial plane of an electric dipole is halved. How will the electric field be affected for the dipole?

(iii) Two identical electric dipoles are placed along the diagonals of a square $ABCD$ of side $\sqrt{2}$ m as shown in the figure. Obtain the magnitude and direction of the net electric field at the centre (O) of the square. [5 marks]



Solution:

Concept:

- An electric dipole consists of charges $-q$ and $+q$ separated by $2a$. Its moment is $\vec{p} = 2aq \hat{x}$ when the positive charge lies along $+\hat{x}$ from the negative charge.
- Electric fields add as vectors. At an equatorial point, the components perpendicular to the dipole axis cancel, while the components opposite to $\vec{p}$ add.
- The far-field dipole formula requires the observation distance to be much larger than the charge separation. At the centre of the square, use the separate point-charge fields instead.

Step 1: (i) Set up the equatorial geometry Place $-q$ at $(-a, 0)$ and $+q$ at $(a, 0)$, with the dipole centre at the origin. Choose an equatorial point $P = (0, r)$. Each charge is a distance

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

from P . With $k = 1/(4\pi\epsilon_0)$, the separate electric-field vectors are

$$\vec{E}_+ = \frac{kq}{R^3}(-a\hat{x} + r\hat{y}),$$

$$\vec{E}_- = \frac{kq}{R^3}(-a\hat{x} - r\hat{y}).$$

The positive-charge field points away from $+q$, and the negative-charge field points towards $-q$. This fixes the signs of both components.

Step 2: (i) Add the fields and obtain the far-field limit Adding the vectors cancels the $\hat{y}$ components

and doubles the negative $\hat{x}$ component:

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

Thus the exact magnitude is $kp/(r^2 + a^2)^{3/2}$, and the field is opposite to the dipole moment. For a far-off point, $r \gg a$, the approximation $(r^2 + a^2)^{3/2} \simeq r^3$ gives $\vec{E}_{\text{eq}} \simeq -k\vec{p}/r^3$.

Step 3: (ii) Compare the fields at the two far-off distances The same dipole has unchanged moment p . Using the far-field dependence, and assuming that the halved distance is still much greater than a ,

$$\frac{E'}{E} = \frac{kp/(r/2)^3}{kp/r^3} = 2^3 = 8.$$

The change affects the magnitude only: the equatorial field remains opposite to $\vec{p}$.

Step 4: (iii) Find the distance from each corner to O The figure has $+q$ at both A, D and $-q$ at both B, C . Let $+\hat{x}$ point horizontally from side AD towards side BC , and let $+\hat{y}$ point upwards. The square side is $s = \sqrt{2}$ m, so its diagonal is $s\sqrt{2} = 2$ m. Hence every corner is a distance $R_0 = 1$ m from O , and the magnitude of each individual field is

$$E_0 = \frac{kq}{R_0^2} = \frac{kq}{(1\text{ m})^2}.$$

Here q denotes the positive magnitude shown in the figure.

Step 5: (iii) Resolve and add the four corner fields At O , the fields due to A and C both point downwards and to the right. The fields due to D and B both point upwards and to the right. Each makes 45° with the horizontal. Therefore,

$$\begin{aligned}E_x &= 4E_0 \cos 45^\circ = 2\sqrt{2} E_0, \\ E_y &= (-E_0 - E_0 + E_0 + E_0) \sin 45^\circ = 0.\end{aligned}$$

The resultant points horizontally towards the negative charges.

Step 6: Conclusion (i) $\vec{E}_{\text{eq}} = -\frac{\vec{p}}{4\pi\epsilon_0(r^2 + a^2)^{3/2}}$, opposite to $\vec{p}$; for $r \gg a$, this becomes $-\vec{p}/(4\pi\epsilon_0 r^3)$. (ii) Halving the far-off distance makes the field eight times as large, with unchanged direction. (iii) At the square's centre,

$$E_O = \frac{2\sqrt{2} q}{4\pi\epsilon_0(1\text{ m})^2},$$

directed parallel to AB and DC , from side AD towards side BC .

Quick Tip to Solve: In the square, all four charges give rightward horizontal field components at O ; cancel the vertical components first, then add four factors of $E_0 \cos 45^\circ$.

- 33(a).** (i) State Biot-Savart's law for the magnetic field due to a current carrying element. Use this law to obtain an expression for the magnetic field at the centre of a circular loop of radius a and carrying a current I . Draw the magnetic field lines for a current loop indicating the direction of magnetic field.
- (ii) An electron is revolving around the nucleus in a circular orbit with a speed of 10^7 m s^{-1} . If the radius of the orbit is 10^{-10} m , find the current constituted by the revolving electron in the orbit.

[5 marks]

Solution:

Concept:

- Biot-Savart's law gives the magnetic field of a small current element: $d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{\ell} \times \hat{r}}{r^2}$. Here $d\vec{\ell}$ points along conventional current, $\hat{r}$ points from the element to the observation point, and μ_0 is the permeability of free space.
- The net field is the vector sum of the contributions of all elements. At the centre of a circular loop, every contribution points along the same normal to the loop, as fixed by the right-hand thumb rule.
- A charge completing one revolution in period T constitutes current of magnitude $I = |q|/T$. For a circular orbit of radius r and speed v , $T = 2\pi r/v$.

Step 1: (i) State Biot-Savart's law The magnetic field due to a small current element is directly proportional to the current, the element length, and the sine of the angle between the current element and the line joining it to the point. It is inversely proportional to the square of the distance from the element:

$$dB = \frac{\mu_0}{4\pi} \frac{I d\ell \sin \theta}{r^2}.$$

Its direction is perpendicular to both $d\vec{\ell}$ and $\vec{r}$, in the direction of $d\vec{\ell} \times \hat{r}$. This directional statement is essential because the contributions must be added as vectors.

Step 2: (i) Integrate around the circular loop Let O be the centre of the loop of radius a . Every current element is tangent to the circle, while the vector from that element to O is radial. Thus $\theta = 90^\circ$, $r = a$, and

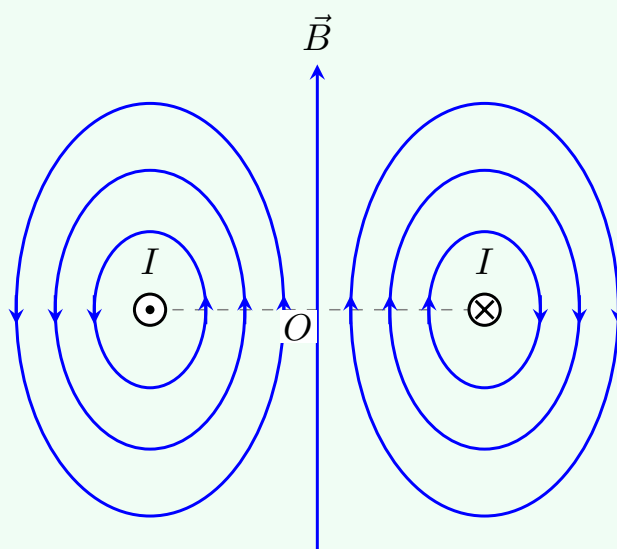
$$dB = \frac{\mu_0 I}{4\pi a^2} d\ell.$$

All these contributions have the same axial direction at O ; consequently their magnitudes add. Integrating over the circumference,

$$\begin{aligned} B_O &= \oint dB = \frac{\mu_0 I}{4\pi a^2} \oint d\ell \\ &= \frac{\mu_0 I}{4\pi a^2} (2\pi a) = \frac{\mu_0 I}{2a}. \end{aligned}$$

The field is perpendicular to the plane of the loop. Curling the fingers of the right hand along the current makes the extended thumb point along the magnetic field through the centre.

Step 3: (i) Indicate the field-line directions The diagram shows a section through the loop's axis: the wire on the left carries current out of the page (dot), and the wire on the right carries current into the page (cross). These are opposite sides of the same circular loop. With this current sense, the magnetic field is upward through the loop centre and returns downward outside. The field lines form continuous closed curves; the axial line shown is the central portion of this field pattern. Reversing the current reverses every field arrow.



⊙: current out of page ⊗: current into page

Magnetic field of a circular current loop, viewed in an axial section (schematic).

Step 4: (ii) Calculate the orbital period and current An electron passes any fixed point of its orbit once per revolution. Using the orbit's circumference and the given speed,

$$T = \frac{2\pi r}{v} = \frac{2\pi \times 10^{-10}}{10^7} = 2\pi \times 10^{-17} \text{ s.}$$

The magnitude of charge passing that point in one period is $e = 1.6 \times 10^{-19} \text{ C}$. Therefore,

$$\begin{aligned} I &= \frac{e}{T} = \frac{ev}{2\pi r} \\ &= \frac{1.6 \times 10^{-19} \times 10^7}{2\pi \times 10^{-10}} \\ &\simeq 2.55 \times 10^{-3} \text{ A.} \end{aligned}$$

Since the moving charge is negative, the conventional current is opposite to the direction of revolution of the electron. The question specifies only its speed, so the magnitude is determined without assigning a clockwise or anticlockwise sense.

Step 5: Conclusion (i) The magnetic field at the loop centre is $B_O = \mu_0 I / (2a)$, normal to the loop in the right-hand-rule direction. (ii) The revolving electron constitutes a current of magnitude $I \simeq 2.55 \times 10^{-3} \text{ A} = 2.55 \text{ mA}$, opposite to its motion.

Quick Tip to Solve: At a loop's centre use $\sin \theta = 1$ and $\oint d\ell = 2\pi a$. For an orbiting particle, divide its charge by the full revolution time, not by the time to travel one radius.

33(b). (i) Derive an expression for the force acting on a current carrying straight conductor kept in a magnetic field. State the rule which is used to find the direction of this force. Give the condition under which this force is (1) maximum, and (2) minimum.

(ii) Two long parallel straight wires *A* and *B* are 2.5 cm apart in air. They carry 5.0 A and 2.5 A currents respectively in opposite directions. Calculate the magnitude of the force exerted by wire *A* on a 10 cm length of wire *B*. [5 marks]

Solution:

Concept:

- A charge moving in a magnetic field experiences the Lorentz force $\vec{f} = q(\vec{v} \times \vec{B})$. Summing the forces on mobile carriers gives the force on a current-carrying conductor.
- For a straight length L carrying conventional current I in a uniform field $\vec{B}$, $\vec{F} = I(\vec{L} \times \vec{B})$, where $\vec{L}$ points along the current.
- A long straight wire produces $B = \mu_0 I / (2\pi d)$ at perpendicular distance d , with $\mu_0 = 4\pi \times 10^{-7} \text{ N A}^{-2}$ in air.

Step 1: (i) Sum the magnetic forces on the charge carriers Consider a straight conductor of cross-sectional area A and length L , entirely in a uniform magnetic field. Let the number density of free electrons be n , their charge be $-e$, and their mean drift velocity be $\vec{v}_d$. The number of free electrons in this length is $N = nAL$. Their random thermal velocities average to zero, so the resultant magnetic force is

$$\vec{F} = N(-e)(\vec{v}_d \times \vec{B}) = -neAL(\vec{v}_d \times \vec{B}).$$

Conventional current is opposite to electron drift. Consequently $I = neAv_d$ and $\vec{L} = -L\vec{v}_d/v_d$. Substitution gives

$$\vec{F} = I(\vec{L} \times \vec{B}), \quad F = BIL \sin \theta,$$

where θ is the angle between the current and magnetic field. The force on the carriers is transmitted to the conductor through their interaction with its lattice.

Step 2: State the direction rule and extreme conditions Use Fleming's left-hand rule: hold the thumb, forefinger and middle finger of the left hand mutually perpendicular. The forefinger indicates magnetic field, the middle finger conventional current, and the thumb the force on the conductor. Thus the force is perpendicular to both current and field. For fixed B , I and L , the force is maximum when $\theta = 90^\circ$, giving $F_{\max} = BIL$. It is minimum, namely zero, when $\theta = 0^\circ$ or 180° , so the conductor is parallel or antiparallel to the field.

Step 3: (ii) Find the magnetic field of wire A at wire B The separation and the length under consideration must first be expressed in SI units:

$$d = 2.5 \text{ cm} = 2.5 \times 10^{-2} \text{ m}, \quad L = 10 \text{ cm} = 0.10 \text{ m}.$$

Using $I_A = 5.0 \text{ A}$, the field produced by A at B is

$$B_A = \frac{\mu_0 I_A}{2\pi d} = \frac{4\pi \times 10^{-7} \times 5.0}{2\pi \times 2.5 \times 10^{-2}} = 4.0 \times 10^{-5} \text{ T}.$$

Step 4: Calculate the force on the specified length of B The magnetic field of A is perpendicular to

the parallel wire B. Hence $\sin \theta = 1$ and, with $I_B = 2.5 \text{ A}$,

$$F = B_A I_B L = (4.0 \times 10^{-5})(2.5)(0.10) = 1.0 \times 10^{-5} \text{ N}.$$

The currents flow in opposite directions, so the interaction is repulsive: the force on B is directed away from A. This direction follows by applying the right-hand rule for A's field and then the force rule to B.

Step 5: Conclusion (i) $\vec{F} = I(\vec{L} \times \vec{B})$, with direction given by Fleming's left-hand rule. Its maximum is BIL at 90° , and its minimum is zero at 0° or 180° . (ii) The force on the 10 cm length of B is $1.0 \times 10^{-5} \text{ N}$, directed away from A.

Quick Tip to Solve: For parallel wires use $F = \mu_0 I_A I_B L / (2\pi d)$ after converting both lengths to metres; opposite currents repel and like currents attract.

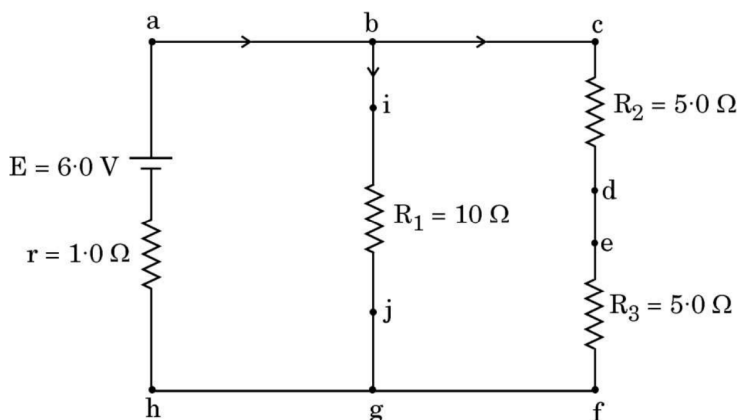
Section E (8 marks)

34(a). The following figure shows a circuit diagram. We can find the currents through and potential differences across different resistors using Kirchhoff's rules.

Answer the following questions based on the above:

Which points are at the same potential in the circuit?

[1 mark]



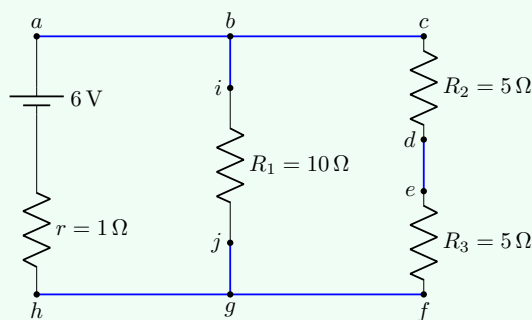
Solution:

Concept:

- All points joined by an ideal connecting wire belong to the same electrical node and have the same potential.
- The potential drop along such a wire is $\Delta V = IR = 0$, since its resistance is neglected. A resistor or cell separates different nodes.

Step 1: Trace the upper and lower continuous wires The upper wire joins a , b and c ; point i is also on the wire connected directly to b , above R_1 . Similarly, the lower wire joins h , g and f , and point j is directly connected to g , below R_1 . No resistor lies between points within either group.

Step 2: Identify the intermediate node on the right Points d and e are joined by a wire between R_2 and R_3 . They form another equipotential group. Do not include c or f in this group: reaching either one requires crossing a resistor carrying current.



The three continuous wire groups are the equipotential nodes.

Step 3: Conclusion The equal-potential groups are $V_a = V_b = V_c = V_i$, $V_h = V_g = V_f = V_j$, and $V_d = V_e$.

Quick Tip to Solve: Start at any labelled point and follow only plain connecting wires; stop at a resistor or cell to identify each equipotential node.

34(b). Refer to the circuit diagram. What is the current through arm bg ?

[1 mark]

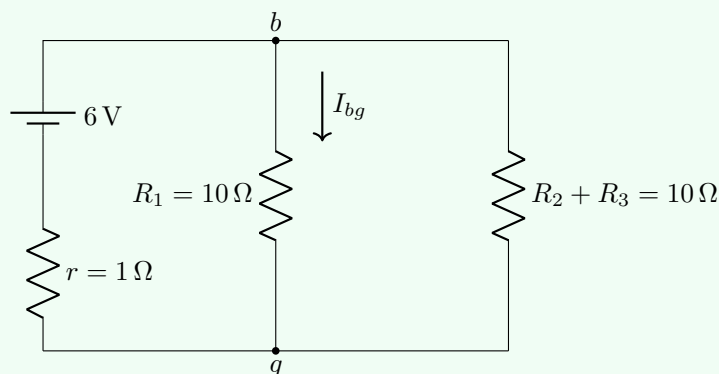
Solution:

Concept:

- Series resistances add, while two equal resistances R in parallel have equivalent resistance $R/2$.
- A cell of emf E and internal resistance r supplies total current $I = E/(R_{\text{ext}} + r)$; equal parallel branches divide this current equally.

Step 1: Reduce the external circuit In the right-hand branch, R_2 and R_3 are in series, so their sum is $5 + 5 = 10\Omega$. This branch is in parallel with the 10Ω resistor in arm bg . Hence

$$R_{\text{ext}} = \frac{10 \times 10}{10 + 10} = 5\Omega.$$



Equivalent circuit: the two external branches each have resistance 10Ω .

Step 2: Include internal resistance and divide the current The cell's internal resistance $r = 1\Omega$ is in series with the external combination. The total current and branch current are therefore

$$I = \frac{6}{5 + 1} = 1\text{ A}, \quad I_{bg} = \frac{I}{2} = 0.50\text{ A}.$$

The positive terminal is connected to the upper wire, so conventional current flows from b down to g . Using $6/10$ for this branch would neglect the voltage drop across the internal resistance.

Step 3: Conclusion The current through arm bg is 0.50 A , from b to g .

Quick Tip to Solve: First combine the two right-hand resistors; the resulting equal parallel branches each carry half the cell current, after including r .

34(c). Refer to the circuit diagram. Find the potential difference across resistance R_3 .

[2 marks]

Solution:

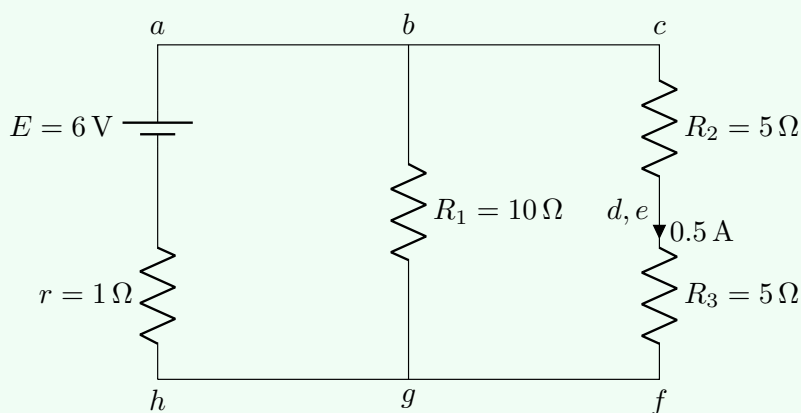
Concept:

- Series resistances add, while two parallel branches have the same potential difference. The cell's internal resistance r is in series with the external network.
- Ohm's law gives $V = IR$, where I is the current through the resistance R ; the total cell current is $I_{\text{total}} = E/(R_{\text{ext}} + r)$.

Step 1: Reduce the external network In the right-hand arm, R_2 and R_3 are in series, so their combined resistance is $5 + 5 = 10\ \Omega$. This arm is parallel to $R_1 = 10\ \Omega$.

$$R_{\text{ext}} = \frac{10 \times 10}{10 + 10} = 5\ \Omega.$$

Including the cell's $1\ \Omega$ internal resistance gives $R_{\text{total}} = 6\ \Omega$, so the cell supplies $I_{\text{total}} = 6/6 = 1\text{ A}$.



Equal external branches share the cell current; the desired drop is across the lower right resistor.

Step 2: Find the current through the right-hand arm The two external branches have equal resistance, so the total current divides equally: $I_{cf} = 0.5\text{ A}$. This is also the current through R_3 , since there is no branching between R_2 and R_3 .

$$V_e - V_f = I_{cf}R_3 = (0.5)(5.0)\text{ V}.$$

Current flows down through R_3 , making its upper end e at higher potential than its lower end f .

Using the full emf directly across this resistor would ignore both the internal voltage drop and the other series resistor.

Step 3: Conclusion The potential difference across R_3 is $\boxed{2.5\text{ V}}$, with e positive relative to f .

Quick Tip to Solve: First reduce the external network, include the internal resistance, and only then divide the current between the equal branches.

OR

34(c). Refer to the circuit diagram. What is the power dissipated in resistance R_2 ?

[2 marks]

Solution:

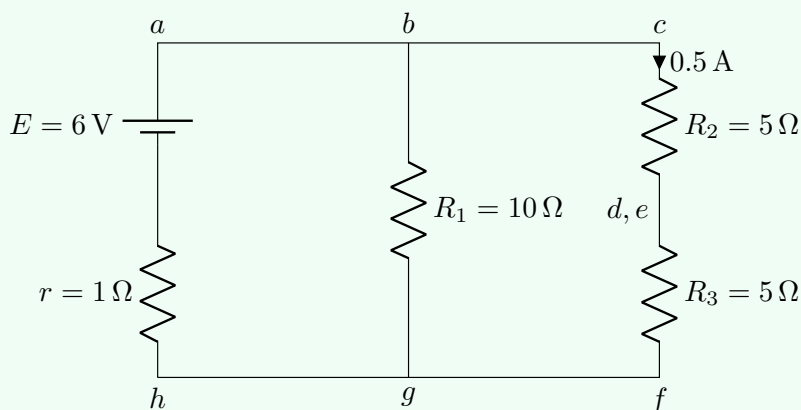
Concept:

- A resistor dissipates electrical power as heat at the rate $P = I^2 R$, where I is the current through that particular resistor.
- The series combination $R_2 + R_3$ is parallel to R_1 . The cell's internal resistance is in series with this complete external network and must be included when finding the total current.

Step 1: Calculate the current supplied by the cell The right-hand series arm has resistance $R_2 + R_3 = 5 + 5 = 10\ \Omega$. It is connected across the same two nodes as $R_1 = 10\ \Omega$, giving

$$R_{\text{ext}} = \frac{10 \times 10}{10 + 10} = 5\ \Omega, \quad I_{\text{total}} = \frac{6.0}{5 + 1} = 1.0\text{ A}.$$

The $1.0\ \Omega$ internal resistance reduces the terminal voltage to $6.0 - (1.0)(1.0) = 5.0\text{ V}$.



The current through each resistor in the right-hand series arm is 0.50 A.

Step 2: Use the current through the specified resistor Each external arm has resistance $10\ \Omega$, so each carries half the total current. Thus the series current through R_2 is $I_2 = 0.50\text{ A}$. Substituting the resistance of R_2 alone into the power formula gives

$$P_2 = I_2^2 R_2 = (0.50)^2 (5.0)\text{ W}.$$

The total cell current must not be used here: only half of it passes through R_2 . Equivalently, its voltage drop is half the terminal voltage, or 2.5 V, which gives the same result from V_2^2/R_2 .

Step 3: Conclusion The power dissipated in R_2 is $\boxed{1.25 \text{ W}}$.

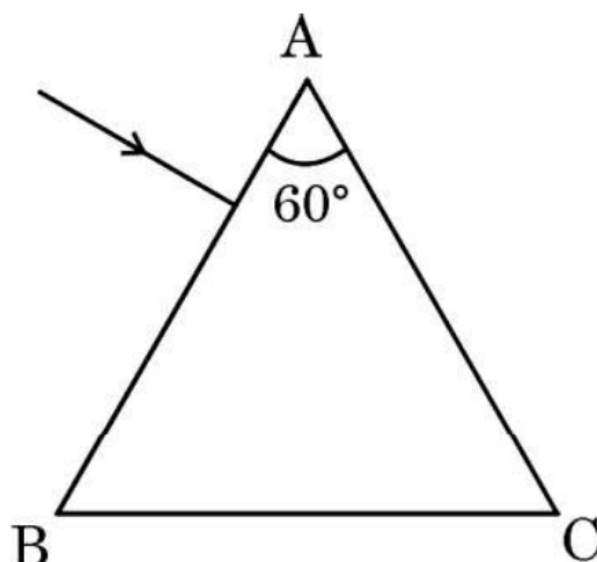
Quick Tip to Solve: Use the branch current in $I^2 R_2$; the cell current splits before reaching the two parallel external arms.

35(a). Strontium titanate is a rare oxide — a natural mineral found in Siberia. It is used as a substitute for diamond because its refractive index and critical angle are 2.41 and 24.5° , respectively, which are approximately equal to the refractive index and critical angle of diamond. It has all the properties of diamond. Even an expert jeweller is unable to differentiate between diamond and strontium titanate. A ray of light is incident normally on one face of an equilateral triangular prism ABC made of strontium titanate.

Answer the following questions based on the above:

Trace the path of the ray showing its passage through the prism.

[1 mark]



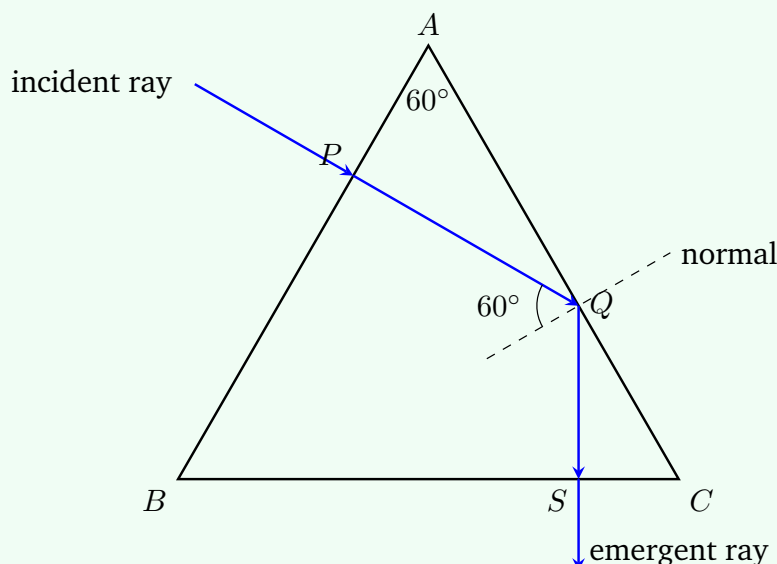
Solution:

Concept:

- At normal incidence, a ray passes through a refracting face without bending: $i = 0^\circ$ implies $r = 0^\circ$.
- Total internal reflection occurs from an optically denser medium to air when the incidence angle exceeds the critical angle $C = 24.5^\circ$. Angles are measured from the normal.

Step 1: Continue the incident ray to the second face The ray enters face AB normally at P , so it travels straight inside the prism and reaches face AC at Q . The angle between the normals to the two faces is 60° ; hence its incidence angle at AC is 60° .

Step 2: Reflect the ray and trace its emergence Since $60^\circ > 24.5^\circ$, the ray undergoes total internal reflection at Q . Applying the law of reflection makes the reflected ray perpendicular to the base BC . It reaches BC at S with normal incidence and emerges straight into air without further bending.



Ray tracing in the equilateral prism: total internal reflection at Q and normal emergence at S .

Step 3: Conclusion The path is straight through AB , totally internally reflected at AC , and then straight out normally through BC , as shown.

Quick Tip to Solve: Draw normals first: entry and exit have zero incidence, while the inclined second face has an incidence of 60° .

35(b). For the strontium titanate prism (refractive index 2.41), find the velocity of light through the prism. [1 mark]

Solution:

Concept:

- The absolute refractive index of a transparent medium is $n = c/v$, where c is the speed of light in vacuum and v is its speed in the medium.
- A refractive index greater than unity implies that light travels more slowly in the material than in vacuum; the index itself has no unit.

Step 1: Rearrange the definition of refractive index For the strontium titanate prism, $n = 2.41$. The required speed is obtained by dividing the vacuum speed by the refractive index:

$$v = \frac{c}{n}.$$

Step 2: Substitute the given index Using $c = 3.0 \times 10^8 \text{ m s}^{-1}$,

$$v = \frac{3.0 \times 10^8}{2.41} \text{ m s}^{-1} = 1.2448 \times 10^8 \text{ m s}^{-1}.$$

This is smaller than c , as expected for an optically dense prism. The direction changes on reflection

inside the prism, but the speed in the same material remains the value calculated here.

Step 3: Conclusion Light travels through the prism at a speed of approximately $1.24 \times 10^8 \text{ m s}^{-1}$.

Quick Tip to Solve: Divide c by 2.41, then check that your result is less than $3.0 \times 10^8 \text{ m s}^{-1}$.

35(c). Briefly explain two applications of total internal reflection.

[2 marks]

Solution:

Concept:

- Total internal reflection is the complete reflection of light back into an optically denser medium at a boundary with a rarer medium, when the incidence angle exceeds the critical angle.
- For refractive indices $n_1 > n_2$, the critical angle C satisfies $\sin C = n_2/n_1$. Incidence angles are measured from the normal to the boundary.

Step 1: Optical fibres for communication and medical viewing An optical fibre has a transparent core surrounded by cladding of a lower refractive index. Light entering within the suitable acceptance range strikes the core-cladding boundary at an angle greater than its critical angle. Repeated total internal reflections guide the light along the core with little loss, even through gentle bends. This allows optical signals to travel over long distances in communication links and permits light to be carried into and out of the body in medical endoscopes.

Step 2: Reflecting prisms in optical instruments A right-angled glass prism can turn a light beam through 90° in instruments such as periscopes and binoculars. With normal incidence on one of the perpendicular faces, the ray strikes the hypotenuse internally at 45° . For ordinary glass in air, the critical angle is about 42° , so this incidence exceeds the critical angle and the ray undergoes total internal reflection. It then emerges normally from the other perpendicular face. The prism thus provides an efficient reflecting surface without a metallic coating.

Step 3: Conclusion Two applications are optical fibres, which guide light by repeated total internal reflection, and reflecting prisms, which redirect light in optical instruments.

Quick Tip to Solve: For each application, identify the denser-to-rarer boundary and explain why the ray strikes it above the critical angle.

OR

35(c). Define total internal reflection of light. Give two conditions for it.

[2 marks]

Solution:

Concept:

- Refraction obeys Snell's law, $n_1 \sin i = n_2 \sin r$, where n_1, n_2 are the refractive indices of the incident and second media, and i, r are measured from the normal.
- The critical angle C is the incidence angle in the denser medium for which the refracted ray in the rarer medium makes 90° with the normal; thus $\sin C = n_2/n_1$.

Step 1: Define the phenomenon Total internal reflection is the phenomenon in which light incident at the boundary of two transparent media is completely reflected back into the optically denser medium,

with no propagating refracted ray in the rarer medium. It occurs when light approaches the boundary from the denser side at an incidence angle greater than the critical angle.

Step 2: State the two necessary conditions First, light must travel from an optically denser medium towards an optically rarer medium, so $n_1 > n_2$. Second, the incidence angle at their boundary must exceed the critical angle for that pair of media: $i > C$. Both conditions are essential. At $i = C$, the refracted ray just grazes the boundary; this is the limiting case and is not total internal reflection. For $i > C$, Snell's law would require $\sin r > 1$, which cannot describe a real refracted ray, so the light is reflected internally.

Step 3: Conclusion Total internal reflection is complete reflection back into the denser medium. Its two conditions are incidence from a denser to a rarer medium and an incidence angle strictly greater than the critical angle.

Quick Tip to Solve: Write $i > C$, not $i \geq C$: at the critical angle the refracted ray travels along the boundary.