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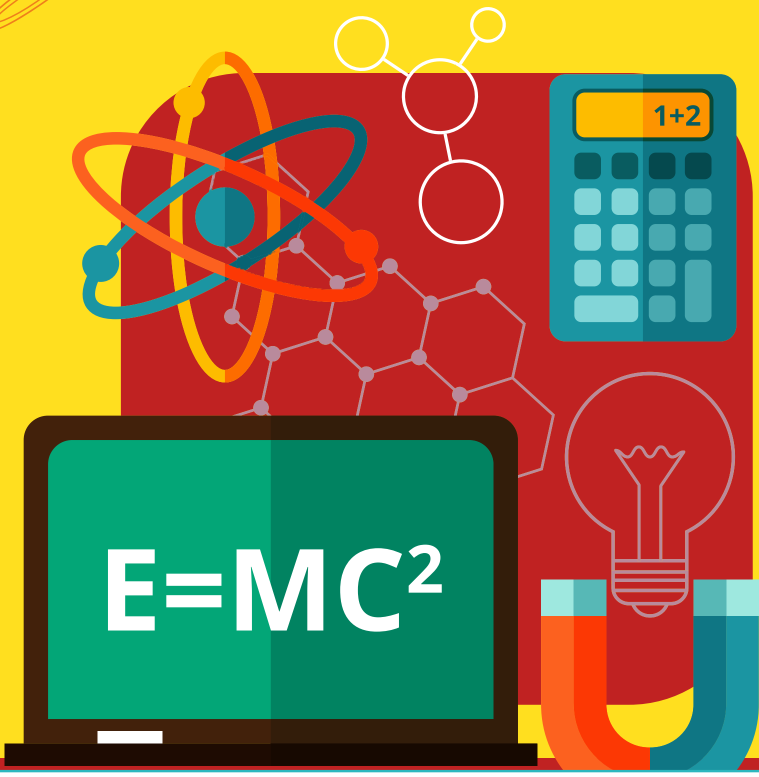

INPhO-2026

PAPER SOLUTION

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WORKSHOP FEE

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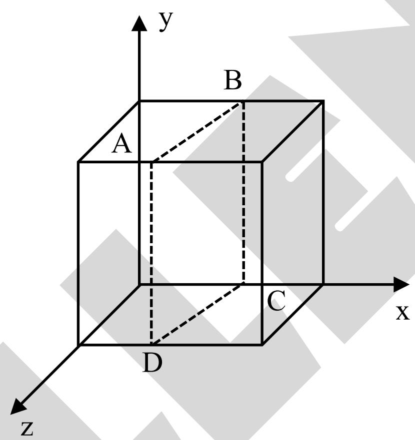
Max. Marks: 75 **Time allowed: 3 hours**

1. [12 Marks] Find the flaw

Consider a non-conducting, charged, thin cubical shell with a uniform surface charge density. Consider the plane ABCD, which vertically and symmetrically divides the cubical shell (see figure). Six students independently solved for the electric field on the plane ABCD and presented six different answers, shown below in figs. (a) to (f), each approximately depicting the electric field lines in the ABCD plane (the field line arrows are not shown). Consider each of the six answers, and for each, give



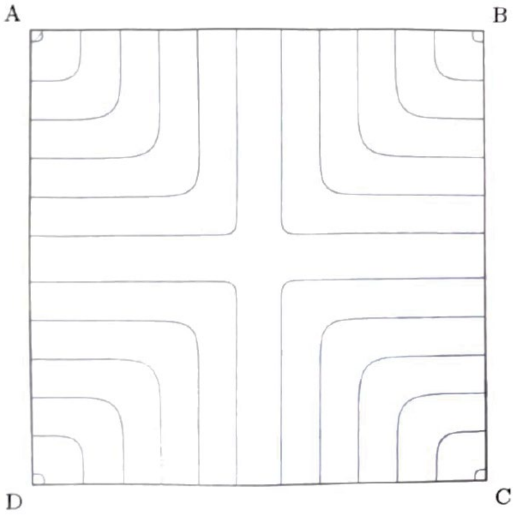
- at least one reason (based on a physics argument), explaining why it is incorrect

OR

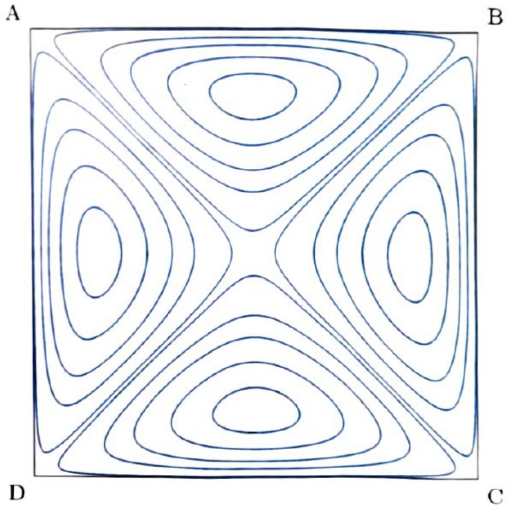
- at least two reasons why it could be correct.

Note that you are not required to obtain the correct depiction of the electric field or to provide a detailed derivation in this question.

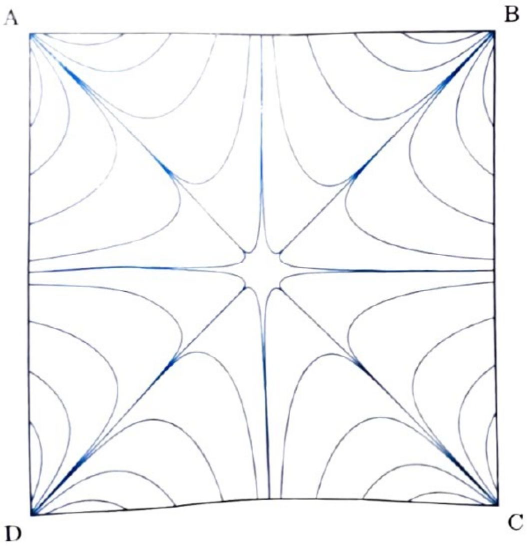
In none of the figures, adjacent field lines touch or intersect each other, although they may appear to do so in figure (c) and figure (e), where they are very close. In figure (d), the diagram indicates that no field is present. In figure (f), ⊗ denotes a field directed along the –x axis, and ⊙ denotes a field directed along +x axis.



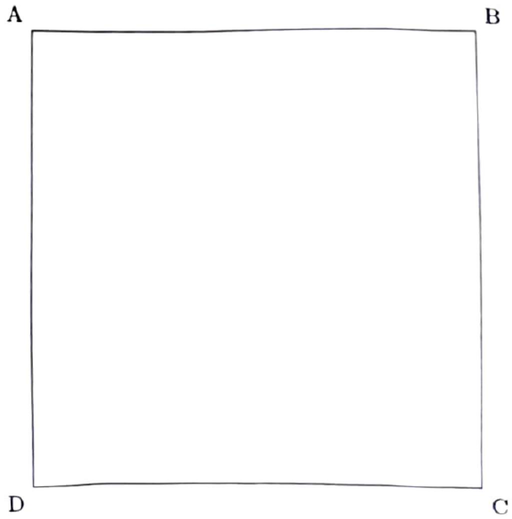
(a)



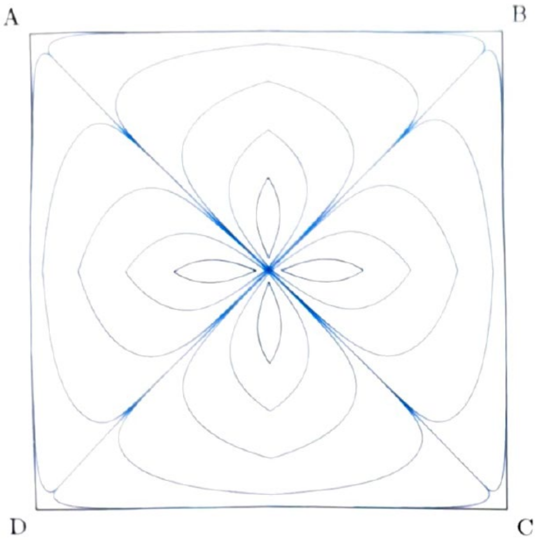
(b)



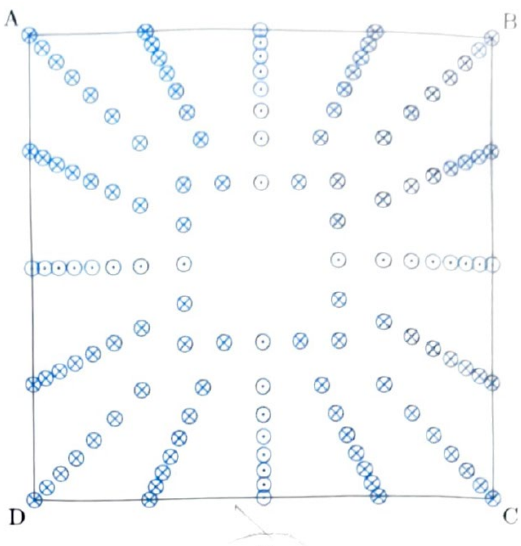
(c)



(d)

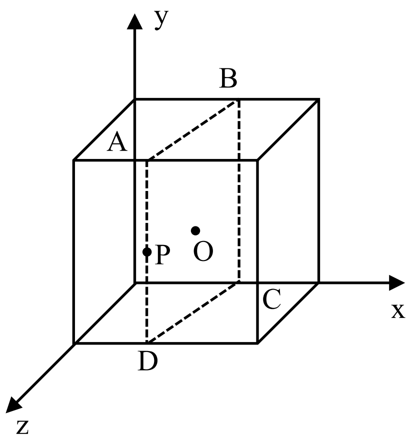


(e)

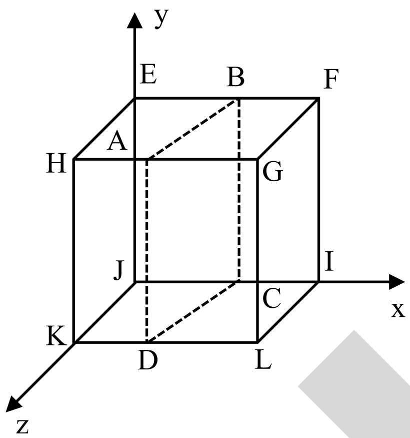


(f)

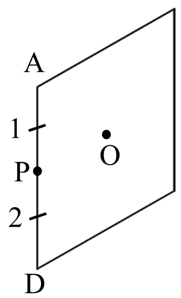
Sol.



Let us consider a point P on the face (mid point of AC). As we approach close to point P, the field must be that of an infinite sheet ($\frac{\sigma}{2\in_0}$ and towards the center of the cube O).



Now let us consider a smaller cube E' F' G' H' I' J' K' L' concentric to the cube EFGHIJKL. Since the charge enclosed in E'F'G'H'I'J'K'L' is zero, ϕ through each surface should be zero.



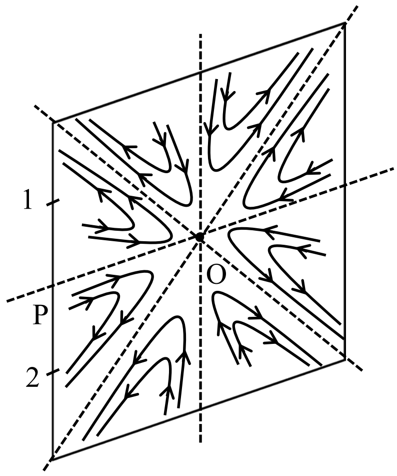
As the field at point P is inwards (towards O) field should be outwards at two points on side AD above and below P.

Now taking into account,

(a) Field at O must be zero.

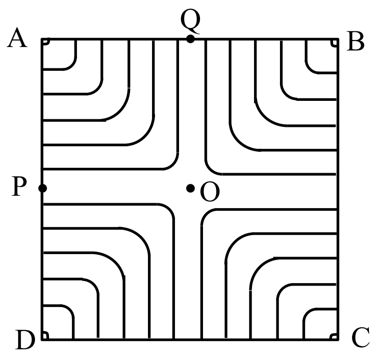
(b) Field at D must be inwards and towards O.

(c) Field must be outwards at two points 1 and 2 above and below P.



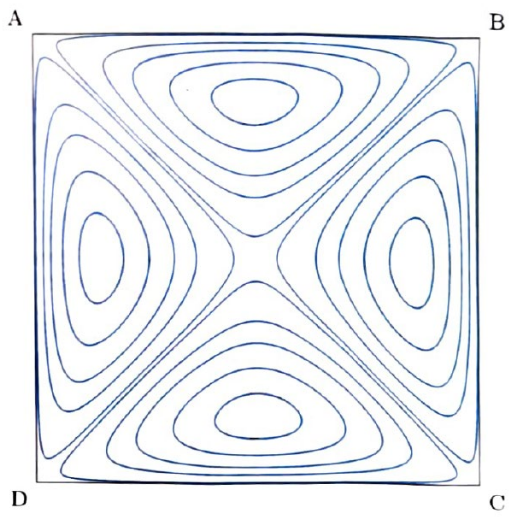
The field lines in ABCD plane must look like which corresponds to diagram (c)

(a)



Incorrect as field at point P and point Q must be pointing inwards towards O which is not possible if they are on same filed line.

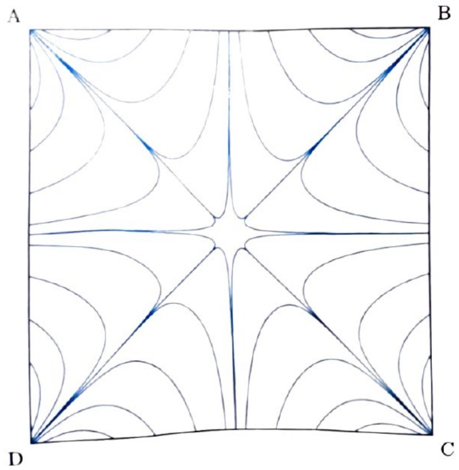
(b)



(b)

Incorrect as EFL form closed loops which is not possible as electric field due to static charges is conservative in nature.

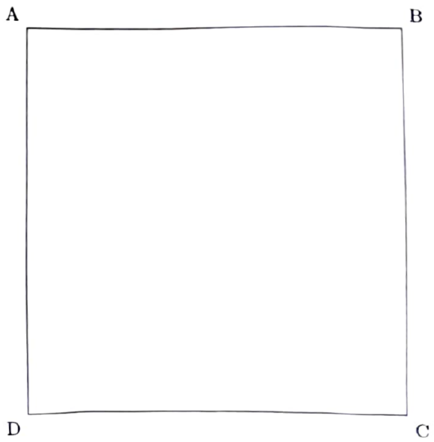
(c)



(c)

Correct as per the explanation given above.

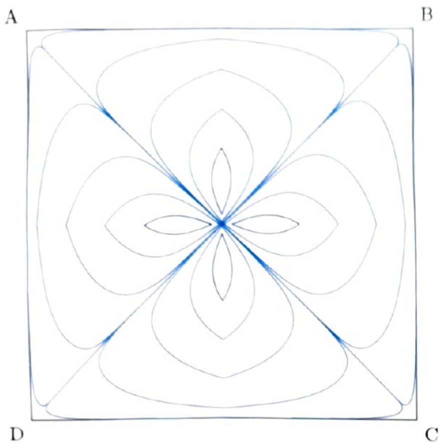
(d)



(d)

Incorrect as EF must be zero only at the center of the cube and not at all points on the surface ABCD

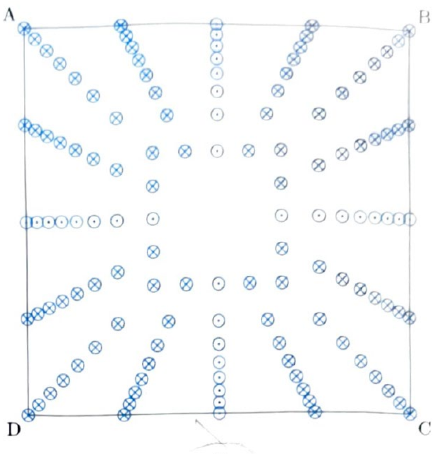
(e)



(e)

Incorrect as EFL form closed loops which is not possible as electric field due to static charges is conservative in nature.

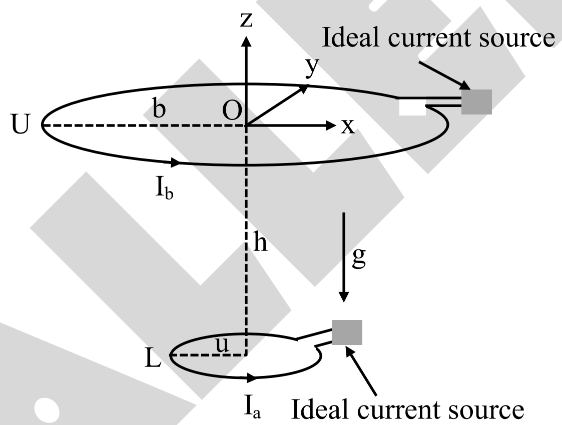
(f)



Incorrect as the field lines should be in the plane ABCD as the charge distribution is symmetric to plane ABCD.

2. [12 marks] Current affairs

Consider two coaxial conducting circular loops; a lower loop L of radius a and an upper loop U of radius b (see figure). The planes of the loops are parallel and separated by a distance h. The loop U is held fixed in the x-y plane, while the loop L is free to move vertically.



Each loop is connected to an ideal current source that maintains a constant current I_a in loop L and I_b in loop U. Assume a << b, so that the magnetic field produced by the loop U may be treated as uniform over the entire area of the loop L. Let g be the acceleration due to gravity. The system is initially in static equilibrium under gravity.

The loop L is then displaced very slowly by an external agent toward the loop U through a distance dh, while the currents in both loops are maintained constant by ideal power supplies.

During this process, let the change in the gravitational potential energy of the loop L be dU_g, and the change in the energy stored in the magnetic field be dU_m. For the same process, let the extra work done by the power supplies connected to the lower and upper loops be dW_L and dW_U, respectively.

Express each of dU_g, dU_m, dW_U, and dW_L in terms of I_a, I_b, the geometrical parameters (a, b, h, dh), and any relevant constants, if they are non-zero.

Sol. Loop U is fixed while loop L is displaced vertically upward

$dU_g = m_L g dh$

where m_L is mass of loop L

Initially L is in equilibrium so

$$m_L g = \mu \frac{dB}{dy}$$

Where μ is magnetic moment of L

$$B = \frac{\mu_0 I_b b^2}{2\left(b^2 + y^2\right)^{\frac{3}{2}}}$$

$$\frac{dB}{dy} = \frac{\mu_0 I_b b^2}{2} \frac{3}{2}\left(b^2 + y^2\right)^{-\frac{3}{2}-1} 2y$$

$$\frac{dB}{dy} = \frac{3\mu_0 I_b b^2 y}{2\left(b^2 + y^2\right)^{\frac{5}{2}}}$$

$$m_L g = I_a \pi a^2 \frac{3\mu_0 I_b b^2 h}{2\left(b^2 + h^2\right)^{\frac{5}{2}}}$$

So $dU_g = I_a \pi a^2 \dfrac{3\mu_0 I_b b^2 h}{2\left(b^2 + h^2\right)^{\frac{5}{2}}} dh$

$dU_m = dU_{self\,L} + dU_{self\,U} + dU_{interaction}$

Since currents in L and U are maintained constant

$dU_m = dU_{interation}$

$U_{interaction} = MI_a I_b$

(M : Mutual inductance)

$dU_{interaction} = I_a I_b dM$

$\phi_a = MI_b + LI_a$

$d\phi_a = dMI_b$

$\pi a^2\, dB = dM\, I_b$

$$\pi a^2 \frac{3\mu_0 I_b b^2 h}{2\left(b^2 + h^2\right)^{\frac{5}{2}}} dh = dMI_b$$

$$dU_m = I_a \pi a^2 \frac{3\mu_0 I_b b^2 h}{2\left(b^2 + h^2\right)^{\frac{5}{2}}} dh$$

dW_U :

$P_U = E_{induced}\, I_b$

$dW_U = d\phi_b\, I_b$

$dW_U = (dM)\, I_a I_b$

$$dW_U = I_a \pi a^2 \frac{3\mu_0 I_b b^2 h}{2\left(b^2+h^2\right)^{\frac{5}{2}}} dh$$

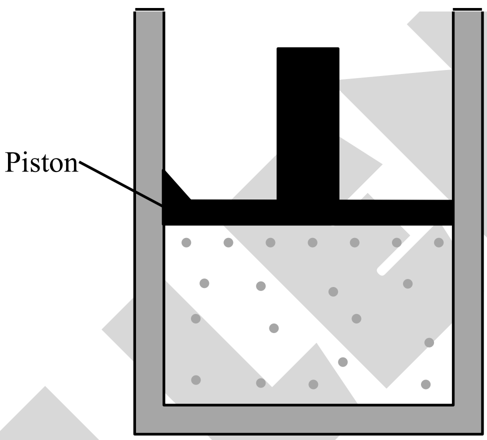
dW_L :

$P_L = E_{Induced}\, I_a$

$dW_L = d\phi_a I_a = (dM)\, I_b I_a$

3. Slow, smooth and sudden

A vertical insulated cylinder fitted with a frictionless, movable thermally conducting massless piston contains air at pressure p_0 = 1 atm, volume V_i = 3.0 L, and temperature T_0 = 300 K. Assume the gas is ideal with a ratio of specific heats γ = 1.4. The system is initially in equilibrium with its surroundings at temperature T_0 and pressure p_0. The piston is then moved so that the gas is compressed to a final volume V_f = 2.0 L.



This compression is performed in three different ways :

(a) [3 marks] The piston is moved slowly so that the compression remains quasistatic and the gas stays in thermal equilibrium with the surroundings throughout (isothermal process). Calculate the total heat exchanged Q_a in the process.

(b) [3 marks] The piston is moved quickly but smoothly, so that during compression heat exchange with the surroundings is negligible (adiabatic and reversible). After compression, the gas is allowed to exchange heat with the surroundings without any change in volume, and it returns to the equilibrium temperature T_0. Calculate the total heat exchanged Q_b in the process.

(c) [5 marks] The piston is moved suddenly, producing a rapid, irreversible adiabatic compression. After compression, the gas is reached a temperature T_c. The gas is now left to exchange heat with the surroundings without further change in the volume, and eventually returns to its equilibrium temperature T_0. Calculate T_c and the total heat exchanged Q_c in the process.

Sol. **(a)** $Q_a = nRT_0 \ell n \frac{V_f}{V_i}$

$= \frac{P_0 V_0}{RT_0} RT_0 \ell n \frac{2}{3}$

$Q_a = P_0 V_0 \ \ell n \frac{2}{3}$

$= (1)\,(3)\ \ell n\left(\frac{2}{3}\right)$

$= -\,3 \times (0.405)$

$= -1.22$ atm – litre

(b) $Q_b = Q_{adia} + Q_{isochoric} = 0 + Q_{isoch}$

$Q_{isoch} = nC_v(T_3 - T_2)$

$$= \frac{P_0V_0}{RT_0}\frac{R}{0.4}\left(T_0 - T_2\right)$$

$$= \frac{P_0V_0}{0.4}\left[1 - \frac{T_2}{T_0}\right]$$

$$T_0 3^{\gamma-1} = T_2 2^{\gamma-1}$$

$T_2 = T_0\,(1.5)^{0.4}$

$T_2 = T_0(1.18)$

$$Q_{isoch} = \frac{P_0V_0}{0.4}\left(1 - 1.18\right)$$

$= -2.5 \times 1 \times 3(0.18)$

$= -7.5 \times 0.18$

$= -\,1.35$ atm-litre

$Q_b = Q_{adia} + Q_{isoch}$

$= 0 - 1.35$

$= -1.35$ atm-litre

(c) $0 = Q = \Delta U + W$

$\Delta U = -W$

$nC_v\,(T_c - T_0) = -P_{ext}\,(V_c - V_i)$

$$\frac{P_0V_0}{RT_0}\frac{R}{\gamma - 1}\left(T_C - T_0\right) = -1\left(2 - 3\right)$$

$$\frac{P_0V_0}{0.4}\frac{T_0}{T_0}\left(\frac{T_C}{T_0} - 1\right) = 1$$

$$\frac{T_C}{T_0} - 1 = \frac{0.4}{P_0V_0}$$

$$= \frac{0.4}{1 \times 3}$$

$$\frac{T_C}{T_0} = \frac{4}{30} + 1$$

$$T_C = \frac{34}{30} \times T_0$$

$$= \frac{34}{30} \times 300$$

$T_C = 340$ K

$Q_C = Q_{adia} + Q_{isoch}$

$= 0 + Q_{isoch}$

$Q_{isoch} = nC_v(T_0 - T_C)$

$= \frac{P_0V_0}{RT_0}\frac{RT_0}{0.4}\left(1 - \frac{T_C}{T_0}\right)$

$= 2.5P_0V_0\left(1 - \frac{34}{30}\right)$

$= -2.5 \times 1 \times 3 \times \frac{4}{30}$

$= -2.5 \times 0.4$

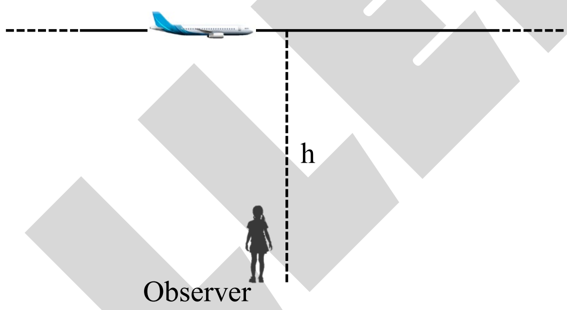
$Q_{iso} = -1$ atm-litre

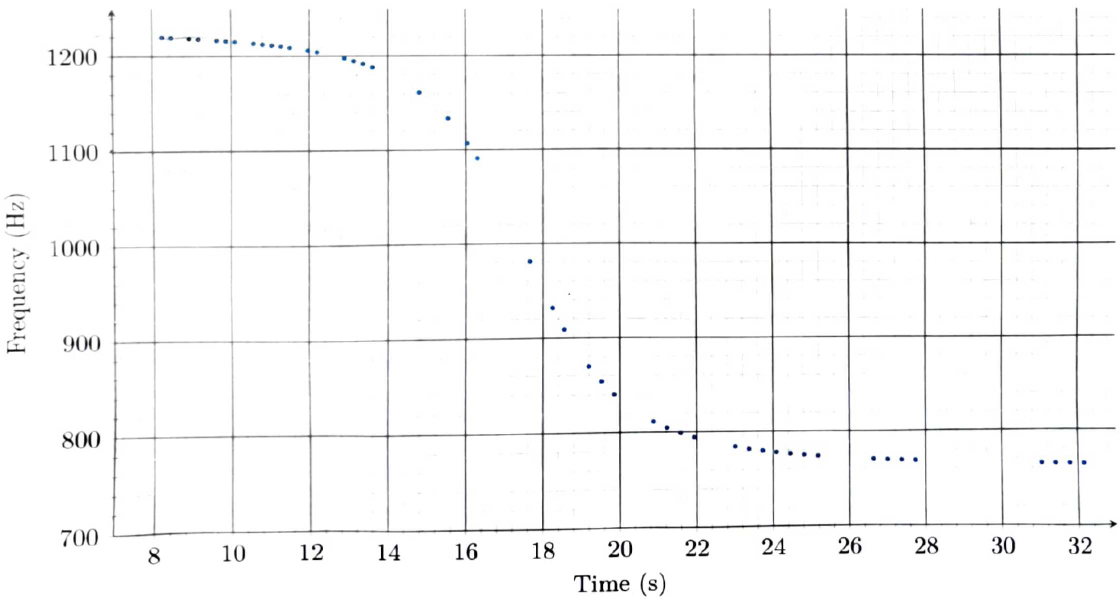
$Q_c = Q_{isoch}$

$= -1$ atm–litre

4. A Curve You Can hear

An aeroplane flies along a horizontal path, emitting sound at a constant frequency f_0. A stationary observer with a detector on the ground directly beneath the flight path records the sound frequency as the plane passes overhead, which is plotted below. The speed of sound in the medium is $c_s = 340\ m\ s^{-1}$.

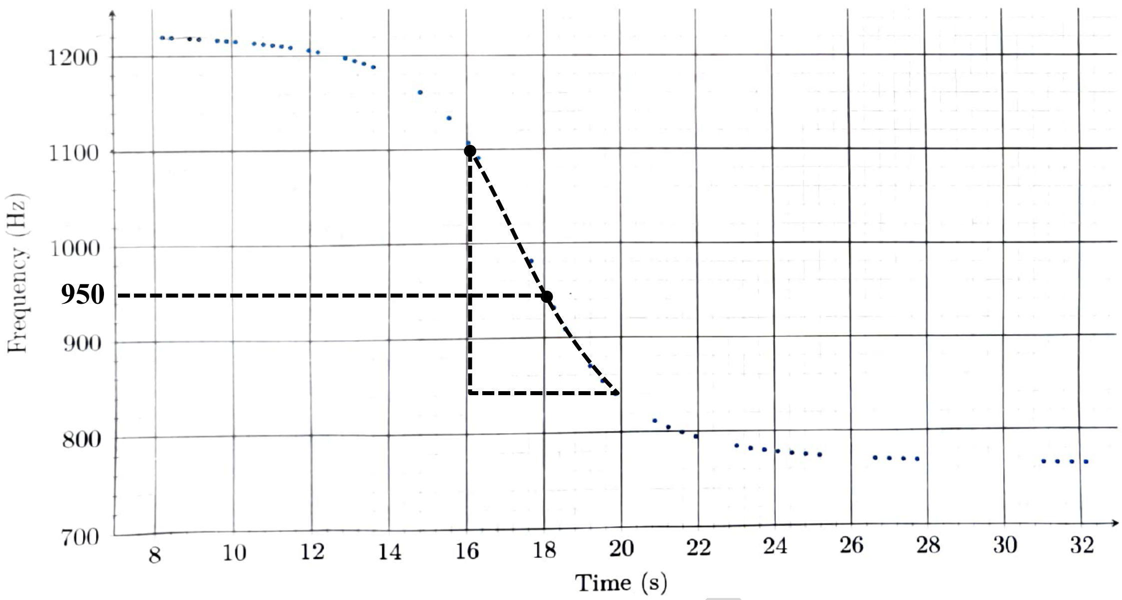




(a) [5 marks] You task is to measure the speed of the aeroplane, v, from the graph. Express v in terms of quantities measurable from the graph, and define/mark these quantities on the graph reproduced in the Summary Answer sheet. Calculate the value of v.

(b) [5 marks] Find the height h of the plane's flight path.

Sol.



Dopler effect

From graph f_{max} = 1220 Hz

f_{min} = 760 Hz

Speed of sound = 340 Hz

(a) Speed of the aeroplane

$$f_{approach} = f_0\left(\frac{C}{C - v\cos\theta}\right)$$

$$\left(f_{approach}\right)_{max} = f_0\left(\frac{C}{C - v}\right)$$

$$\left(f_{reced}\right)_{max} = f_0\left(\frac{C}{C + v\cos\theta}\right)$$

$$\left(f_{reced}\right)_{max} = f_0\left(\frac{C}{C + v}\right)$$

$$\frac{\left(f_{appo}\right)_{max}}{\left(f_{Recede}\right)_{max}} = \frac{C + v}{C - v} \cong \frac{1220}{760}$$

760C + 760v = 1220C – 1220 v

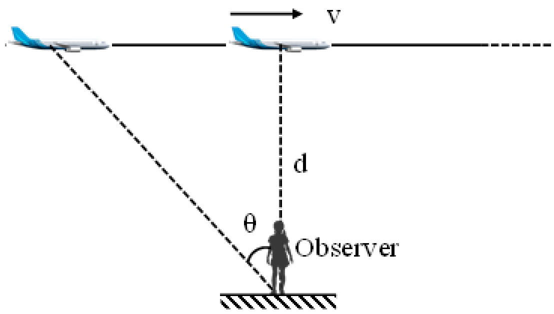
(1220 + 760)v = (1220 – 760) C

$$v \cong \frac{460}{1980}C$$

$v \cong 78.98$

$v \approx 79$ m/s

Height of plane : At the instant plane is directly overhead, the radial velocity is zero so the detected frequency equals the emitted frequency $f_0 \approx 950$ Hz at t = 18 Hz



$$f = \frac{f_0}{1 - \frac{v}{c}\cos\theta}$$

$$\frac{df}{dt} = \frac{f_0\left(\frac{v}{C}\sin\theta\right)}{\left(1 - \frac{v}{C}\cos\theta\right)^2}\frac{d\theta}{dt}$$

at overhead condition $\theta \rightarrow 90°$

$$\frac{df}{dt} = f_0\frac{v}{C}.\frac{d\theta}{dt} \quad \left(\frac{d\theta}{dt} = \frac{v}{d}\right)$$

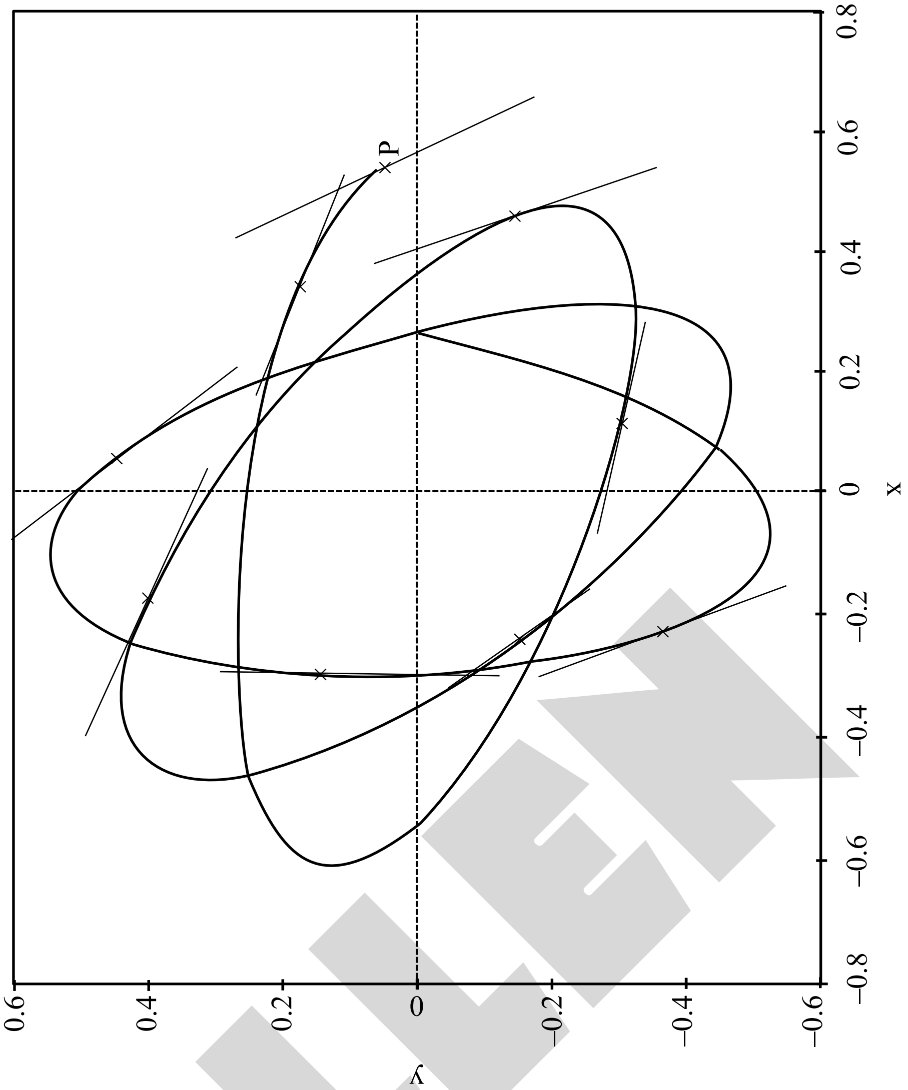
$$\frac{df}{dt} = f_0\frac{v}{C}.\frac{v}{d}$$

$$\frac{250}{4} = \frac{950(79)^2}{340.d}$$

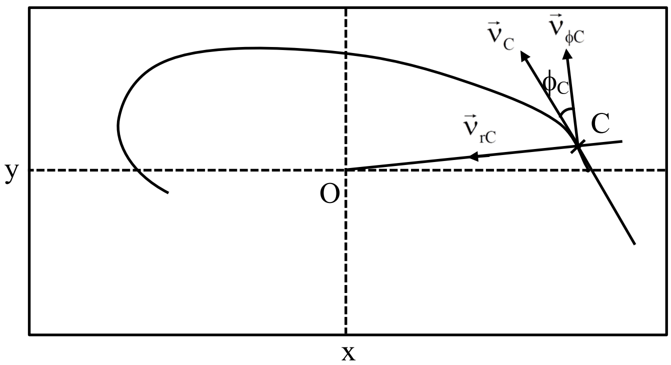
$d \cong 279$m

5. From Kepler's archive

A short note found in Kepler's archive describes a curious central-force problem. The note states that the radial potential has the form $U(r) = kr^n$, where $k > 0$ is a dimensional constant, n is a positive integer, and r is the distance from a fixed origin. Kepler also recorded the particle's precise trajectory by listing its x-y coordinates in its plane of motion (see the figure below). His sketch includes several short tangent segments drawn at selected points, marked by X.



The coordinates x and y are given in arbitrary units. Kepler's notes indicate that at point P, the kinetic energy is exactly one quarter of the total mechanical energy. He further noted that the exponent n could be determined by performing calculations based on the graph and by constructing, a linear plot. Unfortunately, the remainder of the manuscript explaining this method has been lost. To understand what Kepler did, we define a few variables below. The figure below shows the trajectory of a particle moving under a central force.



Consider a fixed point C on the trajectory (shown by X), located at a distance r_C from the origin O. At point C, let the speed of the particle be v_C, and let the radial and tangential components of its velocity be v_{rC} and $v_{\phi C}$, respectively ($\vec{v}_{\phi C}$ is $\perp$ to $\vec{v}_{rC}$).

The angle between $\vec{v}_{\phi C}$ and the velocity vector $\vec{v}_C$ is denoted by ϕ_C.

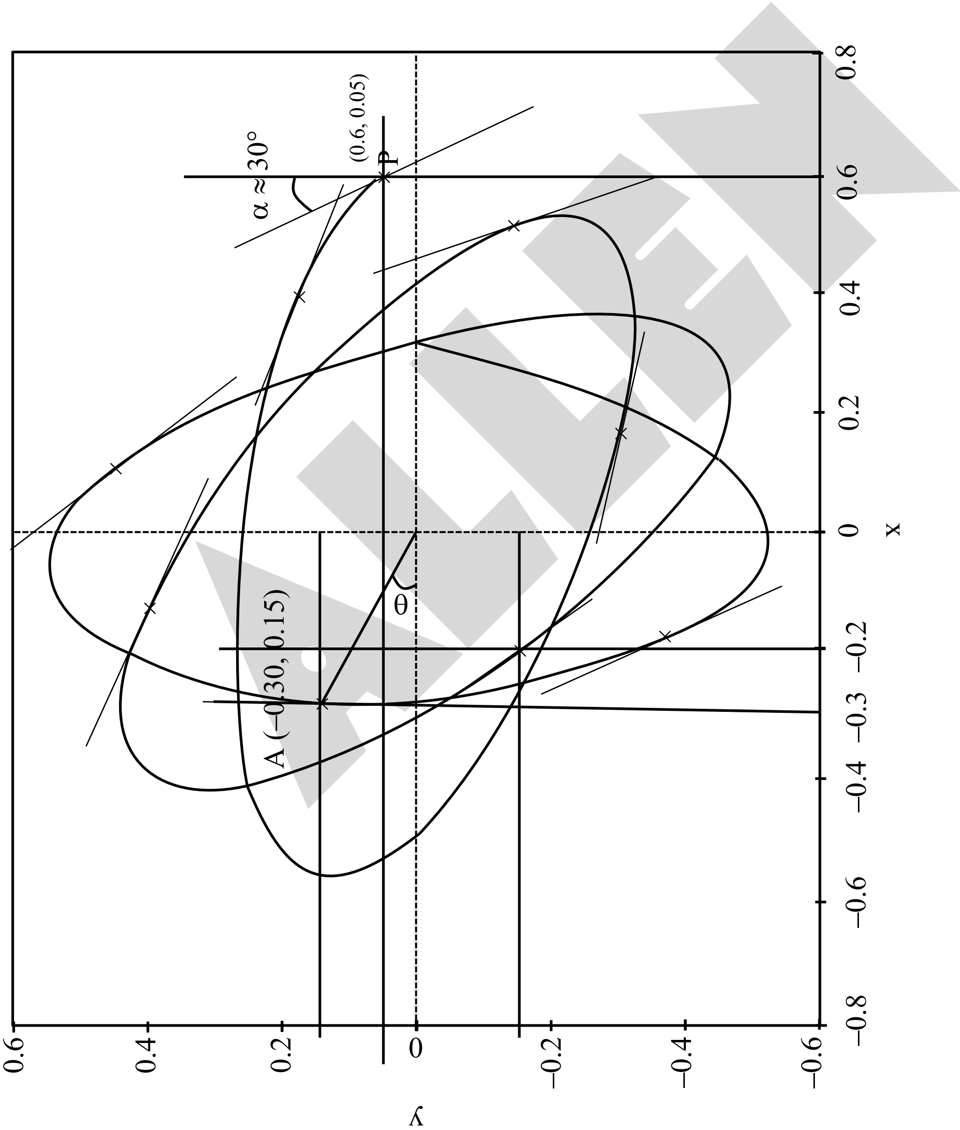
At an arbitrary point on the trajectory the particle is at a distance r from the origin, its speed is v and the corresponding angle between $\vec{v}$ and its tangential component $\vec{v}_\phi$ is ϕ.

(a) [5 marks] The speed v at an arbitrary point can be written in terms of the speed at point C as $v = \alpha v_C$. Express α in terms of r_C, r, ϕ_C, and ϕ.

(b) [13 marks] Two versions of Kepler's diagram are given in the answer sheet : one with tangents drawn and one without. You may use either or both figures as needed.

Use these to devise a method to find the value of n. Perform all relevant analyses using the figures provides on the answer sheet. Finally, use the graph paper at the end of the answer sheet for plotting a linear graph to determine n, and report any necessary data tables in the detailed answer sheet.

Sol.



At point P (0.6, 0.05); $r_p = \sqrt{0.6^2 + 0.5^2}$

$$KE = \frac{1}{4}(KE + PE)$$

$$\frac{1}{2}mv_p^2 = \frac{1}{4}\left(\frac{1}{2}mv_p^2 + kr_p^n\right)$$

$$\frac{3}{2}mv_p^2 = kr_p^n \quad \ldots. \text{(i)}$$

$$\Rightarrow \text{ME} = \text{E} = 2mv_p^2 = \frac{4}{3}kr_p^n$$

$L = mv_p\cos\alpha \cdot r_p$

Angular momentum about O remains conserved.

At A (–0.3, 0.15), velocity is along y-axis.

$$\tan\theta = \frac{0.15}{0.3} = \frac{1}{2} \Rightarrow \cos\theta = \frac{2}{\sqrt{5}}$$

$\Rightarrow$ angular momentum about O is $L = mv_a\cos\theta \cdot r_A = mv_a r_A \frac{2}{\sqrt{5}}$

$$mv_p\cos\alpha r_p = mv_A r_A\cos\theta$$

$$v_A = \frac{r_p v_p\cos\alpha}{r_A\cos\theta}$$

$$KE_A = \frac{1}{2}mv_A^2$$

$PE_A = Kr_A^n$

$$E = \frac{1}{2}mv_A^2 + kr_A^n$$

$$\frac{4}{3}kr_p^n = \frac{1}{2}m\left(\frac{r_p v_p\cos\alpha}{r_A\cos\theta}\right)^2 + Kr_A^n$$

$$\frac{4}{3}kr_p^n = \frac{1}{2}m\cdot v_p^2\cdot\left(\frac{r_p}{r_A}\frac{\cos\alpha}{\cos\theta}\right)^2 + Kr_A^n$$

$$\frac{4}{3}kr_p^n = \frac{K}{3}r_p^n\cdot\left(\frac{r_p\cos\alpha}{r_A\cos\theta}\right)^2 + Kr_A^n$$

$$\frac{r_p^n}{3}\left(4 - \frac{r_p^2\cos^2\alpha}{r_A^2\cos^2\theta}\right) = r_A^n$$

$$\left(\frac{r_p}{r_A}\right)^n\left(4 - \left(\frac{r_p}{r_A}\right)^2\frac{\cos^2\alpha}{\cos^2\theta}\right) = 3$$

Let $\alpha = 30°$

$$\left(\frac{r_p}{r_A}\right)^2 = \frac{0.6^2 + 0.05^2}{0.3^2 + 0.15^2} \approx 3.2$$

$$\Rightarrow (3.2)^{\frac{n}{2}}\left(4-3.2\times\frac{\frac{3}{4}}{\frac{4}{5}}\right)=3$$

$$(3.2)^{n/2}(4-3)=3$$

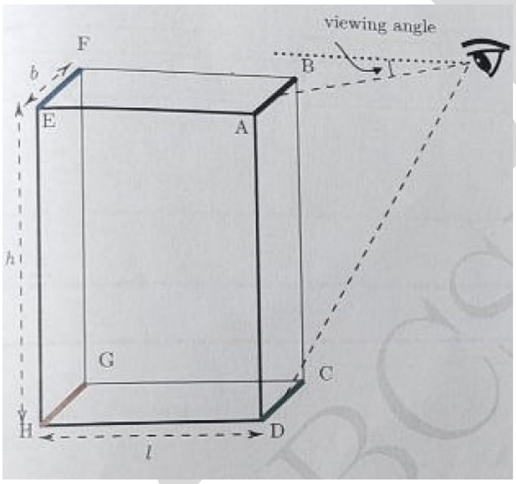
$$(3.2)^{\frac{n}{2}}=3$$

$$\frac{n}{2}\ell n(3.2)=\ell n3$$

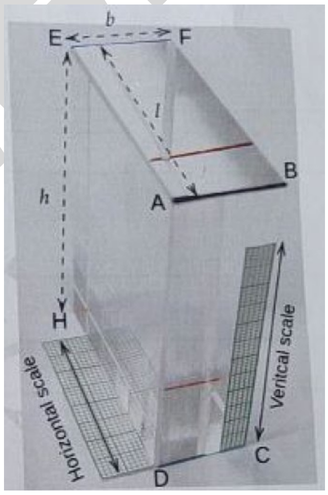
$$n=\frac{2\ell n3}{\ell n3.2}=1.89$$

6. Perspective matters

Consider a glass slab (ABCDHGFE) of dimensions ($\ell \times b \times h$). The slab is placed on its base (CDHG), and viewed at different viewing angles with the vertical face (ABCD) facing the observer (see Fig. (a)). The edges of the glass slab are combined as shown in figure (a). A piece of graph paper is placed next to the base (CDHG). Another piece of graph paper is pasted on the vertical face (ABCD) of the slab (see figure (b)). The least count of both the pasted graph papers is 1 mm.



(a)



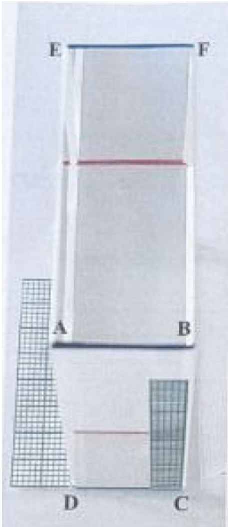
(b)

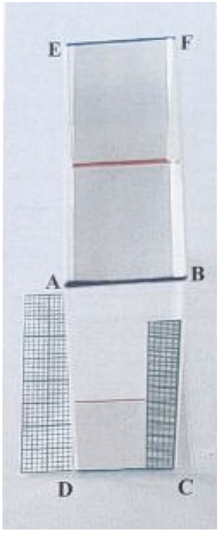
The task is to determine the refractive index μ_g of the glass slab from a series of photographs of the slab taken from different viewing angles (by lowering the eye position) shown in figure (i) to (vi) on the next page. The viewing angle decreases progressively from Figs. (i) to (vi). Take the refractive index of air μ_a to be 1.00. In this exercise, focus your attention on the red line visible through the vertical face (ABCD) only.

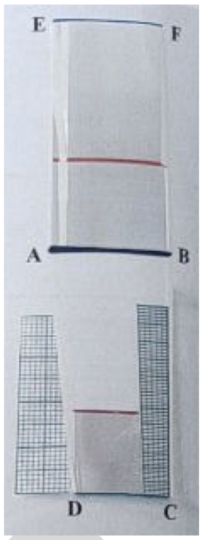
(a) **[2 marks]** Mark and state the measurable quantities in the photo given in the summary answer sheet, that can be used in subsequent parts for measuring the refractive index of the slab.

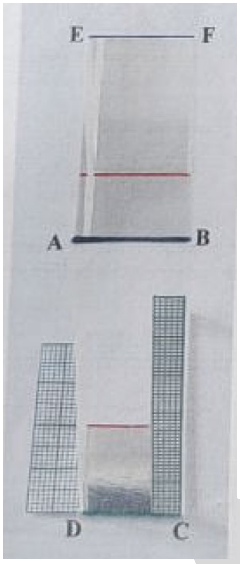
(b) **[4 marks]** Draw a ray diagram showing these measured quantities, and the relevant given dimensions of the slab. Derive an expression for the refractive index μ_g of the glass slab in terms of the measured quantities that you have decided to use.

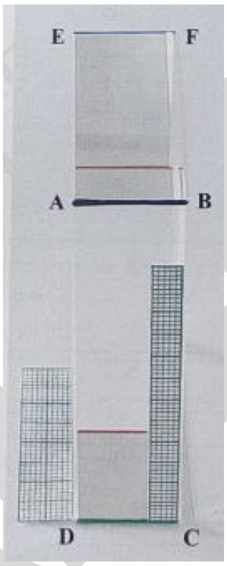
(c) **[6 marks]** Calculate the value of μ_g, by plotting a linear graph. Report your datatable in the detailed answesheet.

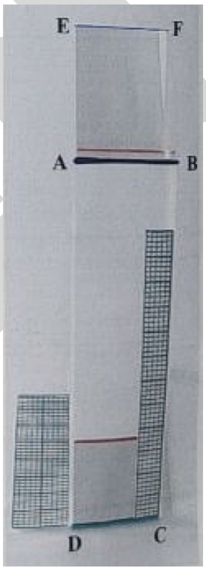
(i) 

(ii) 

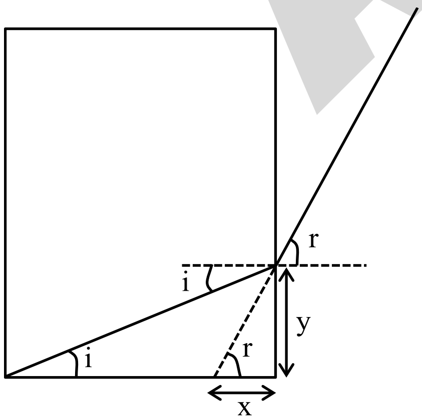
(iii) 

(iv) 

(v) 

(vi) 

Sol.



(i) x = 10 mm, y = 34 mm

(ii) x = 15 mm, y = 31 mm

(iii) x = 18 mm, y = 28 mm

(iv) x = 20 mm, y = 26 mm

(v) x = 23 mm, y = 23 mm

(vi) x = 25 mm, y = 18 mm

n sini = sinr

$$n\frac{y}{\sqrt{y^2+\ell^2}} = \frac{y}{\sqrt{x^2+y^2}}$$

$n^2x^2 + n^2y^2 = y^2 + \ell^2$

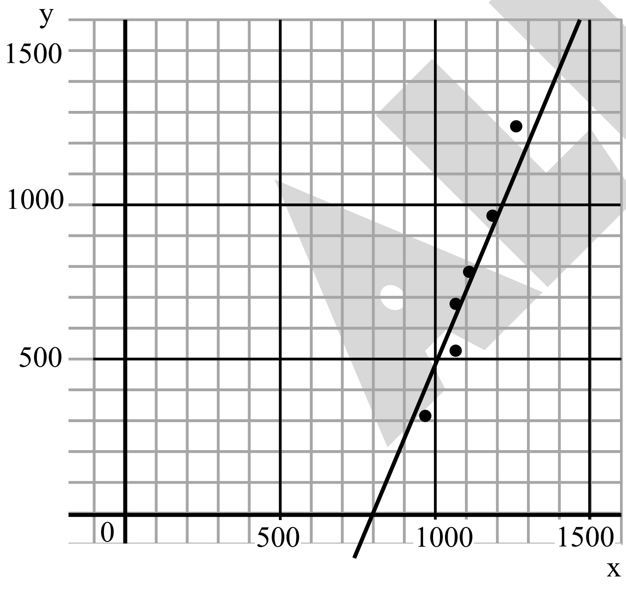
$n^2 (x^2 + y^2) = y^2 + \ell^2$

$Y = y^2$

$X = x^2 + y^2$

$Y = n^2X - \ell^2$

x	y	x^2	y^2	x^2+y^2
10	34	100	1156	1256
15	31	225	961	1186
18	28	324	784	1108
20	26	400	676	1076
23	23	529	529	1058
25	18	625	324	949



$\tan\theta = 2.4$

$n = \sqrt{2.4} = 1.55$

* Solutions to question no. 5 and 6 is based on data taken from the picture shared to us by our students. The exact answer may differ.

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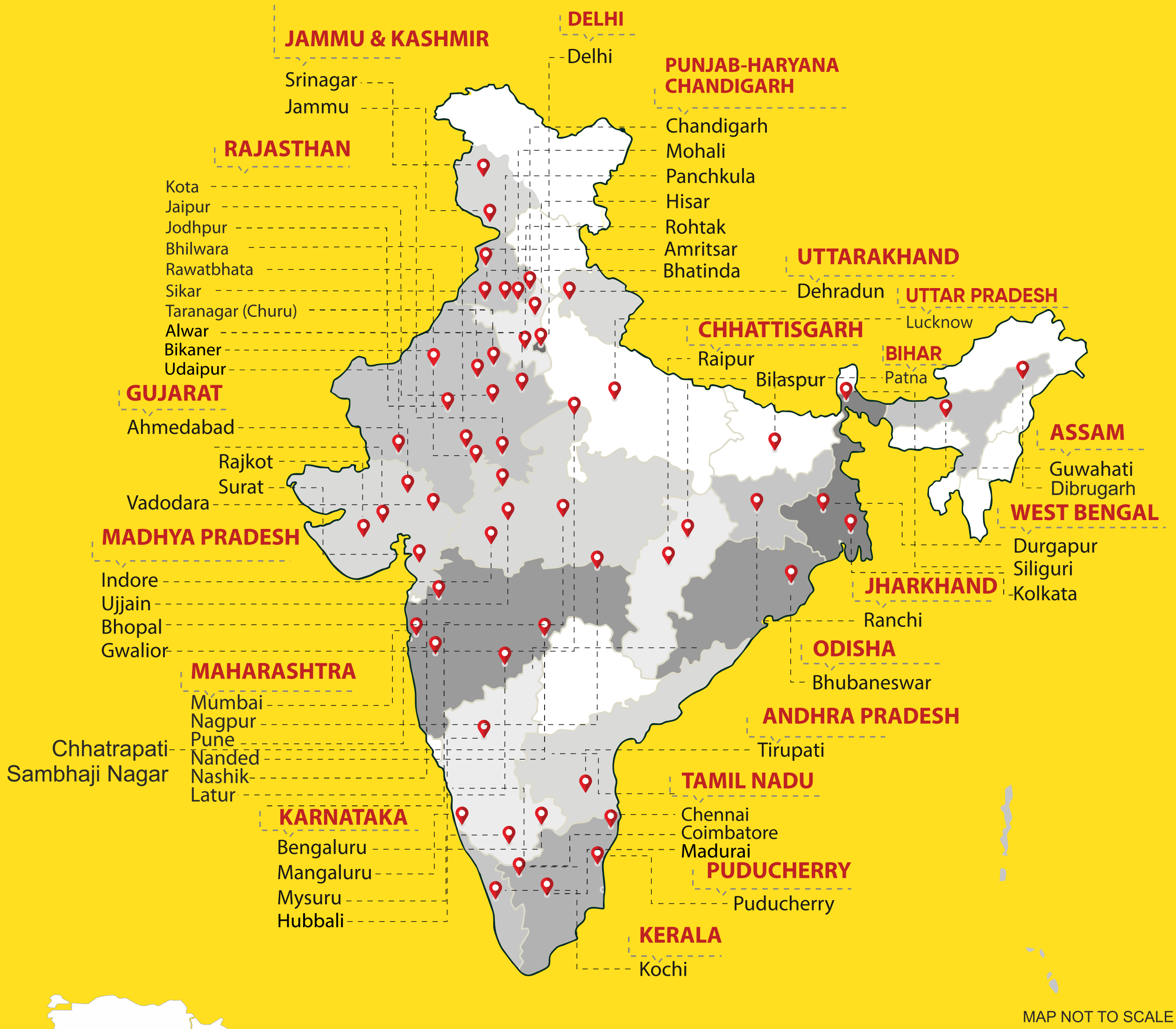

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