

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



Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

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

You may use the following values of physical constants wherever necessary :

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

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

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

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

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

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

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

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

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

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

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

Section A (16 marks)

1. The capacitance of a parallel plate capacitor having a medium of dielectric constant $K = 4$ in between the plates is C . If this medium is removed, then the capacitance of the capacitor becomes:

[1 mark]

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

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

Solution:

Concept:

- For a parallel plate capacitor completely filled with a dielectric, $C = K\epsilon_0 A/d$, where K is the dielectric constant, A the plate area and d the plate separation.
- Removing the dielectric leaves the geometry unchanged and changes the relative permittivity from K to approximately 1.

Step 1: Express the initial capacitance Let $C_0 = \epsilon_0 A/d$ be the capacitance with air between the plates. The given capacitance already includes the dielectric enhancement, so $C = 4C_0$.

Step 2: Remove the dielectric factor On removing the medium, the capacitance returns to C_0 . Thus divide the given value by 4. Options (A) and (D) incorrectly increase it, while (B) incorrectly assumes that permittivity has no effect.

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

Quick Tip to Solve: When a fully filling dielectric is removed without changing the plates, divide the original capacitance by its dielectric constant.

2. Electrons drift with speed v_d in a conductor with potential difference V across its ends. If V is reduced to $\left(\frac{V}{2}\right)$, their drift speed will become:

[1 mark]

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

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

Solution:

Concept:

- The magnitude of electron drift velocity is $v_d = eE\tau/m$, where e is the electron charge magnitude, m its mass and τ the mean relaxation time.
- For a uniform conductor of length l , the electric field is $E = V/l$. At unchanged temperature and geometry, drift speed is directly proportional to the applied potential difference.

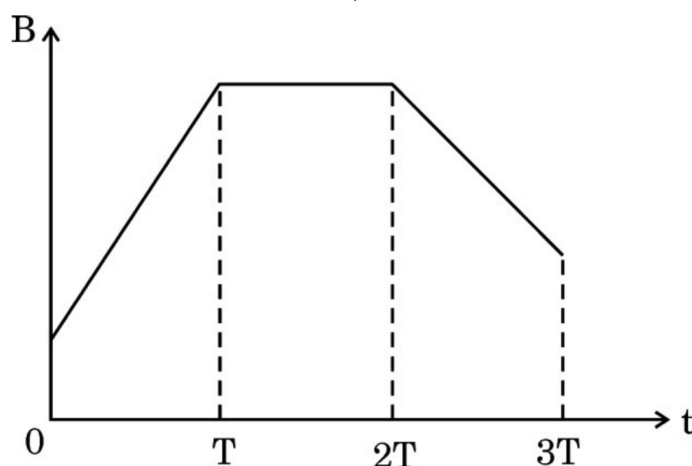
Step 1: Relate drift speed to voltage Substituting the field gives $v_d = e\tau V/(ml)$. All factors other than V remain fixed for the same conductor under the usual constant-temperature assumption.

Step 2: Apply the voltage ratio The new speed satisfies $v'_d/v_d = V'/V = (V/2)/V = 1/2$. It therefore decreases proportionately. Option (B) would require an unchanged field; options (C) and (D) predict increases despite the reduced accelerating field.

Step 3: Conclusion The electron drift speed becomes $v_d/2$. Hence, the correct option is (A).

Quick Tip to Solve: For the same conductor at fixed temperature, use the ratio $v'_d/v_d = V'/V$ directly.

3. A conducting loop is placed in a magnetic field, normal to its plane. The magnitude of the magnetic field varies with time as shown in the figure. If $\varepsilon_1, \varepsilon_2$ and ε_3 are magnitudes of induced emfs during periods $0 \leq t \leq T$, $T \leq t \leq 2T$ and $2T \leq t \leq 3T$, then: [1 mark]



(A) $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$

(B) $\varepsilon_2 > \varepsilon_3 > \varepsilon_1$

(C) $\varepsilon_3 > \varepsilon_1 > \varepsilon_2$

(D) $\varepsilon_1 > \varepsilon_3 > \varepsilon_2$

Correct Answer: (D) $\varepsilon_1 > \varepsilon_3 > \varepsilon_2$

Solution:

Concept:

- Faraday's law gives the induced emf magnitude as $|\varepsilon| = |d\Phi_B/dt|$, where Φ_B is the magnetic flux through the loop.
- For a stationary loop of area A with the field normal to its plane, $\Phi_B = AB$. Thus $|\varepsilon| = A|dB/dt|$: compare absolute slopes on the field-time graph.

Step 1: Identify the zero-slope interval Between T and $2T$, the graph is horizontal, so the flux is constant and $\varepsilon_2 = 0$. A nonzero magnetic field alone does not produce an emf; its flux must change.

Step 2: Compare the rising and falling slopes The first and third intervals both last T . The field rises by a larger amount in the first interval than it falls in the third, so the first absolute slope is larger. Both slopes are nonzero. Hence (A) and (B) wrongly place the zero emf above another, and (C) wrongly makes the final slope largest. The corner instants do not change this comparison of the linear intervals.

Step 3: Conclusion The magnitudes obey $\varepsilon_1 > \varepsilon_3 > \varepsilon_2$. Hence, the correct option is (D).

Quick Tip to Solve: On a field-time graph, compare the steepness of each segment, ignoring the sign when emf magnitudes are requested.

4. A circular coil of radius 10 cm is placed in a magnetic field $\vec{B} = (1.0\hat{i} + 0.5\hat{j}) \text{ mT}$ such that the outward unit vector normal to the surface of the coil is $(0.6\hat{i} + 0.8\hat{j})$. The magnetic flux linked with the coil is: [1 mark]

- (A) $0.314 \mu\text{Wb}$
- (B) $3.14 \mu\text{Wb}$
- (C) $31.4 \mu\text{Wb}$
- (D) $1.256 \mu\text{Wb}$

Correct Answer: (C) $31.4 \mu\text{Wb}$

Solution:

Concept:

- Magnetic flux through a plane area in a uniform field is $\Phi_B = \vec{B} \cdot \vec{A} = A(\vec{B} \cdot \hat{n})$, where $\hat{n}$ is the outward unit normal.
- A circular coil of radius r has area $A = \pi r^2$. Use metres for radius and tesla for magnetic field to obtain flux in webers.

Step 1: Find the normal component of the field Multiply matching vector components and add:

$$\vec{B} \cdot \hat{n} = (1.0 \times 0.6 + 0.5 \times 0.8) \text{ mT} = 1.0 \times 10^{-3} \text{ T}.$$

The dot product is positive for the specified outward normal.

Step 2: Calculate the area and flux The radius is $10 \text{ cm} = 0.10 \text{ m}$, so $A = \pi(0.10)^2 = 0.01\pi \text{ m}^2$. Therefore

$$\Phi_B = (0.01\pi)(10^{-3}) = 3.14 \times 10^{-5} \text{ Wb}.$$

Since $1 \mu\text{Wb} = 10^{-6} \text{ Wb}$, the other three numerical options do not match the dot-product calculation; in particular, (A) and (B) have incorrect powers of ten.

Step 3: Conclusion The magnetic flux is $+31.4 \mu\text{Wb}$. Hence, the correct option is (C).

Quick Tip to Solve: Dot the field with the given unit normal first; then multiply by πr^2 , converting the radius to metres before squaring.

5. Which of the following quantity/quantities remains same in primary and secondary coils of an ideal transformer?

Current, Voltage, Power, Magnetic flux

[1 mark]

- (A) Current only
- (B) Voltage only
- (C) Power only
- (D) Magnetic flux and Power both

Correct Answer: (D) Magnetic flux and Power both

Solution:

Concept:

- An ideal transformer has no energy losses, so input and output powers are equal: $P_p = P_s$, with subscripts p and s denoting the primary and secondary.
- Perfect magnetic coupling means that the same time-varying core flux Φ passes through each turn of both coils. The total flux linkage $N\Phi$ may differ because the turn counts N can differ.

Step 1: Check voltage and current The transformer ratios are $V_s/V_p = N_s/N_p$ and $I_s/I_p = N_p/N_s$. Thus voltage and current generally change when the turn counts differ, ruling out (A) and (B).

Step 2: Check the conserved quantities With no copper loss, core loss or flux leakage, the transferred power equals the supplied power and both windings share the same core magnetic flux. Option (C) is incomplete because it omits this common flux.

Step 3: Conclusion Both magnetic flux and power remain the same in the two coils of an ideal transformer. Hence, the correct option is (D).

Quick Tip to Solve: Distinguish the common core flux Φ from the flux linkage $N\Phi$; only the latter includes the winding's turn count.

6. A series LCR circuit ($L = 2 \text{ mH}$, $C = 0.2 \mu\text{F}$ and $R = 30 \Omega$) is connected to an ac source of variable frequency. The impedance of this circuit will be minimum at a frequency of:

[1 mark]

- (A) $\frac{10^5}{4\pi} \text{ Hz}$
- (B) $\frac{10^5}{2\pi} \text{ Hz}$
- (C) $\frac{10^4}{4\pi} \text{ Hz}$
- (D) $\frac{10^4}{2\pi} \text{ Hz}$

Correct Answer: (A) $\frac{10^5}{4\pi} \text{ Hz}$

Solution:

Concept:

- A series LCR circuit has impedance $Z = \sqrt{R^2 + (\omega L - 1/(\omega C))^2}$, where R , L and C are resistance, inductance and capacitance, and ω is angular frequency.
- Impedance is least at series resonance, when the reactances cancel. Thus $\omega_0 = 1/\sqrt{LC}$ and ordinary frequency $f_0 = \omega_0/(2\pi)$.

Step 1: Convert the component values Here $L = 2 \times 10^{-3} \text{ H}$ and $C = 0.2 \times 10^{-6} = 2 \times 10^{-7} \text{ F}$. Hence $LC = 4 \times 10^{-10}$ in SI units and $\sqrt{LC} = 2 \times 10^{-5} \text{ s}$.

Step 2: Calculate the resonance frequency Substitute into the frequency formula:

$$f_0 = \frac{1}{2\pi(2 \times 10^{-5})} = \frac{10^5}{4\pi} \text{ Hz}.$$

At this frequency $Z_{\min} = R = 30 \Omega$; resistance does not set the resonance frequency here. Option (B) is twice the calculated value, while (C) and (D) have incorrect powers or factors.

Step 3: Conclusion The impedance is minimum at $f_0 = \frac{10^5}{4\pi} \text{ Hz}$. Hence, the correct option is (A).

Quick Tip to Solve: Convert both milli- and micro-prefixes before finding $\sqrt{LC}$, then divide angular frequency by 2π to obtain hertz.

7. Welders wear special glass goggles or face masks with glass windows to protect their eyes from radiations produced by welding arcs. These radiations are: [1 mark]

- (A) X-rays
- (B) Ultraviolet rays
- (C) Infrared waves
- (D) Gamma rays

Correct Answer: (B) Ultraviolet rays

Solution:

Concept:

- A welding arc is an intense source of ultraviolet radiation as well as visible light and infrared radiation.
- Ultraviolet photons have higher energies than visible photons, since $E = h\nu$, where h is Planck's constant and ν is frequency. Exposure to strong ultraviolet radiation can injure the surface of the eye.

Step 1: Identify the radiation highlighted by eye protection The standard reason for the special glass used in welding goggles is to absorb the intense ultraviolet radiation emitted by the arc before it reaches the eyes. This is the radiation targeted by the question.

Step 2: Compare the remaining choices Infrared radiation is also emitted by a hot arc and relates to heating, but it is not the intended radiation in this familiar ultraviolet-protection example. X-rays require suitable high-energy processes, and gamma rays arise in nuclear transitions; neither is the characteristic radiation identified here.

Step 3: Conclusion The radiation referred to is ultraviolet radiation. Hence, the correct option is (B).

Quick Tip to Solve: Associate welding-arc eye protection with ultraviolet absorption; do not confuse the arc's ultraviolet hazard with its infrared heat.

8. A photosensitive surface has a work function of 2.00 eV. The maximum kinetic energy of electrons ejected from this surface by radiation of wavelength 300 nm is: [1 mark]

- (A) 0.54 eV
- (B) 1.07 eV
- (C) 1.61 eV
- (D) 2.14 eV

Correct Answer: (D) 2.14 eV

Solution:

Concept:

- Einstein's photoelectric equation is $K_{\max} = h\nu - \phi = hc/\lambda - \phi$, where ϕ is the work function.
- Photon energy first supplies the work function; its remainder is the maximum kinetic energy of an emitted electron. Use $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$.

Step 1: Calculate the incident photon energy Convert the wavelength to $300 \times 10^{-9} \text{ m}$. With $h = 6.63 \times 10^{-34} \text{ J s}$ and $c = 3.0 \times 10^8 \text{ m s}^{-1}$,

$$E = \frac{(6.63 \times 10^{-34})(3.0 \times 10^8)}{300 \times 10^{-9}} = 6.63 \times 10^{-19} \text{ J} \approx 4.14 \text{ eV}.$$

Step 2: Subtract the work function Since $4.14 \text{ eV} > 2.00 \text{ eV}$, emission is possible. The largest electron energy is

$$K_{\max} = 4.14 - 2.00 = 2.14 \text{ eV}.$$

Options (A), (B) and (C) are all below this maximum and do not equal the energy left after overcoming the work function. The photon energy itself must not be mistaken for the electron's kinetic energy.

Step 3: Conclusion The maximum kinetic energy is 2.14 eV. Hence, the correct option is (D).

Quick Tip to Solve: For wavelength in nanometres, estimate photon energy using $E \approx 1240/\lambda$ in eV, then subtract the work function in eV.

9. Energy levels A, B and C of an atom correspond to increasing values of energy i.e. $E_A < E_B < E_C$. Let λ_1 , λ_2 and λ_3 be the wavelengths of radiation corresponding to the transitions C to B, B to A and C to A, respectively. The correct relation between λ_1 , λ_2 and λ_3 is: [1 mark]

- (A) $\lambda_1^2 + \lambda_2^2 = \lambda_3^2$
- (B) $\frac{1}{\lambda_1} + \frac{1}{\lambda_2} = \frac{1}{\lambda_3}$
- (C) $\lambda_1 + \lambda_2 + \lambda_3 = 0$
- (D) $\lambda_1 + \lambda_2 = \lambda_3$

Correct Answer: (B) $\frac{1}{\lambda_1} + \frac{1}{\lambda_2} = \frac{1}{\lambda_3}$

Solution:

Concept:

- In an atomic transition from higher to lower energy, the emitted photon has energy $\Delta E = hc/\lambda$, where λ is its wavelength.
- Energy differences add along successive transitions: $E_C - E_A = (E_C - E_B) + (E_B - E_A)$. Thus

photon frequencies, or inverse wavelengths, add.

Step 1: Write the three transition energies For the transitions specified in the question,

$$E_C - E_B = \frac{hc}{\lambda_1}, \quad E_B - E_A = \frac{hc}{\lambda_2}, \quad E_C - E_A = \frac{hc}{\lambda_3}.$$

All three differences are positive because $E_A < E_B < E_C$.

Step 2: Add the successive energy gaps Adding the first two equations cancels E_B . Comparing with the third equation and dividing by hc gives

$$\frac{1}{\lambda_1} + \frac{1}{\lambda_2} = \frac{1}{\lambda_3}.$$

The direct transition has the largest energy, so λ_3 is smaller than either other wavelength. This rules out (A) and (D), which make it larger. Option (C) is impossible because wavelengths are positive.

Step 3: Conclusion The inverse wavelengths satisfy $1/\lambda_1 + 1/\lambda_2 = 1/\lambda_3$. Hence, the correct option is (B).

Quick Tip to Solve: Add energy gaps or frequencies, never wavelengths; the largest energy drop must give the shortest wavelength.

10. An alpha particle approaches a gold nucleus in Geiger-Marsden experiment with kinetic energy K . It momentarily stops at a distance d from the nucleus and reverses its direction. Then d is proportional to: [1 mark]

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

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

Solution:

Concept:

- In a head-on approach, the positively charged alpha particle is repelled by the positively charged gold nucleus. Its kinetic energy is converted into electrostatic potential energy.
- Taking potential energy as zero far away, $U(r) = k(2e)(Ze)/r$, where $k = 1/(4\pi\epsilon_0)$, e is the elementary charge and $Z = 79$ for gold.

Step 1: Apply energy conservation at the turning point At the closest approach d , the alpha particle momentarily stops, so its kinetic energy is zero. In the standard heavy-nucleus approximation, all its initial kinetic energy K has become electrostatic potential energy:

$$K = \frac{2kZe^2}{d}.$$

Step 2: Isolate the distance and compare dependencies Rearranging gives

$$d = \frac{2kZe^2}{K}.$$

For the same alpha particle and gold target, the numerator is constant. Doubling K halves d . Options (B) and (D) wrongly predict a larger closest distance at higher energy, while (A) has the wrong inverse power; the Coulomb potential varies as $1/d$, not $1/d^2$.

Step 3: Conclusion The closest-approach distance obeys $d \propto 1/K$. Hence, the correct option is (C).

Quick Tip to Solve: At the head-on turning point set initial kinetic energy equal to Coulomb potential energy, not Coulomb force.

11. An n-type semiconducting Si is obtained by doping intrinsic Si with:

[1 mark]

- (A) Al
- (B) B
- (C) P
- (D) In

Correct Answer: (C) P

Solution:

Concept:

- Silicon is tetravalent: each Si atom normally forms four covalent bonds in its crystal lattice.
- An n-type semiconductor is produced by a pentavalent donor impurity. Its fifth valence electron is weakly bound and can enter the conduction band, making electrons the majority carriers.

Step 1: Identify the donor among the impurities Phosphorus, P, has five valence electrons. When a P atom replaces a Si atom, four of its electrons participate in covalent bonds with neighbouring Si atoms. The fifth is easily released as a conduction electron, so phosphorus acts as a donor.

Step 2: Check the other three choices Aluminium (Al), boron (B) and indium (In) each have three valence electrons. Each leaves an electron deficiency in bonding and acts as an acceptor, producing p-type silicon with holes as majority carriers. Therefore options (A), (B) and (D) give the opposite conductivity type. Doping with a donor does not give the whole crystal a net negative charge; the crystal remains electrically neutral.

Step 3: Conclusion Intrinsic Si must be doped with phosphorus, P, to obtain n-type silicon. Hence, the correct option is (C).

Quick Tip to Solve: Compare the impurity's valence with silicon's four: five gives an extra electron; three creates a hole.

12. When a p-n junction diode is subjected to reverse biasing:

[1 mark]

- (A) the barrier height decreases and the depletion region widens.
- (B) the barrier height increases and the depletion region widens.
- (C) the barrier height decreases and the depletion region shrinks.
- (D) the barrier height increases and the depletion region shrinks.

Correct Answer: (B) the barrier height increases and the depletion region widens.

Solution:

Concept:

- Reverse bias connects the p-side to the negative terminal and the n-side to the positive terminal of the external supply.
- The applied reverse voltage reinforces the built-in junction field. The effective barrier potential becomes $V_{bi} + V_R$, where V_{bi} is the built-in potential and V_R is the reverse-bias magnitude.

Step 1: Follow the majority carriers The negative terminal attracts holes away from the junction on the p-side, while the positive terminal attracts electrons away on the n-side. Additional fixed acceptor and donor ions are exposed near the junction, so the region depleted of mobile majority carriers becomes wider.

Step 2: Determine the barrier change The external reverse-bias field acts in the same direction as the junction's internal field, increasing the potential barrier that majority carriers must overcome. Thus both the barrier height and depletion width increase. Option (A) has the wrong barrier change, (C) describes the usual forward-bias changes, and (D) has the wrong depletion-width change.

Step 3: Conclusion Reverse bias increases the barrier height and widens the depletion region. Hence, the correct option is (B).

Quick Tip to Solve: In reverse bias, draw majority carriers moving away from the junction: a wider depletion region and a higher barrier follow together.

13. Assertion (A): The magnifying power of a compound microscope is negative.

Reason (R): The final image formed is erect with respect to the object.

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

Solution:

Concept:

- A compound microscope uses an objective to form a real, inverted, enlarged intermediate image; the eyepiece magnifies that intermediate image.
- With orientation included, the microscope magnifying power is $M = m_o M_e$, where the objective magnification m_o is negative and the eyepiece magnifying factor M_e is positive.

Step 1: Evaluate the assertion The objective inverts the object. The eyepiece acts as a simple microscope and preserves the orientation of the intermediate image. Consequently the final image is inverted relative to the original object and the signed magnifying power is negative. Assertion (A) is true in the signed convention used in the question.

Step 2: Evaluate the reason The final image is erect relative to the intermediate image, but it remains inverted relative to the original object. Reason (R) incorrectly compares the final image with the original object and calls it erect; it is false.

Step 3: Test the explanation and code A false reason cannot explain a true assertion. The negative sign is explained by the final inversion. Options (A) and (B) incorrectly treat the reason as true, while (D) incorrectly treats the assertion as false.

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

Quick Tip to Solve: Track image orientation through both lenses: the objective inverts once, and the eyepiece introduces no further inversion.

14. Assertion (A): An electron and a proton enter with the same momentum $\vec{p}$ in a magnetic field $\vec{B}$ such that $\vec{p} \perp \vec{B}$. Then both describe a circular path of the same radius.

Reason (R): The radius of the circular path described by the charged particle (charge q , mass m) moving in the magnetic field $\vec{B}$ is given by $r = \frac{mv}{qB}$. [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:

- For motion perpendicular to a uniform magnetic field, the magnetic force supplies centripetal force: $|q|vB = mv^2/r$.
- Hence $r = mv/(|q|B) = p/(|q|B)$, where $p = mv$ is momentum magnitude. An electron and a proton have equal charge magnitudes e , although their charge signs are opposite.

Step 1: Evaluate the assertion Both particles have the same momentum magnitude p , enter the same field perpendicularly and have charge magnitude e . Therefore

$$r_e = \frac{p}{eB} = r_p.$$

Assertion (A) is true. Their unequal masses imply unequal speeds at equal momentum, but do not change this radius comparison.

Step 2: Evaluate the reason Equating magnetic and centripetal forces gives $r = mv/(qB)$ when q denotes the magnitude of charge, as conventionally understood in this radius formula. Thus Reason (R) is true. Radius is positive; a signed charge would be written as $|q|$ in the denominator.

Step 3: Check whether the reason explains the assertion Substituting $mv = p$ into the stated formula directly gives the same radius for the two equal momenta and equal charge magnitudes. The reason therefore explains the assertion, ruling out (B). Options (C) and (D) assign false truth values. Opposite charge signs reverse the sense of curvature, not the radius.

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

Quick Tip to Solve: For a magnetic orbit, rewrite mv as momentum first: compare $p/|q|$, and use the charge sign only for the bending direction.

15. Assertion (A): Lenz's law is a consequence of the law of conservation of energy.

Reason (R): There is no power loss in an ideal inductor.

[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:

- Lenz's law states that the induced current opposes the change in magnetic flux that produces it.
- An ideal inductor has zero resistance: it stores magnetic energy $U = \frac{1}{2}LI^2$, where L is inductance and I is current, without dissipating energy as heat.

Step 1: Evaluate the assertion If the induced current aided the changing flux, that change would reinforce itself and supply energy without external work. Opposition to the change requires external work, which supplies the induced electrical energy. Thus Lenz's law follows from conservation of energy, and A is true.

Step 2: Evaluate the reason For an ideal inductor, resistance is zero, so the dissipated power I^2R is zero. Energy can enter and leave its magnetic field, but no energy is irreversibly lost. Thus R is also true.

Step 3: Test the explanatory connection The absence of dissipation in an ideal inductor describes energy storage; it does not explain why an induced current opposes its cause. The needed explanation is the impossibility of creating energy without external work. Option (A) therefore confuses two true statements with an explanatory link, while (C) and (D) incorrectly reject a true statement.

Step 4: Conclusion Both A and R are true, but R is not the correct explanation of A. Hence, the correct option is (B).

Quick Tip to Solve: For Lenz's law, imagine the induced current aiding the flux change: the resulting free energy shows why opposition is essential.

16. Assertion (A): Photoelectric current increases with an increase in intensity of incident radiation, for a given frequency of incident radiation and the accelerating potential.

Reason (R): Increase in the intensity of incident radiation results in an increase in the number of photoelectrons emitted per second and hence an increase in the photocurrent. [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:

- At a fixed frequency ν , each photon has energy $h\nu$; raising intensity raises the incident photon rate.
- The photocurrent is $I = e\dot{N}$, where $\dot{N}$ is the number of photoelectrons collected per second and e is the magnitude of electronic charge.

Step 1: Evaluate the assertion For photoemission at a frequency above the threshold, increasing intensity increases the number of incident photons per second. At the same accelerating potential, more emitted electrons are collected per second, so the photocurrent increases. A is true.

Step 2: Evaluate the reason Each incident photon can release an electron if its energy is sufficient. Thus, for the same surface and frequency, a greater photon rate produces more photoelectrons per second. Their greater collected charge per second increases current. R is true.

Step 3: Check whether the reason explains the assertion The increased emission rate is precisely the mechanism connecting greater intensity with greater current. It is the number of photoelectrons, not their maximum kinetic energy, that rises: photon energy stays fixed. Hence (B) wrongly denies the explanatory link, and (C) and (D) incorrectly call true statements false.

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

Quick Tip to Solve: At fixed frequency, connect intensity to photon count and current; connect frequency to maximum photoelectron energy.

Section B (10 marks)

17. (a) "The electron drift speed is only a few mm/s for currents in the range of a few amperes for a given conductor." How then is current established almost the instant a circuit is closed? Explain.

(b) " $V = IR$ is a statement of Ohm's Law" is not true. Explain. [2 marks]

Solution:

Concept:

- Drift speed is the small average speed of conduction electrons in an electric field; it is different from the speed at which the electromagnetic signal propagates along a circuit.

- Ohm's law states that $V \propto I$, or $V/I = R = \text{constant}$, for a conductor maintained at constant temperature and other physical conditions.

Step 1: Explain the rapid establishment of current in part (a) Free electrons are already present throughout the conducting wire. Closing the switch establishes an electric field through the circuit by an electromagnetic signal travelling at a very high speed, typically comparable with the speed of light in the surrounding medium. Electrons throughout the wire then acquire drift velocity after a very short propagation delay. An electron from the battery does not have to travel the full wire length before current can flow elsewhere. Thus a small drift speed of a few millimetres per second is consistent with an almost immediate response in an ordinary circuit.

Step 2: State the missing condition in part (b) The equation $V = IR$ alone can simply define $R = V/I$ at a particular operating point. It does not require this ratio to remain unchanged when the applied voltage changes. Ohm's law makes the additional physical statement that R is independent of V and I when temperature and the other physical conditions remain fixed. A non-ohmic device may have a different ratio at each point and so does not obey Ohm's law despite that algebraic definition of resistance.

Step 3: Conclusion (a) Current responds quickly because the electric-field signal propagates rapidly to electrons already throughout the wire. (b) Ohm's law requires a constant V/I at fixed physical conditions; $V = IR$ alone does not express that requirement.

Quick Tip to Solve: Separate the speed of electrons from the speed of the field signal; when stating Ohm's law, always add that resistance stays constant at fixed temperature.

18. A convex lens ($n = 1.52$) has a focal length of 15.0 cm in air. Find its focal length when it is immersed in liquid of refractive index 1.65. What will be the nature of the lens? [2 marks]

Solution:

Concept:

- For a thin lens in a medium, the lens maker's formula is $1/f = (n_\ell/n_m - 1)(1/R_1 - 1/R_2)$, where n_ℓ and n_m are the refractive indices of the lens and medium, and R_1, R_2 are signed surface radii.
- The curvature factor stays unchanged on immersion. A positive focal length indicates a converging lens, while a negative focal length indicates a diverging lens.

Step 1: Eliminate the unchanged curvature factor Write $K = 1/R_1 - 1/R_2$, and take the refractive index of air as unity. In air and liquid respectively,

$$\frac{1}{f_a} = (1.52 - 1)K, \quad \frac{1}{f_m} = \left(\frac{1.52}{1.65} - 1\right)K.$$

Dividing eliminates the unknown radii, giving

$$f_m = f_a \frac{1.52 - 1}{1.52/1.65 - 1}.$$

Step 2: Substitute and interpret the sign With $f_a = +15.0$ cm, the relative-index factor in liquid is negative because the liquid is optically denser than the lens:

$$f_m = 15.0 \frac{0.52 \times 1.65}{1.52 - 1.65} = 15.0 \frac{0.858}{-0.13} = -99.0 \text{ cm}.$$

The negative sign means that incident parallel rays emerge diverging, as though from a virtual principal focus on the incident side. The lens retains its convex shape but its optical action changes in this liquid.

Step 3: Conclusion The focal length in the liquid is -99.0 cm , or -0.990 m . The convex lens behaves as a diverging lens.

Quick Tip to Solve: Use the lens-to-medium relative index, not the lens index alone; if the surrounding liquid has the higher index, a convex lens becomes diverging.

19(a). Two waves, each of amplitude 'a' and frequency ' ω ' emanating from two coherent sources of light superpose at a point. If the phase difference between the two waves is ϕ , obtain an expression for the resultant intensity at that point. [2 marks]

Solution:

Concept:

- For coherent waves the phase difference ϕ remains constant, and the resultant displacement or electric field is the sum of the individual waves.
- Intensity is proportional to the square of amplitude: write $I_0 = Ca^2$ for the intensity of either individual wave, with C the common proportionality constant.

Step 1: Add the two oscillations Choose the first wave as the phase reference and write the two oscillations at the observation point as

$$y_1 = a \sin \omega t, \quad y_2 = a \sin(\omega t + \phi).$$

Here ω denotes the common angular frequency in this wave representation. Using $\sin u + \sin v = 2 \sin[(u + v)/2] \cos[(u - v)/2]$, their sum is

$$y = 2a \cos \frac{\phi}{2} \sin \left(\omega t + \frac{\phi}{2} \right).$$

Thus the resultant amplitude has magnitude $A = 2a |\cos(\phi/2)|$; the constant phase shift does not change its intensity.

Step 2: Relate the resultant amplitude to intensity Squaring the amplitude and using $I_0 = Ca^2$ gives

$$I = CA^2 = 4Ca^2 \cos^2 \frac{\phi}{2} = 4I_0 \cos^2 \frac{\phi}{2}.$$

Equivalently, the identity $2 \cos^2(\phi/2) = 1 + \cos \phi$ gives $I = 2I_0(1 + \cos \phi)$. As checks, in-phase waves give $I = 4I_0$, whereas a phase difference of π gives complete cancellation and zero intensity.

Step 3: Conclusion The resultant intensity is $I = 4I_0 \cos^2(\phi/2) = 2I_0(1 + \cos \phi)$, where I_0 is the intensity of each wave. In amplitude form, $I \propto 4a^2 \cos^2(\phi/2)$.

Quick Tip to Solve: Add amplitudes before squaring; equal coherent waves can produce anything from zero to four times the single-wave intensity.

19(b). What is the effect on the interference pattern in Young's double-slit experiment when (i) the source slit is moved closer to the plane of the slits, and (ii) the separation between the two slits is increased? Justify your answers. [2 marks]

Solution:

Concept:

- In Young's experiment, fringe width is $\beta = \lambda D/d$, where λ is wavelength, D the slit-to-screen distance and d the double-slit separation.
- Fringe visibility depends on spatial coherence: the different points across a source slit of finite width produce slightly displaced patterns which superpose.

Step 1: (i) Move the source slit closer Let the source slit have width s and be at distance L from the double slits. Its angular width is approximately s/L . Decreasing L increases this angular width, so the patterns due to different source points are more displaced relative to one another. Bright regions then overlap dark regions more, reducing contrast: the fringes become less distinct and may disappear. The spacing β is unchanged because λ , D , d are unchanged. For an ideal point-like source moved along the central axis, this loss of visibility does not occur; the incident intensity increases while the spacing stays the same.

Step 2: (ii) Increase the separation of the double slits With wavelength and screen distance fixed, the fringe-width relation gives

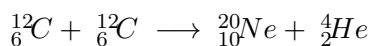
$$\frac{\beta'}{\beta} = \frac{d}{d'}.$$

Therefore $d' > d$ gives $\beta' < \beta$: adjacent bright fringes, and likewise adjacent dark fringes, lie closer together. More fringes fit within a fixed screen interval.

Step 3: Conclusion (i) A finite source slit moved closer reduces fringe visibility without changing fringe width. (ii) Increasing double-slit separation decreases fringe width, since $\beta \propto 1/d$.

Quick Tip to Solve: Distinguish source-slit width and distance, which affect visibility, from double-slit separation, which enters $\beta = \lambda D/d$.

20. Calculate the energy released/absorbed in the following nuclear reaction:



Given: $m({}^6_{12}\text{C}) = 12.000000 \text{ u}$

$m({}^{20}_{10}\text{Ne}) = 19.992439 \text{ u}$

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

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

[2 marks]

Solution:

Concept:

- The reaction energy is $Q = (m_{\text{initial}} - m_{\text{final}})c^2$. Positive Q means energy is released; negative Q means it is absorbed.
- The given conversion is $1 \text{ u } c^2 = 931 \text{ MeV}$. Atomic masses can be used here because total atomic number, and hence the number of electrons in neutral atoms, is the same on both sides.

Step 1: Add the initial and final masses There are two carbon-12 atoms initially and one neon-20 atom plus one helium-4 atom finally. Using the printed masses without rounding prematurely,

$$\begin{aligned} m_{\text{initial}} &= 2(12.000000) = 24.000000 \text{ u}, \\ m_{\text{final}} &= 19.992439 + 4.002603 \\ &= 23.995042 \text{ u}. \end{aligned}$$

Both sides have total mass number 24 and total atomic number 12, consistent with the stated nuclear reaction.

Step 2: Convert the mass decrease into energy Subtract final mass from initial mass, in that order:

$$\begin{aligned} \Delta m &= 24.000000 - 23.995042 = 0.004958 \text{ u}, \\ Q &= 0.004958 \times 931 \text{ MeV} \\ &= 4.615898 \text{ MeV}. \end{aligned}$$

The products have lower rest mass. The missing rest energy becomes energy of the reaction products, so the reaction is exothermic.

Step 3: Conclusion The reaction releases approximately 4.62 MeV per reaction; its Q -value is positive.

Quick Tip to Solve: Always calculate initial mass minus final mass before multiplying by 931; the sign immediately distinguishes release from absorption.

21. How does the energy gap of an intrinsic semiconductor effectively change when doped with a (a) trivalent impurity, and (b) pentavalent impurity? Justify your answer in each case. [2 marks]

Solution:

Concept:

- An intrinsic semiconductor has a filled valence band and an empty conduction band at absolute zero, separated by the forbidden gap $E_g = E_C - E_V$.
- Doping introduces allowed impurity energy levels inside the forbidden gap. These reduce the energy required to generate mobile charge carriers; ordinary dilute doping does not appreciably change the host's actual band separation $E_C - E_V$.

Step 1: (a) Add a trivalent impurity A trivalent atom has one fewer valence electron than the tetravalent host atom it replaces. It introduces an acceptor level E_A just above the valence-band edge E_V . A valence electron can enter this level using the small energy $E_A - E_V$, leaving a mobile hole in the valence band. Thus a p-type semiconductor is formed, and the effective energy needed to create a mobile carrier is much smaller than the intrinsic gap:

$$E_A - E_V \ll E_g.$$

Step 2: (b) Add a pentavalent impurity A pentavalent atom supplies an extra, weakly bound electron and introduces a donor level E_D just below the conduction-band edge E_C . Only the small energy $E_C - E_D$ is needed to move this electron into the conduction band. Electrons become the majority

carriers and the semiconductor is n-type:

$$E_C - E_D \ll E_g.$$

In both cases the nearby impurity level, rather than a large shift of the band edges, explains the effective reduction.

Step 3: Conclusion The effective carrier-excitation gap decreases in both cases: trivalent doping gives acceptor levels just above the valence band, and pentavalent doping gives donor levels just below the conduction band.

Quick Tip to Solve: Remember acceptor levels are near the valence band and donor levels near the conduction band; each provides a small carrier-excitation energy.

Section C (21 marks)

22. (a) On what factors does the speed of an electromagnetic wave in a medium depend?
(b) How is an electromagnetic wave produced?
(c) Sketch a schematic diagram depicting the electric and magnetic fields for an electromagnetic wave propagating along z-axis. [3 marks]

Solution:

Concept:

- The speed of an electromagnetic wave in a homogeneous medium is $v = 1/\sqrt{\mu\epsilon}$, where μ is magnetic permeability and ϵ is electric permittivity.
- Accelerating charges radiate electromagnetic waves. Time-varying electric and magnetic fields sustain one another and propagate away from the source.
- A plane electromagnetic wave is transverse: $\vec{E} \perp \vec{B}$, and both are perpendicular to the propagation direction $\vec{E} \times \vec{B}$.

Step 1: (a) State the factors controlling speed The electrical and magnetic properties of the medium determine its wave speed:

$$v = \frac{1}{\sqrt{\mu\epsilon}} = \frac{c}{\sqrt{\mu_r\epsilon_r}}.$$

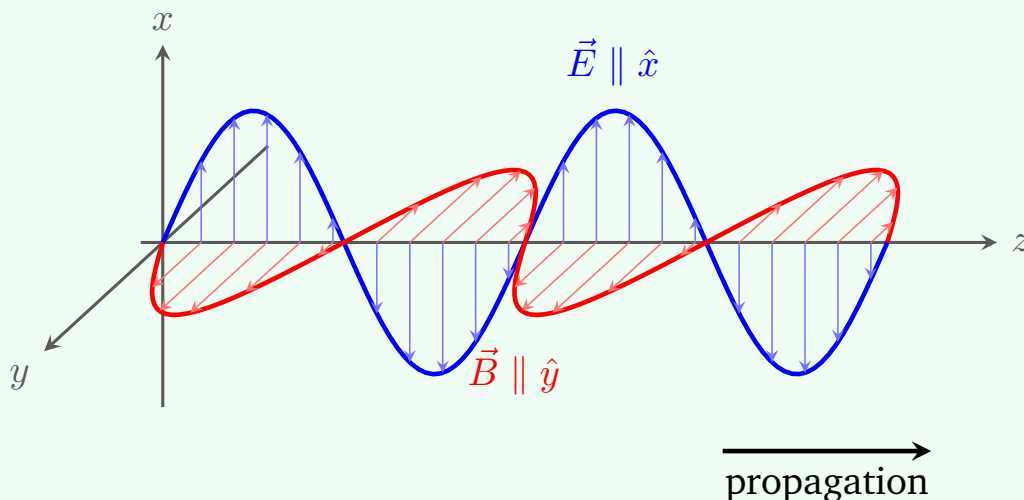
Here μ_r and ϵ_r are relative permeability and relative permittivity, and $c = 1/\sqrt{\mu_0\epsilon_0}$ is the vacuum speed. Increasing either material parameter, with the other fixed, reduces the speed. In a dispersive medium these parameters, and hence speed, can depend on frequency.

Step 2: (b) Explain the production mechanism An accelerated charge, for example a charge oscillating in a transmitting antenna, produces a time-varying electric field. The changing electric field is associated with a changing magnetic field, and the changing magnetic field produces an electric field. These coupled disturbances travel outward as an electromagnetic wave carrying energy. A stationary charge produces only an electrostatic field and does not radiate.

Step 3: (c) Orient and sketch the fields For propagation along the positive z-axis, choose the electric field along x and the magnetic field along y. One possible wave is

$$\begin{aligned}\vec{E}(z, t) &= E_0 \sin(kz - \omega t) \hat{x}, \\ \vec{B}(z, t) &= B_0 \sin(kz - \omega t) \hat{y}.\end{aligned}$$

The fields have the same phase, with simultaneous zeros and extrema; $\hat{x} \times \hat{y} = \hat{z}$. The sketch shows the two perpendicular oscillation planes at one instant, using independent scales for the field amplitudes. The wave travels along the common z -axis, not along either field direction.

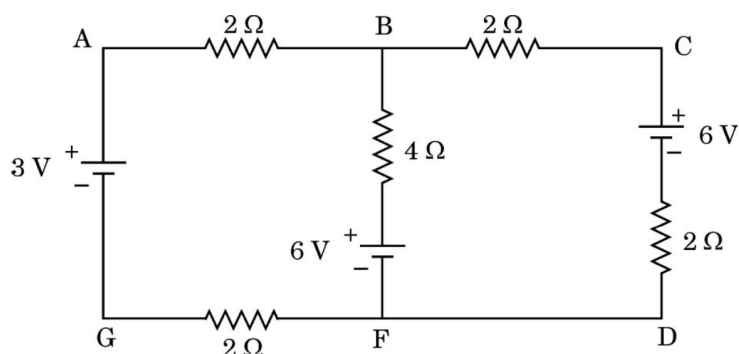


In-phase transverse fields in the xz and yz planes; propagation is along $+z$.

Step 4: Conclusion (a) Speed depends on μ and ϵ . (b) Accelerating charges produce electromagnetic waves. (c) For travel along $+z$, the mutually perpendicular, in-phase fields may point along x and y , as shown.

Quick Tip to Solve: Choose the field axes so the right-hand rule gives $\vec{E} \times \vec{B}$ along the stated propagation axis; put both fields' crests at the same position.

23. The figure shows a circuit with three ideal batteries. Find the magnitude and direction of currents in the branches AG, BF and CD. [3 marks]



Solution:

Concept:

- Kirchhoff's junction rule states that the algebraic sum of currents at a junction is zero, expressing conservation of charge.
- Kirchhoff's loop rule gives the same potential difference along all branches connecting two nodes. Crossing a cell from its positive to negative terminal gives a potential drop equal to its emf.

Step 1: Identify the three branches between B and F Points F and D are joined by an ideal wire and have the same potential. Put $V_F = 0$ and $V_B = V$. Temporarily define all three branch currents from

B towards F: I_L along B–A–G–F, I_M directly along B–F, and I_R along B–C–D–F. The left branch has resistance $2 + 2 = 4\ \Omega$ and a 3 V cell. The middle branch has $4\ \Omega$ and a 6 V cell; the right branch has resistance $2 + 2 = 4\ \Omega$ and a 6 V cell. All three cells have their positive terminals towards the upper side.

Step 2: Apply the loop and junction rules In each chosen B-to-F path, the cell contributes a drop. Thus

$$V = 4I_L + 3 = 4I_M + 6 = 4I_R + 6.$$

There is no external current supplied at B, so the algebraically signed outgoing currents obey

$$\begin{aligned} I_L + I_M + I_R &= 0, \\ \frac{V-3}{4} + \frac{V-6}{4} + \frac{V-6}{4} &= 0, \\ 3V - 15 &= 0, \quad V = 5\text{ V}. \end{aligned}$$

Step 3: Interpret the signs of the currents Substituting the node potential difference gives

$$I_L = \frac{5-3}{4} = 0.50\text{ A}, \quad I_M = I_R = \frac{5-6}{4} = -0.25\text{ A}.$$

The positive left-branch value follows B–A–G–F. The negative middle and right values reverse their assumed paths. Thus the two upper-directed currents of 0.25 A combine at B to supply the left branch, checking charge conservation.

Step 4: Conclusion In AG, the current is 0.50 A from A to G. In BF, it is 0.25 A from F to B. In CD, it is 0.25 A from D to C.

Quick Tip to Solve: Treat this circuit as three parallel B–F branches, each of resistance $4\ \Omega$; choose all branch currents in one direction and let negative answers reverse that direction.

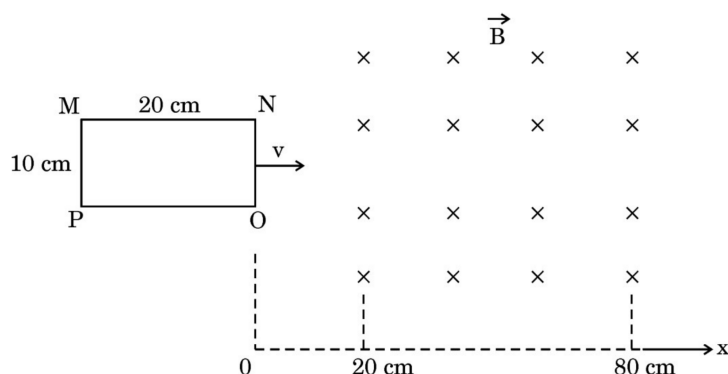
24. A rectangular loop of sides 10 cm $\times$ 20 cm is kept outside a region of uniform magnetic field $|\vec{B}| = 5 \text{ mT}$ as shown in the figure. The loop is moved with the velocity of 5 cm/s till it goes completely out of the magnetic field.

(a) Plot a graph showing variation of the magnetic flux ϕ with x ($0 \leq x \leq 100 \text{ cm}$).

(b) Find the maximum value of magnetic flux linked with the loop.

(c) Will an external work be required to be done to move the loop through the magnetic field?

[3 marks]



Solution:

Concept:

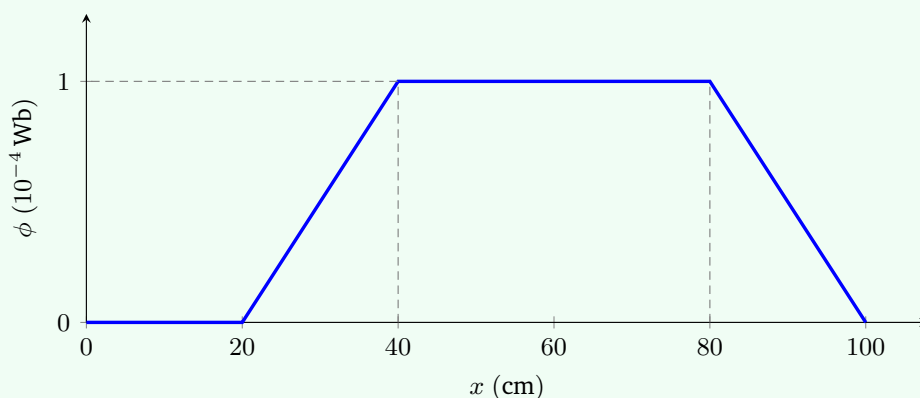
- Magnetic flux is $\phi = BA_{\text{overlap}}$ for a uniform field perpendicular to the loop. Here the positive area normal is chosen into the page, along the field.
- Faraday's law gives $\mathcal{E} = -d\phi/dt$. Lenz's law makes the induced current oppose the change in flux, producing a force that opposes the motion during entry and exit.

Step 1: Locate the edges of the moving loop Let x be the position of the leading edge NO in centimetres, measured from its initial position in the diagram. The trailing edge MP is then at $x - 20$. The magnetic field occupies $20 \leq x \leq 80 \text{ cm}$, while the loop height is $10 \text{ cm} = 0.10 \text{ m}$. No area overlaps the field until $x = 20 \text{ cm}$; entry finishes at $x = 40 \text{ cm}$. The loop remains fully inside up to $x = 80 \text{ cm}$, and leaves completely at $x = 100 \text{ cm}$.

Step 2: Plot the flux for part (a) Multiply the overlap width by the height and by $B = 5 \times 10^{-3} \text{ T}$. With x expressed numerically in centimetres,

$$\phi(x) = \begin{cases} 0, & 0 \leq x \leq 20, \\ 5 \times 10^{-6}(x - 20) \text{ Wb}, & 20 \leq x \leq 40, \\ 1.0 \times 10^{-4} \text{ Wb}, & 40 \leq x \leq 80, \\ 5 \times 10^{-6}(100 - x) \text{ Wb}, & 80 \leq x \leq 100. \end{cases}$$

Thus the graph is initially zero, rises linearly, remains constant and falls linearly to zero. The nonzero slopes occur only while one vertical side crosses a field boundary.



Flux versus the position of the leading edge; positive flux is into the page.

Step 3: Calculate the maximum flux for part (b) When the loop is completely within the field, the entire area contributes:

$$\phi_{\max} = B(0.10)(0.20) = (5 \times 10^{-3})(0.020) = 1.0 \times 10^{-4} \text{ Wb}.$$

Choosing the opposite area normal would reverse the sign of the plotted flux; its maximum magnitude is unchanged.

Step 4: Explain the external work for part (c) Yes. During entry and exit the changing flux induces a current in the conducting loop. Its magnetic force opposes the motion, so an external force must supply positive work to maintain the stated constant speed $v = 5 \text{ cm s}^{-1}$. This work becomes Joule heat. While the loop is fully inside the uniform field, its flux is constant, the net induced emf is zero and no work against an induced magnetic drag is needed. The same is true while the loop is entirely outside the field, neglecting friction.

Step 5: Conclusion The flux rises between 20 and 40 cm, is constant until 80 cm and falls to zero at 100 cm. Its maximum value is $1.0 \times 10^{-4} \text{ Wb}$. External work is required during entry and exit to overcome the induced magnetic resistance to motion.

Quick Tip to Solve: Track the leading and trailing edges separately: shift each field boundary by the loop's 20 cm width to locate the four corners of the flux graph.

25(a). Two long, straight, parallel conductors carry steady currents in opposite directions. Explain the nature of the force of interaction between them. Obtain an expression for the magnitude of the force between the two conductors. Hence define one ampere. [3 marks]

Solution:

Concept:

- A long straight wire carrying current I_1 produces magnetic field $B_1 = \mu_0 I_1 / (2\pi d)$ at perpendicular distance d in vacuum. The field direction follows the right-hand thumb rule.
- The force on a straight length L carrying current I_2 is $\vec{F} = I_2 \vec{L} \times \vec{B}$, where $\vec{L}$ points along the conventional current. Here the wire and field are perpendicular.

Step 1: Determine the nature of interaction Imagine conductor 1 on the left with its current upward, and conductor 2 on the right with its current downward. At conductor 2, the field due to conductor 1 points into the page. Applying $I_2 \vec{L} \times \vec{B}_1$, the force on conductor 2 points to the right, away from

conductor 1. Similarly, the force on conductor 1 points left. Therefore opposite parallel currents repel; the forces have equal magnitudes and opposite directions.

Step 2: Derive the force on a length L Let the currents have magnitudes I_1 and I_2 , and let the separation be d . The magnetic field of conductor 1 is perpendicular to conductor 2, so

$$B_1 = \frac{\mu_0 I_1}{2\pi d},$$

$$F_{21} = I_2 L B_1 \sin 90^\circ = \frac{\mu_0 I_1 I_2 L}{2\pi d},$$

$$\frac{F}{L} = \frac{\mu_0 I_1 I_2}{2\pi d}.$$

Interchanging the two conductors gives the same magnitude. The length L refers to the portion whose force is being calculated; for indefinitely long wires, the meaningful result is the force per unit length. End effects are neglected in this long-wire approximation.

Step 3: State the force-based definition of one ampere Put $I_1 = I_2 = 1 \text{ A}$ and $d = 1 \text{ m}$. Using the usual school value $\mu_0 = 4\pi \times 10^{-7} \text{ N A}^{-2}$,

$$\frac{F}{L} = \frac{4\pi \times 10^{-7} \times 1 \times 1}{2\pi \times 1} = 2 \times 10^{-7} \text{ N m}^{-1}.$$

In the traditional force-based definition asked here, one ampere is the constant current which, if maintained in each of two straight parallel conductors of infinite length and negligible circular cross-section, placed one metre apart in vacuum, produces a force of $2 \times 10^{-7} \text{ N}$ per metre of length between them. Opposite directions give repulsion, while equal directions give attraction of the same magnitude.

Step 4: Conclusion Opposite steady currents repel. The force on length L is $F = \mu_0 I_1 I_2 L / (2\pi d)$, or $F/L = \mu_0 I_1 I_2 / (2\pi d)$. The traditional one-ampere condition gives $2 \times 10^{-7} \text{ N m}^{-1}$ at a separation of 1 m in vacuum.

Quick Tip to Solve: First find the magnetic field of one wire at the other, then use $F = ILB$; opposite current directions change attraction to repulsion without changing the force magnitude.

OR

25(b). Obtain an expression for the torque $\vec{\tau}$ acting on a current carrying loop in a uniform magnetic field $\vec{B}$. Draw the necessary diagram. [3 marks]

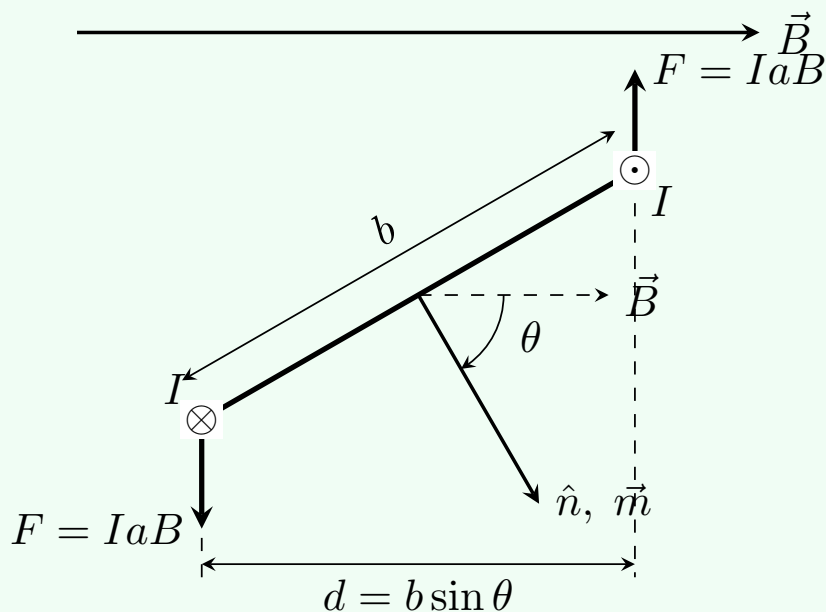
Solution:

Concept:

- A straight conductor carrying current I in a uniform magnetic field experiences $\vec{F} = I\vec{l} \times \vec{B}$, where $\vec{l}$ points along the current.
- A current loop has magnetic dipole moment $\vec{m} = IA\hat{n}$, where A is its area and $\hat{n}$ is the unit normal given by the right-hand rule. A couple has torque equal to either force times the perpendicular distance between their lines of action.

Step 1: Choose a rectangular loop and identify the forces Consider a rectangular loop of sides a and b , carrying current I , with area $A = ab$. Let its normal $\hat{n}$ make angle θ with the uniform field $\vec{B}$. Choose the two sides of length a perpendicular to the field. Each experiences a force $F = IaB$; the

forces are equal and opposite and form a couple. The forces on the other two sides cancel and give no net torque about the centre. Hence the total force on the loop is zero, although its torque need not be zero. In the edge-on view below, the two sides of length a run perpendicular to the page. The symbols $\odot$ and $\otimes$ indicate current out of and into the page, respectively.



Edge-on view of the rectangular loop: the active sides have length a , perpendicular to the page.

Step 2: Calculate the moment of the couple The separation of the two active sides is b in the plane of the loop. Since θ is the angle between the normal and the field, the perpendicular distance between the lines of action of their forces is $d = b \sin \theta$. Adding the equal moments about the centre gives

$$\begin{aligned}\tau &= F \frac{d}{2} + F \frac{d}{2} = Fd \\ &= IaB (b \sin \theta) = IAB \sin \theta.\end{aligned}$$

The couple turns the loop so that its magnetic moment tends to align with the field. Its direction follows $\vec{m} \times \vec{B}$. This result holds for a plane loop of any shape; for N identical turns, the torques add and $\vec{m} = NIA\hat{n}$.

Step 3: Conclusion For a single current-carrying loop, $\vec{\tau} = \vec{m} \times \vec{B} = IA\hat{n} \times \vec{B}$, so $\tau = IAB \sin \theta$. For N turns, $\tau = N IAB \sin \theta$. Torque is zero when the normal is parallel or antiparallel to the field and maximum when the normal is perpendicular to it.

Quick Tip to Solve: Measure θ from the loop's normal, not its plane; then use $\tau = IAB \sin \theta$ and the right-hand rule for its direction.

26. (a) Briefly explain de Broglie hypothesis for wave nature of matter.

(b) Find the ratio of de Broglie wavelength associated with a proton and an alpha particle when both are

(i) accelerated from rest through the same potential difference, and

(ii) moving with the same kinetic energy.

[3 marks]

Solution:

Concept:

- According to de Broglie, every moving material particle has an associated matter wave of wavelength $\lambda = h/p$, where h is Planck's constant and p is the particle's momentum.
- For a non-relativistic particle of mass m and kinetic energy K , $p = \sqrt{2mK}$. A charge q accelerated from rest through a potential difference of magnitude V gains energy $K = qV$.

Step 1: Explain the matter-wave hypothesis (a) De Broglie proposed that wave-particle duality applies to matter as well as radiation: a moving particle is associated with a wave whose wavelength is inversely proportional to its momentum,

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

in the non-relativistic limit. These are matter waves, not electromagnetic waves emitted by the particle. Their wave nature is observable through diffraction and interference. For ordinary macroscopic bodies the momentum is large and the wavelength is too small to be readily observed.

Step 2: Compare wavelengths at equal accelerating potential (b)(i) Write the proton's mass and charge as m_p and e . An alpha particle has approximately $m_\alpha = 4m_p$ and $q_\alpha = 2e$. Using the same accelerating potential V ,

$$\lambda = \frac{h}{\sqrt{2mqV}}, \quad \frac{\lambda_p}{\lambda_\alpha} = \sqrt{\frac{m_\alpha q_\alpha}{m_p e}} = \sqrt{\frac{(4m_p)(2e)}{m_p e}} = \sqrt{8}.$$

The alpha particle gains twice the kinetic energy of the proton because its charge is twice as large; equal potential therefore does not mean equal kinetic energy.

Step 3: Compare wavelengths at equal kinetic energy (b)(ii) When both particles have the same kinetic energy K , the charge no longer enters the momentum expression. Thus

$$\frac{\lambda_p}{\lambda_\alpha} = \frac{h/\sqrt{2m_p K}}{h/\sqrt{2m_\alpha K}} = \sqrt{\frac{m_\alpha}{m_p}} = \sqrt{4} = 2.$$

The heavier alpha particle has the larger momentum for fixed kinetic energy and therefore the smaller de Broglie wavelength.

Step 4: Conclusion De Broglie's hypothesis gives $\lambda = h/p$. In the order proton : alpha particle, the wavelength ratios are $2\sqrt{2} : 1$ for equal accelerating potential and $2 : 1$ for equal kinetic energy, using $m_\alpha \simeq 4m_p$.

Quick Tip to Solve: At equal potential compare mq under a square root; at equal kinetic energy compare only mass. Always invert the momentum ratio to obtain the wavelength ratio.

27. (a) Plot a graph depicting potential energy of a pair of nucleons in a nucleus as a function of their separation.

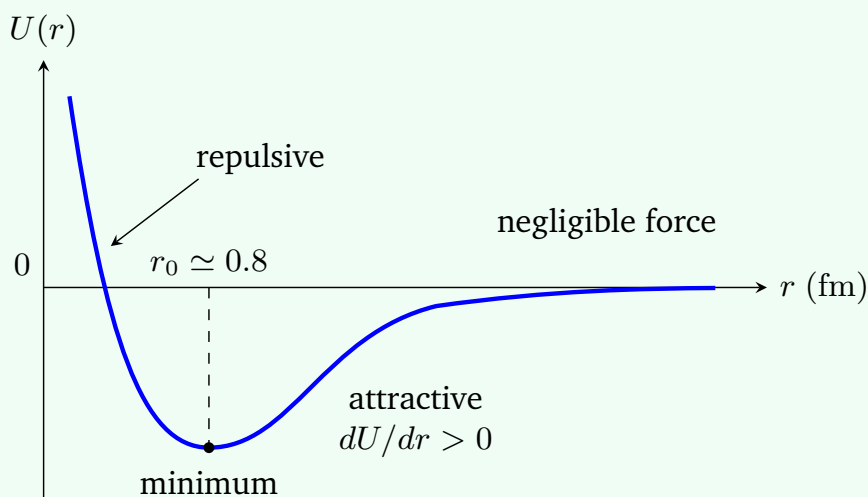
(b) Identify the regions where the nuclear force is (i) attractive, and (ii) repulsive. Justify your answer. [3 marks]

Solution:

Concept:

- Nuclear potential energy $U(r)$ depends on the separation r of two nucleons; choose $U = 0$ at very large separation.
- The radial force is $F_r = -dU/dr$. Positive F_r increases separation (repulsion), while negative F_r decreases separation (attraction).

Step 1: Sketch the nuclear potential well (a) At very small separation the potential rises steeply, representing a strong repulsive core. As separation increases, the curve falls to a negative minimum at $r = r_0$, approximately 0.8 fm. It then rises towards zero as the nucleons move beyond the short range of the nuclear interaction, a few femtometres. The depth and exact profile are schematic; the minimum and the signs of the slopes are the essential features.



Schematic nucleon potential: the force changes sign at the minimum.

Step 2: Use the slope to identify the force (b) For $r > r_0$ within the interaction range, U increases with r , so $dU/dr > 0$ and $F_r < 0$. The force acts towards decreasing separation and is therefore attractive. For $r < r_0$, U decreases as r increases, giving $dU/dr < 0$ and $F_r > 0$; the force pushes the nucleons apart and is repulsive. At the minimum, $dU/dr = 0$, so the force vanishes. At large separation the potential is almost flat and the nuclear force is negligible. Thus the force follows the slope of the curve, not merely the sign of potential energy.

Step 3: Conclusion The graph has a steep repulsive core and a negative potential well. The nuclear force is repulsive for $r < r_0$, attractive for $r > r_0$ within its short range, and negligible far beyond that range.

Quick Tip to Solve: Read the slope of the potential curve: a falling curve means repulsion and a rising curve means attraction, because $F_r = -dU/dr$.

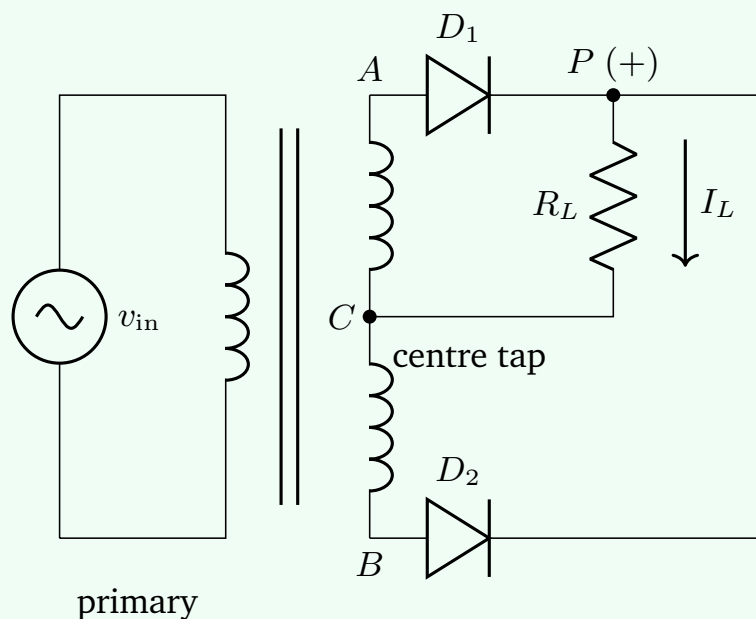
28. With the help of a circuit diagram, explain the working of a p-n junction diode as a full wave rectifier. Draw its input and output waveforms. [3 marks]

Solution:

Concept:

- A p-n junction diode conducts when forward biased and blocks current when reverse biased, in the ideal-diode approximation.
- A centre-tapped transformer and two diodes rectify both half-cycles. The load current has the same direction during each half-cycle, producing pulsating direct current.

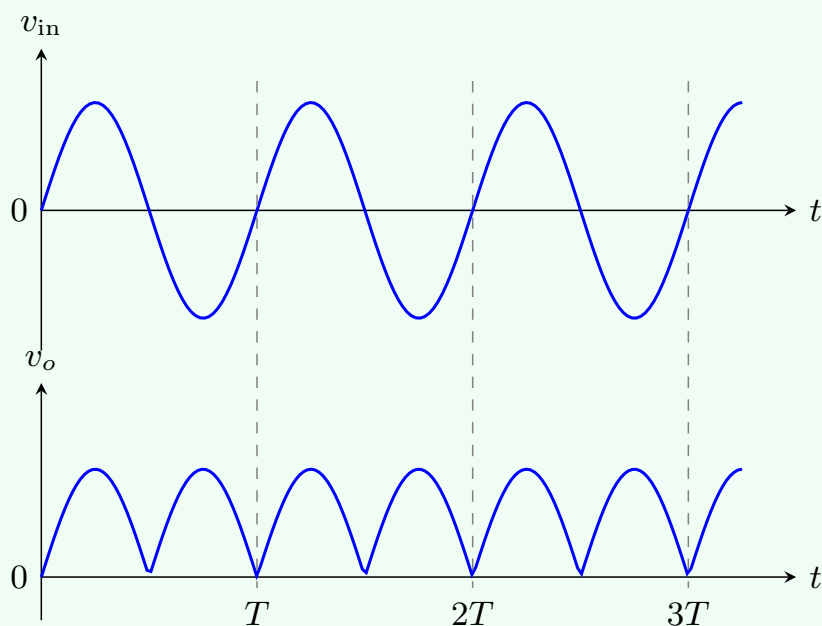
Step 1: Connect the full-wave rectifier Connect the ends A and B of a centre-tapped transformer secondary to the anodes of diodes D_1 and D_2 . Join their cathodes to the positive output terminal P . Connect the load resistance R_L between P and the centre tap C . The primary receives the alternating input. Relative to C , the secondary end voltages have equal amplitudes and opposite phases.



Centre-tapped full-wave rectifier; both cathodes join at the positive output.

Step 2: Follow the current in each half-cycle During the half-cycle in which A is positive relative to C , D_1 is forward biased and D_2 is reverse biased. Current flows from A through D_1 , then from P through R_L to C , returning through the upper secondary winding. During the next half-cycle, B becomes positive relative to C , so D_2 conducts and D_1 blocks. Current flows from B through D_2 and again from P through R_L to C , returning through the lower secondary winding.

Step 3: Draw and interpret the waveforms If the voltage of A relative to C is $v_{AC} = V_m \sin \omega t$, then $v_{BC} = -V_m \sin \omega t$. Neglecting diode voltage drops, the output is $v_o = V_m |\sin \omega t|$. The input waveform alternates in sign, whereas both halves of the output lie above zero. There are two output pulses in one input cycle; thus an input frequency f gives output ripple frequency $2f$. Without a filter, the output is unidirectional but is not constant.



Alternating input and ideal full-wave output versus time (amplitudes schematic).

Step 4: Conclusion The diodes conduct alternately, maintaining current through R_L from P to C during both half-cycles. Hence the circuit produces full-wave rectified, pulsating DC.

Quick Tip to Solve: Trace each conducting loop separately: both diode cathodes meet at the positive output, so both half-cycles drive load current in the same direction.

Section D (8 marks)

Case Study Based Questions

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

29. When a ray of light propagates from a denser medium to a rarer medium, it bends away from the normal. When the incident angle is increased, the refracted ray deviates more from the normal. For a particular angle of incidence in the denser medium, the refracted ray just grazes the interface of the two surfaces. This angle of incidence is called the critical angle for the pair of media involved.

[4 marks]

29(i). For a ray incident at the critical angle, the angle of reflection is:

[1 mark]

- (A) 0°
- (B) $< 90^\circ$
- (C) $> 90^\circ$
- (D) 90°

Correct Answer: (B) $< 90^\circ$

Solution:

Concept:

- The law of reflection gives $\theta_{\text{reflection}} = i$, with both angles measured from the normal.
- For denser-to-rarer refraction, the critical angle i_c satisfies $\sin i_c = n_r/n_d < 1$, where $n_d > n_r$ are

the refractive indices.

Step 1: Distinguish the reflected and refracted rays At critical incidence the refracted ray grazes the boundary, so its angle with the normal is 90° . The reflected ray still obeys the ordinary law of reflection; its angle equals the incident critical angle.

Step 2: Compare the angle with the choices Since $0 < n_r/n_d < 1$, the critical angle lies strictly between 0° and 90° . Hence the reflection angle is acute. Option (A) would require normal incidence; (C) exceeds the possible reflection angle; and (D) confuses refraction at the critical angle with reflection.

Step 3: Conclusion $\theta_{\text{reflection}} = i_c < 90^\circ$. Hence, the correct option is (B).

Quick Tip to Solve: At the critical angle, attach 90° to the refracted ray only; the reflected ray has the same angle as the incident ray.

29(ii). A ray of light of wavelength 600 nm is incident in water $\left(n = \frac{4}{3}\right)$ on the water-air interface at an angle less than the critical angle. The wavelength associated with the refracted ray is: [1 mark]

(A) 400 nm

(B) 450 nm

(C) 600 nm

(D) 800 nm

Correct Answer: (D) 800 nm

Solution:

Concept:

- At refraction across a stationary interface, frequency ν remains unchanged, whereas speed and wavelength change.
- The relations $v = c/n$ and $\lambda = v/\nu$ imply $n_1\lambda_1 = n_2\lambda_2$, with n the refractive index.

Step 1: Interpret the incident wavelength The stated 600 nm is the wavelength of the incident ray in water. The ray passes into air because the incidence angle is below the critical angle. Take $n_{\text{air}} \simeq 1$; the speed therefore increases on leaving water, while frequency is conserved.

Step 2: Calculate the wavelength in air Using the equal-frequency relation,

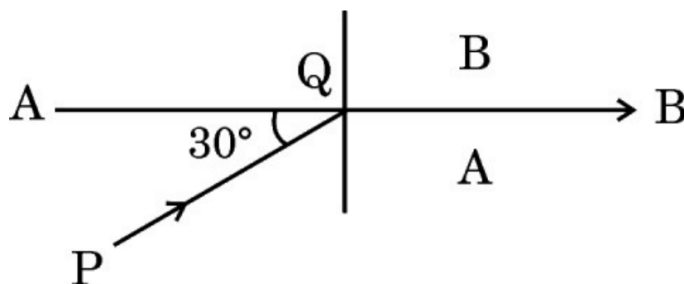
$$\lambda_{\text{air}} = \frac{n_{\text{water}}}{n_{\text{air}}} \lambda_{\text{water}} = \frac{4/3}{1} \times 600 \text{ nm} = 800 \text{ nm}.$$

Options (A) and (B) incorrectly make the wavelength decrease in the optically rarer medium. Option (C) would assume that wavelength, rather than frequency, remains unchanged. The incidence angle determines direction, but does not change this wavelength ratio.

Step 3: Conclusion The refracted wavelength is 800 nm. Hence, the correct option is (D).

Quick Tip to Solve: When light goes from water to air, multiply its wavelength in water by $4/3$; its frequency stays the same while its speed increases.

29(iii)(a). The interface AB between the two media A and B is shown in the figure. In the denser medium A, the incident ray PQ makes an angle of 30° with the horizontal. The refracted ray is parallel to the interface. The refractive index of medium B w.r.t. medium A is: [1 mark]



- (A) $\frac{\sqrt{3}}{2}$
- (B) $\frac{\sqrt{5}}{2}$
- (C) $\frac{4}{\sqrt{3}}$
- (D) $\frac{2}{\sqrt{3}}$

Correct Answer: (A) $\frac{\sqrt{3}}{2}$

Solution:

Concept:

- Snell's law is $n_A \sin i = n_B \sin r$, where angles are measured from the normal.
- The refractive index of B with respect to A is $n_{BA} = n_B/n_A$. For grazing refraction, $r = 90^\circ$.

Step 1: Measure incidence from the normal The marked 30° is the angle between the incident ray and the horizontal interface, not the normal. Since the normal is perpendicular to the interface, the angle of incidence is

$$i = 90^\circ - 30^\circ = 60^\circ.$$

The ray along the interface establishes that this is the critical incidence.

Step 2: Apply Snell's law With $\sin r = 1$, Snell's law gives

$$\frac{n_B}{n_A} = \frac{\sin 60^\circ}{\sin 90^\circ} = \frac{\sqrt{3}}{2}.$$

Each of options (B), (C) and (D) exceeds unity, which cannot represent the refractive index of the rarer medium relative to the denser medium.

Step 3: Conclusion The relative refractive index is $\sqrt{3}/2$. Hence, the correct option is (A).

Quick Tip to Solve: First replace an angle measured from the surface by its complement; a rarer-to-denser index ratio must be below unity.

29(iii)(b). Two media A and B are separated by a plane boundary. The speed of light in medium A and B is $2 \times 10^8 \text{ ms}^{-1}$ and $2.5 \times 10^8 \text{ ms}^{-1}$ respectively. The critical angle for a ray of light going from medium A to medium B is: [1 mark]

- (A) $\sin^{-1} \frac{1}{2}$
 (B) $\sin^{-1} \frac{4}{5}$
 (C) $\sin^{-1} \frac{3}{5}$
 (D) $\sin^{-1} \frac{2}{5}$

Correct Answer: (B) $\sin^{-1} \frac{4}{5}$

Solution:

Concept:

- Absolute refractive index is $n = c/v$, where v is the speed of light in the medium.
- At the critical angle C , $n_A \sin C = n_B$, since the refracted angle is 90° .

Step 1: Identify the denser medium The speeds are $v_A = 2 \times 10^8 \text{ m s}^{-1}$ and $v_B = 2.5 \times 10^8 \text{ m s}^{-1}$. Light is slower in A, so $n_A > n_B$; travel from A to B therefore admits a critical angle.

Step 2: Calculate the critical-angle ratio Substituting the inverse dependence of refractive index on speed gives

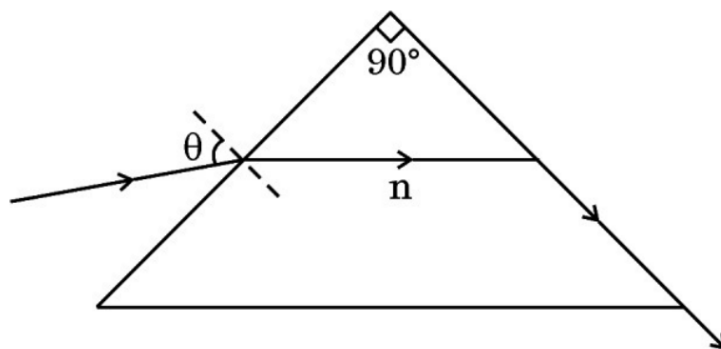
$$\sin C = \frac{n_B}{n_A} = \frac{c/v_B}{c/v_A} = \frac{v_A}{v_B} = \frac{2}{2.5} = \frac{4}{5}.$$

The values $1/2$, $3/5$ and $2/5$ in the other choices do not equal the given speed ratio. Reversing the ratio would give a sine greater than one.

Step 3: Conclusion The critical angle is $C = \sin^{-1}(4/5)$. Hence, the correct option is (B).

Quick Tip to Solve: For the critical angle expressed through speeds, divide the slower speed by the faster speed.

29(iv). The figure shows the path of a light ray through a triangular prism. In this phenomenon, the angle θ is given by: [1 mark]



(A) $\sin^{-1} \sqrt{n^2 - 1}$

(B) $\sin^{-1}(n^2 - 1)$

(C) $\sin^{-1} \sqrt{\frac{1}{n^2 - 1}}$

(D) $\sin^{-1} \frac{1}{(n^2 - 1)}$

Correct Answer: (A) $\sin^{-1} \sqrt{n^2 - 1}$

Solution:

Concept:

- For a prism of apex angle A , the internal angles measured from the two face normals obey $r_1 + r_2 = A$.
- Snell's law at an air-prism interface is $\sin i = n \sin r_1$; at grazing emergence, $n \sin r_2 = 1$.

Step 1: Use the grazing emergent ray The outgoing ray lies along the second face, so its angle to that face's normal is 90° . Thus $r_2 = C$, with $\sin C = 1/n$. Since the apex angle is 90° ,

$$r_1 = 90^\circ - C.$$

The marked θ is the external incidence angle measured from the dashed normal at the first face.

Step 2: Apply refraction at the first face Taking the surrounding medium as air,

$$\begin{aligned} \sin \theta &= n \sin r_1 = n \cos C \\ &= n \sqrt{1 - \frac{1}{n^2}} = \sqrt{n^2 - 1}. \end{aligned}$$

Option (B) omits the square root; options (C) and (D) introduce an unsupported reciprocal. The illustrated path is possible when the derived sine does not exceed one.

Step 3: Conclusion Therefore $\theta = \sin^{-1} \sqrt{n^2 - 1}$. Hence, the correct option is (A).

Quick Tip to Solve: Grazing emergence fixes the second internal angle at the critical angle; then use the prism relation before applying Snell's law at entry.

30. When the terminals of a cell are connected to a conductor of resistance R , an electric current flows through the circuit. The electrolyte of the cell also offers some resistance in the path of the current, like the conductor. This resistance offered by the electrolyte is called internal resistance of the cell (r). It depends upon the nature of the electrolyte, the area of the electrodes immersed in the electrolyte and the temperature. Due to internal resistance, a part of the energy supplied by the cell is wasted in the form of heat.

When no current is drawn from the cell, the potential difference between the two electrodes is known as emf of the cell (ε). With a current drawn from the cell, the potential difference between the two electrodes is termed as terminal potential difference (V). [4 marks]

30(i). Choose the incorrect statement: [1 mark]

- (A) The potential difference (V) between the two terminals of a cell in a closed circuit is always less than its emf (ε), during discharge of the cell.
- (B) The internal resistance of a cell decreases with the decrease in temperature of the electrolyte.
- (C) When current is drawn from the cell then $V = \varepsilon - Ir$.
- (D) The graph between potential difference between the two terminals of the cell (V) and the current (I) through it is a straight line with a negative slope.

Correct Answer: (B) The internal resistance of a cell decreases with the decrease in temperature of the electrolyte.

Solution:

Concept:

- For a discharging cell, $V = \varepsilon - Ir$, where r is internal resistance and I is the delivered current.
- In an electrolyte, increasing temperature generally improves ionic conduction and decreases internal resistance.

Step 1: Check the circuit statements In the stated discharging circuit, $I > 0$ and $r > 0$, so the lost potential Ir is positive and $V < \varepsilon$. Statements (A) and (C) are therefore correct. For fixed emf and internal resistance, $V = \varepsilon - rI$ is a straight-line relation with vertical intercept ε and slope $-r$; statement (D) is also correct.

Step 2: Check the temperature statement Lowering the temperature reduces ionic mobility in the electrolyte and generally increases, rather than decreases, its resistance. Statement (B) reverses the expected temperature dependence of an electrolyte. The question asks for the incorrect statement, so the three consistent circuit statements must be rejected as answers.

Step 3: Conclusion The incorrect statement is the claim that internal resistance decreases when electrolyte temperature decreases. Hence, the correct option is (B).

Quick Tip to Solve: Underline 'incorrect' and remember that electrolyte resistance usually falls on heating, unlike the resistance of a metal.

30(ii). Two cells of emfs 2.0 V and 6.0 V and internal resistances $0.1\ \Omega$ and $0.4\ \Omega$ respectively, are connected in parallel. The equivalent emf of the combination will be: [1 mark]

- (A) 2.0 V
- (B) 2.8 V
- (C) 6.0 V
- (D) 8.0 V

Correct Answer: (B) 2.8 V

Solution:

Concept:

- For two cells connected in parallel with like terminals together, $\varepsilon_{\text{eq}} = (\varepsilon_1/r_1 + \varepsilon_2/r_2)/(1/r_1 + 1/r_2)$.
- The equivalent emf is an average weighted by conductance $1/r$, not the sum of the two emfs.

Step 1: Insert the cell data Here $\varepsilon_1 = 2.0\text{ V}$, $r_1 = 0.1\ \Omega$, $\varepsilon_2 = 6.0\text{ V}$ and $r_2 = 0.4\ \Omega$. Multiplying numerator and denominator of the parallel-cell expression by $r_1 r_2$ gives

$$\varepsilon_{\text{eq}} = \frac{\varepsilon_1 r_2 + \varepsilon_2 r_1}{r_1 + r_2}.$$

Step 2: Evaluate and check the weighting Substitution yields

$$\varepsilon_{\text{eq}} = \frac{2.0(0.4) + 6.0(0.1)}{0.1 + 0.4} = \frac{1.4}{0.5}\text{ V} = 2.8\text{ V}.$$

This lies between the two emfs and closer to the cell with smaller internal resistance. Neither individual emf, options (A) and (C), describes both cells together; 8.0 V would correspond to adding series emfs.

Step 3: Conclusion The equivalent emf is 2.8 V. Hence, the correct option is (B).

Quick Tip to Solve: Use the cross-weighted numerator $\varepsilon_1 r_2 + \varepsilon_2 r_1$; the smaller-resistance cell pulls the equivalent emf closer to its own value.

30(iii). Dipped in the solution, the electrode exchanges charges with the electrolyte. The positive electrode develops a potential V_+ ($V_+ > 0$), and the negative electrode develops a potential $-V_-$ ($V_- \geq 0$), relative to the electrolyte adjacent to it. When no current is drawn from the cell then: [1 mark]

- (A) $\varepsilon = V_+ + V_- > 0$
- (B) $\varepsilon = V_+ - V_- > 0$
- (C) $\varepsilon = V_+ + V_- < 0$
- (D) $\varepsilon = V_+ + V_- = 0$

Correct Answer: (A) $\varepsilon = V_+ + V_- > 0$

Solution:

Concept:

- At open circuit, no current flows and the terminal potential difference equals the cell emf.
- Potential difference is the signed final potential minus initial potential; the negative electrode here has potential $-V_-$, where $V_- \geq 0$.

Step 1: Keep the electrode signs explicit Choose the electrolyte potential as the reference. The positive electrode is at $+V_+$ and the negative electrode is at $-V_-$. The symbols V_+ and V_- denote a positive and a nonnegative magnitude, respectively; the minus sign in the potential of the negative electrode must not be discarded.

Step 2: Find the open-circuit potential difference The emf is the positive-terminal potential minus the negative-terminal potential:

$$\varepsilon = (+V_+) - (-V_-) = V_+ + V_-.$$

This is positive because $V_+ > 0$ and $V_- \geq 0$. Option (B) incorrectly subtracts the magnitude of the negative potential. Options (C) and (D) incorrectly assign a negative or zero value to the sum of a positive magnitude and a nonnegative magnitude.

Step 3: Conclusion Thus $\varepsilon = V_+ + V_- > 0$. Hence, the correct option is (A).

Quick Tip to Solve: Write electrode potentials with their signs before subtracting: subtracting the negative electrode potential adds its magnitude.

30(iv)(a). Five identical cells, each of emf 2 V and internal resistance $0.1 \, \Omega$ are connected in parallel. This combination in turn is connected to an external resistor of $9.98 \, \Omega$. The current flowing through the resistor is: [1 mark]

- (A) 0.05 A
- (B) 0.1 A
- (C) 0.15 A
- (D) 0.2 A

Correct Answer: (D) 0.2 A

Solution:

Concept:

- For N identical cells in parallel with like terminals joined, $\varepsilon_{\text{eq}} = \varepsilon$ and $r_{\text{eq}} = r/N$.
- The current through an external resistance R is $I = \varepsilon_{\text{eq}}/(R + r_{\text{eq}})$.

Step 1: Replace the parallel cells by one equivalent cell All five cells have emf 2 V, so the combination still has emf 2 V. Their equal internal resistances combine in parallel:

$$r_{\text{eq}} = \frac{0.1}{5} \, \Omega = 0.02 \, \Omega.$$

Adding the emfs would incorrectly treat the cells as a series combination.

Step 2: Include the internal resistance in the circuit The equivalent internal resistance is in series with the external resistor. Hence

$$I = \frac{2}{9.98 + 0.02} \, \text{A} = \frac{2}{10.00} \, \text{A} = 0.20 \, \text{A}.$$

The smaller currents in options (A), (B) and (C) do not satisfy Ohm's law for the 2 V, 10.00 Ω equivalent circuit. The current calculated is the total load current, not the current delivered by an individual cell.

Step 3: Conclusion The current through the external resistor is 0.2 A. Hence, the correct option is (D).

Quick Tip to Solve: Identical parallel cells retain one cell's emf while dividing its internal resistance by the number of cells.

OR

30(iv)(b). Potential difference across a cell in the open circuit is 6 V. It becomes 4 V when a current of 2 A is drawn from it. The internal resistance of the cell is: [1 mark]

- (A) 1.0 Ω
- (B) 1.5 Ω
- (C) 2.0 Ω
- (D) 2.5 Ω

Correct Answer: (A) 1.0 Ω

Solution:

Concept:

- An open-circuit terminal voltage equals the emf ε , because $I = 0$ gives no internal voltage drop.
- When a cell supplies current, $V = \varepsilon - Ir$, so $r = (\varepsilon - V)/I$.

Step 1: Identify the emf and the lost voltage The open-circuit reading gives $\varepsilon = 6$ V. When $I = 2$ A is drawn, the terminal voltage is $V = 4$ V. The voltage lost across the cell's internal resistance is therefore

$$Ir = \varepsilon - V = (6 - 4) \text{ V} = 2 \text{ V}.$$

Step 2: Divide the internal voltage drop by current Using Ohm's law for the internal resistance gives

$$r = \frac{2 \text{ V}}{2 \text{ A}} = 1.0 \Omega.$$

Options (B), (C) and (D) would produce internal drops of 3 V, 4 V and 5 V, respectively, inconsistent with the observed 2 V reduction. The ratio $V/I = 2 \Omega$ instead describes the external resistance.

Step 3: Conclusion The cell's internal resistance is 1.0 Ω . Hence, the correct option is (A).

Quick Tip to Solve: Use the decrease from open-circuit to loaded voltage for internal resistance; the loaded voltage alone gives the external resistance.

Section E (15 marks)

- 31(a).** (i) Give any two differences between the interference pattern obtained in Young's double-slit experiment and a diffraction pattern due to a single slit.
- (ii) Draw an intensity distribution graph in case of a double-slit interference pattern.
- (iii) In Young's double-slit experiment using monochromatic light of wavelength λ , the intensity of light at a point on the screen, where path difference is λ , is K units. Find the intensity of light at a point on the screen where the path difference is $\frac{\lambda}{6}$. [5 marks]

Solution:

Concept:

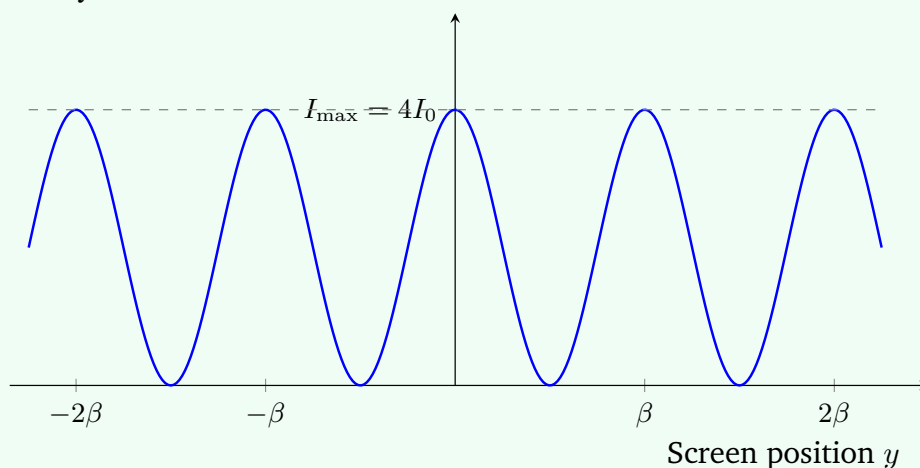
- Interference is the superposition of light from two coherent slits; single-slit diffraction is the superposition of secondary waves from different parts of one slit.
- For two equally illuminated narrow slits, each contributing intensity I_0 , the resultant intensity is $I = 4I_0 \cos^2(\phi/2)$, where $\phi = 2\pi\Delta/\lambda$, Δ is the path difference and λ is the wavelength.
- In Young's experiment, fringe width is $\beta = \lambda D/d$, where D is the screen distance and d is the slit separation. Thus $I(y) = I_{\max} \cos^2(\pi y/\beta)$ for transverse screen coordinate y .

Step 1: (i) Compare the widths of the fringes In the ideal double-slit interference pattern, successive bright fringes and successive dark fringes are equally spaced; every fringe has the same width $\beta = \lambda D/d$. In single-slit diffraction, the central maximum is twice as wide as each secondary maximum, in the usual fringe-width comparison based on the bounding minima. For slit width a , its width on a distant screen is $2\lambda D/a$, whereas the width between successive minima on either side is $\lambda D/a$.

Step 2: (i) Compare the peak intensities For identical narrow slits with equal illumination, all interference maxima have the same intensity $4I_0$, while the minima are dark. This is the ideal Young's pattern, neglecting the finite-slit diffraction envelope. In a single-slit diffraction pattern, the central maximum is the brightest, and the secondary maxima become progressively weaker away from the centre. Thus uniform fringe width and equal peak heights characterise the ideal interference pattern, whereas the diffraction pattern has a broad, dominant central maximum.

Step 3: (ii) Draw the intensity distribution Take position y on the screen along the horizontal axis and resultant intensity I along the vertical axis. Maxima occur at $y = n\beta$, and minima at $y = (n + \frac{1}{2})\beta$, where n is an integer. The graph below shows equal-height, equally spaced maxima, including the central maximum at $y = 0$, with zero intensity halfway between adjacent maxima.

Intensity I



Ideal double-slit interference intensity as a function of screen position.

Step 4: (iii) Determine the maximum intensity from the given point At path difference $\Delta = \lambda$, the phase difference is 2π , so the two waves arrive in phase. Hence the stated intensity K is a maximum:

$$K = 4I_0 \cos^2 \pi = 4I_0 = I_{\max}.$$

Using the standard equal-intensity slit assumption of Young's experiment, this identifies the full intensity scale without requiring either slit intensity separately.

Step 5: (iii) Substitute the required path difference The printed required path difference is $\Delta = \lambda/6$. Convert it to phase before applying the intensity formula:

$$\phi = \frac{2\pi}{\lambda} \frac{\lambda}{6} = \frac{\pi}{3}.$$

The intensity depends on the square of the cosine of half this phase:

$$I = I_{\max} \cos^2 \frac{\phi}{2} = K \cos^2 \frac{\pi}{6} = K \left(\frac{\sqrt{3}}{2} \right)^2.$$

Step 6: Conclusion Interference fringes have uniform width and equal peak intensity in the ideal equal-slit case; diffraction has a central maximum twice as wide as the secondary fringes and successively weaker secondary maxima. The requested interference graph is shown above. At path difference $\lambda/6$, the intensity is $\boxed{3K/4}$ units.

Quick Tip to Solve: First identify K as the maximum using the integer-wavelength path difference. Then use $I/K = \cos^2(\pi\Delta/\lambda)$; the cosine takes half the phase difference.

31(b). (i) Draw a labelled ray diagram of a compound microscope showing image formation at least distance of distinct vision. Derive an expression for its magnifying power.

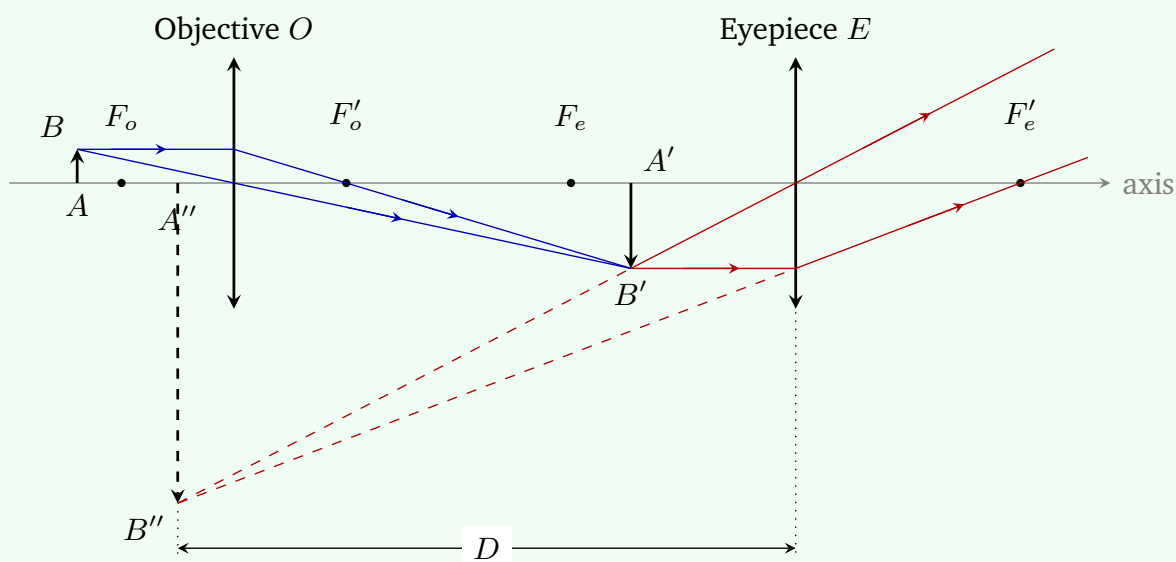
(ii) A telescope consists of two lenses of focal length 100 cm and 5 cm. Find the magnifying power when the final image is formed at infinity. [5 marks]

Solution:

Concept:

- A compound microscope combines the linear magnification of its objective with the angular magnification of its eyepiece: $M = m_o m_e$. The objective forms a real enlarged image, which acts as the object for the eyepiece.
- For a convex lens, $1/f = 1/v - 1/u$, using the Cartesian sign convention. For an eyepiece forming the image at the near point D , its angular magnification is $m_e = 1 + D/f_e$.
- In a telescope adjusted for a final image at infinity, the objective image lies in the focal plane of the eyepiece. Its angular magnifying power is $M = -f_o/f_e$; the minus sign denotes inversion.

Step 1: (i) Construct the microscope ray diagram Place the small object AB just beyond the first focal point F_o of the objective O . A ray from B parallel to the principal axis refracts through F'_o , while a ray through the optical centre of O travels undeviated. They meet at B' , producing the real, inverted and enlarged intermediate image $A'B'$. Arrange this image between the first focus F_e and the eyepiece E . Rays emerging from the eyepiece diverge; their backward extensions meet at B'' . Thus $A''B''$ is virtual, enlarged and inverted relative to AB , at distance D to the left of the eyepiece. The eye is assumed close to the eyepiece, and the sketch is not to scale.



Compound microscope: the eyepiece forms the virtual image at the near point. Dashed lines are backward extensions; the sketch is not to scale.

Step 2: Obtain the objective magnification Let $u_o < 0$ and $v_o > 0$ be the objective's object and image distances. Similar triangles formed by the ray through its optical centre give

$$m_o = \frac{A'B'}{AB} = \frac{v_o}{u_o}.$$

The negative sign indicates that the intermediate image is inverted. For a highly magnifying micro-

scope, the object lies close to the objective's focus, so $|u_o| \simeq f_o$. Taking the effective objective image distance approximately equal to the tube length L , $v_o \simeq L$, gives $m_o \simeq -L/f_o$. This last relation is the usual microscope approximation; v_o/u_o is the expression before that approximation.

Step 3: Derive the eyepiece and total magnifying powers Let the intermediate image height have magnitude h' and its distance from the eyepiece be $|u_e|$. For the final image at the least distance of distinct vision, $v_e = -D$. The eyepiece lens equation yields

$$\frac{1}{f_e} = -\frac{1}{D} + \frac{1}{|u_e|}, \quad \frac{D}{|u_e|} = 1 + \frac{D}{f_e}.$$

For small angles, the angle subtended through the eyepiece is $\beta \simeq h'/|u_e|$; the same intermediate object viewed directly at the near point subtends $\alpha \simeq h'/D$. Consequently,

$$m_e = \frac{\beta}{\alpha} = \frac{D}{|u_e|} = 1 + \frac{D}{f_e}.$$

Multiplying the objective and eyepiece factors gives

$$M = \frac{v_o}{u_o} \left(1 + \frac{D}{f_e}\right) \simeq -\frac{L}{f_o} \left(1 + \frac{D}{f_e}\right).$$

Here f_o, f_e are positive focal lengths and D is usually 25 cm for a normal eye. The magnitude is quoted when only the enlargement is required; the signed value records the inverted orientation.

Step 4: (ii) Calculate the telescope magnification The longer focal length belongs to the objective, so $f_o = 100$ cm and $f_e = 5$ cm. For an object subtending a small angle α , the objective image height is $h \simeq f_o\alpha$. In normal adjustment this image lies at the eyepiece focus, and the emergent angle has magnitude $|\beta| \simeq h/f_e$. Therefore,

$$|M| = \frac{|\beta|}{\alpha} = \frac{f_o}{f_e} = \frac{100}{5} = 20.$$

The telescope's final image is inverted, so its signed angular magnification is -20 . The near-point factor used for the microscope is inapplicable here because the telescope's final image is at infinity.

Step 5: Conclusion (i) The microscope magnifying power at the near point is $M = (v_o/u_o)(1 + D/f_e)$, with magnitude approximately $(L/f_o)(1 + D/f_e)$; the final image is virtual and inverted. (ii) The telescope has magnifying power 20 (signed value -20).

Quick Tip to Solve: Use $1 + D/f_e$ for a microscope eyepiece with the image at the near point; for a telescope at infinity, divide the objective focal length by the eyepiece focal length.

32(a). (i) Obtain an expression for the electric potential due to a small dipole of dipole moment $\vec{p}$, at a point $\vec{r}$ from its centre, for much larger distances compared to the size of the dipole.

(ii) Three point charges q , $2q$ and nq are placed at the vertices of an equilateral triangle. If the potential energy of the system is zero, find the value of n . [5 marks]

Solution:

Concept:

- Electric potential obeys scalar superposition: $V = \frac{1}{4\pi\epsilon_0} \sum_i q_i/r_i$, taking zero potential at infinity.

- An electric dipole has charges $-q_d$ and $+q_d$, separated by $2a$; its moment $\vec{p} = 2aq_d\hat{p}$ points from the negative to the positive charge.
- The electrostatic potential energy of point charges is the sum over distinct pairs: $U = \frac{1}{4\pi\epsilon_0} \sum_{i < j} q_i q_j / r_{ij}$. Each interaction is counted once.

Step 1: (i) Write the exact dipole potential Place the dipole centre at the origin and let P have position vector $\vec{r}$, of magnitude r . Let θ be the angle between $\vec{p}$ and $\vec{r}$. The distances from the positive and negative charges to P , respectively, satisfy

$$r_+^2 = r^2 + a^2 - 2ar \cos \theta, \quad r_-^2 = r^2 + a^2 + 2ar \cos \theta.$$

Since potential is a scalar, the positive and negative contributions add algebraically:

$$V(P) = \frac{q_d}{4\pi\epsilon_0} \left(\frac{1}{r_+} - \frac{1}{r_-} \right).$$

Step 2: (i) Apply the large-distance approximation For $r \gg a$, use $(1 + x)^{-1/2} \simeq 1 - x/2$, retaining terms of first order in a/r . Thus

$$\begin{aligned} \frac{1}{r_+} &\simeq \frac{1}{r} \left(1 + \frac{a \cos \theta}{r} \right), \\ \frac{1}{r_-} &\simeq \frac{1}{r} \left(1 - \frac{a \cos \theta}{r} \right). \end{aligned}$$

Subtraction cancels the $1/r$ terms because the net charge of the dipole is zero. With $p = 2aq_d$,

$$V(P) \simeq \frac{2aq_d \cos \theta}{4\pi\epsilon_0 r^2} = \frac{\vec{p} \cdot \hat{r}}{4\pi\epsilon_0 r^2} = \frac{\vec{p} \cdot \vec{r}}{4\pi\epsilon_0 r^3}.$$

This potential falls as r^{-2} ; it is positive on the positive axial side, negative on the opposite side and zero on the equatorial plane.

Step 3: (ii) Add the three pair-interaction energies Let the common side length of the equilateral triangle be ℓ . All three pair separations are ℓ , so

$$\begin{aligned} U &= \frac{1}{4\pi\epsilon_0 \ell} [q(2q) + (2q)(nq) + (nq)q] \\ &= \frac{q^2}{4\pi\epsilon_0 \ell} (2 + 3n). \end{aligned}$$

For nonzero q , the required condition $U = 0$ gives $2 + 3n = 0$. The third charge must have the opposite sign to the other two so that its attractive pair energies cancel their positive repulsive energy. The value is independent of the triangle's side length.

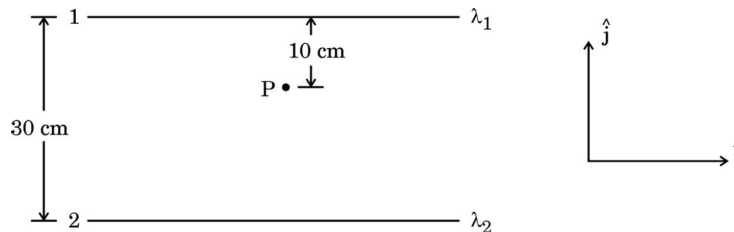
Step 4: Conclusion (i) At a distance much larger than the dipole size, $V(\vec{r}) \simeq \frac{\vec{p} \cdot \vec{r}}{4\pi\epsilon_0 r^3} = \frac{p \cos \theta}{4\pi\epsilon_0 r^2}$. (ii)

The required dimensionless value is $n = -\frac{2}{3}$.

Quick Tip to Solve: In the dipole expansion, cancel the common monopole terms before simplifying. For charges on an equilateral triangle, factor out the common separation and add the three pairwise charge products once each.

32(b). (i) State Gauss's Law in electrostatics. Apply this to obtain the electric field $\vec{E}$ at a point near a uniformly charged infinite plane sheet.

(ii) Two long straight wires 1 and 2 are kept as shown in the figure. The linear charge density of the two wires are $\lambda_1 = 10 \mu\text{C}/\text{m}$ and $\lambda_2 = -20 \mu\text{C}/\text{m}$. Find the net force $\vec{F}$ experienced by an electron held at point P. [5 marks]



Solution:

Concept:

- Gauss's law states that the total electric flux through a closed surface equals the net enclosed charge divided by ϵ_0 : $\oint_S \vec{E} \cdot d\vec{A} = Q_{\text{enc}}/\epsilon_0$. The area vector points outward.
- An infinite uniformly charged sheet produces a field normal to the sheet, with equal magnitude on its two sides. A very long straight wire has field magnitude $E = |\lambda|/(2\pi\epsilon_0 r)$, where r is the perpendicular distance from it.
- Electric fields add vectorially. An electron has charge $-e$, so its force $\vec{F} = -e\vec{E}$ is opposite to the resultant electric field.

Step 1: (i) Choose a Gaussian pillbox across the sheet Let the sheet have uniform surface charge density σ . Translational symmetry makes the electric field independent of position parallel to the sheet; reflection symmetry makes it normal to the sheet and equal in magnitude on both sides. For $\sigma > 0$, the field points away from the sheet. Choose a short cylinder crossing the sheet, with its axis perpendicular to it and each flat face of area A . On the curved surface the field is parallel to the surface, so its flux is zero. Each flat face contributes EA , since the field and the outward area vector have the same direction.

Step 2: (i) Apply Gauss's law to obtain the field The enclosed charge is $Q_{\text{enc}} = \sigma A$. Hence,

$$EA + EA = \frac{\sigma A}{\epsilon_0} \implies E = \frac{\sigma}{2\epsilon_0} \quad (\sigma > 0).$$

In general, if $\hat{n}$ is the unit normal directed from the sheet towards the observation point,

$$\vec{E} = \frac{\sigma}{2\epsilon_0} \hat{n}, \quad |\vec{E}| = \frac{|\sigma|}{2\epsilon_0}.$$

The field is away from a positive sheet and towards a negative sheet. It is independent of distance for the ideal infinite sheet; both faces contribute flux, which accounts for the factor of two.

Step 3: (ii) Establish distances and field directions at P From the printed figure, the electron is 10 cm below wire 1. The wires are 30 cm apart, so its distance above wire 2 is 20 cm. Thus $r_1 = 0.10 \text{ m}$ and $r_2 = 0.20 \text{ m}$. Wire 1 is positively charged, so its field at P points downwards, away from wire 1. Wire 2 is negatively charged, so its field at P also points downwards, towards wire 2. Both fields are along $-\hat{j}$, using the axes in the figure; there is no horizontal component.

Step 4: (ii) Calculate the fields and electron force Using $1/(2\pi\epsilon_0) = 1.8 \times 10^{10} \text{ N m}^2\text{C}^{-2}$,

$$E_1 = \frac{(1.8 \times 10^{10})(10 \times 10^{-6})}{0.10} = 1.8 \times 10^6 \text{ N C}^{-1},$$

$$E_2 = \frac{(1.8 \times 10^{10})(20 \times 10^{-6})}{0.20} = 1.8 \times 10^6 \text{ N C}^{-1}.$$

Therefore $\vec{E}_{\text{net}} = -3.6 \times 10^6 \hat{j} \text{ N C}^{-1}$. Multiplying by the electron's signed charge gives

$$\vec{F} = (-1.6 \times 10^{-19})(-3.6 \times 10^6) \hat{j} \text{ N}.$$

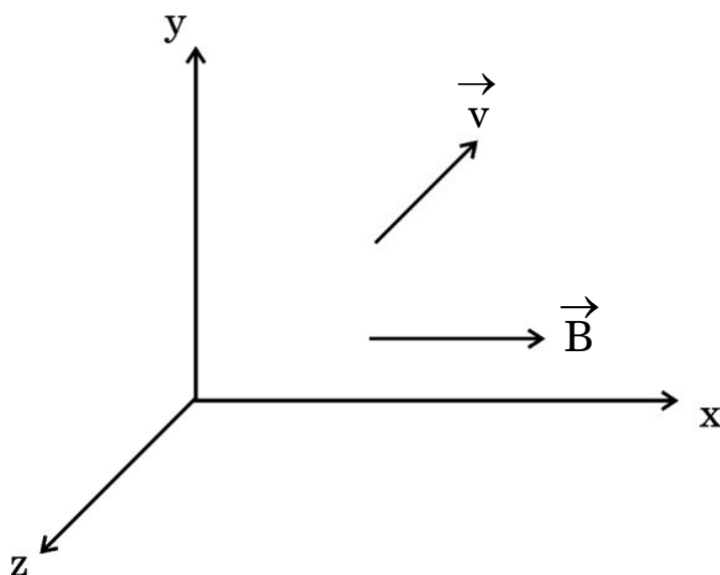
Physically, the positive upper wire attracts the electron upwards and the negative lower wire repels it upwards, confirming that the two forces reinforce each other.

Step 5: Conclusion (i) Gauss's law gives $\vec{E} = (\sigma/2\epsilon_0)\hat{n}$ for the infinite sheet, with $\hat{n}$ directed from the sheet towards the point. (ii) The net electrostatic force on the electron is $\boxed{\vec{F} = +5.76 \times 10^{-13} \hat{j} \text{ N}}$, vertically upwards towards wire 1.

Quick Tip to Solve: Subtract the given 10 cm from the 30 cm wire separation before using the line-charge formula. Add the fields with their directions, then reverse the resultant direction for the negatively charged electron.

33(a). (i) A particle of mass m and charge q is moving with a velocity $\vec{v}$ in a magnetic field $\vec{B}$ as shown in the figure. Show that it follows a helical path. Hence, obtain its frequency of revolution.

(ii) In a hydrogen atom, the electron moves in an orbit of radius $2 \text{ \AA}$ making 8×10^{14} revolutions per second. Find the magnetic moment associated with the orbital motion of the electron. [5 marks]



Solution:

Concept:

- A magnetic field exerts the Lorentz force $\vec{F} = q(\vec{v} \times \vec{B})$. It is perpendicular to the velocity, so it changes the direction of motion without changing the particle's speed or kinetic energy.
- Resolve the velocity into $v_{\parallel} = v \cos \theta$ and $v_{\perp} = v \sin \theta$, where θ is the angle between $\vec{v}$ and $\vec{B}$. The parallel component is unchanged, while the perpendicular component produces circular motion.

- An electron completing f_e revolutions per second constitutes a current of magnitude $I = ef_e$. Its orbital magnetic moment has magnitude $\mu = IA$, where A is the area enclosed by the orbit.

Step 1: (i) Resolve the motion relative to the field In the printed figure the uniform magnetic field is directed along the positive x -axis and the velocity is inclined to it. Write $\vec{v} = \vec{v}_{\parallel} + \vec{v}_{\perp}$. Since $\vec{v}_{\parallel} \times \vec{B} = 0$, the magnetic force has no component along the field. Thus the particle advances along the x -axis at the constant speed $v_{\parallel} = v \cos \theta$.

Step 2: (i) Establish circular motion and the resulting helix In the plane perpendicular to $\vec{B}$, the force has constant magnitude $|q|Bv_{\perp}$ and is perpendicular to the transverse velocity. It supplies the centripetal force:

$$|q|Bv_{\perp} = \frac{mv_{\perp}^2}{r}, \quad r = \frac{mv \sin \theta}{|q|B}.$$

Uniform circular motion in the transverse plane combined with uniform translation along the field gives a helix whose axis is parallel to $\vec{B}$. Both velocity components are nonzero in the figure. If the parallel component vanished the path would be a circle; if the perpendicular component vanished it would be a straight line. The sign of the charge determines the sense of rotation, but not the radius.

Step 3: (i) Derive the period and frequency The time taken for one transverse revolution is the circumference divided by the transverse speed:

$$T = \frac{2\pi r}{v_{\perp}} = \frac{2\pi m}{|q|B}, \quad f = \frac{1}{T} = \frac{|q|B}{2\pi m}.$$

During this time the particle advances through the pitch

$$p = v_{\parallel}T = \frac{2\pi mv \cos \theta}{|q|B}.$$

In the usual nonrelativistic treatment the frequency depends on the mass, charge magnitude and magnetic field, and is independent of the speed and inclination angle.

Step 4: (ii) Calculate the current and orbital magnetic moment Convert the orbital radius to SI units: $r_e = 2 \text{ \AA} = 2 \times 10^{-10} \text{ m}$. With $e = 1.6 \times 10^{-19} \text{ C}$ and $f_e = 8 \times 10^{14} \text{ s}^{-1}$,

$$\begin{aligned} I &= ef_e = (1.6 \times 10^{-19})(8 \times 10^{14}) = 1.28 \times 10^{-4} \text{ A}, \\ A &= \pi r_e^2 = 4\pi \times 10^{-20} \text{ m}^2, \\ \mu &= IA = (1.28 \times 10^{-4})(4\pi \times 10^{-20}) \\ &= 5.12\pi \times 10^{-24} \text{ A m}^2 \simeq 1.61 \times 10^{-23} \text{ A m}^2. \end{aligned}$$

Conventional current is opposite to electron motion, so the magnetic moment is opposite to the electron's orbital angular momentum. Its absolute spatial direction cannot be specified without the orbit's sense of revolution.

Step 5: Conclusion (i) The simultaneous circular and uniform axial motions produce a helical path with frequency $f = |q|B/(2\pi m)$. (ii) The orbital magnetic moment has magnitude $1.61 \times 10^{-23} \text{ A m}^2$, opposite to the electron's orbital angular momentum.

Quick Tip to Solve: Use only the velocity perpendicular to the field in the radius and circumference formulae; it cancels from the period. For an orbiting electron use $\mu = ef_e \pi r_e^2$ after converting angstroms to metres.

33(b). (i) What is current sensitivity of a galvanometer? Show how the current sensitivity of a galvanometer may be increased. “Increasing the current sensitivity of a galvanometer may not necessarily increase its voltage sensitivity.” Explain.

(ii) A moving coil galvanometer has a resistance $15\ \Omega$ and takes $20\ \text{mA}$ to produce full scale deflection. How can this galvanometer be converted into a voltmeter of range 0 to $100\ \text{V}$? [5 marks]

Solution:

Concept:

- The current sensitivity S_I of a galvanometer is its angular deflection per unit current: $S_I = \theta/I$. The voltage sensitivity S_V is its deflection per unit potential difference across it: $S_V = \theta/V$.
- In the radial magnetic field of a moving-coil galvanometer, magnetic torque $NIAB$ balances the restoring torque $k\theta$. Here N is the number of turns, A the area of each turn, B the field strength and k the torsional constant of the suspension.
- A galvanometer of resistance G and full-scale current I_g becomes a voltmeter by connecting a high resistance R in series, so its full-scale voltage is $V_{\max} = I_g(G + R)$.

Step 1: (i) Define and derive current sensitivity Current sensitivity measures how much angular deflection is produced by unit current through the coil. At equilibrium in a radial field,

$$NIAB = k\theta \Rightarrow S_I = \frac{\theta}{I} = \frac{NAB}{k}.$$

If the deflection is expressed in radians, its unit is rad A^{-1} . For a given current, a larger magnetic torque or a smaller restoring torque per unit angle gives a larger deflection.

Step 2: (i) Identify how current sensitivity can be increased From $S_I = NAB/k$, increase the number of turns N , increase the area A of the coil, strengthen the magnetic field B , or reduce the torsional constant k by using a suitable suspension. Each change increases current sensitivity when the other quantities in this expression are held fixed. A soft iron core helps provide a strong radial magnetic field; a small torsional constant permits a greater angular deflection for the same magnetic torque.

Step 3: (i) Compare current sensitivity with voltage sensitivity If the coil resistance is G , the potential difference across it is $V = IG$. Therefore,

$$S_V = \frac{\theta}{V} = \frac{\theta}{IG} = \frac{S_I}{G} = \frac{NAB}{kG}.$$

Voltage sensitivity depends on both current sensitivity and resistance. For example, increasing the number of turns using the same wire and approximately the same area per turn increases both N and the wire length, and hence G , in approximately the same proportion. Current sensitivity then increases, but the ratio N/G , and therefore voltage sensitivity, need not increase. More generally, an increase in G can offset an increase in S_I . Thus the quoted statement is correct; the effect depends on how current sensitivity is increased.

Step 4: (ii) Determine the series resistance for the voltmeter The galvanometer must reach its full-scale current when the applied voltage is $100\ \text{V}$. The given quantities are $G = 15\ \Omega$ and $I_g =$

20 mA = 0.020 A. Since the added resistance carries the same current as the galvanometer,

$$G + R = \frac{V_{\max}}{I_g} = \frac{100}{0.020} = 5000 \, \Omega,$$
$$R = 5000 - 15 = 4985 \, \Omega.$$

Connect this resistance in series with the galvanometer and calibrate the scale from 0 to 100 V. The complete series combination is connected across the two points whose potential difference is measured. As a check, at full scale the galvanometer drop is $I_g G = 0.30 \, \text{V}$, and the series resistor drops 99.70 V; their sum is 100 V.

Step 5: Conclusion (i) $S_I = NAB/k$ increases with N , A or B , or with a decrease in k ; however, $S_V = S_I/G$ may remain unchanged if resistance also increases. (ii) Connect $R = 4985 \, \Omega = 4.985 \, \text{k}\Omega$ in series with the galvanometer to obtain the 0–100 V voltmeter.

Quick Tip to Solve: For a voltmeter use a series multiplier and calculate $V_{\max}/I_g$ first; this is the total resistance, so subtract the galvanometer's own resistance to obtain the resistor to add.