CBSE Class 12 Physics Question Paper 2005 with Solution PDF-Delhi

Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours **Maximum Marks: 70**

General Instructions

(i) All questions are compulsory.

(ii) There is no overall choice. However, an internal choice has been provided in one question of two marks, one question of three marks and one question of five marks. You have to attempt only one of the choices in such questions.

(iii) Question numbers **1 to 5** are very short answer type questions, carrying **one** mark each.

(iv) Question numbers **6 to 12** are short answer type questions, carrying **two** marks each.

(v) Question numbers **13 to 24** are also short answer type questions, carrying **three** marks each.

(vi) Question numbers **25 to 27** are long answer type questions, carrying **five** marks each.

(vii) Use of calculators is not permitted. However, you may use log tables, if necessary.

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

$c = 3 \times 10^8$ ms^{-1}

$h = 6.6 \times 10^{-34}$ Js

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

$m_e = 9.1 \times 10^{-31}$ kg

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

$\frac{1}{4\pi\varepsilon_0} = 9 \times 10^9$ N-m^2 / C^2

Mass of neutron $m_n = 1.6 \times 27^{-27}$ kg

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

Avogadro's number $N_A = 6.023 \times 10^{23}$ / mole

1. An electric dipole of dipole moment 20×10^{-6} C · m is enclosed by a closed surface. What is the net flux coming out of the surface? [1 mark]

Solution:

Concept:

- Gauss's law gives the outward electric flux through any closed surface as $\Phi_E = Q_{\text{enclosed}}/\varepsilon_0$, where Q_{enclosed} is the algebraic sum of the enclosed charges.
- An electric dipole contains equal and opposite charges $+q$ and $-q$; its dipole moment measures their separation, not a net charge.

Step 1: Identify the enclosed charge The entire dipole lies inside the closed surface. Both its positive and negative charges must therefore be counted. Their algebraic sum is $Q_{\text{enclosed}} = q + (-q) = 0$.

Step 2: Apply Gauss's law Substitution gives $\Phi_E = 0/\varepsilon_0$. Electric field lines can still cross the surface: the outward and inward contributions cancel. Thus zero net flux does not mean that the electric field everywhere on the surface is zero.

Step 3: Conclusion The net outward electric flux is $\boxed{0\,\text{N m}^2\,\text{C}^{-1}}$.

Quick Tip to Solve: For a closed surface, add all enclosed charges before using the supplied dipole moment.

2. An electron beam projected along $+X$-axis, experiences a force due to a magnetic field along the $+Y$-axis. What is the direction of the magnetic field? [1 mark]

Solution:

Concept:

- The magnetic force is $\mathbf{F} = q(\mathbf{v} \times \mathbf{B})$; for an electron, $q = -e$.
- In right-handed Cartesian axes, $\hat{\mathbf{x}} \times \hat{\mathbf{z}} = -\hat{\mathbf{y}}$. The negative electron charge reverses this cross-product direction.

Step 1: Account for the negative charge The velocity is along $+X$, whereas the electron force is along $+Y$. Because the charge is negative, $\mathbf{v} \times \mathbf{B}$ must point along $-Y$, opposite to the stated force.

Step 2: Find the transverse field direction Taking $\mathbf{B}$ along $+Z$ gives $\mathbf{v} \times \mathbf{B} = -vB\hat{\mathbf{y}}$, and therefore $\mathbf{F} = +evB\hat{\mathbf{y}}$, as required. A field along $-Z$ would produce a force along $-Y$. A field component parallel to the beam produces no magnetic force.

Step 3: Conclusion The required magnetic field direction is $\boxed{+Z\text{-axis}}$ (the force-producing component).

Quick Tip to Solve: Apply the right-hand rule to a positive charge first, then reverse the force for an electron.

3. The power factor of an a.c. circuit is 0.5. What will be the phase difference between voltage and current in this circuit? [1 mark]

Solution:

Concept:

- The power factor of a sinusoidal a.c. circuit is $\cos\phi$, where ϕ is the phase difference between voltage and current.
- Power factor specifies the magnitude of the phase difference; by itself it does not specify whether current leads or lags voltage.

Step 1: Write the phase relation The supplied power factor is 0.5. Hence $\cos\phi = 0.5 = 1/2$. We use the usual physical phase-difference magnitude between voltage and current.

Step 2: Evaluate the inverse cosine Since $\cos 60^\circ = 1/2$, the magnitude is $|\phi| = 60^\circ = \pi/3$ rad. An inductive circuit has current lagging voltage, while a capacitive circuit has current leading voltage; either can have the given power factor.

Step 3: Conclusion The phase difference has magnitude $\boxed{60^\circ\ (\pi/3\,\text{rad})}$.

Quick Tip to Solve: Recall the standard cosine values; a power factor of one-half corresponds to sixty degrees.

4. Electrons are emitted from a photosensitive surface when it is illuminated by green light but electron emission does not take place by yellow light. Will the electrons be emitted when the surface is illuminated by (i) red light, and (ii) blue light? [1 mark]

Solution:

Concept:

- Photoelectric emission occurs when the photon energy $h\nu$ is at least the work function $\phi_0 = h\nu_0$, where ν_0 is the threshold frequency.
- Visible-light frequency increases from red through yellow and green to blue. Greater intensity cannot compensate for frequency below threshold.

Step 1: Use the given threshold information Green light causes emission, so $\nu_{\text{green}} \geq \nu_0$. Yellow light does not, so $\nu_{\text{yellow}} < \nu_0$. The threshold therefore lies above yellow frequency and no higher than green frequency.

Step 2: Check each requested colour (i) Red has a lower frequency than yellow, so $\nu_{\text{red}} < \nu_0$: its photons cannot liberate electrons. (ii) Blue has a higher frequency than green, so $\nu_{\text{blue}} > \nu_0$: its photons have sufficient energy and emission occurs.

Step 3: Conclusion $\boxed{\text{(i) Red: no emission; (ii) Blue: emission occurs.}}$

Quick Tip to Solve: Compare each colour with a known emitting or non-emitting colour using frequency, not brightness.

5. What should be the length of the dipole antenna for a carrier wave of frequency 3×10^8 Hz? [1 mark]

Solution:

Concept:

- For an electromagnetic carrier, $\lambda = c/f$, where c is the speed of light and f is its frequency.
- A usual resonant dipole has total length $L = \lambda/2$, consisting of two arms each approximately $\lambda/4$.

Step 1: Calculate the carrier wavelength Using $c = 3 \times 10^8\,\text{m s}^{-1}$ and $f = 3 \times 10^8\,\text{Hz}$,

$$\lambda = \frac{3 \times 10^8}{3 \times 10^8}\,\text{m} = 1\,\text{m}.$$

The equal powers of ten cancel.

Step 2: Use the dipole length relation The total tip-to-tip length of the half-wave dipole is $L = \lambda/2 = 1/2\,\text{m}$. Each of its two conducting arms is $\lambda/4 = 0.25\,\text{m}$; that arm length should not be confused with the total dipole length.

Step 3: Conclusion The dipole antenna should have total length $\boxed{0.50\,\text{m}}$, with each arm $0.25\,\text{m}$ long.

Quick Tip to Solve: Calculate the wavelength first; a dipole has two quarter-wave arms, so its total length is half a wavelength.

6. Define 'electric line of force' and give its two important properties. [2 marks]

Solution:

Concept:

- An electric line of force is an imaginary curve whose tangent at any point gives the direction of the electric field at that point.
- Field-line direction is the direction of force on a positive test charge. Line density qualitatively indicates the magnitude of the field.

Step 1: Define an electric line of force Consider a small positive test charge placed in an electric field. The tangent to a field line gives the direction in which the electric force acts on it. This defines the line locally at each point; a curved line has a changing tangent and therefore depicts a changing field direction.

Step 2: State the first property: endpoints Electric field lines originate on positive charges and terminate on negative charges. If an opposite charge is absent, they may start or end at infinity. In electrostatics they do not form closed loops, since the electrostatic field is conservative.

Step 3: State the second property: no intersections Two electric field lines never intersect. If they crossed, two distinct tangents would assign two directions to the electric field at the same point. The field has a unique direction at any point where it is nonzero, so such an intersection is impossible.

Step 4: Conclusion An electric line of force has its tangent along the electric field. Its two properties are: it runs from positive to negative charge (or infinity), and it never intersects another field line.

Quick Tip to Solve: To justify non-intersection, draw the two imagined tangents and note that the field cannot have two directions.

7. (a) Why does the electric field inside a dielectric decrease when it is placed in an external electric field?

(b) A parallel plate capacitor with air between the plates has a capacitance of 8 pF. What will be the capacitance if the distance between the plates be reduced by half and the space between them is filled with a substance of dielectric constant $K = 6$? [2 marks]

Solution:

Concept:

- An external electric field polarises a dielectric. Bound surface charges create an induced field opposing the applied field, reducing the net field inside.
- For a parallel-plate capacitor completely filled with dielectric, $C = K\varepsilon_0 A/d$, where K is relative permittivity, A is plate area and d is separation.

Step 1: Explain the reduced field inside the dielectric (a) In an external field the centres of positive and negative charge in dielectric molecules shift slightly, or existing molecular dipoles tend to align. This polarisation produces bound charges on the dielectric faces. Their field opposes the external field: $\mathbf{E}_{\text{net}} = \mathbf{E}_{\text{ext}} + \mathbf{E}_{\text{polarisation}}$. Thus the resultant field is reduced rather than reinforced.

Step 2: Compare the new and original capacitances (b) Initially air gives $C_0 = \varepsilon_0 A/d = 8\,\text{pF}$. The new separation is $d/2$, with the entire space filled by dielectric of $K = 6$. Hence

$$C_{\text{new}} = \frac{6\varepsilon_0 A}{d/2} = 12\frac{\varepsilon_0 A}{d} = 12C_0 = 12 \times 8\,\text{pF}.$$

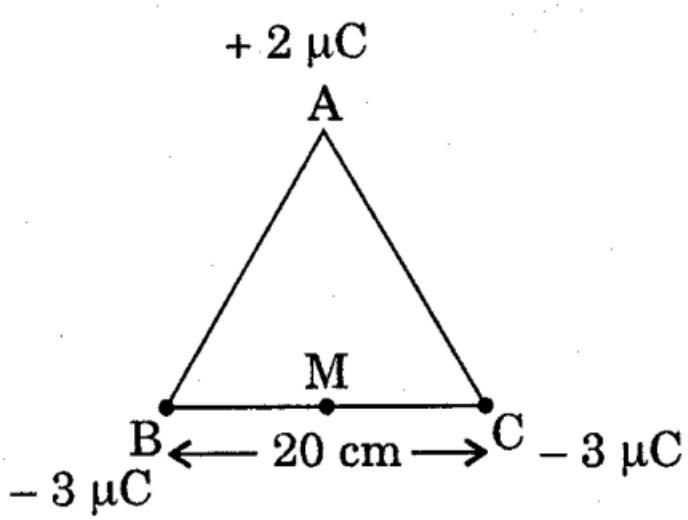
Halving the separation doubles capacitance, and inserting the dielectric multiplies it by six.

Step 3: Conclusion (a) Polarisation produces a field opposing the external field. (b) The new capacitance is $\boxed{96\,\text{pF}}$.

Quick Tip to Solve: Use the ratio C-new/C-old: multiply by the dielectric constant and by the inverse separation ratio.

OR

7. Three point charges of $+2\ \mu$C, $-3\ \mu$C and $-3\ \mu$C are kept at the vertices A, B and C respectively of an equilateral triangle of side 20 cm as shown in the figure. What should be the sign and magnitude of the charge to be placed at the mid-point (M) of side BC so that the charge at A remains in equilibrium? [2 marks]



Solution:

Concept:

- Coulomb's law gives the force magnitude between charges separated by r: $F = k|q_1 q_2|/r^2$, where $k = 1/(4\pi\varepsilon_0)$.
- Equilibrium of the charge at A requires the vector sum of forces on it to vanish. Symmetry cancels the horizontal components due to the equal charges at B and C.

Step 1: Find the resultant attraction towards the midpoint Let the triangle side be $a = 0.20$ m. Each negative charge attracts the positive charge at A with magnitude $F = k(2 \times 10^{-6})(3 \times 10^{-6})/a^2$. The median AM bisects the vertex angle, so each force makes 30° with AM. Their components parallel to BC cancel, while their components towards M add. Thus the net force due to B, C is $2F\cos 30^\circ$, directed down AM.

Step 2: Balance this force using the charge at the midpoint The new charge q must repel $+2\,\mu$C upwards, so it must be positive. The perpendicular distance is $AM = \sqrt{3}a/2$. Equating the upward repulsive force to the downward resultant gives

$$\frac{k(2 \times 10^{-6})q}{(\sqrt{3}a/2)^2} = 2\frac{k(2 \times 10^{-6})(3 \times 10^{-6})}{a^2}\cos 30^\circ,$$

$$q = 2(3 \times 10^{-6})\frac{3}{4}\frac{\sqrt{3}}{2} = \frac{9\sqrt{3}}{4} \times 10^{-6}\ \text{C}.$$

Both the Coulomb constant and the charge at A cancel, since every force acts on that same charge.

Step 3: Conclusion The required midpoint charge is $q = +\dfrac{9\sqrt{3}}{4}\,\mu\text{C} \approx +3.90\,\mu\text{C}$, positive.

Quick Tip to Solve: Resolve the two equal attractions along the median before balancing; use the shorter midpoint distance $AM = \sqrt{3}a/2$, not the side length.

8. Draw V-I graph for ohmic and non-ohmic materials. Give one example for each. [2 marks]

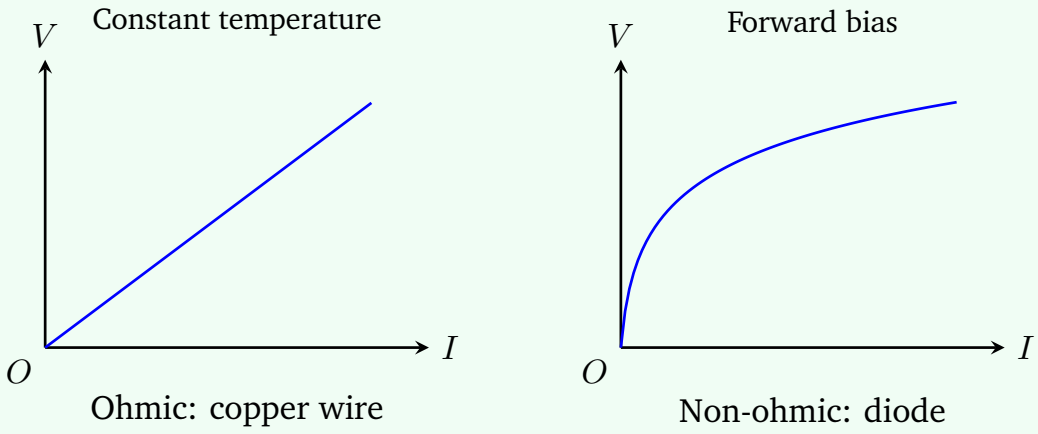
Solution:

Concept:

- An ohmic material obeys Ohm's law, $V = IR$, at constant temperature. Its resistance R is independent of the applied voltage and current within this condition.
- A non-ohmic material does not maintain a constant ratio V/I, so its voltage-current characteristic is not a straight line through the origin.

Step 1: Draw and interpret the ohmic characteristic Take current I along the horizontal axis and voltage V along the vertical axis. For an ohmic conductor, doubling I doubles V, so the graph is a straight line passing through the origin. Its constant slope is $\Delta V/\Delta I = R$. A metallic copper wire maintained at constant temperature is an example; keeping its temperature fixed is necessary because metallic resistance changes when the wire heats up.

Step 2: Draw and interpret a non-ohmic characteristic For a semiconductor diode, the forward current increases very rapidly once the forward voltage becomes sufficiently large. Therefore, with V plotted vertically against I horizontally, the forward characteristic bends and becomes progressively less steep. This curved characteristic shows that V/I is not constant. A semiconductor p-n junction diode is a non-ohmic example. The graph shown is its qualitative forward-bias branch; voltage and current scales are arbitrary.



Qualitative V-I graphs: an ohmic wire and the forward branch of a non-ohmic diode.

Step 3: Conclusion Ohmic example: copper wire at constant temperature, with a straight V-I line through the origin. Non-ohmic example: a semiconductor diode, with a curved V-I characteristic.

Quick Tip to Solve: Label the axes before sketching: with voltage vertical, an ohmic line has slope R, and a forward diode curve flattens as current increases.

9. Define the terms 'Magnetic Dip' and 'Magnetic Declination' with the help of relevant diagrams.

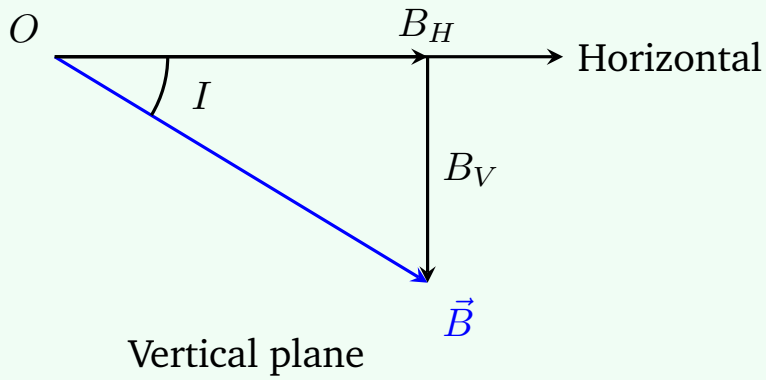
[2 marks]

Solution:

Concept:

- The magnetic meridian is the vertical plane containing the Earth's magnetic field at a place; its horizontal direction is given by a compass needle.
- The geographical meridian is the vertical plane containing the geographical north-south direction. Dip and declination refer to different planes.

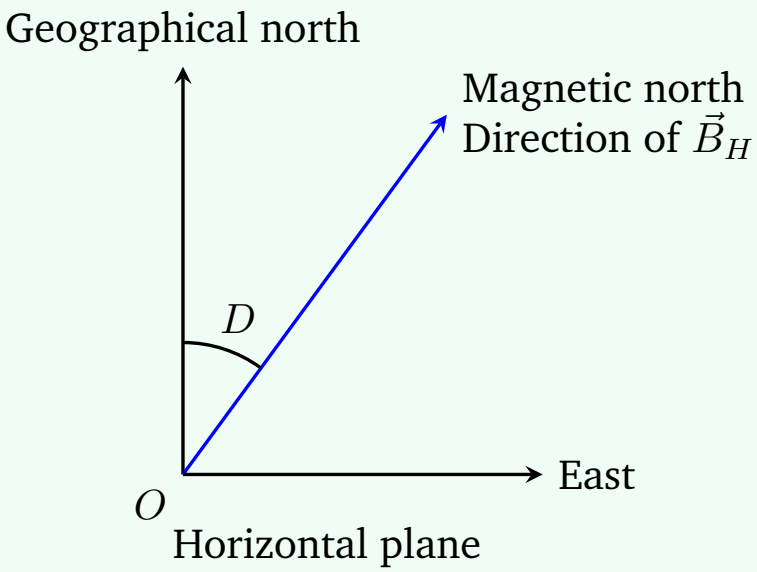
Step 1: Define magnetic dip in a vertical plane Magnetic dip or inclination, I, is the angle made by the Earth's total magnetic field $\vec{B}$ with the horizontal in the magnetic meridian at a place. A freely suspended magnetic needle allowed to rotate in this vertical plane aligns with $\vec{B}$. In the diagram, B_H and B_V are the horizontal and vertical field components, respectively, so $\tan I = B_V/B_H$. The field is shown inclined downwards, as at a typical northern-hemisphere location.



Magnetic dip in the vertical magnetic meridian.

Step 2: Define magnetic declination in the horizontal plane Magnetic declination, D, is the angle between the geographical meridian and the magnetic meridian at a place. In a horizontal view it is the angle between geographical north and the direction of the horizontal magnetic field $\vec{B}_H$, which a compass indicates. The second diagram shows easterly declination; magnetic north lies east of geographical north. This angle measures a horizontal change of direction, whereas dip measures a vertical inclination.

Quick Tip to Solve: Draw dip in a vertical cross-section and declination in a horizontal plan; label the horizontal reference and geographical north clearly.

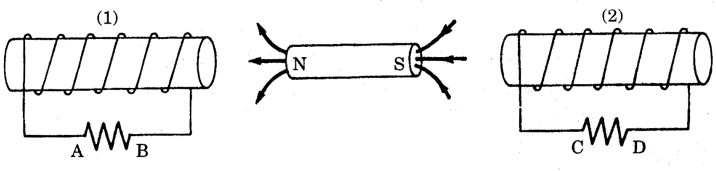


Magnetic declination viewed in the horizontal plane.

Step 3: Conclusion Magnetic dip I is the inclination of the Earth's field to the horizontal in the magnetic meridian. Magnetic declination D is the angle between the magnetic and geographical meridians.

Quick Tip to Solve: Draw dip in a vertical cross-section and declination in a horizontal plan; label the horizontal reference and geographical north clearly.

10. In the figure given below, a bar magnet moving towards the right or left induces an e.m.f. in the coils (1) and (2). Find, giving reason, the directions of the induced currents through the resistors AB and CD when the magnet is moving (a) towards the right, and (b) towards the left. [2 marks]



Solution:

Concept:

- Lenz's law: the induced current produces a magnetic field that opposes the change of magnetic flux which causes it. An approaching pole is repelled and a receding pole is attracted.
- For a coil face, anticlockwise current viewed from that face makes it a north pole; clockwise current makes it a south pole. Trace the printed winding to translate the face polarity into resistor current.

Step 1: Magnet moving towards the right The north pole moves away from coil (1). Its right face must become south to attract the receding north pole and oppose its motion. Thus the current is clockwise when viewed from the magnet at the right end of coil (1). Following the winding shown in

Quick Tip to Solve: First assign each coil's face nearest the magnet using attraction or repulsion, then trace the actual winding to find the resistor current.

the paper gives current through AB from B to A. The south pole approaches coil (2). Its left face must become south to repel the approaching south pole. The current is therefore clockwise viewed from the magnet at the left end of coil (2), giving current through CD from C to D.

Step 2: Magnet moving towards the left The north pole now approaches coil (1), whose right face must become north to repel it. The south pole recedes from coil (2), whose left face must become north to attract it. Both facing ends consequently carry anticlockwise currents when viewed from the magnet. Reversing the direction of motion reverses the flux changes and both induced currents: current through AB is from A to B, while that through CD is from D to C. These directions also follow directly by reversing the clockwise currents found in the first case.

Step 3: Conclusion For motion to the right: $AB:\ B \to A$, $CD:\ C \to D$. For motion to the left: $AB:\ A \to B$, $CD:\ D \to C$.

Quick Tip to Solve: First assign each coil's face nearest the magnet using attraction or repulsion, then trace the actual winding to find the resistor current.

11. (i) Draw the graphs showing variation of inductive reactance and capacitive reactance with frequency of applied a.c. source.

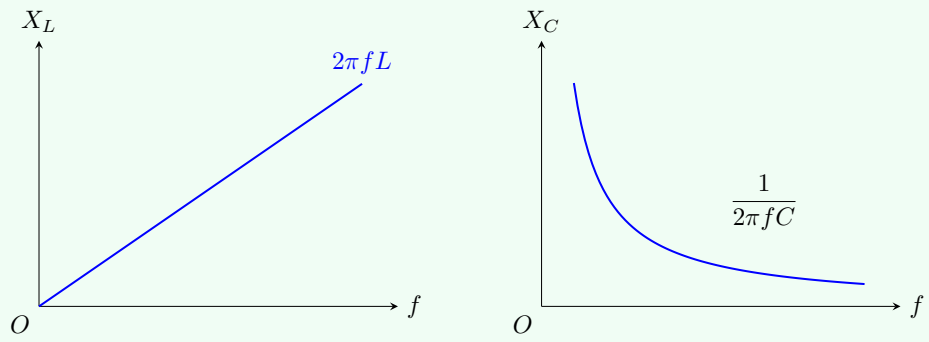
(ii) Can the voltage drop across the inductor or the capacitor in a series LCR circuit be greater than the applied voltage of the a.c. source? Justify your answer. [2 marks]

Solution:

Concept:

- Inductive reactance is $X_L = \omega L = 2\pi f L$, while capacitive reactance is $X_C = 1/(\omega C) = 1/(2\pi f C)$. Here f is the source frequency, L the inductance and C the capacitance.
- In a series circuit the same rms current I flows through all elements. The applied rms voltage is a phasor sum: $V = \sqrt{V_R^2 + (V_L - V_C)^2}$.

Step 1: (i) Plot reactance against frequency For fixed L, X_L is directly proportional to f; its graph is a straight line through the origin, with slope $2\pi L$. For fixed C, X_C is inversely proportional to f; its graph is a decreasing rectangular hyperbola in the first quadrant. As $f \to 0^+$, $X_C \to \infty$, while as $f \to \infty$, $X_C \to 0$. Thus the capacitive graph approaches both axes without meeting them at any finite positive frequency.



Reactance versus frequency for fixed inductance and capacitance (schematic scales).

Quick Tip to Solve: At resonance compare IX with IR: voltage magnification occurs when the reactance exceeds the resistance.

Step 2: (ii) Compare an individual voltage with the source voltage Yes. The inductor voltage leads the current by 90°, whereas the capacitor voltage lags it by 90°. These voltages therefore oppose each other in the phasor sum; their magnitudes are not added arithmetically. At resonance, $X_L = X_C = X$, so $V_L = V_C = IX$, while the applied voltage is $V = IR$. If $X > R$, each reactive voltage is greater than V. For example, if $X = 5R$, then $V_L = V_C = 5V$, but their equal and opposite phasors cancel. This is consistent with the source voltage and Kirchhoff's voltage law.

Step 3: Conclusion X_L increases linearly with frequency, whereas X_C decreases as $1/f$. Yes, either reactive voltage can exceed the applied voltage, because the applied voltage is the vector sum of the component voltages.

Quick Tip to Solve: At resonance compare IX with IR: voltage magnification occurs when the reactance exceeds the resistance.

12. The image of a candle is formed by a convex lens on a screen. The lower half of the lens is painted black to make it completely opaque. Draw the ray diagram to show the image formation. How will this image be different from the one obtained when the lens is not painted black? [2 marks]

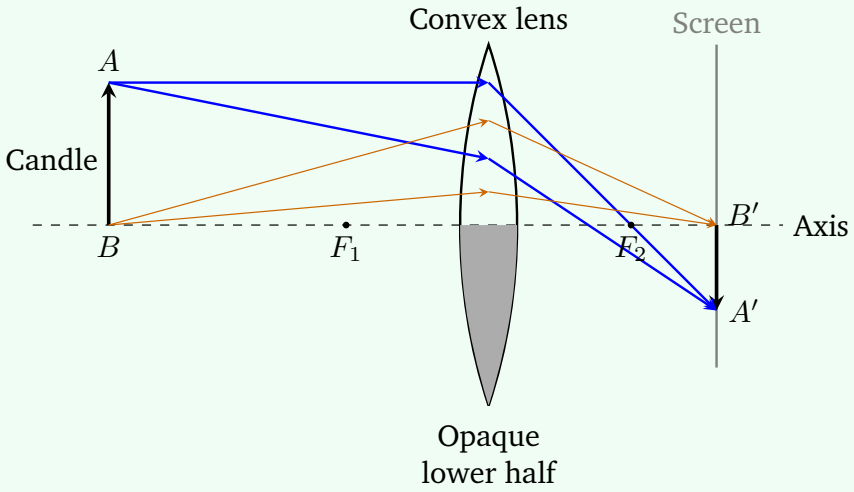
Solution:

Concept:

- Each object point sends rays through different portions of a convex lens; every unobstructed portion can form the whole image.
- For fixed object and focal length, image position follows $1/f = 1/v - 1/u$, and magnification is $m = v/u$. Reducing the transmitting aperture changes the amount of light, not these geometrical relations.

Step 1: Trace rays through the uncovered upper half The screen image is real, so the candle lies beyond the focal point. In the schematic below, rays from the candle tip pass through two different points in the transparent upper half of the lens and converge at the inverted image tip. Rays from the candle base likewise pass through the upper half and meet at the corresponding image base. The lower half is shaded to show the opaque paint; no transmitted ray is drawn through that part. Since each intermediate point of the candle also contributes rays through the uncovered aperture, the entire candle is imaged on the screen.

Quick Tip to Solve: Blocking part of a lens reduces rays from every object point, so retain the whole image and reduce only its brightness.



Two rays from each of the candle tip and base pass through the uncovered upper half and converge on the screen.

Step 2: Compare the two images Painting the lower half does not change the lens curvature or focal length, and neither the candle nor the screen is moved. Therefore u, v and m are unchanged: the complete image stays at the same position, has the same size and remains inverted. The opaque half blocks some of the rays from every object point, reducing the light reaching the screen. Hence the image is dimmer. It is not an image of just the upper or lower half of the candle; the lens aperture controls brightness rather than which half of the object is visible.

Step 3: Conclusion The screen still receives the complete inverted image, at the same position and with the same size, but with reduced brightness.

Quick Tip to Solve: Blocking part of a lens reduces rays from every object point, so retain the whole image and reduce only its brightness.

13. An electric dipole is held in a uniform electric field. (i) Using a suitable diagram, show that it does not undergo any translatory motion, and (ii) derive an expression for the torque acting on it and specify its direction. [3 marks]

Solution:

Concept:

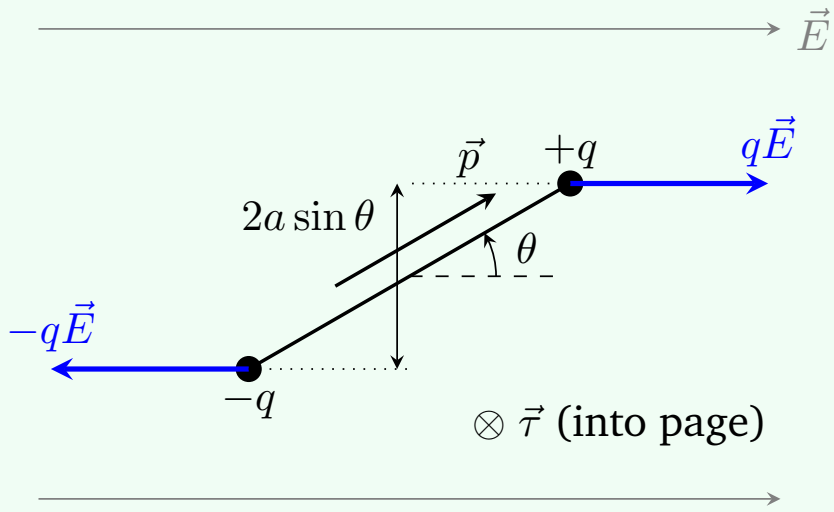
- An electric dipole consists of charges $-q$ and $+q$ separated by distance $2a$. Its dipole moment $\vec{p}$ points from $-q$ to $+q$, with magnitude $p = q(2a)$.
- A uniform electric field $\vec{E}$ exerts forces $+q\vec{E}$ and $-q\vec{E}$ on the two charges. Equal opposite forces can produce a couple even when their resultant is zero.

Step 1: (i) Show that the resultant force is zero Let the dipole axis make an angle θ with the uniform field, as shown. The positive charge experiences a force qE along the field and the negative charge experiences a force of the same magnitude in the opposite direction. Since the field is identical at both charges,

$$\vec{F}_{\text{net}} = q\vec{E} - q\vec{E} = \vec{0}.$$

Quick Tip to Solve: Add the forces to test translation, then use the perpendicular separation of their lines of action to find the couple's torque.

Thus the electric field produces no translational acceleration of the dipole's centre of mass. In particular, a dipole initially held at rest does not acquire translatory motion when released in this uniform field. However, unless the dipole is aligned with the field, the two forces act along distinct parallel lines and can rotate it.



Equal and opposite forces in a uniform field form a couple; the dipole moment points from the negative to the positive charge.

Step 2: (ii) Derive the torque and give its direction The perpendicular distance between the lines of action of the forces is $2a\sin\theta$. Therefore the magnitude of the torque of the couple is

$$\begin{aligned}\tau &= (\text{one force})(\text{perpendicular separation})\\ &= qE(2a\sin\theta) = pE\sin\theta.\end{aligned}$$

Equivalently, each force has a moment arm $a\sin\theta$ about the centre, and the two torques add. In vector form,

$$\vec{\tau} = \vec{p}\times\vec{E}.$$

The torque is perpendicular to the plane containing $\vec{p}$ and $\vec{E}$, with sense given by the right-hand rule. For the orientation drawn, it points into the page and rotates the dipole clockwise, decreasing θ and tending to align $\vec{p}$ with $\vec{E}$. Its magnitude vanishes at $\theta = 0$ or π, and is maximum, pE, at $\theta = 90°$.

Step 3: Conclusion A uniform electric field gives the dipole zero net force and hence no field-induced translation, but produces the torque $\boxed{\vec{\tau} = \vec{p}\times\vec{E}}$, of magnitude $pE\sin\theta$, tending to align the dipole with the field.

Quick Tip to Solve: Add the forces to test translation, then use the perpendicular separation of their lines of action to find the couple's torque.

14. A galvanometer with a coil of resistance $120\ \Omega$ shows full scale deflection for a current of 2.5 mA. How will you convert the galvanometer into an ammeter of range 0 to 7.5 A? Determine the net resistance of the ammeter. When an ammeter is put in a circuit, does it read slightly less or more than the actual current in the original circuit? Justify your answer. [3 marks]

Solution:

Concept:

- An ammeter must be connected in series and have a very small resistance. A galvanometer is converted into an ammeter by connecting a low resistance shunt in parallel with its coil.
- Parallel branches have equal potential differences: $I_g G = I_s S$, where G is the galvanometer resistance, S the shunt resistance, and $I_s = I - I_g$.

Step 1: Calculate and connect the shunt Here $G = 120\,\Omega$, the full scale galvanometer current is $I_g = 2.5 \times 10^{-3}$ A, and the required full scale ammeter current is $I = 7.5$ A. Connect a shunt across the galvanometer terminals so that most of the measured current bypasses the delicate coil. At full scale,

$$S = \frac{I_g G}{I - I_g} = \frac{(2.5 \times 10^{-3})(120)}{7.5 - 0.0025} = \frac{0.300}{7.4975}\,\Omega \simeq 0.040013\,\Omega.$$

Thus the coil carries only 0.0025 A, while the shunt carries 7.4975 A. Calibrate the full scale reading of the combined instrument as 7.5 A.

Step 2: Find the net resistance of the ammeter The coil and shunt form a parallel combination. Its voltage at full scale is $V = I_g G = 0.300$ V, so

$$R_A = \frac{GS}{G + S} = \frac{I_g G}{I} = \frac{0.300}{7.5} = 0.0400\,\Omega.$$

The small distinction between S and R_A follows because the galvanometer itself also provides a parallel conducting path.

Step 3: Explain the effect of inserting the ammeter Let the fixed source emf be $\mathcal{E}$ and let R be the total original circuit resistance, including source resistance. Before inserting the instrument, $I_0 = \mathcal{E}/R$. With the ammeter in series, $I' = \mathcal{E}/(R + R_A)$. Since $R_A > 0$, $I' < I_0$. The instrument reads the current in the modified circuit, which is slightly smaller than the current that flowed in the original circuit.

Step 4: Conclusion Connect a shunt of resistance $S \simeq 0.040013\,\Omega$ in parallel with the galvanometer. The resulting 0 to 7.5 A ammeter has resistance $0.0400\,\Omega$ and reads slightly less than the original circuit current because it adds a small series resistance.

Quick Tip to Solve: Calculate the shunt with $I - I_g$, but find the complete ammeter resistance directly from $I_g G/I$.

15. Define the term 'resistivity' and write its S.I. unit. Derive the expression for the resistivity of a conductor in terms of number density of free electrons and relaxation time. [3 marks]

Solution:

Concept:

- Resistivity ρ is a material property defined by $R = \rho L/A$; it is the resistance of a conductor of unit length and unit cross-sectional area at a specified temperature.
- Relaxation time τ is the mean time between successive collisions of conduction electrons. An applied electric field produces a drift velocity superposed on their random thermal motion.
- The magnitude of current density is $J = nev_d$, where n is the number of free electrons per unit volume, e the magnitude of electron charge and v_d their drift speed.

Step 1: Define resistivity and its unit For a uniform conductor of length L, cross-sectional area A, and resistance R,

$$\rho = \frac{RA}{L}.$$

Thus its SI unit is $\Omega\,\text{m}$. At a fixed temperature, resistivity depends on the material rather than the conductor's length or cross-sectional area. The equivalent microscopic definition is $\rho = E/J$, relating electric field magnitude to current density magnitude.

Step 2: Obtain the drift velocity from the electric force In an electric field $\vec{E}$, an electron of mass m and charge $-e$ experiences $\vec{F} = -e\vec{E}$, so its acceleration is $\vec{a} = -e\vec{E}/m$. Random thermal velocities average to zero. In the relaxation-time description, averaging the velocity gained between collisions gives

$$\vec{v}_d = -\frac{e\tau}{m}\vec{E}, \qquad v_d = \frac{eE\tau}{m}.$$

The minus sign indicates that the electron drift is opposite the field; conventional current is along the field.

Step 3: Relate current density to the electric field Using $J = nev_d$,

$$J = ne\left(\frac{eE\tau}{m}\right) = \frac{ne^2\tau}{m}E.$$

Comparing this with microscopic Ohm's law $J = \sigma E = E/\rho$ gives $\sigma = ne^2\tau/m$. Alternatively, substituting $E = V/L$ and $I = JA$ gives $R = V/I = mL/(ne^2\tau A)$; comparison with $R = \rho L/A$ yields the same resistivity. A larger number density or longer relaxation time therefore increases conductivity in this model.

Step 4: Conclusion Resistivity is $\rho = RA/L$, with SI unit $\Omega\,\text{m}$. In the free-electron relaxation-time model,

$$\boxed{\rho = \frac{m}{ne^2\tau}}.$$

Here m is the electron mass, n the free-electron number density, e the charge magnitude, and τ the relaxation time.

Quick Tip to Solve: First derive $J = (ne^2\tau/m)E$; the coefficient is conductivity, so invert it to obtain resistivity.

OR

15. State the principle of potentiometer. Draw a circuit diagram used to compare the e.m.f. of two primary cells. Write the formula used. How can the sensitivity of a potentiometer be increased?

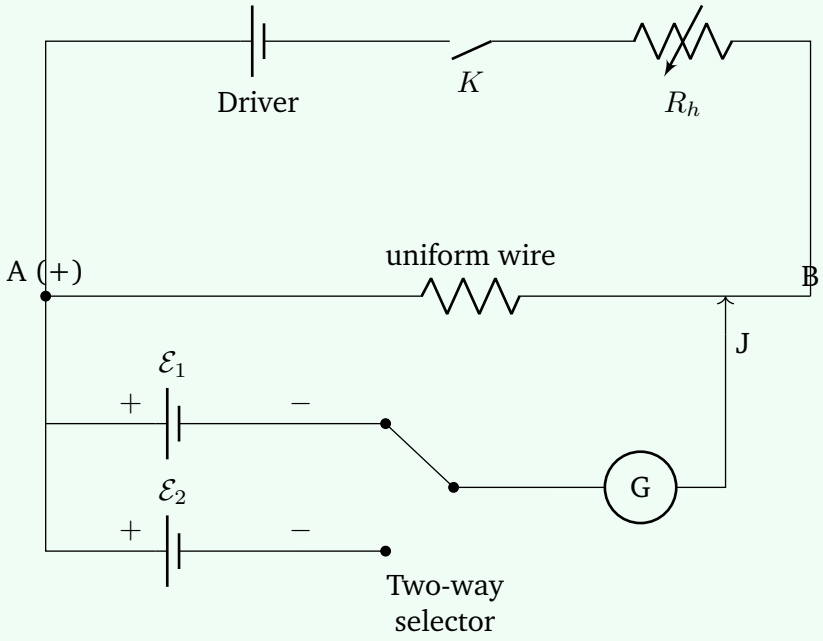
[3 marks]

Solution:

Concept:

- For a uniform potentiometer wire carrying a steady current, the potential difference across a length l is proportional to that length: $V = kl$, where k is the potential gradient.
- At balance the galvanometer current is zero, so no current is drawn from the test cell and its emf equals the potential drop along the balancing length.

Step 1: State the principle and arrange the circuit The principle is that the potential difference between two points of a uniform wire is directly proportional to their separation, provided the wire carries a constant current and its temperature remains constant. A driver cell, key K, and rheostat R_h send a steady current through wire AB, with A at the higher potential. The positive terminals of both primary cells are joined to A. A two-way selector connects the negative terminal of either cell through galvanometer G to jockey J. The driver must produce a potential drop along AB greater than either test emf so that both balance points can lie on the wire.



Potentiometer comparison circuit: select one negative terminal at a time; both cell positives connect to A.

Step 2: Compare the emfs using the balance lengths Select cell $\mathcal{E}_1$, move the jockey until the galvanometer shows zero deflection, and measure $l_1 = AJ_1$. Then select cell $\mathcal{E}_2$, keeping the driver current and hence k unchanged, and find $l_2 = AJ_2$. At the respective null points,

$$\mathcal{E}_1 = kl_1, \qquad \mathcal{E}_2 = kl_2, \qquad \frac{\mathcal{E}_1}{\mathcal{E}_2} = \frac{l_1}{l_2}.$$

Quick Tip to Solve: Keep the driver current unchanged when switching cells; reduce its current only when deliberately adjusting sensitivity.

Since no current flows through the selected primary cell at balance, its internal resistance causes no terminal voltage loss. The comparison therefore measures emfs.

Step 3: Increase the sensitivity Sensitivity is increased by reducing the potential gradient k. For a small emf difference $\Delta\mathcal{E}$, the separation between balance points is $\Delta l = \Delta\mathcal{E}/k$, so a smaller k gives a more easily measured change in balancing length. Reduce the wire current by increasing the rheostat resistance, while ensuring that both balance points still lie within AB. Alternatively, use a longer uniform wire for the same total potential drop. A sensitive galvanometer also helps locate the null accurately.

Step 4: Conclusion The potentiometer uses $V \propto l$ for a uniform wire at steady current. The circuit compares the two primary cells at null deflection, giving $\mathcal{E}_1/\mathcal{E}_2 = l_1/l_2$. Decreasing the potential gradient increases sensitivity.

Quick Tip to Solve: Keep the driver current unchanged when switching cells; reduce its current only when deliberately adjusting sensitivity.

16. Explain, with the help of a diagram, the principle and working of an a.c. generator. Write the expression for the e.m.f. generated in the coil in terms of its speed of rotation. [3 marks]

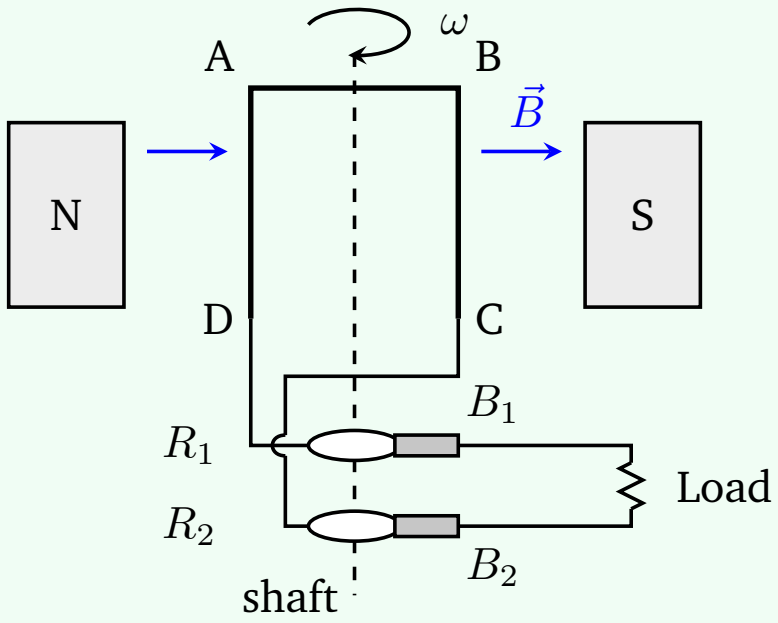
Solution:

Concept:

- An a.c. generator converts mechanical energy into electrical energy by electromagnetic induction: a changing magnetic flux induces an emf in a coil.
- Faraday's law is $e = -d\Phi_{\text{link}}/dt$, where Φ_{link} is the flux linked with all turns. For a uniform field, $\Phi_{\text{link}} = NBA\cos\theta$; N is the number of turns, A their area and B the field strength.
- Separate slip rings maintain contact with fixed carbon brushes while the coil rotates; they do not interchange the external connections every half-turn.

Step 1: Principle, construction and electrical connections A rectangular coil $ABCD$ of N turns rotates between the pole pieces N and S of a strong magnet. The two ends of the coil connect to two separate conducting slip rings R_1 and R_2, insulated from each other and from the shaft. Fixed brushes B_1 and B_2 press on the rings and connect the rotating coil to the external load. A mechanical source turns the shaft. The sketch shows the functional arrangement; the rotation changes the angle between the coil's normal and the magnetic field.

Quick Tip to Solve: Write the flux first, then differentiate it: this gives both the factor of angular speed and the correct sine dependence.



A.c. generator: rotating coil, separate slip rings, brushes and external load (schematic).

Step 2: Working and emf as a function of rotation speed Let the coil rotate uniformly with angular speed ω, and choose $t = 0$ when its normal is parallel to the magnetic field. Then $\theta = \omega t$, so

$$\begin{aligned} \Phi_{\text{link}} &= NBA\cos(\omega t), \\ e &= -\frac{d}{dt}[NBA\cos(\omega t)] \\ &= NBA\omega\sin(\omega t). \end{aligned}$$

The flux is greatest when the normal is parallel to the field, but its rate of change, and hence the emf, is then zero. The emf has maximum magnitude when the normal is perpendicular to the field. After each half rotation, the direction of induced emf reverses. Through the slip rings and brushes the load therefore receives an alternating emf. Its peak value is $e_0 = NBA\omega$. If the rotation rate is n revolutions per second, $\omega = 2\pi n$ and $e = 2\pi nNBA\sin(2\pi nt)$.

Step 3: Conclusion The generator works on Faraday's law and delivers alternating emf $\boxed{e = NBA\omega\sin(\omega t)}$, with peak $\boxed{e_0 = NBA\omega}$. The phase depends on the chosen initial position; the amplitude is proportional to the rotation speed.

Quick Tip to Solve: Write the flux first, then differentiate it: this gives both the factor of angular speed and the correct sine dependence.

17. Give reasons for the following:

(i) Long distance radio broadcasts use short-wave bands.

(ii) The small ozone layer on top of the stratosphere is crucial to human survival.

(iii) Satellites are used for long distance TV transmission. [3 marks]

Solution:

Concept:

- Radio-wave propagation depends on frequency. Suitable short-wave frequencies can return to Earth through the ionosphere; successive returns allow sky-wave communication beyond the horizon.
- The ozone layer absorbs strongly in the ultraviolet region. Ultraviolet radiation has more energetic photons than visible radiation and can damage living tissue.
- Very high frequency television signals travel predominantly along line-of-sight paths and are not effectively returned by the ionosphere.

Step 1: (i) Long-distance radio broadcasts use short-wave bands Short-wave radio signals in suitable frequency bands are refracted by the ionised layers of the upper atmosphere and can return to Earth. This is commonly described as reflection by the ionosphere. A transmitter can thus reach receivers far beyond its direct line-of-sight horizon. Further returns between Earth and the ionosphere extend the range still more. This sky-wave route is why short-wave bands are useful for long-distance radio broadcasting; reception depends on choosing a frequency appropriate to the ionospheric conditions.

Step 2: (ii) The ozone layer is crucial to human survival Ozone in the stratosphere absorbs much of the Sun's harmful ultraviolet radiation before it reaches Earth's surface. This protective filtering reduces radiation that can damage DNA, cause skin cancers and injure the eyes, and also protects other organisms on which human life depends. Although the ozone layer is small in thickness, its absorption of ultraviolet radiation gives it a major protective role.

Step 3: (iii) Satellites are used for long-distance television transmission Television transmission uses high-frequency radio waves that are not effectively reflected back by the ionosphere. Such waves mainly travel in straight lines, so Earth's curvature limits direct ground transmission to a line-of-sight range. A high-altitude communication satellite receives an uplink signal, amplifies it and retransmits it on a downlink to a distant ground station. Its large visible area of Earth allows transmission over long distances beyond the ground transmitter's horizon.

Step 4: Conclusion Short-wave radio achieves long range by ionospheric sky-wave propagation; ozone protects life by absorbing harmful solar ultraviolet radiation; satellites relay line-of-sight television signals across large distances.

Quick Tip to Solve: Match each part to its mechanism: ionospheric return for short waves, UV absorption for ozone, and a high-altitude relay for television.

18. A figure divided into squares, each of size 1 mm^2, is being viewed at a distance of 9 cm through a magnifying lens of focal length 10 cm, held close to the eye.

(a) Draw a ray diagram showing the formation of the image.

(b) What is the magnification produced by the lens? How much is the area of each square in the virtual image?

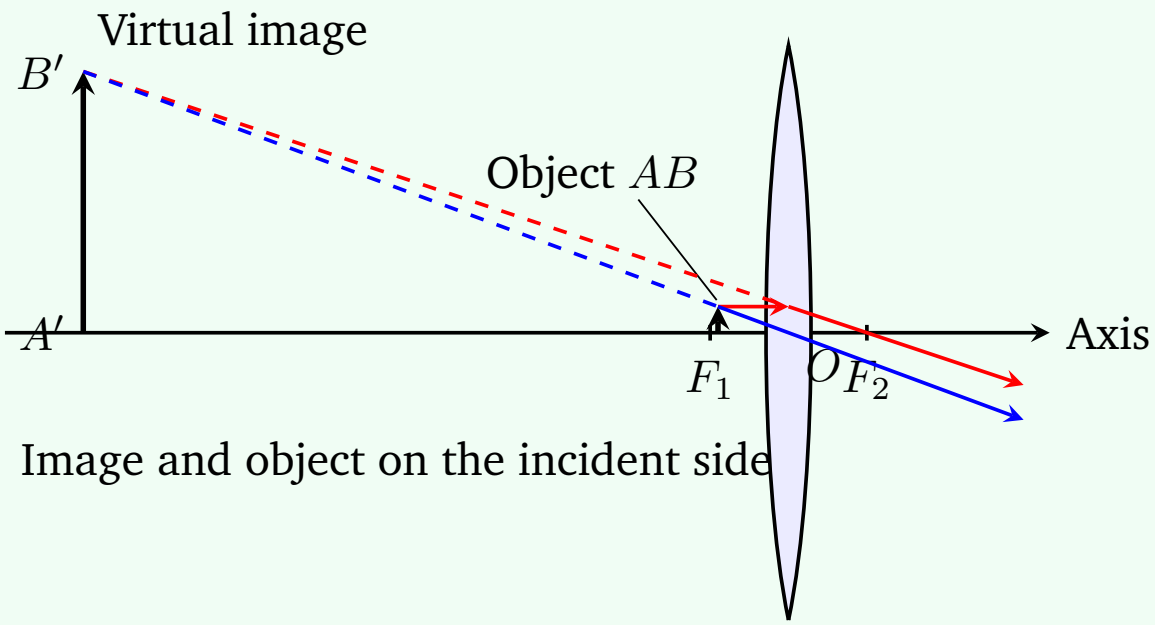
(c) What is the angular magnification of the lens? [3 marks]

Solution:

Concept:

- For a thin convex lens, the Cartesian sign convention gives $1/f = 1/v - 1/u$, with $f > 0$ and $u < 0$ for a real object on the incident side.
- Transverse magnification is $m = v/u$. Both dimensions of a square scale by m, so its area scales by m^2.
- Angular magnification compares the image's apparent angle through the lens with the same object's angle when viewed without the lens at the least distance of distinct vision, $D = 25\,\text{cm}$.

Step 1: (a) Image formation and ray diagram Here $u = -9\,\text{cm}$ and $f = +10\,\text{cm}$, so the object lies between the optical centre O and the first principal focus F_1. A ray from its top parallel to the principal axis is refracted towards F_2. Another ray passes through O without deviation. The emerging rays diverge; their backward extensions intersect on the object's side of the lens, giving an upright, enlarged virtual image. The diagram is schematic and is not drawn to the actual longitudinal scale.



Virtual-image formation by a convex magnifying lens; backward ray extensions meet at the upright image (schematic).

Step 2: (b) Linear magnification and area of a square Substitute the signed distances into the lens

Quick Tip to Solve: Use the actual object distance for angular magnification, and square the linear magnification when converting an area.

formula:

$$\frac{1}{v} = \frac{1}{f} + \frac{1}{u} = \frac{1}{10} - \frac{1}{9} = -\frac{1}{90}\,\text{cm}^{-1},$$
$$v = -90\,\text{cm},$$
$$m = \frac{v}{u} = \frac{-90}{-9} = +10.$$

The negative image distance confirms a virtual image on the same side as the object; the positive magnification confirms it is upright. Each square originally has area $1\,\text{mm}^2$, hence side $1\,\text{mm}$. Its image has side $10\,\text{mm}$ and area

$$A_{\text{image}} = m^2 A_{\text{object}} = 10^2 \times 1 = 100\,\text{mm}^2.$$

Step 3: (c) Angular magnification for the stated object position Let a small object height be h. Since the lens is held close to the eye, its image subtends approximately $\alpha = h'/|v| = 10h/90 = h/9$, with lengths in centimetres. The same object at the normal near point subtends $\beta = h/D = h/25$. Therefore

$$M = \frac{\alpha}{\beta} = \frac{D}{|u|} = \frac{25}{9} \simeq 2.78.$$

Equivalently, $M = D(1/f + 1/|v|) = 25(1/10 + 1/90)$. The image is at $90\,\text{cm}$, so the near-point formula $1 + D/f$ does not describe this specified viewing arrangement.

Step 4: Conclusion The image is virtual, upright and enlarged, at $v = -90\,\text{cm}$. The linear magnification is $\boxed{m = +10}$, each image square has area $\boxed{100\,\text{mm}^2}$, and the angular magnification is $\boxed{M = 25/9 \simeq 2.78}$, taking $D = 25\,\text{cm}$.

Quick Tip to Solve: Use the actual object distance for angular magnification, and square the linear magnification when converting an area.

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19. Ultraviolet light of wavelength 2271 Å from a 100 W mercury source radiates a photo cell made of molybdenum metal. If the stopping potential is 1.3 V, estimate the work function of the metal. How would the photo cell respond to high intensity (10^5 W m^{-2}) red light of wavelength 6328 Å produced by a He-Ne laser?

Plot a graph showing the variation of photoelectric current with anode potential for two light beams of same wavelength but different intensity. [3 marks]

Solution:

Concept:

- Einstein's photoelectric equation is $h\nu = \phi + K_{\max}$, where ϕ is the work function and $K_{\max} = eV_s$ is the maximum kinetic energy measured by stopping potential V_s.
- A photon of wavelength λ has energy hc/λ. Photoemission requires this energy to be at least ϕ; increasing intensity increases the photon arrival rate, not the energy per photon.
- For a fixed emitting wavelength shorter than the threshold wavelength, saturation current increases with intensity, while stopping potential remains unchanged.

Quick Tip to Solve: Compare photon energy with the work function before considering intensity; read stopping potential from the negative voltage-axis intercept.

Step 1: Calculate the work function Convert the ultraviolet wavelength: $2271\,\text{Å} = 2.271 \times 10^{-7}\,\text{m}$. Using $h = 6.626 \times 10^{-34}\,\text{J s}$, $c = 3.00 \times 10^{8}\,\text{m s}^{-1}$ and $e = 1.602 \times 10^{-19}\,\text{C}$,

$$E_{\text{UV}} = \frac{hc}{\lambda} = 8.75 \times 10^{-19}\,\text{J} \simeq 5.46\,\text{eV}.$$

The stopping potential gives $K_{\max} = e(1.3\,\text{V}) = 1.30\,\text{eV}$. Therefore

$$\phi = 5.46 - 1.30 = 4.16\,\text{eV} \simeq 6.66 \times 10^{-19}\,\text{J}.$$

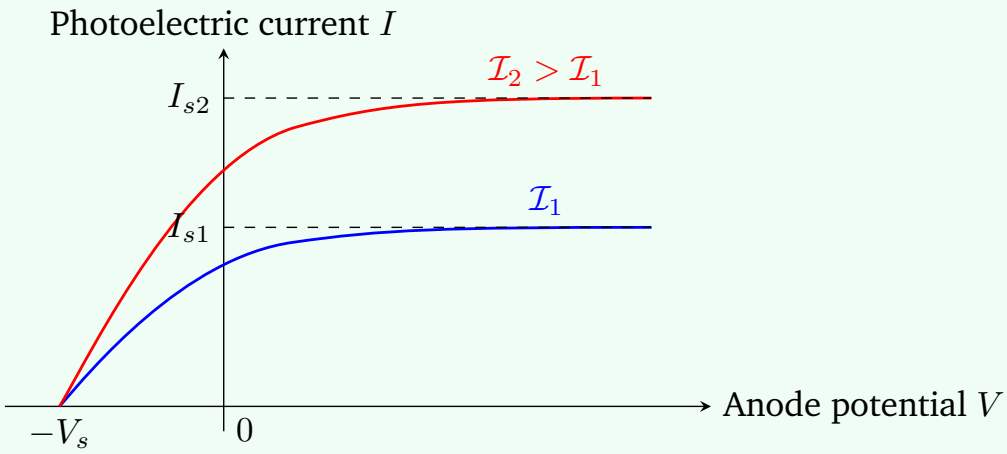
The source power $100\,\text{W}$ does not enter this photon-energy calculation.

Step 2: Test the red laser against the threshold For $\lambda_{\text{red}} = 6328\,\text{Å} = 6.328 \times 10^{-7}\,\text{m}$,

$$E_{\text{red}} = \frac{hc}{\lambda_{\text{red}}} \simeq 1.96\,\text{eV}.$$

This is less than the work function $4.16\,\text{eV}$, so a red photon cannot liberate an electron. Equivalently, the threshold wavelength is $\lambda_0 = hc/\phi \simeq 2980\,\text{Å}$, and the red wavelength is longer. Within the ordinary photoelectric effect, even the intensity $10^5\,\text{W m}^{-2}$ produces no photoelectric current: more subthreshold photons do not increase the energy of each photon.

Step 3: Draw and interpret the current-potential curves The curves below refer to two emitting beams of the same wavelength, with intensities $\mathcal{I}_2 > \mathcal{I}_1$. Both currents fall to zero at the same negative anode potential $-V_s$, because their maximum electron energies are equal. The brighter beam liberates more electrons per second and hence has the greater saturation current $I_{s2} > I_{s1}$. Increasing positive anode potential collects an increasing fraction of the emitted electrons, until all are collected and the current saturates. The sketch is qualitative; the light frequency must exceed the threshold frequency, equivalently its wavelength must be shorter than the threshold wavelength.



Photoelectric current for equal wavelengths and different intensities

Step 4: Conclusion The molybdenum work function is approximately $\boxed{4.16\,\text{eV} = 6.66 \times 10^{-19}\,\text{J}}$. The specified red laser causes no ordinary photoemission. At a common emitting wavelength, higher intensity gives higher saturation current but the same stopping potential.

Quick Tip to Solve: Compare photon energy with the work function before considering intensity; read stopping potential from the negative voltage-axis intercept.

20. (a) Draw a graph showing the variation of potential energy of a pair of nucleons as a function of their separation. Indicate the regions in which nuclear force is (i) attractive, and (ii) repulsive.
(b) Write two characteristic features of nuclear force which distinguish it from the coulomb force.

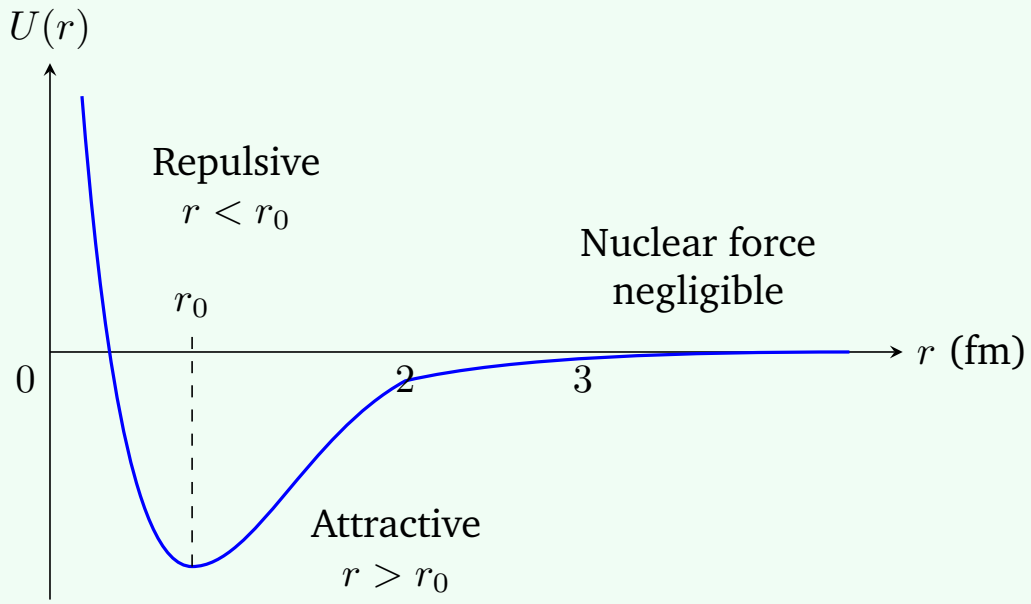
[3 marks]

Solution:

Concept:

- The radial nuclear force and potential energy are related by $F_r = -dU/dr$, where r is the separation of the two nucleons and positive force points toward increasing separation.
- The nucleon-nucleon potential has a strongly repulsive core, an attractive well and a vanishingly small tail beyond a few femtometres; $1\,\text{fm} = 10^{-15}\,\text{m}$.
- The nuclear interaction is approximately charge independent and short ranged, unlike the electrostatic interaction.

Step 1: (a) Sketch the potential-energy curve Choose $U = 0$ for nucleons far apart. At very small separation, the potential rises steeply to large positive values: the nucleons encounter a repulsive core. As separation increases, U falls to a negative minimum at a characteristic separation r_0, of order $0.8\,\text{fm}$. Beyond the minimum, U rises toward zero, becoming negligible at separations of a few femtometres. The negative well represents binding relative to two isolated nucleons. The following is a qualitative nuclear potential; precise depths and distances depend on the nucleon state.



Qualitative nuclear potential and its force regions

Step 2: (a) Identify the force from the slope On the left of the minimum, $dU/dr < 0$, so $F_r > 0$: the force pushes the nucleons apart and is repulsive. On the right of the minimum, within the interaction range, $dU/dr > 0$, so $F_r < 0$: the force pulls the nucleons together and is attractive. At the minimum $dU/dr = 0$, so the radial force is zero. At large separation the curve is nearly flat and the nuclear force is negligible. Thus the sign of the force is determined by the slope of the potential, not by whether the potential itself is positive or negative.

Quick Tip to Solve: Label force regions using the slope: a falling potential gives repulsion and a rising potential gives attraction.

Step 3: (b) State two differences from the Coulomb force First, nuclear force is short ranged: it is appreciable only over nuclear distances, roughly a few femtometres, and rapidly becomes negligible beyond them. Coulomb force is long ranged and falls as $1/r^2$, with no finite distance cutoff. Second, nuclear force is approximately charge independent: after excluding electromagnetic effects and comparing corresponding states, it acts with nearly the same strength between proton-proton, neutron-neutron and proton-neutron pairs. Coulomb force depends on the product of charges; it repels two protons and has no direct electrostatic interaction for an uncharged neutron. These are two independent distinctions.

Step 4: Conclusion The potential has a repulsive core and an attractive well: the falling part gives repulsion and the rising part gives attraction, since $F_r = -dU/dr$. Nuclear force differs from Coulomb force through its short range and approximate charge independence.

Quick Tip to Solve: Label force regions using the slope: a falling potential gives repulsion and a rising potential gives attraction.

21. (a) Show that the decay rate 'R' of a sample of a radionuclide is related to the number of radioactive nuclei 'N' at the same instant by the expression $R = \lambda N$.

(b) The half-life of $^{238}_{92}$U against α-decay is 1.5×10^{17} s. What is the activity of a sample of $^{238}_{92}$U having 25×10^{20} atoms? [3 marks]

Solution:

Concept:

- Radioactive decay is random, with constant decay probability per nucleus per unit time λ, called the decay constant.
- The activity or decay rate is the positive quantity $R = -dN/dt$; N is the number of undecayed radioactive nuclei at that instant.
- The half-life $T_{1/2}$ and decay constant satisfy $\lambda = \ln 2/T_{1/2}$. Activity is measured in becquerel, with $1\,\text{Bq} = 1\,\text{s}^{-1}$.

Step 1: (a) Derive the relation between rate and population Consider a short interval dt, small enough that the decay probability per nucleus is $\lambda\,dt$. Since the nuclei decay independently, a population of N undecayed nuclei has an expected number of decays $\lambda N\,dt$. Each decay removes one radioactive parent nucleus, so the population change is

$$dN = -\lambda N\,dt.$$

Dividing by dt gives $dN/dt = -\lambda N$. The decrease has a negative derivative, whereas the number of decays per unit time is positive. Consequently the activity is

$$R = -\frac{dN}{dt} = \lambda N.$$

This is the mean macroscopic decay rate; individual events remain random.

Step 2: (b) Obtain the decay constant from the half-life Integrating the decay equation yields

Quick Tip to Solve: Write activity as a positive rate and combine $R = (\ln 2)N/T_{1/2}$; rewrite 25 times ten to the twentieth before tracking powers.

$N(t) = N_0 e^{-\lambda t}$. At one half-life, $N(T_{1/2}) = N_0/2$, hence $e^{-\lambda T_{1/2}} = 1/2$. Taking logarithms gives

$$\lambda = \frac{\ln 2}{T_{1/2}} = \frac{0.693}{1.5 \times 10^{17}\,\text{s}} = 4.62 \times 10^{-18}\,\text{s}^{-1}.$$

Use the half-life given in the question for the alpha-decay of ^{238}U.

Step 3: (b) Calculate the sample activity The sample contains $N = 25 \times 10^{20} = 2.5 \times 10^{21}$ radioactive atoms. Using the population at the same instant as the requested activity,

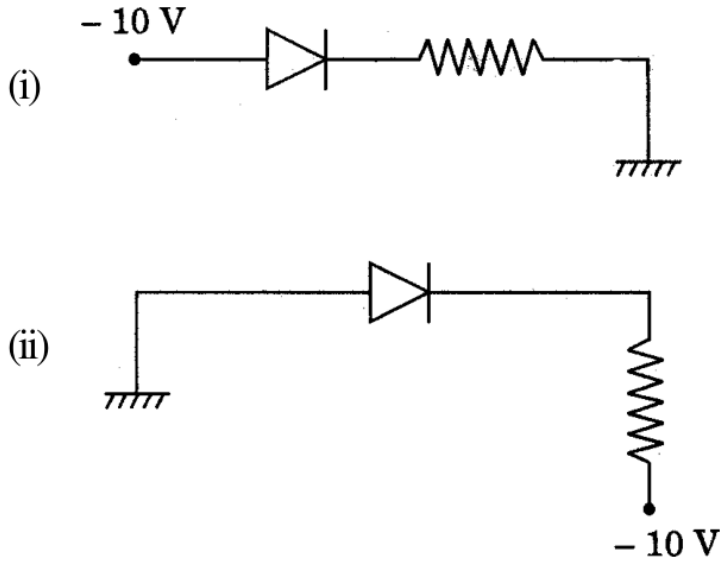
$$\begin{aligned} R &= \lambda N \\ &= (4.62 \times 10^{-18}\,\text{s}^{-1})(25 \times 10^{20}) \\ &= 115.5 \times 10^{2}\,\text{s}^{-1} \\ &= 1.155 \times 10^{4}\,\text{Bq}. \end{aligned}$$

Each parent decay contributes one event to the activity. No elapsed time or initial mass is required because the current number of parent atoms is supplied. The result denotes about eleven thousand five hundred decays per second.

Step 4: Conclusion The decay law gives $\boxed{R = \lambda N}$. For the specified sample, $\boxed{R \simeq 1.16 \times 10^{4}\,\text{Bq}}$, or approximately 1.2×10^{4} Bq to two significant figures.

Quick Tip to Solve: Write activity as a positive rate and combine $R = (\ln 2)N/T_{1/2}$; rewrite 25 times ten to the twentieth before tracking powers.

22. Explain, with the help of a circuit diagram, how the thickness of depletion layer in a p-n junction diode changes when it is forward biased. In the following circuit which one of the two diodes is forward biased and which is reverse biased? [3 marks]

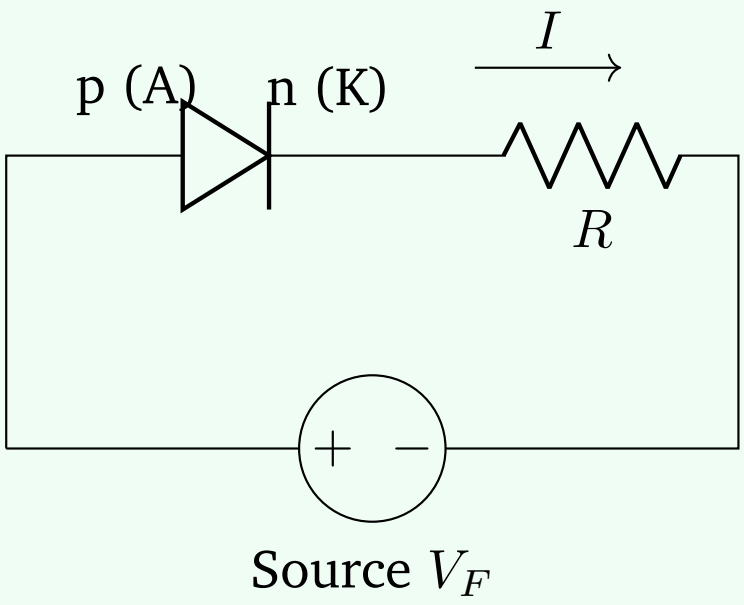


Solution:

Concept:

- A depletion layer contains immobile donor and acceptor ions but very few mobile carriers. Its electric field creates a potential barrier opposing further majority-carrier diffusion.
- Forward bias means connecting the p-side (anode A) to the positive terminal and the n-side (cathode K, shown by the bar) to the negative terminal of a source.
- Diode bias depends on the difference $V_A - V_K$, rather than the sign of either terminal potential relative to earth. Ground denotes $0\,\text{V}$.

Step 1: Connect the junction in forward bias Connect the p-side to the positive terminal and the n-side to the negative terminal through a current-limiting resistor, as shown. The applied electric field opposes the junction's internal field, reducing the effective barrier. For an applied forward voltage V_F, the barrier changes approximately from V_b to $V_b - V_F$, where V_b is the unbiased barrier potential.



Forward-bias connection: p-side to positive and n-side to negative

Step 2: Explain the decrease in depletion width The positive terminal pushes holes in the p-region towards the junction, while the negative terminal pushes electrons in the n-region towards it. Near the junction, these carriers neutralise some of the exposed fixed ions. The region depleted of mobile carriers consequently becomes narrower. With the reduced barrier, majority carriers cross the junction more readily and a forward current flows.

Step 3: Compare the terminal potentials in circuit (i) The anode is connected to $-10\,\text{V}$, while the cathode is connected through the resistor to ground. To determine the initial bias, the negligible reverse current makes the resistor drop negligible, so $V_K \simeq 0\,\text{V}$. Thus $V_A - V_K \simeq -10\,\text{V}$: the anode is at lower potential than the cathode, so this junction is reverse biased.

Step 4: Compare the terminal potentials in circuit (ii) The anode is grounded, and the cathode is connected through the resistor to $-10\,\text{V}$. The applied supply therefore tends to make the anode more positive than the cathode, so this junction is forward biased. When it conducts, part of the supply

Quick Tip to Solve: Locate the cathode bar first, then compare anode and cathode potentials: a grounded anode is more positive than a cathode supplied from a negative voltage.

voltage drops across the resistor; one must not then identify the conducting cathode potential as exactly $-10\,\text{V}$.

Step 5: Conclusion Forward bias reduces the potential barrier and decreases the thickness of the depletion layer. Circuit (i) is reverse biased, and circuit (ii) is forward biased.

Quick Tip to Solve: Locate the cathode bar first, then compare anode and cathode potentials: a grounded anode is more positive than a cathode supplied from a negative voltage.

23. Distinguish between analog and digital communication. Write any two modulation techniques employed for the digital data. Describe briefly one of the techniques used. [3 marks]

Solution:

Concept:

- Communication transmits information through a channel. Analog information is represented by continuously varying signals, whereas digital information is represented by a discrete set of symbols, usually binary digits 0 and 1.
- Digital modulation changes a selected parameter of a high-frequency carrier according to the transmitted symbols. Amplitude shift keying (ASK) and frequency shift keying (FSK) are two such techniques.

Step 1: Distinguish the information signals In analog communication, a signal such as a microphone's output voltage varies continuously with the information. It can take any value within its allowed range. In digital communication, information is encoded as a sequence of discrete symbols, commonly a stream of binary pulses representing 0 and 1. Even an originally analog message can be sampled, quantised and encoded for digital transmission. Analog disturbances directly alter the transmitted waveform and hence the recovered information. Digital receivers can decide which allowed symbol a received signal represents and regenerate its nominal level, provided noise remains below the decision margin. Digital communication is therefore generally more resistant to accumulated noise, although excessive noise can still cause bit errors.

Step 2: Name two digital modulation techniques Two techniques employed for digital data are **amplitude shift keying (ASK)** and **frequency shift keying (FSK)**. In ASK, carrier amplitude changes between allowed levels according to the bit. In FSK, two distinct carrier frequencies commonly represent binary 0 and binary 1.

Step 3: Describe amplitude shift keying In binary ASK, the amplitude of a sinusoidal carrier is switched between two prescribed values for successive bit intervals, while its frequency remains fixed. A simple form is on-off keying: transmit the carrier for a binary 1 and suppress it for a binary 0. If A is the carrier amplitude, f_c its frequency and t time, the ideal transmitted signal during a bit interval is

$$s(t) = \begin{cases} A\cos(2\pi f_c t), & \text{for bit 1,} \\ 0, & \text{for bit 0.} \end{cases}$$

The receiver detects the carrier envelope or its energy in each bit interval and compares it with

Quick Tip to Solve: When describing a keying technique, name the carrier parameter that changes and state explicitly how the two binary digits are represented.

a threshold to recover the binary sequence. General ASK may use two nonzero amplitudes; the presence-or-absence method is its simplest special case.

Step 4: Conclusion Analog communication uses continuously varying information signals; digital communication uses discrete symbols. ASK and FSK are two digital modulation techniques. In on-off ASK, carrier presence represents 1 and carrier absence represents 0.

Quick Tip to Solve: When describing a keying technique, name the carrier parameter that changes and state explicitly how the two binary digits are represented.

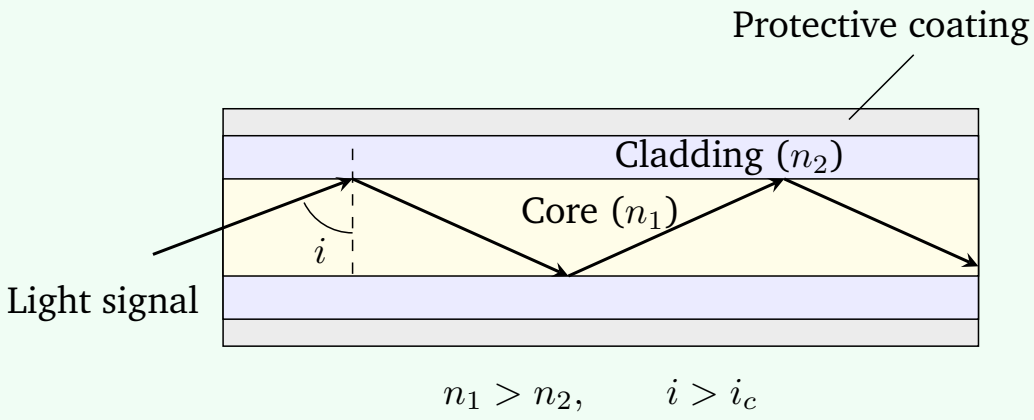
24. Draw a schematic diagram of a single optical fibre structure. Explain briefly how an optical fibre is fabricated. Describe in brief, the mechanism of propagation of light signal through an optical fibre. [3 marks]

Solution:

Concept:

- An optical fibre is a thin, flexible dielectric waveguide. It contains a transparent core of refractive index n_1, surrounding cladding of lower index n_2, and an outer protective coating, with $n_1 > n_2$.
- Total internal reflection occurs for light travelling from the denser core towards the rarer cladding when the incidence angle i, measured from the normal, exceeds the critical angle i_c: $\sin i_c = n_2/n_1$.

Step 1: Identify the parts of a single fibre The schematic shows a longitudinal section of one fibre. The central core carries the light signal. The cladding surrounds the core and provides the lower-index boundary needed to confine light. The outer polymer coating or jacket protects the fine glass fibre from moisture, scratches and mechanical damage; it does not provide the reflecting boundary used for guidance. In cross-section, the core and cladding are concentric circular regions.



Longitudinal schematic of a single fibre and a guided light ray

Step 2: Describe the fabrication A very pure glass or silica preform is prepared with a central core material surrounded by cladding material of slightly lower refractive index. Suitable composition or dopants provide the required index difference. The preform is heated until its lower end softens and is drawn into a long, fine, flexible strand. The drawn fibre retains the core-and-cladding structure of the preform. A protective polymer coating is applied, and the fibre is wound or incorporated into a

Quick Tip to Solve: Label the core with the larger refractive index and measure the incidence angle from the normal, not from the fibre's surface.

cable. High purity minimises optical losses.

Step 3: Explain propagation by total internal reflection Light is launched into the core through its end within the fibre's acceptance cone. A suitable ray reaches the core-cladding interface from the higher-index core with incidence angle $i > i_c$. It is then totally internally reflected back into the core. Repeated reflections at successive boundaries guide the ray along the fibre, as shown by the zigzag path. Rays outside the permitted launching range need not satisfy the critical-angle condition and may leak into the cladding. Pulses of guided light can thus convey information over long distances with low loss.

Step 4: Conclusion A single optical fibre consists of a higher-index core, lower-index cladding and a protective coating. It is fabricated by drawing a heated core-cladding preform into a thin strand. Light propagates through repeated total internal reflection at the core-cladding boundary, provided $n_1 > n_2$ and $i > i_c$.

Quick Tip to Solve: Label the core with the larger refractive index and measure the incidence angle from the normal, not from the fibre's surface.

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25. (a) With the help of a labelled diagram, explain the principle and working of a moving coil galvanometer.

(b) Two parallel coaxial circular coils of equal radius R and equal number of turns N, carry equal currents I in the same direction and are separated by a distance $2R$. Find the magnitude and direction of the net magnetic field produced at the mid-point of the line joining their centres. [5 marks]

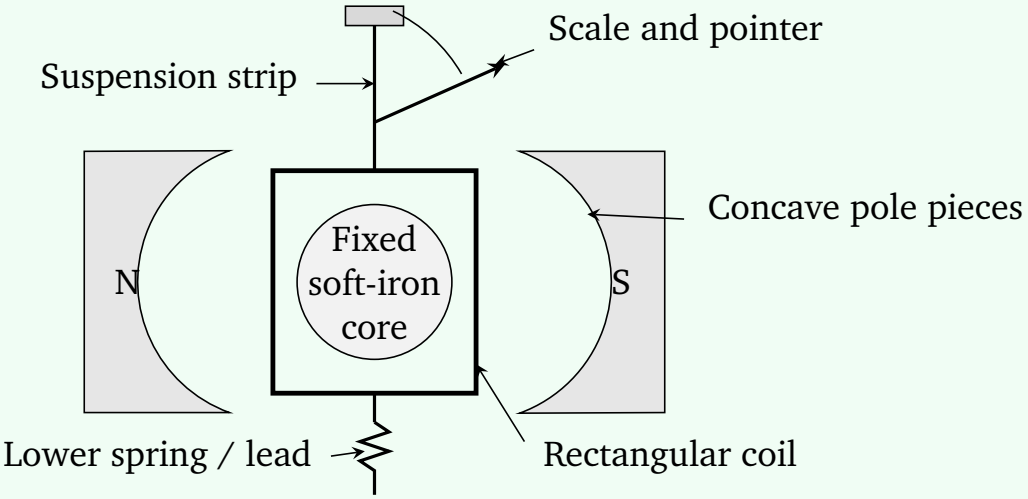
Solution:

Concept:

- A current-carrying coil in a magnetic field experiences a torque. For a coil of n turns and area A, $\tau_m = nIAB\sin\theta$, where θ is the angle between the coil's normal and the field.
- In a moving coil galvanometer, concave magnetic pole pieces and a cylindrical soft-iron core produce a strong radial field. The plane of the coil remains parallel to the local field, so $\theta = 90^\circ$ and $\tau_m = nIAB$.
- The suspension provides a restoring torque $\tau_r = C\phi$, where C is its torsional constant and ϕ is the angular deflection. At equilibrium, magnetic and restoring torques balance.
- The magnetic field at axial distance x from the centre of an N-turn circular coil of radius R is $B(x) = \mu_0 NIR^2/[2(R^2 + x^2)^{3/2}]$. Fields from separate coils combine by vector superposition.

Step 1: (a) Construction and labelled diagram A light rectangular coil of many turns of insulated wire is wound on an aluminium frame and suspended between the concave pole pieces of a strong permanent magnet. A stationary cylindrical soft-iron core inside the coil increases the field strength and makes the field radial. A fine suspension strip and a lower conducting spring connect the coil to the external circuit; the suspension also supplies the restoring torque. A pointer attached to the coil indicates its rotation on a calibrated scale. The schematic below identifies the essential parts; the core remains fixed while the coil turns around the vertical suspension axis.

Quick Tip to Solve: At the midpoint first halve the centre separation to get the axial distance; same-sense coaxial currents produce reinforcing axial fields even between the coils.



Moving coil galvanometer: schematic front view with concave pole pieces and a fixed soft-iron core; the coil rotates about the suspension axis.

Step 2: (a) Principle, motion and equilibrium When current passes through the coil, the forces on its two opposite vertical sides form a couple. In the radial magnetic field the effective angle in the torque formula stays 90° throughout the permitted rotation, giving

$$\tau_m = nIAB.$$

This couple rotates the coil and pointer, twisting the suspension. Its opposing torque increases with deflection: $\tau_r = C\phi$. The coil comes to rest when

$$nIAB = C\phi \quad \Rightarrow \quad I = \frac{C}{nAB}\phi.$$

Thus deflection is directly proportional to the current, so a uniform scale can measure small currents. Reversing the current reverses the magnetic couple and hence the pointer's direction of deflection. Eddy currents in the aluminium frame damp oscillations, allowing the pointer to settle quickly without changing the equilibrium relation.

Step 3: (b) Field of each coil at the midpoint Let the coil centres be O_1 and O_2, and their midpoint be M. Since $O_1O_2 = 2R$, the distance of M from each centre is R. Applying the axial-field expression to either coil,

$$B_1 = B_2 = \frac{\mu_0 NIR^2}{2(R^2+R^2)^{3/2}} = \frac{\mu_0 NI}{2^{5/2}R}.$$

The currents circulate in the same sense when both coils are viewed from the same end of their common axis. Their magnetic moments therefore point along the same axial direction. The axial field of a circular coil points in this same direction on both sides of its centre, so the two fields at M reinforce each other, although M lies between the coils.

Quick Tip to Solve: At the midpoint first halve the centre separation to get the axial distance; same-sense coaxial currents produce reinforcing axial fields even between the coils.

Step 4: (b) Superpose the two axial fields As the two equal fields are parallel, their magnitudes add:

$$B_{\text{net}} = B_1 + B_2 = 2\left(\frac{\mu_0 NI}{2^{5/2}R}\right) = \frac{\mu_0 NI}{2^{3/2}R}.$$

To specify the sense, curl the fingers of the right hand in the current direction around either coil: the thumb gives the direction of the resultant field along the common axis. For example, if the currents appear anticlockwise to an observer looking from one end, the net field points towards that observer. Without a specified viewing direction, an absolute left or right direction cannot be assigned.

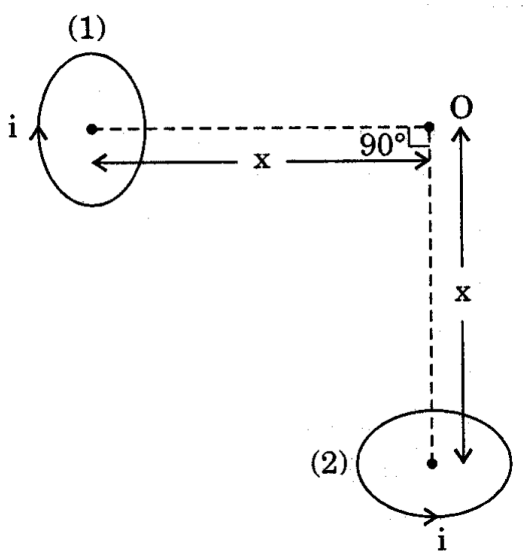
Step 5: Conclusion (a) The radial field gives a current-dependent couple; balancing it against the suspension torque yields $\phi = (nAB/C)I$, the working relation of the moving coil galvanometer. (b) The midpoint field is $\boxed{B_{\text{net}} = \mu_0 NI/(2\sqrt{2}R)}$, along the common axis in the direction given by the right-hand rule for either coil.

Quick Tip to Solve: At the midpoint first halve the centre separation to get the axial distance; same-sense coaxial currents produce reinforcing axial fields even between the coils.

OR

25. (a) State Biot-Savart's law. Using this law, derive the expression for the magnetic field due to a current carrying circular loop of radius R, at a point which is at a distance x from its centre along the axis of the loop.

(b) Two small identical circular loops, marked (1) and (2), carrying equal currents, are placed with the geometrical axes perpendicular to each other as shown in the figure. Find the magnitude and direction of the net magnetic field produced at the point O. [5 marks]



Solution:

Concept:

- Biot-Savart's law gives the field of a current element: $d\vec{B} = \dfrac{\mu_0 I}{4\pi}\dfrac{d\vec{\ell}\times\hat{r}}{r^2}$. Here I is the steady current, $d\vec{\ell}$ points along it, $\vec{r}$ points from the element to the observation point, and μ_0 is the permeability of free space.
- For a circular loop, symmetry cancels the components perpendicular to its axis. The surviving axial components add, and their direction follows the right-hand grip rule.
- Magnetic fields obey vector superposition. Two equal perpendicular field vectors of magnitude B_0 have resultant $\sqrt{2}B_0$, directed along the bisector between their directions.

Step 1: (a) State Biot-Savart's law and set up the geometry The magnetic field due to a small current element is directly proportional to I, its length $d\ell$, and $\sin\alpha$, and inversely proportional to the square of its distance r from the point:

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

Its direction is perpendicular to both $d\vec{\ell}$ and $\vec{r}$, as given by the cross product. Consider a loop of radius R with centre C, and a point P on its axis at distance x from C. Every current element is at the same distance $r = \sqrt{R^2+x^2}$ from P. Since the tangent to the loop is perpendicular both to its radius and to the axis, it is perpendicular to $\vec{r}$; hence $\alpha = 90^\circ$.

Step 2: (a) Resolve and integrate the field Pair each element with the diametrically opposite element. Their components perpendicular to the axis cancel, while their axial components have the same direction. If θ is the angle between $\vec{r}$ and the axis, then $\sin\theta = R/r$. Because $d\vec{B}$ is perpendicular to $\vec{r}$, its projection on the axis is $dB\sin\theta$. Therefore,

$$\begin{aligned} dB_{\text{axis}} &= \frac{\mu_0 I}{4\pi}\frac{R\,d\ell}{r^3}, \\ B(x) &= \frac{\mu_0 IR}{4\pi(R^2+x^2)^{3/2}}\oint d\ell \\ &= \frac{\mu_0 IR}{4\pi(R^2+x^2)^{3/2}}(2\pi R) \\ &= \frac{\mu_0 IR^2}{2(R^2+x^2)^{3/2}}. \end{aligned}$$

The field is along the loop axis, in the direction of the thumb when the fingers curl with the current. At $x = 0$, this reduces to the centre field $\mu_0 I/(2R)$, which checks the expression.

Step 3: (b) Find the field from each small loop at O Let each identical loop have radius R and current i, as indicated in the figure. Point O is on each loop's axis at the same distance x from its centre. Thus both fields have magnitude

$$B_0 = \frac{\mu_0 iR^2}{2(R^2+x^2)^{3/2}}.$$

Applying the right-hand grip rule to the indicated current arrows, the field of loop (1) at O points horizontally left, while that of loop (2) points vertically upward. Their axes, and therefore their field vectors, are perpendicular. With $\hat{e}_x$ toward the right and $\hat{e}_y$ upward on the diagram, $\vec{B}_1 = -B_0\hat{e}_x$ and

Quick Tip to Solve: First use symmetry to cancel the transverse components of a loop's field; for the two loops, apply the right-hand rule separately before adding their equal perpendicular fields.

$\vec{B}_2 = B_0\hat{e}_y$.

Step 4: (b) Add the perpendicular vectors and use the small-loop limit Vector addition gives

$$\vec{B}_{\text{net}} = B_0(-\hat{e}_x + \hat{e}_y),$$
$$B_{\text{net}} = \sqrt{B_0^2 + B_0^2} = \frac{\mu_0 i R^2}{\sqrt{2}(R^2 + x^2)^{3/2}}.$$

Since the two components are equal, $\tan\phi = B_0/B_0 = 1$, so the resultant makes 45° with each field direction. It points diagonally upward to the left from O. For the stated small loops, when $R \ll x$, $(R^2 + x^2)^{3/2} \simeq x^3$, so $B_{\text{net}} \simeq \mu_0 i R^2/(\sqrt{2}x^3)$. Equivalently, if $m = i\pi R^2$ is the magnetic moment of either loop, the small-loop result is $\mu_0\sqrt{2}m/(2\pi x^3)$.

Step 5: Conclusion The axial field of a circular loop is $B(x) = \dfrac{\mu_0 I R^2}{2(R^2 + x^2)^{3/2}}$. The two loops produce $B_{\text{net}} = \dfrac{\mu_0 i R^2}{\sqrt{2}(R^2 + x^2)^{3/2}}$, or $\dfrac{\mu_0 i R^2}{\sqrt{2}x^3}$ in the small-loop limit. Its direction is upward to the left, at 45° to the two axes.

Quick Tip to Solve: First use symmetry to cancel the transverse components of a loop's field; for the two loops, apply the right-hand rule separately before adding their equal perpendicular fields.

26. (a) How is a wavefront different from a ray? Draw the geometrical shape of the wavefronts when (i) light diverges from a point source, and (ii) light emerges out of a convex lens when a point source is placed at its focus.

(b) State Huygens' principle. With the help of a suitable diagram, prove Snell's law of refraction using Huygens' principle. [5 marks]

Solution:

Concept:

- A wavefront is the locus of points of a wave that have the same phase at an instant. A ray gives the local direction of propagation and is normal to the wavefront in an isotropic medium.
- Huygens' principle: every point of a wavefront acts as a source of secondary wavelets that spread with the wave speed in that medium. The forward envelope of these wavelets gives the new wavefront.
- The refractive index is $n = c/v$, where c is the speed of light in vacuum and v is its speed in the medium. Refraction follows from the different distances travelled in the two media in the same time.

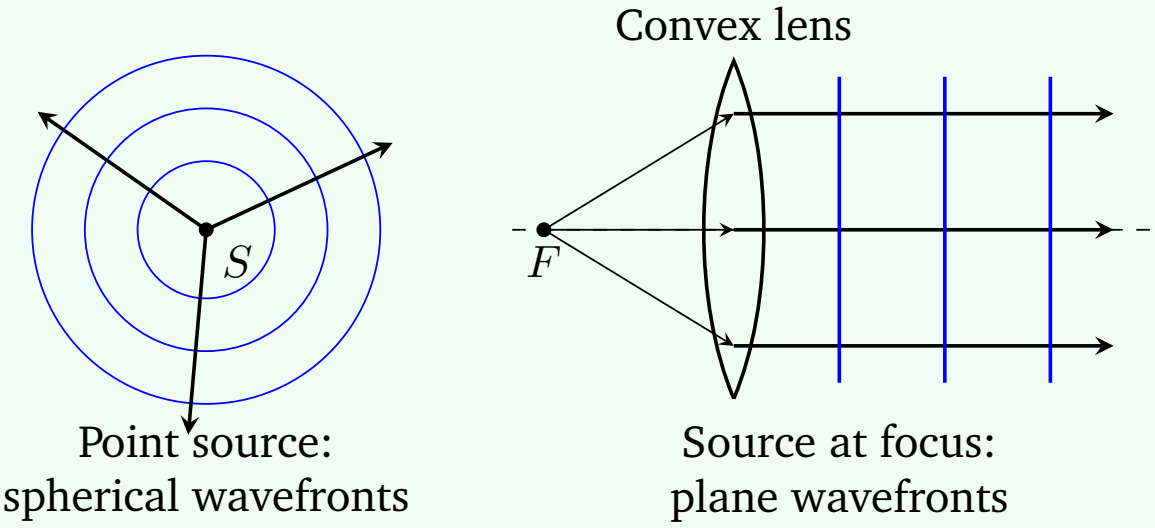
Step 1: (a) Distinguish a wavefront from a ray A wavefront is a surface joining points in the same phase; a ray is a directed line showing the direction in which light energy propagates. Thus the two describe different geometrical objects. Rays intersect a wavefront normally in an isotropic medium. For example, radial rays are normal to a spherical wavefront, while parallel rays are normal to a plane wavefront.

Step 2: (a)(i) Wavefronts from a point source In a homogeneous medium, a point source S emits light

Quick Tip to Solve: In the Huygens proof, use the same time for BC and AD; divide their sine ratios so that the common hypotenuse AC cancels.

in all directions. After a time t, all points at distance vt from S have the same phase. The wavefront is therefore spherical, with S as its centre. Successive wavefronts are concentric spherical surfaces and their rays diverge radially. The circles in the sketch represent cross-sections of these spheres.

Step 3: (a)(ii) Wavefronts after a convex lens Place a point source at the principal focus F of a convex lens. In the paraxial approximation, rays emerging from the lens are parallel to its principal axis. Their wavefronts are therefore planes perpendicular to that axis. The straight lines in the sketch are cross-sections of the plane wavefronts; they should not be confused with the horizontal rays.



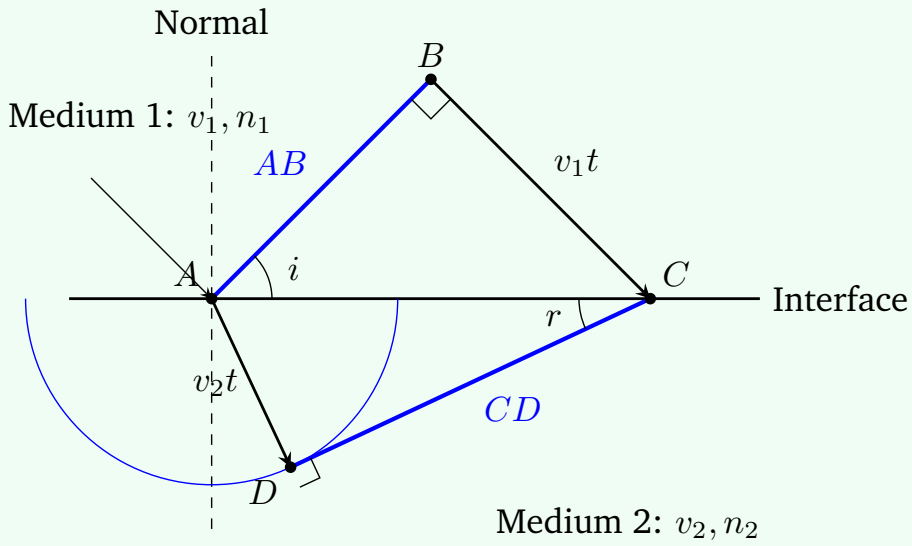
Cross-sections of spherical wavefronts from a point source (left), and plane wavefronts emerging from a convex lens with its source at F (right).

Step 4: (b) Apply Huygens' construction at the interface Let a plane wavefront AB be incident on a plane interface AC, separating media with light speeds v_1 and v_2. Point A reaches the interface first. While the disturbance at B advances along the incident ray to C in time t, the secondary wavelet from A spreads into the second medium through a radius AD. Hence

$$BC = v_1 t, \qquad AD = v_2 t.$$

Draw the tangent CD to the secondary wavelet from A. By Huygens' principle, CD is the refracted wavefront. Since BC is normal to AB, and a radius is normal to its tangent, $AB \perp BC$ and $AD \perp CD$. The sketch shows the case $v_2 < v_1$; the same construction applies when the second medium is optically rarer.

Quick Tip to Solve: In the Huygens proof, use the same time for BC and AD; divide their sine ratios so that the common hypotenuse AC cancels.



Huygens' construction: AB is the incident wavefront, CD the refracted wavefront, BC = v1t and AD = v2t. The arc is the secondary wavelet from A.

Step 5: (b) Obtain Snell's law from the two right triangles Let i and r be the angles that the incident and refracted rays make with the interface normal. Because each ray is perpendicular to its wavefront, the angles between AB and the interface, and between CD and the interface, are also i and r, respectively. Thus $\angle BAC = i$ and $\angle ACD = r$. The right triangles ABC and ADC have the same hypotenuse AC, so

$$\sin i = \frac{BC}{AC} = \frac{v_1 t}{AC},$$
$$\sin r = \frac{AD}{AC} = \frac{v_2 t}{AC},$$
$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}.$$

Rearranging gives $n_1 \sin i = n_2 \sin r$. For entry into a slower medium, this also gives $r < i$, consistent with bending towards the normal.

Step 6: Conclusion A ray indicates propagation direction, whereas a wavefront joins equal-phase points. A point source gives spherical wavefronts, and a point source at the focus of a convex lens gives plane wavefronts after the lens. Huygens' construction establishes Snell's law: $\boxed{n_1 \sin i = n_2 \sin r}$.

Quick Tip to Solve: In the Huygens proof, use the same time for BC and AD; divide their sine ratios so that the common hypotenuse AC cancels.

OR

26. (a) In Young's double slit experiment, deduce the conditions for (i) constructive, and (ii) destructive interference at a point on the screen. Draw a graph showing variation of the resultant intensity in the interference pattern against position x on the screen.

(b) Compare and contrast the pattern which is seen with two coherently illuminated narrow slits in Young's experiment with that seen for a coherently illuminated single slit producing diffraction.

[5 marks]

Solution:

Concept:

- Coherent waves have the same frequency and a constant phase difference. Their amplitudes add by superposition, while intensity is proportional to the square of the resultant amplitude.
- A path difference Δ produces a phase difference $\phi = 2\pi\Delta/\lambda$, where λ is the wavelength. For two equal individual intensities I_0, the resultant intensity is $I = 4I_0\cos^2(\phi/2)$.
- For slit separation d, screen distance D, and transverse position x, the small-angle approximation gives $\Delta \simeq dx/D$. The interference fringe width is $\beta = \lambda D/d$.
- Single-slit diffraction results from interference of secondary wavelets across one aperture of width a. Its minima obey $a\sin\theta = m\lambda$, where m is a nonzero integer.

Step 1: (a) Obtain the intensity and constructive-interference condition Let the two narrow slits S_1 and S_2 be coherently illuminated in phase and supply equal intensities I_0 at a screen point P. If their displacement amplitudes are both A, adding their oscillations with phase difference ϕ gives resultant amplitude $2A\cos(\phi/2)$. Since intensity is proportional to amplitude squared,

$$I = I_0 + I_0 + 2\sqrt{I_0 I_0}\cos\phi = 2I_0(1+\cos\phi) = 4I_0\cos^2\left(\frac{\phi}{2}\right).$$

For slit separation d and observation angle θ, the path difference is $\Delta = d\sin\theta$. With $D \gg d$ and $|x| \ll D$, $\sin\theta \simeq x/D$, so

$$\phi = \frac{2\pi\Delta}{\lambda}, \qquad I(x) = 4I_0\cos^2\left(\frac{\pi dx}{\lambda D}\right).$$

Constructive interference occurs when the waves arrive in phase: $\phi = 2n\pi$, or $\Delta = n\lambda$, with integer n. Thus bright fringes occur at $x_n = n\lambda D/d = n\beta$, and their maximum intensity is $4I_0$. The central point $x = 0$ is a bright fringe because its path difference vanishes.

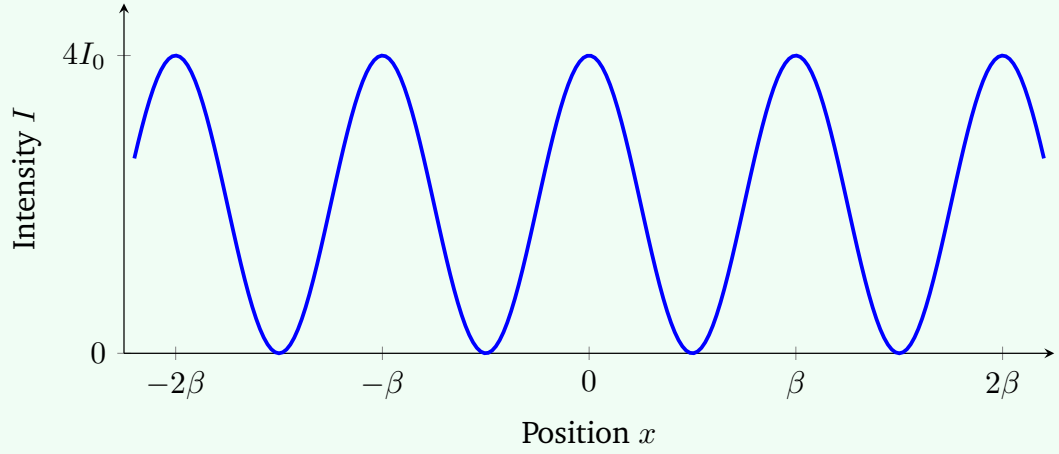
Step 2: (a) Obtain destructive interference and plot the fringes For destructive interference the two waves arrive with opposite phase, so $\phi = (2n+1)\pi$. Their equal amplitudes cancel, giving

$$\Delta = \left(n+\frac{1}{2}\right)\lambda, \qquad x = \left(n+\frac{1}{2}\right)\beta, \qquad I_{\min} = 0.$$

Here n runs over all integers and therefore describes fringes on both sides of the centre. Successive bright fringes, as well as successive dark fringes, are separated by $\beta = \lambda D/d$. A neighbouring bright and dark fringe are separated by $\beta/2$. The graph below shows the ideal intensity variation for equal, very narrow slits: all bright peaks have the same height and the pattern is symmetric about

Quick Tip to Solve: First write the path difference, then convert it to phase: whole wavelengths give bright fringes and half-odd wavelengths give dark fringes. For the comparison, remember the diffraction central maximum is twice the width of a secondary region.

$x = 0$. If the individual slit intensities are unequal, destructive interference gives a nonzero minimum $(\sqrt{I_1} - \sqrt{I_2})^2$; exact darkness requires equal amplitudes.



Ideal Young's interference intensity for equal narrow slits; $\beta = \lambda D/d$.

Step 3: (b) Compare two-slit interference with single-slit diffraction Both patterns arise from superposition of coherent light and contain alternating bright and dark regions, with a central bright maximum and symmetry about the central axis. In Young's experiment, the interfering contributions mainly come from two distinct coherent narrow slits. In single-slit diffraction, the interfering contributions come from different portions of the same coherently illuminated aperture.

In the ideal two-slit pattern, successive bright fringes are equally spaced and have equal intensities; bright fringes and dark intervals have equal characteristic widths. The spacing is $\lambda D/d$, controlled by the separation of the two slits. For real slits of finite width, a diffraction envelope modulates the interference peaks, so their equality applies to the narrow-slit idealisation used here.

In single-slit diffraction, the central maximum is the brightest and is twice as wide as each secondary bright region between adjacent minima. The secondary maxima become progressively weaker away from the centre. For small angles, the minima lie at $x_m = m\lambda D/a$ for $m = \pm 1, \pm 2, \ldots$. Thus the central maximum extends from $-\lambda D/a$ to $+\lambda D/a$, with width $2\lambda D/a$, while successive minima on either side are spaced by $\lambda D/a$. The aperture width a, rather than the separation d, controls this scale. Secondary diffraction maxima are not simply at the equally spaced bright-fringe positions of the two-slit pattern.

Step 4: Conclusion Constructive interference requires $\Delta = n\lambda$; destructive interference requires $\Delta = (n + \frac{1}{2})\lambda$. For equal narrow slits, $I(x) = 4I_0 \cos^2(\pi x/\beta)$, with $\beta = \lambda D/d$. The ideal interference fringes have equal spacing and equal peak intensity, whereas single-slit diffraction has a central maximum of double width and weaker secondary maxima.

Quick Tip to Solve: First write the path difference, then convert it to phase: whole wavelengths give bright fringes and half-odd wavelengths give dark fringes. For the comparison, remember the diffraction central maximum is twice the width of a secondary region.

27. (a) Distinguish between metals, insulators and semiconductors on the basis of their energy bands. (b) Why are photodiodes used preferably in reverse bias condition? A photodiode is fabricated from a semiconductor with band gap of 2.8 eV. Can it detect a wavelength of 6000 nm? Justify. [5 marks]

Solution:

Concept:

- The valence band contains the electrons participating in bonds, whereas electrons in the conduction band can move through the solid and carry electric current. The forbidden energy gap is $E_g = E_C - E_V$, where E_C and E_V denote the conduction-band bottom and valence-band top.
- A photon can generate an electron-hole pair by exciting an electron across the band gap only if its energy satisfies $E_\gamma = h\nu = hc/\lambda \geq E_g$.
- In a reverse-biased photodiode, the junction electric field separates photogenerated electron-hole pairs. The resulting photocurrent is measured against a small dark reverse current.

Step 1: (a) Compare the band structures **Metals:** The valence and conduction bands overlap, or the highest occupied band is only partly filled. Thus nearby empty states are available without the need to cross a significant forbidden gap. An applied electric field readily changes the motion of electrons, giving high conductivity.

Insulators: The valence band is completely filled and the conduction band is empty at low temperature, with a large forbidden gap between them. Ordinary thermal energy cannot excite an appreciable number of electrons into the conduction band; hence their conductivity is very small.

Semiconductors: At absolute zero the valence band is filled and the conduction band is empty, but the forbidden gap is relatively small, typically of the order of 1 eV. At ordinary temperatures some electrons acquire sufficient thermal energy to enter the conduction band, leaving holes in the valence band. Both electrons and holes contribute to conduction, and conductivity generally increases with temperature. Thus it is the availability of mobile carriers, determined by the band filling and the gap, that distinguishes the three classes.

Step 2: (b) Explain the preference for reverse bias Reverse bias widens the depletion region and establishes a strong electric field across it. When light produces electron-hole pairs in or near this region, the field sweeps electrons towards the n side and holes towards the p side before they recombine. This gives a readily measurable change in reverse current. The dark reverse current is small, so the illumination-dependent current can be distinguished sensitively; in forward bias the much larger ordinary majority-carrier current would obscure this change. Rapid collection of the photogenerated carriers also permits a fast response.

Step 3: Compare the photon energy with the band gap The printed wavelength is $6000\,\text{nm} = 6.0 \times 10^{-6}\,\text{m}$. Using $hc \simeq 1240\,\text{eV nm}$, the photon energy is

$$E_\gamma = \frac{1240}{6000}\,\text{eV} \simeq 0.207\,\text{eV}.$$

This is smaller than the given band gap $E_g = 2.8\,\text{eV}$, so such a photon cannot excite a valence-band electron into the conduction band and generate the required electron-hole pair. Equivalently, the

Quick Tip to Solve: Use $E_\gamma(\text{eV}) = 1240/\lambda(\text{nm})$: a longer wavelength means less photon energy, and detection requires $\lambda \leq 1240/E_g$.

longest detectable wavelength for band-to-band absorption is

$$\lambda_{\max} = \frac{hc}{E_g} = \frac{1240}{2.8}\,\text{nm} \simeq 443\,\text{nm}.$$

The incident wavelength is longer than this threshold, confirming the same result.

Step 4: Conclusion Metals have overlapping or partly filled bands, insulators have a large forbidden gap, and semiconductors have a small forbidden gap. Reverse bias provides efficient carrier collection and a sensitive photocurrent measurement. The given photodiode cannot detect $6000\,\text{nm}$ radiation by band-to-band absorption because $0.207\,\text{eV} < 2.8\,\text{eV}$.

Quick Tip to Solve: Use $E_\gamma(\text{eV}) = 1240/\lambda(\text{nm})$: a longer wavelength means less photon energy, and detection requires $\lambda \le 1240/E_g$.

OR

27. (a) Explain briefly, with the help of a circuit diagram, how V-I characteristics of a p-n junction diode are obtained in (i) forward bias, and (ii) reverse bias. Draw the shape of the curves obtained.

(b) A semiconductor has equal electron and hole concentration of $6 \times 10^8/\text{m}^3$. On doping with certain impurity, electron concentration increases to $9 \times 10^{12}/\text{m}^3$.

(i) Identify the new semiconductor obtained after doping.

(ii) Calculate the new hole concentration. [5 marks]

Solution:

Concept:

- Forward bias connects the p-side to the positive supply terminal and the n-side to the negative terminal; it reduces the junction potential barrier. Reverse bias reverses these connections and increases the barrier.
- A series current meter measures diode current I, while a voltmeter connected across the diode measures its potential difference V. A variable resistance limits and adjusts the current.
- At a fixed temperature in thermal equilibrium, electron and hole concentrations obey the mass-action law $np = n_i^2$, where n_i is the intrinsic concentration. Donor doping produces an n-type semiconductor with electrons as majority carriers.

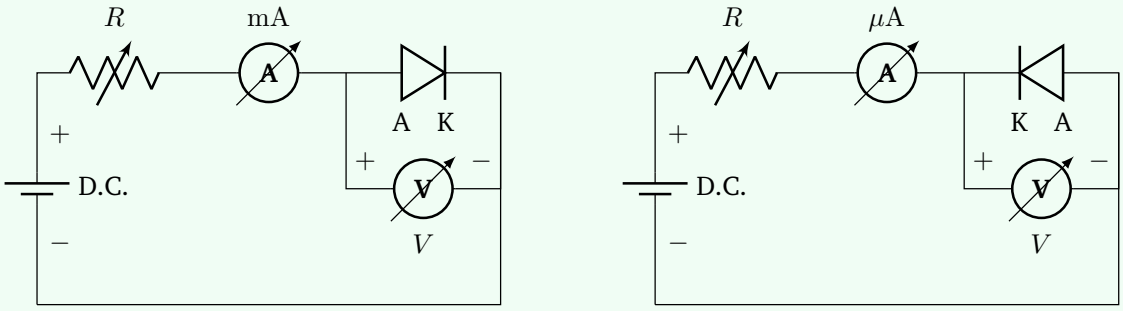
Step 1: (a)(i) Obtain the forward-bias characteristic Connect the p-side (anode A) to the positive terminal of a variable d.c. supply through a current-limiting variable resistance and a milliammeter. Connect the n-side (cathode K) to the negative terminal. Connect a voltmeter across the diode, with its positive lead at A. Start at zero supply voltage and increase it gradually, adjusting the resistance to keep the current within safe limits. For each setting record the diode voltage V_F and current I_F; plot I_F against V_F.

Initially the current is very small. Near the knee voltage the current begins to increase rapidly, and thereafter a small increase in voltage produces a large increase in current. Typical knee voltages are about $0.3\,\text{V}$ for germanium and $0.7\,\text{V}$ for silicon. The sketch is qualitative.

Quick Tip to Solve: Use a milliammeter for forward bias and a microammeter for reverse bias; for doping, square the original intrinsic concentration before dividing by the new electron concentration.

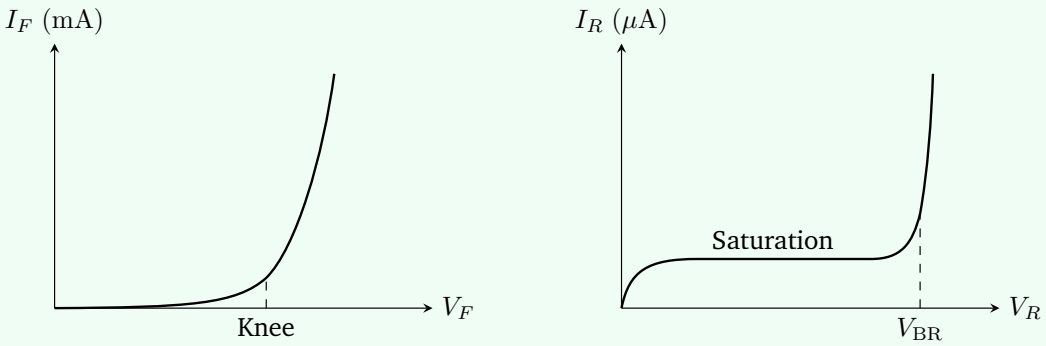
Step 2: (a)(ii) Obtain the reverse-bias characteristic Reverse the diode connections so that K is connected to the positive terminal of the supply and A to the negative terminal. Use a microammeter in series, because the reverse current is much smaller than the forward current, and connect the positive voltmeter lead to K. Increase the reverse voltage gradually and record the magnitudes V_R and I_R. Plot these readings to obtain the reverse characteristic.

The minority carriers give a small reverse saturation current, nearly independent of reverse voltage over a considerable range. At the breakdown voltage V_{BR}, the reverse current rises sharply. The series resistance must limit current, and an ordinary diode should not be driven into breakdown during routine measurements. The graphs below use positive magnitudes separately for each bias; in a signed combined graph the reverse branch lies in the third quadrant.



Forward bias Reverse bias

Forward and reverse measurement circuits: the upper, longer battery plate is positive. R limits current; the voltmeter is across the diode. A and K denote anode and cathode.



Forward bias Reverse bias

Qualitative V-I characteristics; separate positive-magnitude axes are used, with different current scales.

Step 3: (b)(i) Identify the doped semiconductor Initially $n = p = n_i = 6 \times 10^8\ \mathrm{m}^{-3}$, so the specimen is intrinsic. The printed question gives the doped electron concentration as $n = 9 \times 10^{12}\ \mathrm{m}^{-3}$. Its electron concentration has increased greatly above the intrinsic value. The impurity therefore acts as a donor: electrons become majority carriers and holes minority carriers, producing an n-type semiconductor.

Step 4: (b)(ii) Calculate the new hole concentration Assuming the temperature is unchanged, the intrinsic concentration and hence the product np remain unchanged. Substituting the printed values

Quick Tip to Solve: Use a milliammeter for forward bias and a microammeter for reverse bias; for doping, square the original intrinsic concentration before dividing by the new electron concentration.

into the mass-action law,

$$p = \frac{n_i^2}{n} = \frac{(6 \times 10^8)^2}{9 \times 10^{12}}\,\mathrm{m}^{-3}$$
$$= \frac{36 \times 10^{16}}{9 \times 10^{12}}\,\mathrm{m}^{-3} = 4 \times 10^4\,\mathrm{m}^{-3}.$$

The reduced hole concentration is consistent with electrons becoming the majority carriers; thermal equilibrium maintains the carrier product.

Step 5: Conclusion Forward bias gives a rapidly rising current beyond the knee; reverse bias gives a small saturation current until breakdown. After doping the material is $\boxed{\text{n-type}}$, and the new hole concentration is $\boxed{p = 4 \times 10^4\,\mathrm{m}^{-3}}$ at the same temperature.

Quick Tip to Solve: Use a milliammeter for forward bias and a microammeter for reverse bias; for doping, square the original intrinsic concentration before dividing by the new electron concentration.