

CBSE Class 12 Physics Question Paper 2026 with Solution PDF-Set 55/1/1



Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

- (i) This question paper contains **33** questions. **All** questions are **compulsory**.
- (ii) Question paper is divided into **FIVE** sections – Sections **A, B, C, D** and **E**.
- (iii) In **Section A** : Question numbers **1** to **16** are Multiple Choice (MCQ) type questions. Each question carries **1** mark.
- (iv) In **Section B** : Question numbers **17** to **21** are Very Short Answer (VSA) type questions. Each question carries **2** marks.
- (v) In **Section C** : Question numbers **22** to **28** are Short Answer (SA) type questions. Each question carries **3** marks.
- (vi) In **Section D** : Question numbers **29** & **30** are Case Study-Based questions. Each question carries **4** marks.
- (vii) In **Section E** : Question numbers **31** to **33** are Long Answer (LA) 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 calculator is **NOT** allowed.

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

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

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

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

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

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

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

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

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

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

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

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

Section A (16 marks)

1. In a region, the electric potential varies as $V = 10 - 50x$, where V is in volts and x in meters. The electric field in the region is: [1 mark]

- (A) 10 N/C along $+x$
- (B) 10 N/C along $-x$
- (C) 50 N/C along $+x$
- (D) 50 N/C along $-x$

Correct Answer: (C) 50 N/C along $+x$

Solution:

Concept:

- The electric field is the negative potential gradient. For a potential depending only on x , $E_x = -dV/dx$; the other field components vanish.
- A constant added to the potential does not change the field. The field points towards decreasing potential, and $1 \text{ V m}^{-1} = 1 \text{ N C}^{-1}$.

Step 1: Differentiate the potential The given potential is $V = 10 - 50x$. The derivative of the constant 10 is zero, while the coefficient of x gives the slope:

$$\frac{dV}{dx} = -50 \text{ V m}^{-1}.$$

Step 2: Apply the minus sign and check the choices Therefore $E_x = -(-50) = +50 \text{ N C}^{-1}$. The positive sign means the field points along $+x$, consistent with the potential decreasing as x increases. Options (A) and (B) incorrectly use the constant potential term as the field magnitude. Option (D) has the right magnitude but omits the minus sign in the field-potential relation.

Step 3: Conclusion The electric field is 50 N C^{-1} along $+x$. Hence, the correct option is (C).

Quick Tip to Solve: For $V = a + bx$, use $E_x = -b$: ignore the constant term and reverse the sign of the slope.

2. A conducting wire connects two charged metallic spheres A and B of radii r_1 and r_2 respectively. The distance between the spheres is very large compared to their radii. The ratio of electric fields, (E_A/E_B) at the surfaces of spheres A and B will be: [1 mark]

- (A) $\frac{r_1}{r_2}$
 (B) $\frac{r_2}{r_1}$
 (C) $\frac{r_1^2}{r_2^2}$
 (D) $\frac{r_2^2}{r_1^2}$

Correct Answer: (B) $\frac{r_2}{r_1}$

Solution:

Concept:

- Conductors joined by a conducting wire reach the same electrostatic potential after charge redistribution.
- For a widely separated spherical conductor of radius r and charge Q , its potential is $V = kQ/r$ and its surface field is $E = kQ/r^2 = V/r$, where $k = 1/(4\pi\epsilon_0)$.

Step 1: Equate the potentials of the spheres Let the final charges on A and B be Q_A and Q_B . Their large separation allows each sphere to be treated as isolated when finding its potential. Since the connecting wire makes $V_A = V_B$,

$$\frac{kQ_A}{r_1} = \frac{kQ_B}{r_2} \Rightarrow \frac{Q_A}{Q_B} = \frac{r_1}{r_2}.$$

Step 2: Compare the surface fields The field depends on both charge and radius. Using the charge ratio gives

$$\frac{E_A}{E_B} = \frac{Q_A}{Q_B} \frac{r_2^2}{r_1^2} = \frac{r_1}{r_2} \frac{r_2^2}{r_1^2} = \frac{r_2}{r_1}.$$

Option (A) is the charge ratio, not the field ratio. The squared-radius ratios in (C) and (D) neglect the charge redistribution required for equal potential. The smaller sphere has the stronger surface field.

Step 3: Conclusion The surface-field ratio is $E_A/E_B = r_2/r_1$. Hence, the correct option is (B).

Quick Tip to Solve: For connected spheres, first set their potentials equal; then use $E = V/r$ to invert the radius ratio directly.

3. A long straight wire of circular cross-section (radius a) carries a steady current I . The current is uniformly distributed across this cross-section. The magnitude of the magnetic field produced at a point at a distance $(a/2)$ from the axis of the wire will be: [1 mark]

- (A) Zero
(B) $\frac{\mu_0 I}{2\pi a}$
(C) $\frac{\mu_0 I}{4\pi a}$
(D) $\frac{\mu_0 I}{6\pi a}$

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

Solution:

Concept:

- Ampere's circuital law gives $\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{\text{enc}}$, where I_{enc} is the current enclosed by the chosen loop.
- A uniform current density in a wire of radius a gives $I_{\text{enc}} = I r^2 / a^2$ for a concentric circular loop of radius $r < a$. Symmetry makes the magnetic field tangential and constant on this loop.

Step 1: Find the current enclosed at half the radius The observation point lies inside the wire, so the loop encloses only part of its cross-section. At $r = a/2$, the enclosed area is one quarter of the total area:

$$I_{\text{enc}} = I \frac{\pi(a/2)^2}{\pi a^2} = \frac{I}{4}.$$

Step 2: Apply Ampere's law to the loop With loop circumference $2\pi(a/2) = \pi a$,

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

The field is zero only on the axis, ruling out (A). Option (B) gives the surface field at $r = a$, which is twice the field at $a/2$. Option (D) is inconsistent with the enclosed current and loop circumference.

Step 3: Conclusion The magnetic field magnitude is $\mu_0 I / (4\pi a)$. Hence, the correct option is (C).

Quick Tip to Solve: Inside a uniformly current-carrying wire, B increases linearly with radius; at half the radius, use half the surface field.

4. The shape of the interference fringes in Young's double-slit experiment, when the distance between the slit and the screen is very large as compared to the slit-separation, is nearly: [1 mark]

- (A) straight
- (B) parabolic
- (C) circular
- (D) hyperbolic

Correct Answer: (A) straight

Solution:

Concept:

- An interference fringe joins points with the same path difference between the waves from the two coherent slits. Bright fringes satisfy $\Delta = m\lambda$, where m is an integer and λ is the wavelength.
- In the usual distant-screen, small-angle approximation for Young's experiment, $\Delta \simeq dx/D$, where d is slit separation, D is screen distance, and x is displacement across the fringes from the centre.

Step 1: Use the distant-screen approximation Since the screen is far from the slits compared with their separation, the rays reaching a point in the observed central region make small angles with the axis. For a bright fringe,

$$\frac{dx}{D} = m\lambda \quad \Rightarrow \quad x = \frac{m\lambda D}{d}.$$

Each order therefore lies at an approximately fixed transverse coordinate x .

Step 2: Identify the shape of a constant-order fringe The line of fixed x on the screen runs parallel to the slits, so the visible fringes are nearly straight. The exact constant-path-difference geometry can produce hyperbolic fringes, but their central portions have negligible curvature in this approximation. Thus (D) ignores the word "nearly" and the distant-screen condition, while parabolic and circular fringes in (B) and (C) do not describe this arrangement.

Step 3: Conclusion The interference fringes are nearly straight. Hence, the correct option is (A).

Quick Tip to Solve: In Young's experiment, a distant screen leads to $x_m = m\lambda D/d$; fixed x_m means nearly straight fringes parallel to the slits.

5. An electromagnetic wave passes from vacuum into a dielectric medium with relative electrical permittivity $(3/2)$ and relative magnetic permeability $(8/3)$. Then, its: [1 mark]

- (A) wavelength is doubled and frequency remains unchanged.
- (B) wavelength is doubled and frequency is halved.
- (C) wavelength is halved and frequency remains unchanged.
- (D) wavelength and frequency both will remain unchanged.

Correct Answer: (C) wavelength is halved and frequency remains unchanged.

Solution:

Concept:

- The speed of an electromagnetic wave in a medium is $v = c/\sqrt{\epsilon_r \mu_r}$, where c is its vacuum speed and ϵ_r, μ_r are the relative permittivity and permeability.
- Frequency f remains fixed by the source when a wave crosses a stationary boundary. Its wavelength changes according to $\lambda = v/f$.

Step 1: Calculate the wave speed in the medium Both the electric and magnetic properties must be included. Their product is

$$\epsilon_r \mu_r = \frac{3}{2} \times \frac{8}{3} = 4, \quad v = \frac{c}{\sqrt{4}} = \frac{c}{2}.$$

Thus the wave travels at half its vacuum speed.

Step 2: Use the unchanged frequency to find the wavelength Write the vacuum wavelength as $\lambda_0 = c/f$. Since the frequency stays the same on transmission,

$$\lambda = \frac{v}{f} = \frac{c}{2f} = \frac{\lambda_0}{2}.$$

Options (A) and (B) incorrectly predict a doubled wavelength when the speed decreases. Option (B) also changes the frequency. Option (D) cannot retain the original wavelength at unchanged frequency because the propagation speed is halved.

Step 3: Conclusion The wavelength is halved and the frequency remains unchanged. Hence, the correct option is (C).

Quick Tip to Solve: Calculate $n = \sqrt{\epsilon_r \mu_r}$ first: frequency stays fixed and wavelength becomes λ_0/n .

6. In a series LCR circuit, the voltage across the resistor, capacitor and inductor is 10 V each. If the capacitor is short circuited, the voltage across the inductor will be: [1 mark]

- (A) 10 V
- (B) $5\sqrt{2}$ V
- (C) $\frac{5}{\sqrt{2}}$ V
- (D) $10\sqrt{2}$ V

Correct Answer: (B) $5\sqrt{2}$ V

Solution:

Concept:

- In a series LCR circuit, the supply voltage magnitude is $V_s = \sqrt{V_R^2 + (V_L - V_C)^2}$. Inductive and capacitive voltages are opposite in phase.
- At a fixed supply frequency, $V_R = IR$ and $V_L = IX_L$, where I is the current and $X_L = \omega L$. After the capacitor is shorted, the RL circuit has impedance $Z' = \sqrt{R^2 + X_L^2}$.

Step 1: Determine the supply voltage and reactance ratio Initially $V_L = V_C = 10$ V, so their phasors cancel and the supply voltage is

$$V_s = \sqrt{10^2 + (10 - 10)^2} = 10 \text{ V}.$$

Also, $IR = IX_L = 10$ V for the same series current, so $X_L = R$.

Step 2: Calculate the inductor voltage after shorting the capacitor With the same supply voltage and frequency, shorting the capacitor leaves a series RL circuit. Its new impedance and current are

$$Z' = \sqrt{R^2 + R^2} = \sqrt{2}R, \quad I' = \frac{10}{\sqrt{2}R}.$$

Hence $V'_L = I'X_L = 10/\sqrt{2} = 5\sqrt{2}\text{ V}$. Option (A) ignores the reduced current; (C) is too small by a factor of two. Option (D) would require the current to increase, although the impedance has increased from R to $\sqrt{2}R$.

Step 3: Conclusion The new voltage across the inductor is $5\sqrt{2}\text{ V}$. Hence, the correct option is (B).

Quick Tip to Solve: First cancel the initial equal inductor and capacitor voltages; removing the capacitor then changes the impedance from R to $\sqrt{2}R$.

7. Electromagnetic waves used in a diagnostic tool in medicine have a wavelength range: [1 mark]

- (A) 1 nm to 10^{-3} nm
- (B) 400 nm to 1 nm
- (C) 1 mm to 700 nm
- (D) 0.1 m to 1 mm

Correct Answer: (A) 1 nm to 10^{-3} nm

Solution:

Concept:

- X-rays are electromagnetic waves used in medical radiography. Different absorption by bone and soft tissue produces contrast in a diagnostic image.
- In the standard school-level electromagnetic spectrum, the X-ray wavelength range is approximately 1 nm to 10^{-3} nm. The conversion is $1\text{ nm} = 10^{-9}\text{ m}$.

Step 1: Identify the diagnostic radiation The medical diagnostic tool referred to is X-ray imaging. X-rays can pass through soft tissues more readily than through dense bone, so the transmitted intensity records the internal structure. This identifies the relevant part of the electromagnetic spectrum.

Step 2: Match the wavelength interval The listed interval from 1 nm down to 10^{-3} nm corresponds to

$$10^{-9}\text{ m to }10^{-12}\text{ m,}$$

which is the stated X-ray band. The other intervals represent the school-level ranges of ultraviolet radiation in (B), infrared radiation in (C), and microwaves in (D). Their longer wavelengths do not match the X-rays used for radiography.

Step 3: Conclusion The required wavelength range is 1 nm to 10^{-3} nm. Hence, the correct option is (A).

Quick Tip to Solve: Link bone radiography with X-rays, then select the sub-nanometre range; do not confuse it with the neighbouring ultraviolet band.

8. The 'distance of closest approach' of an alpha-particle is ' d ' when it moves with a velocity v head-on towards the target nucleus. If the velocity of alpha particle is halved, the new 'distance of closest approach' will be: [1 mark]

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

Correct Answer: (D) $4d$

Solution:

Concept:

- In a head-on approach, the alpha-particle momentarily stops at the closest point, so its initial kinetic energy becomes electrostatic potential energy.
- For a fixed target nucleus, $\frac{1}{2}mv^2 = k(2e)(Ze)/d$, where m is the alpha-particle mass, Ze is the nuclear charge and $k = 1/(4\pi\epsilon_0)$.

Step 1: Express the closest distance in terms of speed Taking the potential energy at a large initial separation as zero and the heavy target nucleus as fixed, energy conservation gives

$$d = \frac{2k(2e)(Ze)}{mv^2}.$$

Thus, for the same projectile and target, $d \propto 1/v^2$. A slower alpha-particle has less kinetic energy and turns back farther from the repelling nucleus.

Step 2: Apply the change in speed Let the new closest distance be d' . With $v' = v/2$,

$$\frac{d'}{d} = \left(\frac{v}{v'}\right)^2 = \left(\frac{v}{v/2}\right)^2 = 4.$$

Options (A) and (C) incorrectly predict a smaller turning distance. Option (B) uses an inverse first-power dependence instead of the inverse-square dependence on speed.

Step 3: Conclusion The new distance of closest approach is $4d$. Hence, the correct option is (D).

Quick Tip to Solve: For the same alpha-particle and nucleus, keep dv^2 constant; halving the speed makes the turning distance four times as large.

9. A concave lens of focal length 10 cm is cut into two identical plano-concave lenses. The focal length of each lens will be:

[1 mark]

- (A) 20 cm
- (B) 30 cm
- (C) 40 cm
- (D) 5 cm

Correct Answer: (A) 20 cm

Solution:

Concept:

- The lens-maker formula in air is $P = 1/f = (\mu - 1)(1/R_1 - 1/R_2)$, where P is lens power, f is focal length and μ is the refractive index of its material.
- A plane surface has infinite radius of curvature and contributes zero power. Each identical plano-concave half retains one of the original two equally curved surfaces.

Step 1: Compare the powers of the original lens and each half For the symmetric biconcave lens, choose light travelling left to right. If the magnitude of each curved radius is R , then $R_1 = -R$ and $R_2 = +R$. Thus,

$$P = (\mu - 1) \left(-\frac{1}{R} - \frac{1}{R} \right) = -\frac{2(\mu - 1)}{R}.$$

Replacing one curved surface by a plane surface gives each half the power $P' = -(\mu - 1)/R = P/2$.

Step 2: Convert the power change into a focal-length change Since $P' = 1/f'$, halving the power doubles the focal length:

$$f' = 2f = 2(-10 \text{ cm}) = -20 \text{ cm}.$$

The printed options give magnitudes, so the relevant magnitude is 20 cm. Values 30 cm and 40 cm do not follow from halving the power. The value 5 cm would require doubling the power.

Step 3: Conclusion Each plano-concave lens has focal-length magnitude 20 cm, or signed focal length -20 cm. Hence, the correct option is (A).

Quick Tip to Solve: When a symmetric lens is split into two plano-curved halves, each half has half the original power and twice the focal-length magnitude.

10. Four independent waves are expressed as:

(i) $y_1 = A_1 \sin \omega t$ **(ii)** $y_2 = A_2 \sin 2\omega t$

(iii) $y_3 = A_3 \cos \omega t$ **(iv)** $y_4 = A_4 \sin(\omega t + \pi/3)$

The interference between two of these waves is possible in:

[1 mark]

- (A) (i) and (iii) only
(B) (iii) and (iv) only
(C) (i), (iii) and (iv) only
(D) All of them

Correct Answer: (C) (i), (iii) and (iv) only

Solution:

Concept:

- Sustained interference requires two coherent waves: their frequencies must be equal and their phase difference must remain constant.
- Expressing each wave as $y = A \sin(\Omega t + \phi)$ identifies its angular frequency Ω and phase constant ϕ . A cosine is a sine with a fixed phase shift: $\cos \omega t = \sin(\omega t + \pi/2)$.

Step 1: Identify the frequencies and phases For the phase relations specified in the question, the four waves have

$$y_1 : \Omega_1 = \omega, \quad \phi_1 = 0,$$

$$y_2 : \Omega_2 = 2\omega, \quad \phi_2 = 0,$$

$$y_3 : \Omega_3 = \omega, \quad \phi_3 = \pi/2,$$

$$y_4 : \Omega_4 = \omega, \quad \phi_4 = \pi/3.$$

Thus (i), (iii) and (iv) have the same frequency, with fixed phase differences for every pair among them. Unequal amplitudes do not prevent interference.

Step 2: Check the listed choices Waves (i) and (iii), (i) and (iv), and (iii) and (iv) can each give sustained interference. Options (A) and (B) each omit other permitted pairs. Wave (ii) has twice the frequency, so its phase difference from any of these three changes with time; including all four as eligible waves, as in option (D), is incorrect.

Step 3: Conclusion Any pair selected from (i), (iii) and (iv) satisfies the stated interference conditions. Hence, the correct option is (C).

Quick Tip to Solve: First compare the coefficients of t ; then rewrite cosine as a phase-shifted sine. A fixed phase shift does not destroy interference.

11. Two heaters rated as (P_1, V) and (P_2, V) are connected in series across a dc source of $\frac{V}{2}$ volt. The power consumed by the combination will be: [1 mark]

- (A) $(P_1 + P_2)$
 (B) $\frac{P_1 + P_2}{2}$
 (C) $\frac{P_1 P_2}{2(P_1 + P_2)}$
 (D) $\frac{P_1 P_2}{4(P_1 + P_2)}$

Correct Answer: (D) $\frac{P_1 P_2}{4(P_1 + P_2)}$

Solution:

Concept:

- A heater rated (P, V) has resistance $R = V^2/P$, where P is its power when the full rated voltage V is applied.
- Resistances add in series. If the actual supply voltage is U , the total power is $P_{\text{total}} = U^2/(R_1 + R_2)$. Treat the heater resistances as constant, as in the standard rating model.

Step 1: Determine the total series resistance Both heaters have the same rated voltage V , so their resistances are

$$R_1 = \frac{V^2}{P_1}, \quad R_2 = \frac{V^2}{P_2}.$$

In series, their combined resistance is

$$R_s = R_1 + R_2 = \frac{V^2(P_1 + P_2)}{P_1 P_2}.$$

The rated powers cannot simply be added because neither heater is separately connected across its rated voltage.

Step 2: Use the actual supply voltage The printed source voltage is $U = V/2$, so

$$\begin{aligned} P_{\text{total}} &= \frac{(V/2)^2}{R_s} \\ &= \frac{V^2}{4} \frac{P_1 P_2}{V^2(P_1 + P_2)} \\ &= \frac{P_1 P_2}{4(P_1 + P_2)}. \end{aligned}$$

Options (A) and (B) do not account for the series resistance. Option (C) uses a factor of $1/2$, whereas halving a voltage reduces power by $1/4$ at fixed resistance.

Step 3: Conclusion The power consumed by the combination is $\boxed{\frac{P_1 P_2}{4(P_1 + P_2)}}$. Hence, the correct option is (D).

Quick Tip to Solve: Convert each rating to resistance first, then square the actual supply voltage; the source here is $V/2$, which supplies the factor $1/4$.

12. In an unbiased p-n junction, at equilibrium, which of the following statements is true? [1 mark]

- (A) Diffusion current is zero but drift current exists.
- (B) Diffusion current exists but drift current is zero.
- (C) Diffusion and drift currents are equal and opposite.
- (D) Both the diffusion and drift currents exist but are unequal.

Correct Answer: (C) Diffusion and drift currents are equal and opposite.

Solution:

Concept:

- Diffusion carries charge carriers from a region of high concentration to a region of low concentration across a p-n junction.
- The electric field in the depletion region drives a drift current opposite to the diffusion current. At thermal equilibrium, the net junction current is zero.

Step 1: Identify the two current mechanisms Electrons diffuse from the n-side to the p-side, and holes diffuse from the p-side to the n-side. Their diffusion leaves fixed ions near the junction, creating the depletion region and its built-in electric field. This field produces a drift current in the opposite direction to the conventional diffusion current. An unbiased junction therefore still has both current mechanisms.

Step 2: Apply the equilibrium condition Taking signed currents along one common reference direction, equilibrium requires

$$I_{\text{net}} = I_{\text{diffusion}} + I_{\text{drift}} = 0, \quad I_{\text{drift}} = -I_{\text{diffusion}}.$$

Their magnitudes are equal and their directions are opposite. Options (A) and (B) incorrectly suppress one current. Option (D) would give a nonzero net current and hence would not describe equilibrium.

Step 3: Conclusion Diffusion and drift currents are equal in magnitude and opposite in direction. Hence, the correct option is (C).

Quick Tip to Solve: In an unbiased junction, zero net current means cancellation of drift and diffusion currents, not the absence of either mechanism.

13. Assertion (A): All atoms have a net magnetic moment.

Reason (R): A current loop does not always behave as a magnetic dipole.

[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) Both Assertion (A) and Reason (R) are false.

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

Solution:

Concept:

- An atom's net electronic magnetic moment is the vector sum of the orbital and spin magnetic moments of its electrons; these contributions can cancel.

- A planar current loop acts as a magnetic dipole with magnetic moment $\mathbf{m} = I\mathbf{A}$, where I is the current and $\mathbf{A}$ is the area vector given by the right-hand rule.

Step 1: Evaluate the Assertion The claim that all atoms have a net magnetic moment is false. In atoms with completely filled electron shells, paired spin contributions and orbital contributions can cancel, leaving zero permanent electronic magnetic moment. Thus a nonzero net moment is not a universal property of atoms.

Step 2: Evaluate the Reason The Reason is false. A current-carrying loop behaves as a magnetic dipole, with one face acting as a north pole and the other as a south pole. Its magnetic moment is $\mathbf{m} = I\mathbf{A}$; in an external magnetic field it experiences the dipole torque $\boldsymbol{\tau} = \mathbf{m} \times \mathbf{B}$.

Step 3: Check the explanatory relation Atomic moments can vanish because individual electronic contributions cancel, not because a current loop ceases to have dipole behaviour. Since both statements are false, there is no valid explanatory relation. Options (A), (B) and (C) all assert that the Assertion is true, so none of them is consistent with this evaluation.

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

Quick Tip to Solve: Test the word “all” using a filled-shell atom, then recall that a current loop has the dipole moment $\mathbf{m} = I\mathbf{A}$.

14. Assertion (A): If accelerated electrons are passed through a narrow slit, a diffraction pattern is observed.

Reason (R): Electrons behave as both particles and waves.

[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) Both Assertion (A) and Reason (R) are false.

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

Solution:

Concept:

- A moving electron has a de Broglie wavelength $\lambda = h/p$, where h is Planck's constant and p is the electron momentum.
- Diffraction is a wave phenomenon. For slit width a , its characteristic angular spread is of order λ/a , so a sufficiently narrow slit makes the diffraction observable.

Step 1: Evaluate the Assertion The Assertion is true. Accelerated electrons possess momentum and an associated de Broglie wavelength. When an electron beam passes through a sufficiently narrow slit under suitable experimental conditions, the probability distribution spreads and forms a diffraction pattern. The slit must be narrow enough for this spreading to be observable.

Step 2: Evaluate the Reason The Reason is true. Electrons exhibit wave-particle duality: they are detected as individual localized particles, while a large number of detections can build up a wave-like diffraction distribution. Acceleration changes their momentum and therefore their wavelength, but

does not remove their wave character.

Step 3: Relate the Reason to the Assertion The wave aspect of the electron is precisely what allows diffraction at the slit. Thus the Reason explains the Assertion, rather than merely stating an unrelated fact. Option (B) incorrectly denies this explanatory link; options (C) and (D) incorrectly declare one or both of the true statements false.

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

Quick Tip to Solve: When an electron experiment shows diffraction or interference, identify its de Broglie wave character as the direct explanation.

15. Reason (A): The mass of a nucleus is less than the sum of the masses of the constituent nucleons.

Reason (R): Energy is absorbed when the nucleons are bound together to form a nucleus. [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) Both Assertion (A) and Reason (R) are false.

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

Solution:

Concept:

- The mass defect is $\Delta m = Zm_p + (A - Z)m_n - M$, where M is the nuclear mass, Z the proton number and A the nucleon number.
- Nuclear binding energy is $B = \Delta mc^2 > 0$. It is released when free nucleons form a bound nucleus and must be supplied to separate that nucleus into free nucleons.

Step 1: Evaluate statement (A) The first statement, printed as Reason (A), serves as the assertion in the answer codes. For a bound nucleus, $\Delta m > 0$, so

$$M = Zm_p + (A - Z)m_n - \frac{B}{c^2}.$$

Its mass is therefore smaller than the sum of the masses of its separated constituent nucleons. Statement (A) is true.

Step 2: Evaluate reason (R) Binding lowers the total energy of the nucleons. The energy difference is released to the surroundings during formation of the bound nucleus; absorption is required for the reverse process of breaking it apart. Thus reason (R), which says energy is absorbed during binding, is false.

Step 3: Test the explanation and answer codes A false reason cannot explain the true assertion.

Options (A) and (B) both incorrectly require R to be true, while option (D) incorrectly requires the assertion to be false.

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

Quick Tip to Solve: Remember the direction of energy flow: forming a bound nucleus releases binding energy; separating it requires that energy.

16. Reason (A): In Bohr model of hydrogen atom, the energy levels are discrete and quantised.

Reason (R): In a hydrogen atom, the electrostatic force on the electron provides the necessary centripetal force to it to revolve around the nucleus. [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) Both Assertion (A) and Reason (R) are false.

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

Solution:

Concept:

- Bohr's angular-momentum postulate, $m_e v r = n \hbar$ with $n = 1, 2, 3, \dots$, selects allowed electron orbits; $\hbar = h/(2\pi)$.
- Coulomb attraction supplies the centripetal force: $m_e v^2/r = e^2/(4\pi\epsilon_0 r^2)$. This force equation alone does not restrict the radius r to discrete values.

Step 1: Evaluate statement (A) The first statement, printed as Reason (A), is the assertion referred to by the answer codes. In the Bohr model, the allowed energies of hydrogen are

$$E_n = -\frac{13.6}{n^2} \text{ eV}, \quad n = 1, 2, 3, \dots$$

Since n takes only positive integer values, these levels are discrete and quantised. The assertion is true.

Step 2: Evaluate reason (R) The negatively charged electron is attracted towards the positively charged nucleus. In a circular Bohr orbit, this inward electrostatic force supplies exactly the required centripetal force. Hence the reason is also true.

Step 3: Test whether the reason explains quantisation Coulomb attraction and the centripetal-force condition also apply in a classical orbital model, which permits continuously varying radii and energies. Discreteness follows only after imposing Bohr's angular-momentum quantisation. Thus the reason describes the force maintaining an orbit but does not explain quantisation. This rules out option (A);

options (C) and (D) wrongly treat the reason as false.

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

Quick Tip to Solve: For a claim about discrete Bohr levels, look for the integer condition $m_e v r = n\hbar$; the Coulomb-force equation by itself is insufficient.

Section B (10 marks)

17. In a photo-electric experiment, the emitter plate is irradiated with radiation of 200 nm. The photocurrent becomes zero when the collector plate potential is -0.80 V. Calculate the work function (in eV) of the emitter. [2 marks]

Solution:

Concept:

- Einstein's photoelectric equation is $hc/\lambda = \phi + K_{\max}$, where ϕ is the emitter's work function and $K_{\max}$ is the maximum photoelectron kinetic energy.
- A stopping potential of magnitude V_s gives $K_{\max} = eV_s$. Thus an electron stopped by 0.80 V has a maximum kinetic energy of 0.80 eV.

Step 1: Interpret the negative collector potential The collector is at -0.80 V relative to the emitter, so it repels the emitted electrons. As the current just becomes zero, even the fastest electrons fail to reach it. Use the positive magnitude of this stopping potential:

$$V_s = 0.80 \text{ V}, \quad K_{\max} = 0.80 \text{ eV}.$$

The negative sign specifies the retarding polarity; it does not make the kinetic energy negative.

Step 2: Calculate the incident photon energy Convert the wavelength to metres: $\lambda = 200 \times 10^{-9}$ m. Using the paper's values of h , c and e ,

$$E_\gamma = \frac{(6.63 \times 10^{-34})(3 \times 10^8)}{200 \times 10^{-9}} = 9.945 \times 10^{-19} \text{ J},$$
$$E_\gamma = \frac{9.945 \times 10^{-19}}{1.6 \times 10^{-19}} \text{ eV} = 6.215625 \text{ eV}.$$

Step 3: Apply energy conservation Part of each absorbed photon's energy overcomes the surface binding; the remainder appears as the maximum kinetic energy. Therefore subtract the stopping energy from the photon energy:

$$\phi = E_\gamma - K_{\max} = (6.215625 - 0.80) \text{ eV}.$$

Step 4: Conclusion The work function is $\phi \simeq 5.42 \text{ eV}$, or about 5.4 eV to two significant figures.

Quick Tip to Solve: Convert the photon energy to eV first; then subtract the numerical magnitude of the stopping potential in volts, here 0.80.

18(a). A beam of light consisting of two wavelengths 400 nm and 600 nm is used to illuminate a single slit of width 1 mm. Find the least distance of the point from the central maximum where the dark fringes due to both wavelengths coincide on the screen placed 1.5 m from the slit. [2 marks]

Solution:

Concept:

- For a single slit of width a , a diffraction minimum obeys $a \sin \theta = m\lambda$, where the order $m = 1, 2, 3, \dots$. The central point $m = 0$ is a maximum, not a minimum.
- At small angles on a screen a distance D away, the distance from the centre is $y_m \simeq m\lambda D/a$. Minima of two wavelengths coincide when their products $m\lambda$ are equal.

Step 1: Find the smallest allowed pair of orders Let m be the minimum order for $\lambda_1 = 400$ nm, and n that for $\lambda_2 = 600$ nm. At a common dark point the slit width and diffraction angle are the same, so

$$m(400) = n(600) \Rightarrow 2m = 3n.$$

The least positive integer solution is $m = 3, n = 2$. Thus the third minimum of the shorter wavelength coincides with the second minimum of the longer wavelength. Smaller positive orders do not satisfy the equality.

Step 2: Calculate the distance on the screen With $a = 1 \times 10^{-3}$ m and $D = 1.5$ m, use the common value $m\lambda_1 = 3(400 \times 10^{-9})$ m:

$$y \simeq \frac{m\lambda_1 D}{a} = \frac{3(400 \times 10^{-9})(1.5)}{1 \times 10^{-3}} \text{ m}.$$

Here $\sin \theta = m\lambda_1/a = 1.2 \times 10^{-3}$, so the small-angle approximation is well justified. The same substitution with $n = 2$ and 600 nm gives the identical distance.

Step 3: Conclusion The least distance is $y = 1.8 \times 10^{-3}$ m = 1.8 mm. A common dark fringe occurs at this distance on either side of the central maximum.

Quick Tip to Solve: Reduce 400 : 600 to 2 : 3; the first coincident minima have the reversed order ratio 3 : 2. Exclude zero order for a dark fringe.

OR

18(b). In a Young's double-slit experimental set-up with slit separation 0.6 mm a beam of light consisting of two wavelengths 440 nm and 660 nm is used to obtain interference pattern on a screen kept 1.5 m in front of the slits. Find the least distance of the point from the central maximum where the bright fringes due to both the wavelengths coincide. [2 marks]

Solution:

Concept:

- In Young's experiment, a bright fringe satisfies $d \sin \theta = m\lambda$. At small angles its distance from the centre is $y_m = m\lambda D/d$, where d is slit separation and D is screen distance.
- Bright fringes for two wavelengths coincide when $m\lambda_1 = n\lambda_2$. Their central maxima already coincide at zero; the required least distance away from the centre comes from the smallest positive orders.

Step 1: Determine the first coincident bright orders Let m and n denote the bright-fringe orders for $\lambda_1 = 440 \text{ nm}$ and $\lambda_2 = 660 \text{ nm}$, respectively. Equating their distances on the common screen gives

$$m(440) = n(660) \Rightarrow 2m = 3n.$$

The smallest positive integer solution is $m = 3$ and $n = 2$. Hence the first common bright point beyond the central maximum corresponds to the third bright fringe of 440 nm and the second bright fringe of 660 nm .

Step 2: Substitute the experimental dimensions Convert the slit separation to $d = 0.6 \times 10^{-3} \text{ m}$; the screen distance is $D = 1.5 \text{ m}$. The common path difference is $3\lambda_1 = 1320 \times 10^{-9} \text{ m}$, giving

$$y = \frac{3\lambda_1 D}{d} = \frac{3(440 \times 10^{-9})(1.5)}{0.6 \times 10^{-3}} \text{ m}.$$

Since $\sin \theta = 3\lambda_1/d = 2.2 \times 10^{-3}$, the small-angle fringe-position formula is appropriate. Using the second order of 660 nm gives the same result.

Step 3: Conclusion The least nonzero distance of coincident bright fringes from the central maximum is $y = 3.3 \times 10^{-3} \text{ m} = 3.3 \text{ mm}$, on either side of the centre.

Quick Tip to Solve: The wavelength ratio $440 : 660 = 2 : 3$ gives the smallest positive bright-fringe orders $3 : 2$; use the slit separation 0.6 mm in the denominator.

19. A wire of length L is bent round into (i) a square coil having N turns and (ii) a circular coil having N turns. The coil in both cases is free to turn about a vertical axis coinciding with the plane of the coil, in a uniform, horizontal magnetic field and carry the same currents. Find the ratio of the maximum value of the torque acting on the square coil to that on the circular coil. [2 marks]

Solution:

Concept:

- The torque on a plane coil is $\tau = NIAB \sin \theta$, where N is the number of turns, I the current, A the area of one turn, B the magnetic field and θ the angle between the coil's normal and the field.
- The maximum torque is $\tau_{\max} = NIAB$. For a fixed total wire length L , the perimeter of each of the N identical turns is L/N .

Step 1: Find the area of one square turn Let the side of the square be a . The total wire forms N square turns, so

$$4Na = L, \quad a = \frac{L}{4N}, \quad A_s = a^2 = \frac{L^2}{16N^2}.$$

When the normal to the coil is perpendicular to the magnetic field, $\sin \theta = 1$, giving

$$\tau_{s,\max} = NIB \frac{L^2}{16N^2} = \frac{IBL^2}{16N}.$$

Step 2: Find the area of one circular turn Let the radius of each circular turn be r . Using its circumference,

$$2\pi rN = L, \quad r = \frac{L}{2\pi N}, \quad A_c = \pi r^2 = \frac{L^2}{4\pi N^2}.$$

The same current flows and the number of turns and field are unchanged. Thus,

$$\tau_{c,\max} = NIB \frac{L^2}{4\pi N^2} = \frac{IBL^2}{4\pi N}.$$

Step 3: Conclusion The required ratio is

$$\frac{\tau_{s,\max}}{\tau_{c,\max}} = \frac{IBL^2/(16N)}{IBL^2/(4\pi N)} = \frac{\pi}{4}.$$

Hence, $\tau_{s,\max} : \tau_{c,\max} = \pi : 4$.

Quick Tip to Solve: With the same wire length, turn count, current and field, compare only the areas per turn; the circle encloses the larger area and gives the larger maximum torque.

20. What is the order of magnitude of drift velocity of electrons in a conductor? Deduce the relation between the current flowing through a conductor and drift velocity of electrons in it. [2 marks]

Solution:

Concept:

- Drift velocity is the small average velocity acquired by free electrons in a conductor under an applied electric field, superposed on their random thermal motion.
- Current is the rate of flow of charge: $I = \Delta Q / \Delta t$. Let n be the number of free electrons per unit volume, A the cross-sectional area, e the magnitude of an electron's charge, and v_d the magnitude of drift velocity.

Step 1: State the typical drift speed In an ordinary metallic conductor carrying current, the electron drift speed is typically of the order

$$v_d \sim 10^{-4} \text{ m s}^{-1}.$$

It is very small compared with the electrons' random thermal speeds. Random motion alone gives no net current; the field produces the small directed average motion. The drift velocity of electrons is opposite to the electric field.

Step 2: Count the charge crossing a section During a time interval Δt , electrons drift a distance $v_d \Delta t$. The volume whose electrons effectively cross a section of area A is $Av_d \Delta t$. Hence the number crossing is $nAv_d \Delta t$, and the magnitude of charge transported is

$$\Delta Q = (nAv_d \Delta t)e.$$

Dividing by the time interval gives the current magnitude:

$$I = \frac{\Delta Q}{\Delta t} = \frac{neAv_d \Delta t}{\Delta t} = neAv_d.$$

Step 3: Conclusion The typical order of electron drift speed is 10^{-4} m s^{-1} , and $I = neAv_d$. Conventional current is opposite to electron drift; in vector form the current density is $\vec{J} = -ne\vec{v}_d$.

Quick Tip to Solve: Use the drift cylinder of length $v_d \Delta t$: multiply its volume by n and e , then divide by Δt to obtain $I = neAv_d$.

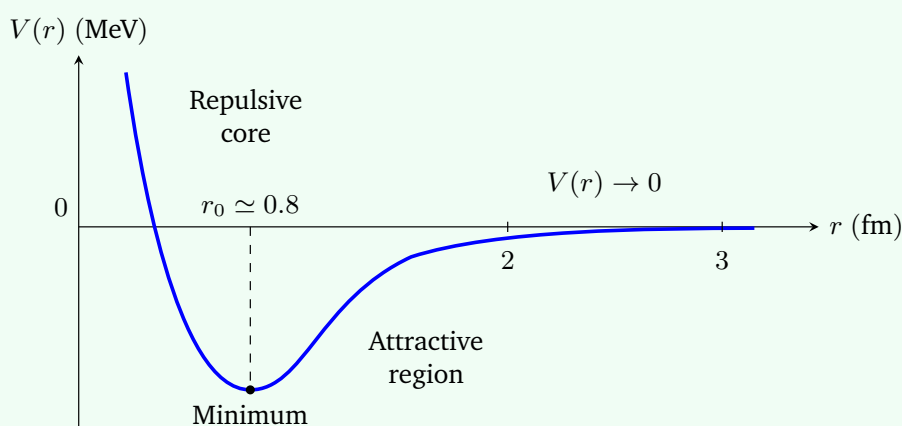
21. Draw the plot of potential energy of a pair of nucleons as a function of their separation. Write two important conclusions that can be drawn from this plot. [2 marks]

Solution:

Concept:

- The nuclear potential energy $V(r)$ depends on the separation r of the nucleons. Take $V = 0$ at infinite separation; a negative potential-energy well represents binding.
- The radial nuclear force is $F_r = -dV/dr$, with positive F_r directed towards increasing separation. The sign of the slope, rather than the sign of V alone, determines attraction or repulsion.

Step 1: Sketch the potential-energy curve At very small separation the potential rises steeply to positive values. It falls to a negative minimum at approximately $r_0 = 0.8$ fm, then rises towards zero as the separation increases. The curve is essentially zero beyond a few femtometres. The sketch is qualitative; $1 \text{ fm} = 10^{-15} \text{ m}$.



Schematic nuclear potential energy versus nucleon separation; the vertical scale is qualitative.

Step 2: Read two conclusions from the slope and range **1. Attraction and a repulsive core:** For $r < r_0$, the slope $dV/dr < 0$, so $F_r > 0$: the force is strongly repulsive at short separation. For $r > r_0$ within the nuclear range, $dV/dr > 0$, so $F_r < 0$: the force is attractive. The minimum marks the separation where the force vanishes.

2. Short range: At separations greater than about 2–3 fm, $V(r)$ is nearly zero and its slope is negligible. Thus the nuclear force is significant only over distances comparable with nuclear dimensions.

Step 3: Conclusion The nuclear potential has a negative well and a steep repulsive core. The plot shows that the nuclear interaction is attractive at intermediate separations, repulsive at very small separations, and effective only over a short range of a few femtometres.

Quick Tip to Solve: Draw the positive core, negative well and near-zero tail, then use $F_r = -dV/dr$ to label the repulsive and attractive regions correctly.

Section C (21 marks)

22(a). (a) Using Gauss's law, deduce an expression for electric field at a point due to a uniformly charged infinite plane thin sheet.

(b) Two large thin plane sheets, each having surface charge density σ , are held close and parallel to each other in air. What is the net electric field at a point (i) inside and (ii) outside, the sheets?

[3 marks]

Solution:

Concept:

- Gauss's law states $\oint \vec{E} \cdot d\vec{A} = Q_{\text{enc}}/\epsilon_0$, where Q_{enc} is the enclosed charge and ϵ_0 is the permittivity of free space.
- Symmetry makes the field of an infinite uniform sheet perpendicular to it and equal in magnitude on both sides. The fields of multiple sheets add as vectors. For air, use the permittivity ϵ_0 .

Step 1: Choose a Gaussian surface for part (a) Let the sheet have positive surface charge density σ . Choose a cylindrical pillbox with its axis normal to the sheet and two end faces, each of area A , at equal distances on opposite sides. The charge enclosed is $Q_{\text{enc}} = \sigma A$.

The field points away from the sheet on both sides. It is parallel to each end face's outward area vector, so each end contributes flux EA . The field is tangent to the curved surface, whose flux is zero.

Step 2: Apply Gauss's law The total flux through the closed pillbox is therefore

$$EA + EA + 0 = \frac{\sigma A}{\epsilon_0},$$
$$E = \frac{\sigma}{2\epsilon_0}.$$

The area cancels, and the field is independent of distance from the infinite sheet. For a negative sheet, the direction reverses; the general magnitude is $|\sigma|/(2\epsilon_0)$.

Step 3: Superpose the fields for part (b) The two sheets have the same surface charge density σ , including its sign. Neglect edge effects for these large sheets. Each sheet alone produces a field of magnitude $E_0 = |\sigma|/(2\epsilon_0)$.

(i) Between the sheets: For positive sheets, the left sheet's field points right and the right sheet's field points left. These equal, opposite fields cancel:

$$E_{\text{inside}} = E_0 - E_0 = 0.$$

(ii) Outside the sheets: The two fields point in the same direction and add:

$$E_{\text{outside}} = E_0 + E_0 = \frac{|\sigma|}{\epsilon_0}.$$

For positive σ , the external field points away from the pair, on each side. For negative σ , all individual field directions reverse: cancellation inside still holds, and the external field points towards the pair.

Step 4: Conclusion The single-sheet field has magnitude $E = |\sigma|/(2\epsilon_0)$. For two equally charged sheets, $E_{\text{inside}} = 0$ and $E_{\text{outside}} = |\sigma|/\epsilon_0$, perpendicular to the sheets. For positive σ , the absolute-value signs may be omitted.

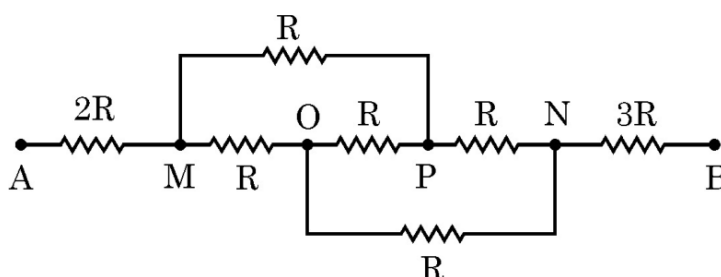
Quick Tip to Solve: Count both pillbox end faces to obtain the factor 2. Equal like-charged sheets produce opposing fields between them and reinforcing fields outside.

OR

22(b). (a) Obtain the condition of balance of a Wheatstone bridge.

(b) Find net resistance of the network of resistors connected between A and B, as shown in figure.

[3 marks]



Solution:

Concept:

- A Wheatstone bridge is balanced when no current flows through its central branch. Its two intermediate junctions are then at the same potential.
- Ohm's law gives the potential drop across a resistor as IR . Resistors in series add, whereas parallel branches satisfy $R_{\text{eq}}^{-1} = R_1^{-1} + R_2^{-1}$.

Step 1: (a) Assign the four bridge arms Use the junctions in the given figure to describe a general bridge. Let the resistances along MO , ON , MP and PN be r_1 , r_2 , r_3 and r_4 , respectively. Connect the source across M and N , with the galvanometer in the branch OP . At balance, its current is zero, so $V_O = V_P$. Hence the same current I_1 flows through r_1, r_2 , and the same current I_2 flows through r_3, r_4 .

Step 2: Equate the potential drops and obtain the condition The drops from M to the equipotential junctions O, P are equal; the drops from these junctions to N are also equal. Thus

$$\begin{aligned} V_M - V_O &= V_M - V_P \Rightarrow I_1 r_1 = I_2 r_3, \\ V_O - V_N &= V_P - V_N \Rightarrow I_1 r_2 = I_2 r_4. \end{aligned}$$

Dividing the first relation by the second eliminates the branch currents and gives $r_1/r_2 = r_3/r_4$, or $r_1 r_4 = r_2 r_3$. This is the Wheatstone bridge balance condition.

Step 3: (b) Identify the balanced bridge in the network Here $MO = ON = MP = PN = R$, where these equalities denote resistances. Therefore

$$\frac{R_{MO}}{R_{ON}} = \frac{R}{R} = 1 = \frac{R_{MP}}{R_{PN}}.$$

The bridge is balanced, so the resistor between O and P carries no current and may be omitted when

finding the equivalent resistance. The remaining paths $M \rightarrow O \rightarrow N$ and $M \rightarrow P \rightarrow N$ each have resistance $2R$, and are in parallel:

$$R_{MN} = \frac{(2R)(2R)}{2R + 2R} = R.$$

Step 4: Include the outer series resistors Every current entering at A first crosses the $2R$ resistor to M , then the equivalent resistance between M, N , and finally the $3R$ resistor from N to B . These three portions are in series, so

$$R_{AB} = 2R + R_{MN} + 3R = (2 + 1 + 3)R.$$

Step 5: Conclusion The bridge balances when $r_1/r_2 = r_3/r_4$. For the given network, the central resistor OP carries no current and the net resistance is $R_{AB} = 6R$.

Quick Tip to Solve: Look at the paths MON and MPN : their equal resistance ratios make O and P equipotential. Remove only the OP branch before combining resistors.

23. A parallel plate capacitor of capacitance C has a dielectric slab between its plates. It is charged to a potential difference V by connecting it across a battery. The battery is then disconnected. If the dielectric slab is now withdrawn from the capacitor, how will the following be affected?

- Capacitance of the capacitor,
- Energy stored in the capacitor, and
- The potential difference between the plates of the capacitor.

Justify your answer in each case.

[3 marks]

Solution:

Concept:

- An isolated capacitor retains its free charge: after the battery is disconnected, $Q = CV$ is constant, where C, V are the initial capacitance and potential difference.
- For fixed charge, $V = Q/C$ and $U = Q^2/(2C)$, where U is the stored electrostatic energy. Both vary inversely with capacitance.
- A dielectric increases capacitance by polarisation. Let C_0 be the capacitance after removing the slab and define $K = C/C_0 > 1$. If the dielectric fills the entire gap, K is its relative permittivity and $C_0 = \epsilon_0 A/d$.

Step 1: Establish what stays constant Initially the battery charges the plates to equal and opposite charges of magnitude $Q = CV$, with stored energy $U_i = \frac{1}{2}CV^2$. Once the battery is disconnected, there is no conducting path for charge to leave either plate. Thus removing the dielectric keeps Q fixed; the original voltage V is no longer maintained by a battery.

Step 2: (a) Determine the change in capacitance The polarisation of the dielectric reduces the potential difference produced by a given free charge, thereby increasing capacitance. Withdrawal removes this effect, so the capacitance falls to its value without the slab:

$$C_f = C_0 = \frac{C}{K} < C.$$

For complete filling, the familiar expressions are $C = K\epsilon_0 A/d$ with the dielectric and $C_0 = \epsilon_0 A/d$ without it; the plate area A and separation d do not change.

Step 3: (b) Determine the change in stored energy Use the energy formula containing the conserved charge. Since $C_f < C$,

$$\begin{aligned} U_f &= \frac{Q^2}{2C_f} = \frac{(CV)^2}{2(C/K)} \\ &= \frac{1}{2}KCV^2 = KU_i > U_i. \end{aligned}$$

Hence the stored energy increases. The slab is attracted into the capacitor, so an external agent must do work to withdraw it. For slow withdrawal without losses, this work supplies the increase $U_f - U_i = (K - 1)U_i$.

Step 4: (c) Determine the change in potential difference Since the charge remains CV while the capacitance decreases,

$$V_f = \frac{Q}{C_f} = \frac{CV}{C/K} = KV > V.$$

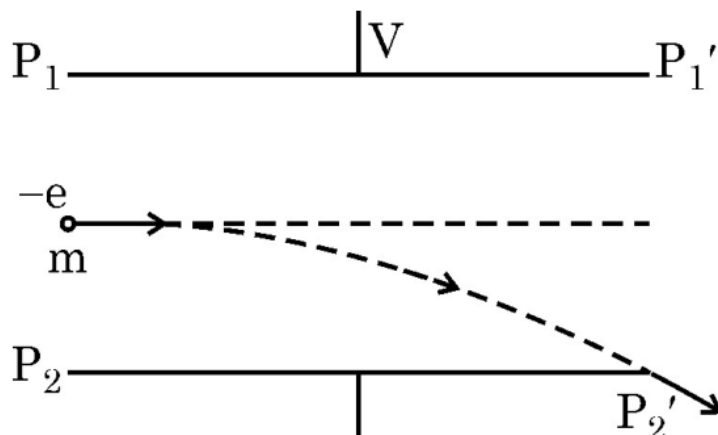
The potential difference therefore increases. This is also consistent with removal of the dielectric's opposing polarisation field.

Step 5: Conclusion On withdrawing the slab with the battery disconnected, $C_f = C/K$ decreases, $U_f = KU_i = \frac{1}{2}KCV^2$ increases, and $V_f = KV$ increases. Here $K = C/C_0 > 1$, equal to the dielectric constant when the slab initially fills the gap; the plate charge remains $Q = CV$.

Quick Tip to Solve: Write $Q = \text{constant}$ immediately after reading “battery disconnected”, then use $U = Q^2/(2C)$ and $V = Q/C$ to infer both increases.

24. Figure shows a narrow beam of electrons entering with a velocity of 3×10^7 m/s, symmetrically through the space between two parallel horizontal plates P_1P_1' and P_2P_2' kept 2 cm apart.

If each plate is 3 cm long, calculate the potential difference V applied between the plates so that the beam just strikes the end P_2' . [3 marks]



Solution:

Concept:

- Between parallel plates separated by d , the uniform electric-field magnitude is $E = |V|/d$, neglecting edge effects.
- An electron of mass m and charge $-e$ accelerates opposite to the electric field with magnitude $a = eE/m$. Its horizontal speed u stays constant because the electric force is vertical.
- For entry parallel to the plates, the initial vertical velocity is zero. The transit time is $t = L/u$, and the vertical displacement is $y = \frac{1}{2}at^2$, where L is the plate length.

Step 1: Identify the required displacement and transit time The beam enters midway between the plates, so it must move downward through half their separation to strike the lower plate at its far end P_2' . Thus

$$d = 2 \text{ cm} = 2 \times 10^{-2} \text{ m},$$

$$y = d/2 = 1 \times 10^{-2} \text{ m},$$

$$L = 3 \text{ cm} = 3 \times 10^{-2} \text{ m}.$$

Since the horizontal speed is $u = 3 \times 10^7 \text{ m s}^{-1}$, the time to reach the far end is

$$\begin{aligned} t &= \frac{L}{u} \\ &= \frac{3 \times 10^{-2}}{3 \times 10^7} \\ &= 1 \times 10^{-9} \text{ s}. \end{aligned}$$

Step 2: Find the vertical acceleration and electric field Taking downward displacement as positive,

the electron starts with zero vertical velocity. Apply the uniformly accelerated motion equation:

$$\begin{aligned}a &= \frac{2y}{t^2} \\&= \frac{2 \times 10^{-2}}{(10^{-9})^2} \\&= 2 \times 10^{16} \text{ m s}^{-2}.\end{aligned}$$

Using $m = 9.1 \times 10^{-31} \text{ kg}$ and $e = 1.6 \times 10^{-19} \text{ C}$, the required field magnitude is

$$\begin{aligned}E &= \frac{ma}{e} \\&= \frac{(9.1 \times 10^{-31})(2 \times 10^{16})}{1.6 \times 10^{-19}} \\&= 1.1375 \times 10^5 \text{ V m}^{-1}.\end{aligned}$$

Step 3: Calculate the potential difference and determine its polarity The potential difference acts across the full separation d , although the beam is displaced by only $d/2$. Therefore

$$\begin{aligned}|V| &= Ed \\&= (1.1375 \times 10^5)(2 \times 10^{-2}) \\&= 2.275 \times 10^3 \text{ V}.\end{aligned}$$

The electron must accelerate downward, so its negative charge requires an upward electric field. Electric field points from higher to lower potential; hence the lower plate $P_2P'_2$ must be at higher potential than the upper plate $P_1P'_1$.

Step 4: Conclusion The required potential difference has magnitude

$$|V| = 2.275 \times 10^3 \text{ V} \approx 2.28 \text{ kV}.$$

The lower plate is positive relative to the upper plate. This produces the required downward deflection of 1 cm at the far end.

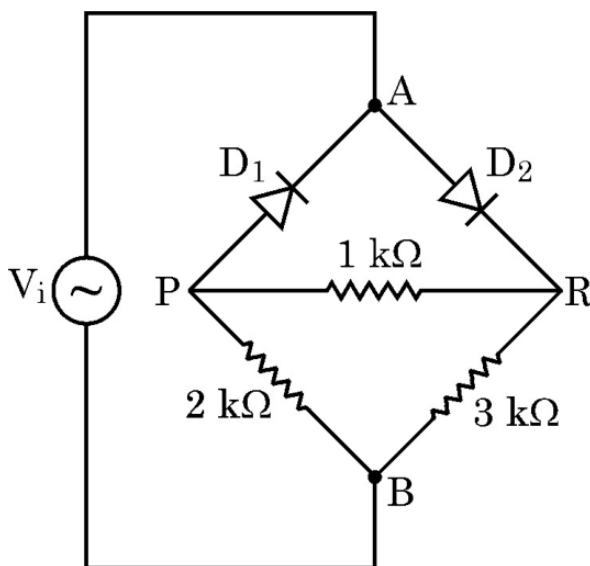
Quick Tip to Solve: Use half the plate spacing in $y = \frac{1}{2}at^2$, but the full spacing in $|V| = Ed$. For midpoint entry these combine to $|V| = mu^2d^2/(eL^2)$.

25. An ac voltage $V_i = 12 \sin(100\pi t)$ V is applied between points A and B in a network of two ideal diodes and three resistors as shown in figure.

During the positive half-cycle of the input voltage V_i supplied to the network:

- Identify which of the two diodes will conduct and why?
- Redraw an equivalent circuit diagram to show the flow of current.
- Calculate the output voltage drops V_o across the three resistors when the input voltage attains its peak value.

[3 marks]



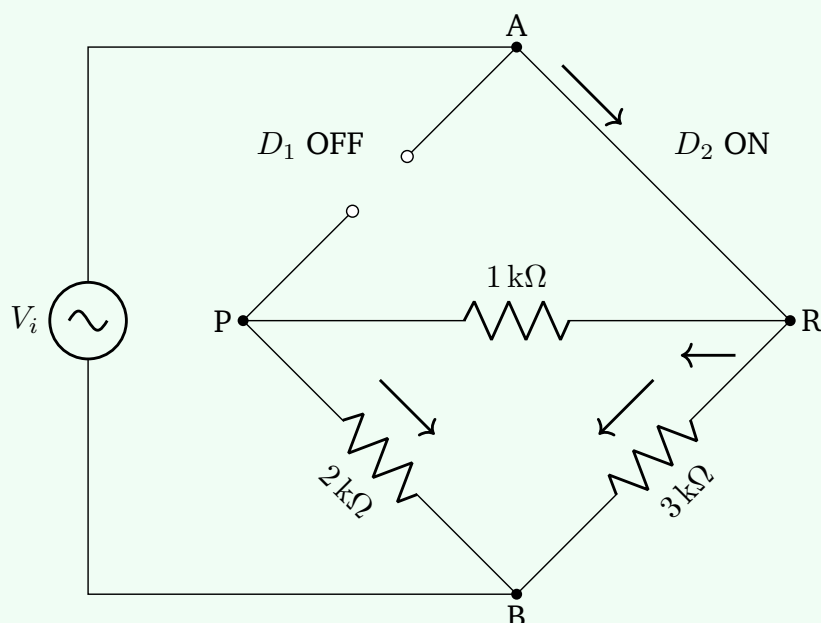
Solution:

Concept:

- An ideal forward-biased diode has zero voltage drop and acts as a closed switch; a reverse-biased ideal diode acts as an open switch.
- Ohm's law is $V = IR$, where V is the potential drop, I is the current and R is the resistance. Series resistors carry the same current, while parallel branches have the same potential difference.

Step 1: (a) Identify the conducting diode During the positive half-cycle, A is at a higher potential than B. The anode of D_2 is connected to A and its cathode is towards R, so D_2 is forward biased and conducts from A to R. The cathode of D_1 is towards A, whereas its anode is towards P. Thus D_1 is reverse biased and does not conduct. Consequently, A and R are at the same potential and there is no current in the A–P arm.

Step 2: (b) Replace the diodes by their ideal equivalents Replace D_2 by a wire and D_1 by an open gap, as drawn below. Current reaches R from A and splits into two paths: R to B through $3\text{ k}\Omega$, and R to P to B through $1\text{ k}\Omega$ followed by $2\text{ k}\Omega$. Thus the $1\text{ k}\Omega$ and $2\text{ k}\Omega$ resistors are in series, and this combination is in parallel with $3\text{ k}\Omega$. The arrows show conventional current during the positive half-cycle.



Positive half-cycle equivalent: D_1 open, D_2 shorted; arrows indicate current.

Step 3: (c) Calculate the drops at the positive peak The input is $V_i = 12 \sin(100\pi t)$ V, so its positive peak is 12 V. With B chosen as zero potential, $V_A = V_R = 12$ V. The current in the series branch is

$$I_{RPB} = \frac{12}{(1 + 2) \times 10^3} = 4 \times 10^{-3} \text{ A.}$$

Hence the drops along the direction of current are

$$V_R - V_P = (4 \times 10^{-3})(1 \times 10^3) = 4 \text{ V,}$$

$$V_P - V_B = (4 \times 10^{-3})(2 \times 10^3) = 8 \text{ V,}$$

$$V_R - V_B = 12 \text{ V.}$$

The $3 \text{ k}\Omega$ branch also carries $12/(3 \times 10^3) = 4 \text{ mA}$. As a consistency check, $V_P = 8 \text{ V} < V_A$, so D_1 is indeed reverse biased.

Step 4: Conclusion D_2 conducts and D_1 is off during the positive half-cycle. At the positive peak, the voltage drops across $1 \text{ k}\Omega$, $2 \text{ k}\Omega$ and $3 \text{ k}\Omega$ are respectively 4 V , 8 V , 12 V , with higher-potential ends R, P and R.

Quick Tip to Solve: First replace each ideal diode by a wire or an open gap. Here the wire makes A and R one node, revealing a $1 : 2$ voltage divider across the full input.

26. Briefly explain the two important processes that occur during the formation of a p-n junction.

[3 marks]

Solution:

Concept:

- Diffusion is the movement of charge carriers from a region of higher concentration to a region of lower concentration, caused by a concentration gradient.
- Drift is the directed motion of charge carriers under an electric field: electrons move opposite to the field and holes move along it.

Step 1: Explain diffusion and the formation of the depletion region On forming a p-n junction, the n-region has a high concentration of free electrons and the p-region has a high concentration of holes. Therefore, majority-carrier electrons diffuse from n to p, while holes diffuse from p to n. Near the junction, electrons recombine with holes.

The n-side close to the junction is left with immobile positive ionised donor atoms, and the p-side is left with immobile negative ionised acceptor atoms. The region containing these uncovered ions is depleted of mobile charge carriers and is called the depletion region. Both electron diffusion from n to p and hole diffusion from p to n produce conventional diffusion current from p to n.

Step 2: Explain drift and the establishment of equilibrium The fixed positive charge on the n-side and negative charge on the p-side produce an electric field directed from n to p. This field creates a potential barrier that opposes further diffusion of majority carriers. At the same time, it drives minority electrons in the p-region towards the n-region and minority holes in the n-region towards the p-region. This motion under the field is drift, and its conventional current is from n to p, opposite to the diffusion current.

As the depletion region and barrier develop, diffusion is reduced. For an unbiased junction at thermal equilibrium, the drift and diffusion currents have equal magnitudes and opposite directions:

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

Here the two currents are signed along a common reference direction. Thus the net current is zero even though carrier motion continues.

Step 3: Conclusion The two processes are **diffusion**, driven by the carrier concentration gradient, and **drift**, driven by the junction's electric field. Their opposing currents balance at thermal equilibrium, establishing the depletion region and potential barrier.

Quick Tip to Solve: Remember the cause of each process: concentration gradient causes diffusion; electric field causes drift. Draw the junction field mentally from positive donor ions on the n-side to negative acceptor ions on the p-side.

27. (a) Draw the ray diagram to show the image formation by a refracting telescope and write the expression for angular magnification for the telescope in normal adjustment.

(b) Give two reasons to explain why a reflecting telescope is preferred over a refracting telescope.

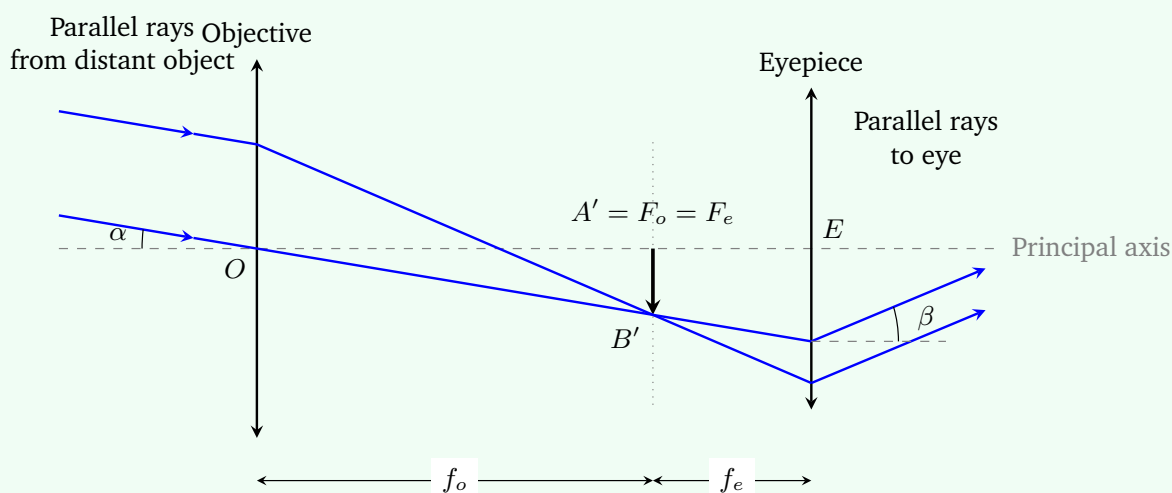
[3 marks]

Solution:

Concept:

- An astronomical refracting telescope uses a convex objective of focal length f_o and a convex eyepiece of shorter focal length f_e . The objective forms a real, inverted image of a distant object.
- In normal adjustment, the intermediate image lies in the common focal plane of the lenses, so the final image is at infinity. Angular magnification is $M = \beta/\alpha$, where α and β are the small angles subtended by the object and final image.

Step 1: (a) Form the intermediate and final images Parallel rays from a distant off-axis object point enter the objective and converge at B' . The real, inverted intermediate image $A'B'$ lies at the second focus F_o of the objective and at the first focus F_e of the eyepiece. After refraction by the eyepiece, rays from B' emerge parallel. Thus the final image is viewed at infinity with the eye relaxed. The separation of the lenses is $f_o + f_e$.



Refracting telescope in normal adjustment: the common focal-plane image is inverted and the emergent rays are parallel.

Step 2: Obtain the angular magnification Let the magnitude of the intermediate image height be $h = A'B'$. In the paraxial approximation,

$$|\alpha| \simeq \frac{h}{f_o}, \quad |\beta| \simeq \frac{h}{f_e}.$$

Dividing gives $|M| = f_o/f_e$. The image is inverted relative to the object, so the signed angular magnification carries a negative sign. A large objective focal length and a short eyepiece focal length give a large angular magnification.

Step 3: (b) Explain two advantages of a reflecting telescope **Freedom from chromatic aberration:** a mirror reflects all visible wavelengths according to the same law, so its focal length does not depend on colour. A lens objective refracts different colours differently and can produce coloured fringes.

Practical large aperture: a large mirror can be supported from behind, making a large objective easier to construct and support than a heavy lens supported at its rim. Its larger aperture collects more light and improves the diffraction-limited resolving power, allowing fainter and more closely

spaced objects to be studied.

Step 4: Conclusion In normal adjustment, the lens separation is $f_o + f_e$, the final image is at infinity, and

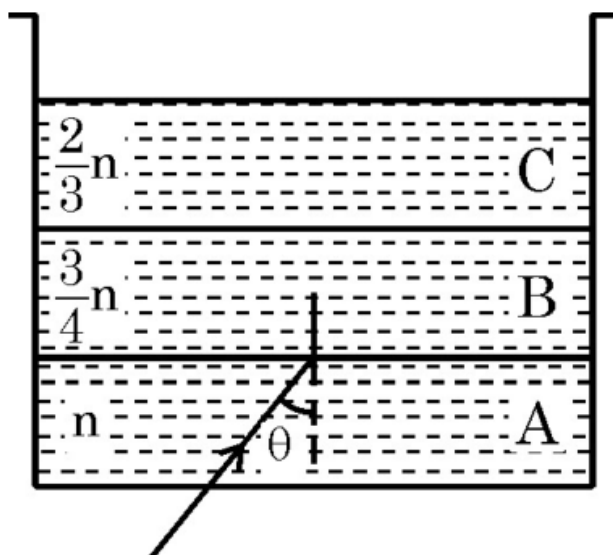
$$M = -\frac{f_o}{f_e}, \quad |M| = \frac{f_o}{f_e}.$$

Reflecting telescopes avoid chromatic aberration and permit larger, well-supported apertures with greater light collection and resolving power.

Quick Tip to Solve: Place the objective's image at the eyepiece's front focus; parallel emergent rays then identify normal adjustment, and the common image height cancels to give f_o/f_e .

28. (a) State the two conditions under which total internal reflection occurs.

(b) A transparent container contains layers of three immiscible transparent liquids A, B and C of refractive indices n , $\frac{3}{4}n$ and $\frac{2}{3}n$, respectively. A laser beam is incident at the interface between A and B at an angle θ as shown in figure. Prove that the beam does not enter region C at all for $\sin \theta \geq \frac{2}{3}$. [3 marks]



Solution:

Concept:

- Total internal reflection occurs when light travels from an optically denser medium toward a rarer medium and the incidence angle exceeds the critical angle. All angles are measured from the normal.
- Snell's law is $n_1 \sin i = n_2 \sin r$. For $n_1 > n_2$, the critical angle i_c satisfies $\sin i_c = n_2/n_1$; at $i = i_c$, the refracted ray grazes the interface.
- The liquid interfaces are parallel, so a ray transmitted into B has the same angle to the normal at the A–B and B–C interfaces.

Step 1: (a) State the two necessary conditions First, light must be incident from the optically denser medium on an optically rarer medium, so $n_1 > n_2$. Second, the angle of incidence must be strictly greater than the critical angle for the two media, $i > i_c$. Equality is the limiting case of grazing

refraction, not total internal reflection.

Step 2: (b) Check whether the beam can enter B From the printed data,

$$n_A = n, \quad n_B = \frac{3n}{4}, \quad n_C = \frac{2n}{3}.$$

At the A–B interface, $\sin i_{c,AB} = n_B/n_A = 3/4$. If $\sin \theta > 3/4$, the beam is totally internally reflected in A and cannot reach C. If $\sin \theta = 3/4$, the limiting transmitted ray travels along the A–B boundary and does not reach the B–C interface. It remains to examine $2/3 \leq \sin \theta < 3/4$, for which the beam enters B.

Step 3: Apply Snell's law at the B–C interface Let r be the refracted angle inside B at the first interface. Snell's law gives

$$n \sin \theta = \frac{3n}{4} \sin r \quad \Rightarrow \quad \sin r = \frac{4}{3} \sin \theta.$$

The incidence angle at the second interface is also r . Its critical angle satisfies

$$\sin i_{c,BC} = \frac{n_C}{n_B} = \frac{2/3}{3/4} = \frac{8}{9}.$$

Therefore $\sin \theta > 2/3$ implies $\sin r > 8/9$, giving total internal reflection at B–C whenever that interface is reached. At $\sin \theta = 2/3$, $r = i_{c,BC}$; the limiting refracted ray runs along the B–C boundary and does not propagate into region C.

Step 4: Conclusion The two conditions for total internal reflection are incidence from denser to rarer material and $i > i_c$. For $\sin \theta \geq 2/3$, no transmitted beam propagates into region C: reflection occurs at one of the interfaces, or a boundary is reached at the limiting grazing angle.

Quick Tip to Solve: Check the first interface before using the second: $\sin \theta > 3/4$ already reflects the beam in A. Treat equality at a critical angle as grazing refraction, not total internal reflection.

Section D (8 marks)

29. A galvanometer is used to detect or/and measure small currents in an electrical circuit. It essentially works on the fact that a current-carrying coil experiences a deflecting torque when placed in a magnetic field. This deflection in the coil can be measured and it is related to the current flowing in the coil, the number of turns in the coil, area of the coil and the magnetic field. A hair spring attached to the coil provides a counter torque and helps in measuring the deflection. A galvanometer can be converted to an ammeter or a voltmeter of desired range by using suitable resistances. [4 marks]

29(i). The torque on the coil remains constant irrespective of the coil's orientation during rotation due to: [1 mark]

- (A) use of soft iron core which increases the magnetic field.
- (B) radial magnetic field
- (C) hair spring which provides the counter torque
- (D) eddy current in the iron core which causes damping.

Correct Answer: (B) radial magnetic field

Solution:

Concept:

- The magnetic torque on a plane coil is $\tau = NIAB \sin \phi$, where N is its number of turns, I the current, A its area and ϕ the angle between the coil's normal and the magnetic field B .
- A radial field stays parallel to the plane of the rotating galvanometer coil, keeping $\phi = 90^\circ$ throughout its motion.

Step 1: Remove the orientation dependence In the radial field, the coil's normal remains perpendicular to the field. Thus $\sin \phi = 1$ at every allowed position, giving $\tau = NIAB$. For a fixed current, the deflecting torque is independent of the coil's orientation.

Step 2: Distinguish the other functions A soft iron core strengthens the field, but increasing field strength alone does not remove the angular factor, so (A) does not identify the required property. The spring in (C) supplies the restoring torque, which varies with deflection. Eddy currents in (D) damp the motion; damping does not make the magnetic deflecting torque independent of orientation.

Step 3: Conclusion The radial magnetic field keeps the angle between the coil's normal and the field equal to 90° . Hence, the correct option is (B).

Quick Tip to Solve: When a galvanometer question says torque is independent of rotation, look for the radial field: it fixes the torque factor $\sin \phi$ at unity.

29(ii). The best way to increase current sensitivity of a galvanometer is by:

[1 mark]

- (A) increasing number of turns of the coil
- (B) increasing area of coil and magnetic field strength
- (C) decreasing area of coil and magnetic field strength
- (D) increasing torsional constant of the hair spring

Correct Answer: (B) increasing area of coil and magnetic field strength

Solution:

Concept:

- Current sensitivity is the angular deflection per unit current, $S_I = \theta/I$. At equilibrium in a radial field, magnetic and spring torques balance: $NIAB = k\theta$.
- Therefore $S_I = NAB/k$, where N is the number of turns, A the coil area, B the magnetic field and k the torsional constant of the spring.

Step 1: Identify the intended improvement Increasing both A and B , as in (B), increases two factors in the numerator of $S_I = NAB/k$. This gives the intended choice for the combined improvement described as the best way in the question.

Step 2: Check all the alternatives carefully Increasing N , option (A), also increases the ideal current sensitivity when the other quantities are fixed; it must not be described as decreasing sensitivity. However, adding turns also adds wire and coil inertia, so it has a practical cost. Option (C) reduces both numerator factors, and (D) increases the denominator; both decrease sensitivity. The word “best” is qualitative here: the question gives no numerical sizes for comparing the increases in (A) and (B).

Step 3: Conclusion Increasing the coil area and magnetic field increases $S_I = NAB/k$, and is the intended combined improvement. Hence, the correct option is (B).

Quick Tip to Solve: Write $S_I = NAB/k$ before comparing choices: increasing N , A or B helps, whereas increasing the spring constant hurts sensitivity.

29(iii)(a). A moving coil galvanometer has a coil with area of cross-section $4.0 \times 10^{-3} \text{ m}^2$ and number of turns 50. The coil is rotating in a magnetic field of 0.25 T. The torque acting on the coil when a current of 5 A passes through it is:

[1 mark]

- (A) 1.0 N m
- (B) 2.0 N m
- (C) 0.50 N m
- (D) 0.25 N m

Correct Answer: (D) 0.25 N m

Solution:

Concept:

- In a moving-coil galvanometer, the radial magnetic field lies in the plane of the coil. The torque magnitude is therefore $\tau = NIAB$, with the normal to the coil perpendicular to the field.
- Here N is the number of turns, I is the current in amperes, A is the area of one turn in square metres and B is the field in tesla; the torque is in N m.

Step 1: Identify the quantities in SI units The stated values are $N = 50$, $A = 4.0 \times 10^{-3} \text{ m}^2$, $B = 0.25 \text{ T}$

and $I = 5 \text{ A}$. All are already in SI units. The factor N counts the torque contributions of all turns; the given area is not multiplied by an extra factor beyond this.

Step 2: Calculate and compare the choices Substitute directly into the radial-field torque formula:

$$\begin{aligned}\tau &= 50 \times 5 \times (4.0 \times 10^{-3}) \times 0.25 \\ &= 0.25 \text{ N m}.\end{aligned}$$

The intermediate product $NIA = 50 \times 5 \times 0.004 = 1.0 \text{ A m}^2$ must still be multiplied by B . Thus 1.0 N m , option (A), misses this factor. Options (B) and (C), 2.0 N m and 0.50 N m , also do not equal the product of the four stated quantities.

Step 3: Conclusion The torque is 0.25 N m . Hence, the correct option is (D).

Quick Tip to Solve: Multiply $50 \times (4.0 \times 10^{-3}) = 0.20$ first; then $0.20 \times 5 \times 0.25 = 0.25$. Keep the area exponent unchanged.

OR

29(iii)(b). A galvanometer coil has a resistance of 15Ω and the meter shows full scale deflection for a current of 3 mA . The value of resistance required to convert it into a voltmeter of range $(0\text{-}12 \text{ V})$ is: [1 mark]

- (A) 4015Ω
- (B) 3985Ω
- (C) 415Ω
- (D) 385Ω

Correct Answer: (B) 3985Ω

Solution:

Concept:

- A galvanometer becomes a voltmeter when a high resistance R is connected in series with its coil resistance G .
- At the upper limit V , the current must equal the full-scale current I_g : $V = I_g(G + R)$.

Step 1: Find the total resistance required Convert the full-scale current to amperes: $I_g = 3 \times 10^{-3} \text{ A}$. For a maximum reading of 12 V , Ohm's law gives

$$G + R = \frac{V}{I_g} = \frac{12}{3 \times 10^{-3}} = 4000 \Omega.$$

Step 2: Subtract the coil resistance The coil already supplies 15Ω , so the external resistance is

$$R = 4000 - 15 = 3985 \Omega.$$

Option (A) incorrectly adds the coil resistance. The resistances in (C) and (D) are much too small: with this full-scale current they would give voltage ranges of only 1.29 V and 1.20 V, respectively.

Step 3: Conclusion Connect $3985\ \Omega$ in series with the galvanometer. Hence, the correct option is (B).

Quick Tip to Solve: For a voltmeter, calculate V/I_g first, then subtract the galvanometer's own resistance; convert milliamperes to amperes before dividing.

29(iv). A galvanometer with coil of resistance $20\ \Omega$ shows full scale deflection for a current of 5 mA. To convert it into an ammeter of range (0-10 A), a resistance of: [1 mark]

- (A) $0.05\ \Omega$ should be connected in series with it
- (B) $0.05\ \Omega$ should be connected in parallel with it
- (C) $0.01\ \Omega$ should be connected in parallel with it
- (D) $0.01\ \Omega$ should be connected in series with it

Correct Answer: (C) $0.01\ \Omega$ should be connected in parallel with it

Solution:

Concept:

- A low shunt resistance S connected in parallel converts a galvanometer into an ammeter by carrying most of the measured current.
- At full scale the equal voltage drops satisfy $I_g G = (I - I_g)S$, where G is the coil resistance and I is the desired current range.

Step 1: Find the current through the shunt The coil must carry only $I_g = 5 \times 10^{-3}\text{ A}$ when the total current is 10 A. The parallel branch therefore carries

$$I_s = 10 - 0.005 = 9.995\text{ A}.$$

Its voltage drop equals the coil voltage, $I_g G = 0.005 \times 20 = 0.100\text{ V}$.

Step 2: Calculate and compare the shunt resistance Using the common voltage across the two parallel branches,

$$S = \frac{0.100}{9.995} = 0.010005 \dots \Omega \simeq 0.01\ \Omega.$$

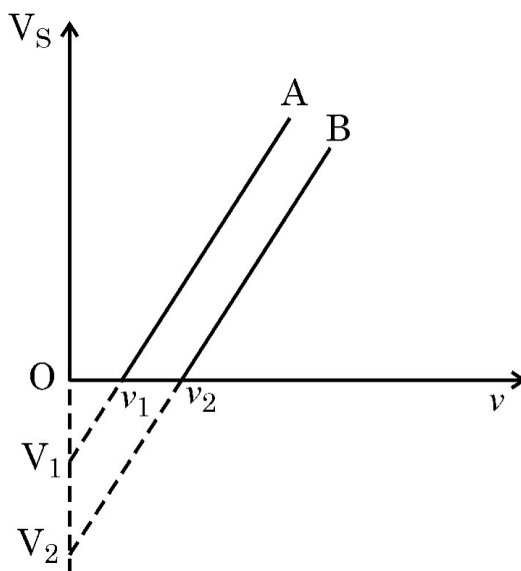
Options (A) and (D) use a series connection, which cannot divert current away from the coil. Option (B) has the wrong shunt value; $0.05\ \Omega$ would give a full-scale range of only $0.005 + 0.100/0.05 = 2.005\text{ A}$.

Step 3: Conclusion A resistance of approximately $0.01\ \Omega$ must be connected in parallel. Hence, the correct option is (C).

Quick Tip to Solve: For an ammeter, use a parallel shunt and calculate $S = I_g G / (I - I_g)$; when $I \gg I_g$, $I_g G / I$ is a quick estimate.

30. A researcher performs an experiment on photo-electric effect using two metals A and B with unknown work functions. She illuminates the surfaces of A and B with monochromatic radiation of various frequencies and records the value of corresponding stopping potentials (V_s). The graph shows the variation of stopping potential (V_s) with the frequency of incident radiation (ν) for metals A and B. [4 marks]

30(i). From the graph, the work functions of A and B are (h is Planck's constant and e value of charge on an electron): [1 mark]



- (A) ν_1 and ν_2
- (B) V_1 and V_2
- (C) $h\nu_1$ and $h\nu_2$
- (D) $\frac{h\nu_1}{e}$ and $\frac{h\nu_2}{e}$

Correct Answer: (C) $h\nu_1$ and $h\nu_2$

Solution:

Concept:

- Einstein's equation is $eV_s = h\nu - \phi$, where ϕ is the work function and e is the electron charge magnitude.
- At threshold frequency ν_0 , $V_s = 0$, so $\phi = h\nu_0$.

Step 1: Read the threshold frequencies At the frequency-axis intercept, $V_s = 0$. The graph therefore gives threshold frequencies ν_1 for A and ν_2 for B.

Step 2: Convert threshold frequency to work function At threshold, all the photon energy goes into freeing the electron:

$$\phi_A = h\nu_1, \quad \phi_B = h\nu_2.$$

Option (A) gives frequencies. Options (B) and (D) give potentials, not energies: dividing $h\nu$ by charge gives volts.

Step 3: Conclusion $\phi_A = h\nu_1$ and $\phi_B = h\nu_2$. Hence, the correct option is (C).

Quick Tip to Solve: On a stopping-potential versus frequency graph, multiply each frequency-axis intercept by h to obtain the corresponding work function.

30(ii). For radiation of frequency $\nu > \nu_2$ incident on the surfaces of A and B, the maximum kinetic energy of ejected electron is: [1 mark]

- (A) greater for metal A because it has a smaller work function.
- (B) greater for metal B because it has a larger work function.
- (C) greater for metal B because it has higher threshold frequency.
- (D) the same for both metal A and metal B because it is independent of work functions of metals.

Correct Answer: (A) greater for metal A because it has a smaller work function.

Solution:

Concept:

- For incident frequency ν , the maximum photoelectron kinetic energy is $K_{\max} = h\nu - \phi$, where ϕ is the work function.
- Work function and threshold frequency obey $\phi = h\nu_0$. A smaller threshold frequency means a smaller energy cost for emission.

Step 1: Compare the work functions from the graph Metal A has threshold frequency ν_1 , whereas B has threshold frequency ν_2 . Since the graph shows $\nu_1 < \nu_2$, their work functions satisfy $\phi_A = h\nu_1 < \phi_B = h\nu_2$. The condition $\nu > \nu_2$ ensures that both metals emit photoelectrons.

Step 2: Compare the energies at the same frequency Both metals receive photons of the same energy $h\nu$. Subtracting their maximum kinetic energies gives

$$K_A - K_B = (h\nu - \phi_A) - (h\nu - \phi_B) = \phi_B - \phi_A > 0.$$

Options (B) and (C) reverse the effect: a larger work function or threshold leaves less kinetic energy. Option (D) is false because kinetic energy explicitly depends on the work function.

Step 3: Conclusion The maximum kinetic energy is greater for metal A because it has the smaller work function. Hence, the correct option is (A).

Quick Tip to Solve: At one common incident frequency, choose the metal with the smaller frequency-axis intercept: less photon energy is spent freeing the electron.

30(iii). If the intensity of the incident radiation for both metals A and B, is doubled keeping its frequency constant, then: [1 mark]

- (A) the slope of the parallel lines will increase.
- (B) the slope of the parallel lines will decrease.
- (C) the threshold frequencies for both A and B will decrease.
- (D) the slope of the parallel lines will not change but more electrons will be emitted per second.

Correct Answer: (D) the slope of the parallel lines will not change but more electrons will be emitted per second.

Solution:

Concept:

- The stopping potential follows $V_s = (h/e)\nu - \phi/e$, where ϕ is the work function. The graph's slope is the universal ratio h/e .
- At fixed frequency, intensity measures the photon arrival rate per unit area; it does not change each photon's energy $h\nu$.

Step 1: Check the slope and threshold Doubling intensity changes neither Planck's constant h nor the electron charge magnitude e . Thus the slope h/e cannot increase or decrease, eliminating (A) and (B). The threshold frequency $\nu_0 = \phi/h$ depends on the metal's work function, which is unchanged; (C) is therefore false.

Step 2: Determine the effect on emission rate With frequency held constant above threshold, doubling the intensity supplies twice as many photons per second to the same illuminated area. More photoelectrons are therefore emitted per second. The maximum kinetic energy $h\nu - \phi$, and hence the stopping potential, remain unchanged because each photon retains the same energy.

Step 3: Conclusion The slope stays unchanged, while more electrons are emitted per second. Hence, the correct option is (D).

Quick Tip to Solve: Separate photon energy from photon number: frequency controls maximum kinetic energy, while intensity at fixed frequency controls the emission rate.

30(iv)(a). The threshold frequency for a metal surface is ν_0 . If the radiation of frequency $3\nu_0$ illuminates the surface, the maximum kinetic energy (KE) of photoelectrons is E_1 . If the frequency were increased to $6\nu_0$, the maximum KE of the photoelectrons becomes E_2 . Then $\frac{E_1}{E_2}$ equals: [1 mark]

- (A) 1/3
- (B) 1/2
- (C) 2/5
- (D) 3/4

Correct Answer: (C) 2/5

Solution:

Concept:

- Einstein's equation gives maximum kinetic energy $K_{\max} = h\nu - \phi$, where $h\nu$ is photon energy and ϕ is the work function.
- For threshold frequency ν_0 , $\phi = h\nu_0$, so $K_{\max} = h(\nu - \nu_0)$.

Step 1: Calculate the two maximum kinetic energies The work function is the same at both incident frequencies. Subtract $h\nu_0$ from each photon energy:

$$E_1 = h(3\nu_0) - h\nu_0 = 2h\nu_0,$$

$$E_2 = h(6\nu_0) - h\nu_0 = 5h\nu_0.$$

Step 2: Form the requested ratio The common factor $h\nu_0$ cancels:

$$\frac{E_1}{E_2} = \frac{2h\nu_0}{5h\nu_0} = \frac{2}{5}.$$

Option (B), $1/2$, is the ratio of incident photon energies and incorrectly ignores the energy spent overcoming the work function. Options (A) and (D) also disagree with the ratio of the excess frequencies, $(3 - 1)/(6 - 1)$.

Step 3: Conclusion The required ratio is $E_1/E_2 = 2/5$. Hence, the correct option is (C).

Quick Tip to Solve: When incident frequencies are multiples of ν_0 , subtract 1 from each multiplier before taking the maximum-kinetic-energy ratio.

OR

30(iv)(b). Let m be the slope of the graph line for metal B. If e is the value of electron charge, then Planck's constant ' h ' is given by: [1 mark]

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

Correct Answer: (A) me

Solution:

Concept:

- The stopping potential satisfies $eV_s = h\nu - \phi_B$, where ϕ_B is metal B's work function and e is the electron charge magnitude.
- In a straight-line equation $y = mx + c$, the coefficient of the horizontal-axis variable is the slope m .

Step 1: Express stopping potential as a linear function Divide Einstein's photoelectric equation by e :

$$V_s = \frac{h}{e}\nu - \frac{\phi_B}{e}.$$

Here V_s is plotted vertically and ν horizontally. Comparing with $y = mx + c$ gives $m = h/e$. The work function changes the intercept, but not the slope.

Step 2: Isolate Planck's constant Multiplying $m = h/e$ by e gives

$$h = me.$$

The slope has units $\text{V/Hz} = \text{V s}$; multiplying by charge gives $\text{C V s} = \text{J s}$, the units of h . Options (B),

(C), and (D) invert or divide the required factors and fail this equation and unit check.

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

Quick Tip to Solve: Check the vertical axis before using the slope: a V_s -versus- ν graph has slope h/e , so multiply its slope by e .

Section E (15 marks)

31(a). An electric dipole consists of two point charges q and $-q$ separated by a distance $2a$. Derive an expression for the electric field $\vec{E}$ due to this dipole at a point distant r from the centre of the dipole on the equatorial plane. Write the expression for the electric field at a far off point, i.e. $r \gg a$.

(b) A dipole is placed in x - y plane such that charges q and $-q$ are located at $x = a$ and $x = b$ respectively. There exists an electric field $\vec{E} = 2\hat{i}$ N/C in the region. Calculate the force $\vec{F}$ and torque $\vec{\tau}$ experienced by the dipole. [5 marks]

Solution:

Concept:

- The electric field of a point charge Q at displacement $\vec{s}$ from it is $\vec{E} = kQ\vec{s}/s^3$, where $k = 1/(4\pi\epsilon_0)$. Fields obey vector superposition.
- The dipole moment $\vec{p}$ points from the negative charge to the positive charge and has magnitude $p = q(2a)$. The equatorial plane is perpendicular to $\vec{p}$ through the dipole centre.
- In a uniform external electric field, the two charges have forces $+q\vec{E}$ and $-q\vec{E}$. Their net force is zero, while the torque is $\vec{\tau} = \vec{p} \times \vec{E}$.

Step 1: (a) Set up the equatorial-point geometry Put the dipole centre at the origin, with $+q$ at $(a, 0)$ and $-q$ at $(-a, 0)$. Choose the equatorial point P at $(0, r)$. Any point on the equatorial plane can be treated this way by choosing the transverse axis through it. Both charges are at the same distance from P :

$$s = \sqrt{r^2 + a^2}, \quad \vec{p} = 2qa\hat{i}.$$

The field due to $+q$ points away from that charge; the field due to $-q$ points towards it. Their transverse components are opposite, whereas their components along the dipole axis both point from $+q$ towards $-q$.

Step 2: (a) Add the fields and obtain the distant-point limit Using the displacement vectors from each charge to P , write

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

On addition, the $\hat{j}$ components cancel and the $\hat{i}$ components add:

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

The minus sign gives the direction opposite to the dipole moment. At a far off point $r \gg a$, neglect a^2

in comparison with r^2 . Thus $(r^2 + a^2)^{3/2} \simeq r^3$, giving

$$\vec{E}_{\text{eq}} \simeq -\frac{1}{4\pi\epsilon_0} \frac{\vec{p}}{r^3}.$$

Step 3: (b) Calculate the two forces in the given uniform field The printed external field is $\vec{E} = 2\hat{i}$ N/C, independent of position. Hence it has the same value at $x = a$ and $x = b$. Taking q in coulombs, the forces on the positive and negative charges are

$$\vec{F}_+ = 2q\hat{i} \text{ N}, \quad \vec{F}_- = -2q\hat{i} \text{ N}.$$

Therefore their vector sum is

$$\vec{F} = \vec{F}_+ + \vec{F}_- = \vec{0}.$$

The separate charges experience nonzero forces, but those forces exactly cancel for the dipole as a whole.

Step 4: (b) Evaluate the torque for the stated alignment For the given charge locations along the x -axis, the displacement from $-q$ at $x = b$ to $+q$ at $x = a$ is $(a - b)\hat{i}$. The moment in this part is therefore $\vec{p} = q(a - b)\hat{i}$. It is parallel or antiparallel to the external field, so

$$\vec{\tau} = \vec{p} \times \vec{E} = q(a - b)\hat{i} \times (2\hat{i}) = \vec{0}.$$

Equivalently, both charge forces act along the dipole axis, with no perpendicular lever arm about its centre. Since the resultant force is zero, the zero torque is independent of the chosen origin.

Step 5: Conclusion (a) $\vec{E}_{\text{eq}} = -\frac{\vec{p}}{4\pi\epsilon_0(r^2 + a^2)^{3/2}}$, and for $r \gg a$, $\vec{E}_{\text{eq}} \simeq -\frac{\vec{p}}{4\pi\epsilon_0 r^3}$; both point opposite to $\vec{p}$. (b) In the printed uniform field, the net force is $\vec{F} = \vec{0}$ N and the torque is $\vec{\tau} = \vec{0}$ N m.

Quick Tip to Solve: At an equatorial point, cancel the transverse field components and add the axial ones. For part (b), first check that the printed field has no position dependence, then check the dipole's alignment before evaluating torque.

31(b). (a) Two cells of emf E_1 and E_2 with internal resistances r_1 and r_2 respectively, are connected in parallel by connecting their positive terminals together and negative terminals together. Deduce an expression for equivalent emf and equivalent internal resistance of the combination.

(b) A parallel combination, as stated in (a) above, of two cells of emfs E and $3E$ and internal resistances R each is connected across a resistance $2R$. Find the current that flows through resistance $2R$.

[5 marks]

Solution:

Concept:

- Cells connected in parallel between like terminals have a common terminal potential difference V . For a cell of emf E_i , internal resistance r_i , and outgoing current I_i , $V = E_i - I_i r_i$.
- Kirchhoff's junction rule gives the current delivered to the external circuit as $I = I_1 + I_2$. A negative branch current means that branch is receiving current.
- An equivalent source obeys $V = E_{\text{eq}} - I r_{\text{eq}}$. Comparing the constant term and the coefficient of I with the original combination identifies its equivalent emf and internal resistance.

Step 1: (a) Express the current supplied by each cell Let the joined positive terminals form terminal A , and the joined negative terminals form terminal B . Define $V = V_A - V_B$. Let I_1 and I_2 be positive when each cell supplies current out of its positive terminal. Since both cells are connected across the same terminals,

$$V = E_1 - I_1 r_1 = E_2 - I_2 r_2.$$

Rearranging the two cell equations separately gives

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

These equations remain valid for unequal emfs even when the weaker cell receives current from the other cell.

Step 2: (a) Deduce the equivalent source equation By the junction rule, the current in the external circuit is

$$\begin{aligned} I &= I_1 + I_2 \\ &= \frac{E_1}{r_1} + \frac{E_2}{r_2} - V \left(\frac{1}{r_1} + \frac{1}{r_2} \right). \end{aligned}$$

Solve this equation for the terminal voltage:

$$\begin{aligned} V &= \frac{E_1/r_1 + E_2/r_2}{1/r_1 + 1/r_2} - I \frac{1}{1/r_1 + 1/r_2} \\ &= \frac{E_1 r_2 + E_2 r_1}{r_1 + r_2} - I \frac{r_1 r_2}{r_1 + r_2}. \end{aligned}$$

Comparing with $V = E_{\text{eq}} - I r_{\text{eq}}$, obtain

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

Thus the equivalent emf is weighted by the branch conductances, and the equivalent internal resistance is the parallel combination of the internal resistances. In particular, E_{eq} is the open-circuit terminal voltage, found when the external current $I = 0$.

Step 3: (b) Substitute the given cell values Here $E_1 = E$, $E_2 = 3E$, and $r_1 = r_2 = R$. Substitution into the expressions just derived gives

$$E_{\text{eq}} = \frac{ER + (3E)R}{R + R} = 2E,$$

$$r_{\text{eq}} = \frac{R \cdot R}{R + R} = \frac{R}{2}.$$

The arithmetic mean of the two emfs applies here because the two internal resistances are equal. The external resistance $2R$ is in series with the internal resistance of the equivalent source.

Step 4: (b) Calculate and check the load current Apply Ohm's law to the complete equivalent circuit, including its internal resistance:

$$I = \frac{E_{\text{eq}}}{2R + r_{\text{eq}}} = \frac{2E}{2R + R/2} = \frac{4E}{5R}.$$

As a check, the terminal voltage is $V = I(2R) = 8E/5$. The original cell currents are then

$$I_1 = \frac{E - 8E/5}{R} = -\frac{3E}{5R}, \quad I_2 = \frac{3E - 8E/5}{R} = \frac{7E}{5R}.$$

Their sum is $4E/(5R)$, consistent with the load current. The negative value of I_1 means current enters the weaker cell's positive terminal; this does not change the direction of current through the external resistance.

Step 5: Conclusion (a) $E_{\text{eq}} = \frac{E_1 r_2 + E_2 r_1}{r_1 + r_2}$ and $r_{\text{eq}} = \frac{r_1 r_2}{r_1 + r_2}$. (b) The current through $2R$ is $I = \frac{4E}{5R}$ amperes when E is in volts and R in ohms, flowing externally from the joined positive terminals towards the joined negative terminals.

Quick Tip to Solve: For equal internal resistances, average the emfs and halve either internal resistance. Add that equivalent internal resistance to the load before calculating the current.

32(a). Using the relation for refraction at a curved spherical surface, derive the expression for lens maker's formula.

(b) Three lenses L_1 , L_2 and L_3 , each of focal length 40 cm, are placed coaxially. The distance between L_1 and L_2 and between L_2 and L_3 are 120 cm and 20 cm respectively. An object is kept at a distance of 80 cm to the left of lens L_1 . Find the distance of the final image formed from the object. [5 marks]

Solution:

Concept:

- For paraxial refraction from a medium of refractive index n_1 to one of index n_2 at a spherical surface, $\frac{n_2}{v} - \frac{n_1}{u} = \frac{n_2 - n_1}{R}$. Here u , v and R are signed object distance, image distance and radius of curvature, measured from the pole.
- A thin lens consists of two refracting surfaces. Its thickness is neglected compared with the object and image distances and radii of curvature, and only rays close to the principal axis are considered.
- The thin-lens formula is $\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$. With light travelling from left to right, distances to the right are positive and those to the left are negative. The image from each lens supplies the object, or incident beam, for the next lens.

Step 1: (a) Apply spherical refraction at the first surface Consider a thin lens of absolute refractive index n_ℓ immersed on both sides in a medium of refractive index n_m . Let its first and second surfaces have signed radii R_1 and R_2 , respectively. An axial object is at signed distance u . If the first surface alone would form an image at signed distance v_1 , refraction from the surrounding medium into the lens gives

$$\frac{n_\ell}{v_1} - \frac{n_m}{u} = \frac{n_\ell - n_m}{R_1}.$$

The position v_1 represents the intermediate image that would be obtained if the second refracting surface were absent.

Step 2: (a) Apply refraction at the second surface and add The rays emerging from the first surface fall on the second surface, so the intermediate image acts as its object. Since the lens is thin, the signed object distance for this surface is approximately v_1 . Refraction now occurs from the lens into the surrounding medium. If the final image distance is v ,

$$\frac{n_m}{v} - \frac{n_\ell}{v_1} = \frac{n_m - n_\ell}{R_2}.$$

Adding the two surface equations cancels the intermediate-image term:

$$n_m \left(\frac{1}{v} - \frac{1}{u} \right) = (n_\ell - n_m) \left(\frac{1}{R_1} - \frac{1}{R_2} \right).$$

On defining the relative refractive index $\mu = n_\ell/n_m$, this becomes

$$\frac{1}{v} - \frac{1}{u} = (\mu - 1) \left(\frac{1}{R_1} - \frac{1}{R_2} \right).$$

Step 3: (a) Identify the focal length For an object at infinity on the left, $u \rightarrow -\infty$, the incident rays are parallel and the image is formed at the image-side focus, so $v = f$. Therefore,

$$\frac{1}{f} = (\mu - 1) \left(\frac{1}{R_1} - \frac{1}{R_2} \right).$$

This is the lens maker's formula. In air, $n_m \simeq 1$, so μ is the refractive index of the lens material relative to air. The radii retain their signs; for a biconvex lens with light incident from the left, $R_1 > 0$ and $R_2 < 0$.

Step 4: (b) Locate the image produced by the first lens Take L_1 as the origin of a common coordinate axis. The object, L_2 and L_3 are then at -80 cm, $+120$ cm and $+140$ cm, respectively. Using the given positive focal lengths, $f_1 = f_2 = f_3 = +40$ cm. For L_1 , $u_1 = -80$ cm, hence

$$\begin{aligned} \frac{1}{v_1} &= \frac{1}{f_1} + \frac{1}{u_1} = \frac{1}{40} - \frac{1}{80} = \frac{1}{80} \text{ cm}^{-1}, \\ v_1 &= +80 \text{ cm}. \end{aligned}$$

Thus L_1 forms a real intermediate image at coordinate $+80$ cm, between the first and second lenses.

Step 5: (b) Determine the beam emerging from the second lens The first image lies $120 - 80 = 40$ cm to the left of L_2 , so it is a real object for L_2 with $u_2 = -40$ cm. Applying the lens formula,

$$\frac{1}{v_2} = \frac{1}{f_2} + \frac{1}{u_2} = \frac{1}{40} - \frac{1}{40} = 0.$$

The object is exactly at the first focus of L_2 ; consequently, the rays emerging from L_2 are parallel to the principal axis and its image is at infinity.

Step 6: (b) Locate the image formed by the third lens The parallel beam travels the 20 cm separation to L_3 without changing its convergence. It therefore corresponds to an object at infinity for L_3 . Thus

$$\frac{1}{v_3} = \frac{1}{f_3} + 0 = \frac{1}{40} \text{ cm}^{-1}, \quad v_3 = +40 \text{ cm}.$$

The final image is real and lies 40 cm to the right of L_3 . Its coordinate measured from L_1 is $x_I = 120 + 20 + 40 = 180 \text{ cm}$. The original object coordinate remains $x_O = -80 \text{ cm}$.

Step 7: Conclusion (a) The lens maker's formula is

$$\frac{1}{f} = (\mu - 1) \left(\frac{1}{R_1} - \frac{1}{R_2} \right),$$

where μ is the lens material's refractive index relative to the surrounding medium. (b) The distance of the final image from the original object is

$$x_I - x_O = 180 - (-80) = 260 \text{ cm}.$$

The final real image is 260 cm to the right of the object.

Quick Tip to Solve: After each lens, locate its image on one common coordinate axis before assigning the next object distance. Here the first image is at the focus of L_2 , so the parallel beam immediately places the last image one focal length beyond L_3 .

OR

32(b). (a) Draw a ray diagram to show the image formation by a concave mirror when the object is kept between its focus and the centre of curvature. Using this diagram, derive the mirror formula.

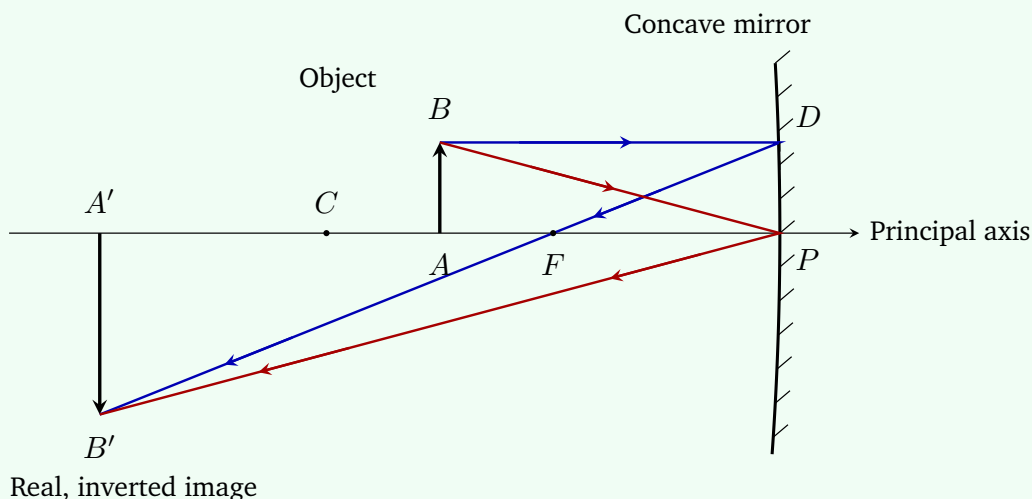
(b) A concave mirror produces a two times magnified virtual image of an object kept 10 cm in front of it. Calculate the focal length of the mirror. [5 marks]

Solution:

Concept:

- For a spherical mirror of small aperture, paraxial rays obey the laws of reflection. A ray parallel to the principal axis of a concave mirror is reflected through its principal focus F .
- In the Cartesian convention, distances are measured from the pole P , positive along incident light. For a real object and a real image in front of a concave mirror, $u < 0$, $v < 0$ and $f < 0$.
- The linear magnification of a mirror is $m = h_i/h_o = -v/u$, where h_o, h_i are signed object and image heights. An erect virtual image has positive magnification.

Step 1: (a) Construct the image for an object between the focus and centre Let AB be the upright object, with its foot A between F and the centre of curvature C . From B , draw a ray parallel to the principal axis; it strikes the mirror at D and is reflected through F . A second ray from B strikes the pole P and is reflected making an equal angle with the principal axis. The reflected rays meet at B' , giving the image $A'B'$ beyond C . This image is real, inverted and magnified. The diagram uses the paraxial approximation, with the transverse scale enlarged for clarity.



Concave mirror: object between F and C , image beyond C ; paraxial ray diagram.

Step 2: (a) Obtain two relations from similar triangles First use positive lengths $U = PA$, $V = PA'$, $F_0 = PF$, $h = AB$ and $H = A'B'$. Here H denotes the magnitude of the inverted image height. The equal angles of incidence and reflection at P , together with the right angles at A and A' , give similar triangles ABP and $A'B'P$. Hence,

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

The incident ray BD is parallel to the axis, so the height of D is h . For a small aperture the axial displacement of D from P is negligible; thus $DP \simeq h$, taken perpendicular to the axis. The triangles DPF and $B'A'F$ are then similar. Since $A'F = V - F_0$,

$$\frac{H}{h} = \frac{A'F}{PF} = \frac{V - F_0}{F_0}.$$

Step 3: (a) Derive the mirror formula with signed distances Equating the two expressions for the height ratio and rearranging gives

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

The incident light travels from left to right. For the configuration shown, the object, real image and focus all lie to the left of the pole, so $u = -U$, $v = -V$ and $f = -F_0$. Therefore,

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

This is the mirror formula in the paraxial approximation. With the Cartesian sign convention, the same formula also applies to a virtual image.

Step 4: (b) Use the virtual-image magnification to find the focal length The object is in front of the mirror, so $u = -10$ cm. A virtual image of a real object in a concave mirror is erect; hence the given

magnification is $m = +2$. Using the magnification relation,

$$2 = -\frac{v}{-10 \text{ cm}} \implies v = +20 \text{ cm}.$$

The positive image distance correctly places this virtual image behind the mirror. Substitute these signed distances in the mirror formula:

$$\begin{aligned}\frac{1}{f} &= \frac{1}{-10 \text{ cm}} + \frac{1}{+20 \text{ cm}} \\ &= -\frac{1}{20 \text{ cm}}, \\ f &= -20 \text{ cm}.\end{aligned}$$

The object distance has magnitude $10 \text{ cm} < |f|$, consistent with an object between the pole and focus producing an erect, enlarged virtual image.

Step 5: Conclusion (a) For an object between F and C , the concave mirror forms a real, inverted, enlarged image beyond C , and the mirror formula is $\boxed{1/f = 1/u + 1/v}$. (b) The focal length is $\boxed{f = -20 \text{ cm}}$, with magnitude 20 cm.

Quick Tip to Solve: For the virtual image here, enter $m = +2$ first. Then $v = -mu$ gives a positive image distance; carry that sign into the mirror formula.

33(a). State Faraday's law of electromagnetic induction.

(b) Derive an expression for the self-inductance of an air-filled long solenoid of length l and cross-sectional area A having N turns.

(c) A conducting rod of length 50 cm, with one end pivoted, is rotated with angular speed of 60 rpm in a uniform magnetic field of 4.0 mT directed perpendicular to the plane of rotation of rod. Find the emf induced in the rod. [5 marks]

Solution:

Concept:

- Magnetic flux through one turn is $\Phi_B = \int \vec{B} \cdot d\vec{A}$. Faraday's law relates the induced emf $\mathcal{E}$ to the rate of change of total flux linkage: $\mathcal{E} = -d(N\Phi_B)/dt$.
- Self-inductance L is the flux linkage per unit current: $N\Phi_B = LI$. For a long air-filled solenoid, the nearly uniform interior field is $B = \mu_0 nI$, where $n = N/l$ is the number of turns per unit length.
- A small element of a rotating rod at distance r from its pivot moves with speed $v = \omega r$. Its motional emf is $d\mathcal{E} = Bv dr$ when the magnetic field is perpendicular to the plane of rotation.

Step 1: (a) State Faraday's law and its sign convention Whenever the magnetic flux linked with a circuit changes, an emf is induced in it. The magnitude of the induced emf equals the rate of change of magnetic flux linkage. For a coil of N turns, each linked by the same flux Φ_B ,

$$\mathcal{E} = -\frac{d(N\Phi_B)}{dt} = -N\frac{d\Phi_B}{dt}.$$

The negative sign expresses Lenz's law: the induced emf drives a current, if the circuit is closed, whose magnetic effect opposes the change in flux producing it. An induced emf can exist even when the circuit is open.

Step 2: (b) Find the flux linked with the solenoid Consider a long solenoid of length l , cross-sectional area A , and N closely wound turns carrying current I . Neglect the end effects, so that the field is uniform inside and negligible outside. Air has relative permeability approximately unity. Applying the long-solenoid field expression gives

$$B = \mu_0 \frac{N}{l} I.$$

The field is directed along the solenoid axis, perpendicular to the area of each turn. Thus the flux through one turn and the total flux linkage are

$$\begin{aligned}\Phi_B &= BA = \frac{\mu_0 N I A}{l}, \\ N\Phi_B &= \frac{\mu_0 N^2 A I}{l}.\end{aligned}$$

Multiplication by N in the second line is essential because the same interior flux links every turn.

Step 3: (b) Identify the self-inductance By definition, the flux linkage produced by the solenoid's own current is LI . Comparing this with the expression above,

$$LI = \frac{\mu_0 N^2 A I}{l}, \quad L = \frac{\mu_0 N^2 A}{l}.$$

The SI unit of L is the henry, H. For this fixed geometry and air core, L is independent of current. If the current changes, the induced emf is $\mathcal{E} = -L dI/dt$, which opposes that change.

Step 4: (c) Derive the emf across the rotating rod Denote the rod length by a to distinguish it from the solenoid length l . The pivot has zero speed, while the free end has speed ωa , so the speed is not constant along the rod. For a radial element of length dr at distance r , the magnetic force per unit charge along the rod has magnitude $B\omega r$. Integrating the elemental emf from the pivot to the free end gives

$$|\mathcal{E}| = \int_0^a B\omega r dr = B\omega \left[\frac{r^2}{2} \right]_0^a = \frac{1}{2} B\omega a^2.$$

The factor $1/2$ accounts for the increase of speed from zero to the tip speed along the rod.

Step 5: (c) Convert the data and substitute Convert the given length and field to SI units:

$$a = 50 \text{ cm} = 0.50 \text{ m}, \quad B = 4.0 \text{ mT} = 4.0 \times 10^{-3} \text{ T}.$$

The quoted rotation rate is 60 revolutions per minute, so its angular speed in radians per second is

$$\omega = 2\pi \left(\frac{60}{60} \right) = 2\pi \text{ rad s}^{-1}.$$

Hence the emf magnitude is obtained as

$$\begin{aligned}|\mathcal{E}| &= \frac{1}{2} (4.0 \times 10^{-3}) (2\pi) (0.50)^2 \text{ V} \\ &= \pi \times 10^{-3} \text{ V} \simeq 3.14 \times 10^{-3} \text{ V}.\end{aligned}$$

The sense of rotation and the direction of the field relative to the observer are not specified, so a particular end cannot be assigned a positive polarity.

Step 6: Conclusion Faraday's law is $\mathcal{E} = -d(N\Phi_B)/dt$. The air-filled long solenoid has self-inductance $L = \mu_0 N^2 A/l$. The emf induced between the pivot and the free end of the rod has magnitude

$$|\mathcal{E}| \simeq 3.14 \text{ mV}, \text{ or } 3.1 \text{ mV to two significant figures.}$$

Quick Tip to Solve: Use total flux linkage $N\Phi_B$, not flux per turn, when finding L . For a rod rotating about one end use $\frac{1}{2}B\omega a^2$, and convert rpm to radians per second before substitution.

OR

33(b). (a) Draw a labelled diagram of a step-up transformer. State the principle on which it works and obtain the ratio of secondary voltage to primary voltage in terms of number of turns and currents in the two coils.

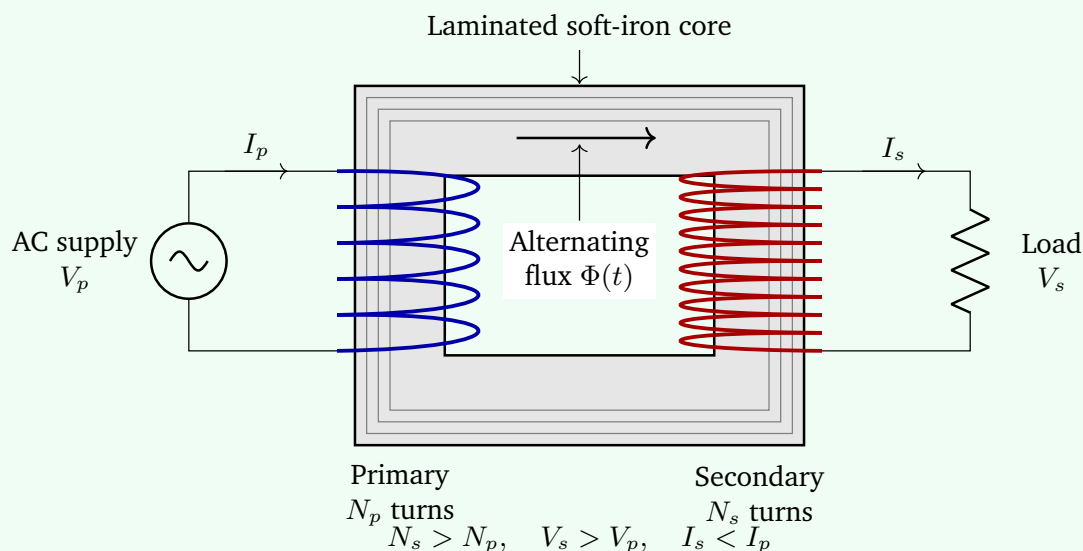
(b) The ratio of the number of turns in the primary to the secondary of an ideal transformer is 1 : 5. If 5 kW power at 200 V is supplied to the primary, find (i) current in the primary, and (ii) output voltage. [5 marks]

Solution:

Concept:

- A transformer works on mutual induction: alternating current in the primary coil produces a changing magnetic flux in the core, which induces an emf in the secondary coil.
- Faraday's law gives $e_p = -N_p d\Phi/dt$ and $e_s = -N_s d\Phi/dt$, where Φ is the common flux through one turn and N_p, N_s are the primary and secondary turns.
- For an ideal transformer, voltage is proportional to turns and input power equals output power. Thus $V_s/V_p = N_s/N_p$ and $V_p I_p = V_s I_s$, with voltages and currents expressed as rms values for the usual resistive-load case.

Step 1: (a) Draw and explain the step-up transformer The primary and secondary are separate insulated coils wound on a common laminated soft-iron core. The primary is connected to an AC supply and the secondary to the load. In a step-up transformer, the secondary has more turns than the primary, $N_s > N_p$. The diagram is schematic; it shows this inequality, not the numerical turns ratio in part (b). The alternating primary current sets up an alternating flux in the core. This flux links both coils and, by mutual induction, induces an alternating secondary emf. The core provides a common magnetic path; laminations reduce eddy-current losses in a practical transformer. A steady DC supply cannot produce the continuously changing flux required for transformer action.



Step-up transformer: separate windings on a common laminated core, with $N_s > N_p$.

Step 2: (a) Obtain the voltage ratio from Faraday's law Assume an ideal transformer with negligible winding resistance and no flux leakage, so each turn of either winding links the same flux $\Phi(t)$. Taking corresponding winding senses, the induced emfs are

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

Dividing the emf equations eliminates the common rate of change of flux. The same ratio holds for their rms magnitudes, E_p and E_s :

$$\frac{E_s}{E_p} = \frac{N_s}{N_p}.$$

With negligible voltage drops, the applied primary voltage has magnitude $V_p = E_p$, while the secondary terminal voltage is $V_s = E_s$. Hence

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}.$$

Step 3: (a) Relate the voltage ratio to the currents An ideal transformer has no energy loss. For the usual resistive-load treatment, equality of input and output powers gives

$$V_p I_p = V_s I_s \quad \Rightarrow \quad \frac{V_s}{V_p} = \frac{I_p}{I_s}.$$

Combining this with the turns relation,

$$\boxed{\frac{V_s}{V_p} = \frac{N_s}{N_p} = \frac{I_p}{I_s}}.$$

Therefore, increasing the voltage requires a corresponding decrease in current: a step-up transformer does not increase the power. For an ideal transformer with a reactive load, the matching input and output power factors cancel and the same current ratio holds.

Step 4: (b)(i) Calculate the primary current The supplied power is $P_p = 5 \text{ kW} = 5000 \text{ W}$ and the

primary voltage is $V_p = 200 \text{ V}$. Using the standard transformer numerical relation $P_p = V_p I_p$,

$$I_p = \frac{P_p}{V_p} = \frac{5000}{200} = 25 \text{ A}.$$

Step 5: (b)(ii) Calculate the output voltage The stated ratio is primary to secondary: $N_p : N_s = 1 : 5$. Therefore the ratio required for the secondary voltage is $N_s/N_p = 5$, giving

$$V_s = V_p \frac{N_s}{N_p} = 200 \times 5 = 1000 \text{ V}.$$

As a consistency check, the ideal secondary current would be $I_s = I_p/5 = 5 \text{ A}$, so the secondary power is $1000 \times 5 = 5000 \text{ W}$, equal to the input power.

Step 6: Conclusion A step-up transformer works on mutual induction and has $N_s > N_p$. For an ideal transformer,

$$\boxed{\frac{V_s}{V_p} = \frac{N_s}{N_p} = \frac{I_p}{I_s}}.$$

The primary current is $\boxed{25 \text{ A}}$, and the output voltage is $\boxed{1000 \text{ V}}$.

Quick Tip to Solve: Write the stated ratio as $N_p/N_s = 1/5$ before using it. The voltage increases fivefold while the current decreases fivefold; convert 5 kW to 5000 W before dividing by 200 V.