Past-paper walk-through

Refraction ▪ 13.3

eXercise

Questions in this set

- 2023 Q1
- 2022 Q1
- 2019 Q4
- 2017 Q3
- 2016 Q2
- 2015 Q1

Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

Question 1

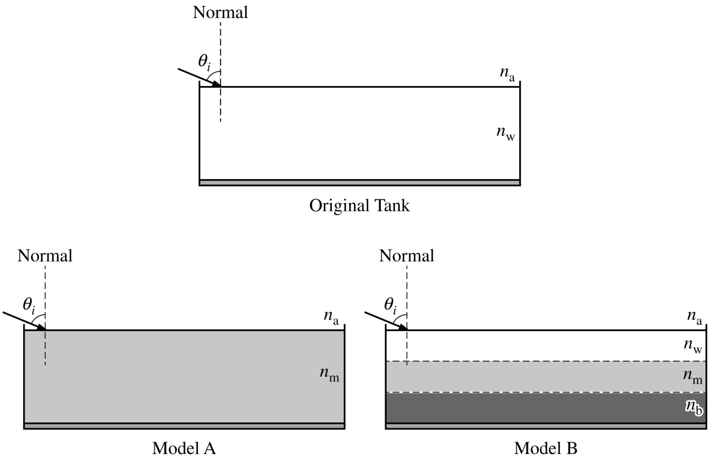
2023 ▪ Q1

(10 points, suggested time 20 minutes)
A rectangular tank with a mirrored bottom is filled with water (index of refraction n_w). A beam of light passes from air (index of refraction n_a) into the water at angle θ_i from the normal, as shown in Figure 1. Index of refraction n_w is greater than index of refraction n_a.
[Figure 1: A rectangular tank of water with a mirrored bottom, labeled "Mirror" along the bottom. A dashed vertical line labeled "Normal" is drawn at the point where a beam enters the top surface of the water at angle θ_i from the normal. The region above the water surface is labeled n_a; the region inside the tank (the water) is labeled n_w.]
(a) On the following diagram, sketch the entire path of the beam as the beam enters, travels through, and then exits the water.

Question 1

[Diagram: A blank rectangular tank with a mirrored bottom, same as Figure 1, showing "Normal" (dashed vertical line) and incident angle θ_i at the entry point, with n_a labeled above the water surface and n_w labeled inside the tank, for the student to sketch the beam's path.]

Question 1



Normal
θ_i
n_a
n_w
Original Tank
Normal
θ_i
n_a
n_m
Model A
Normal
θ_i
n_a
n_w
n_m
n_b
Model B

Question 1

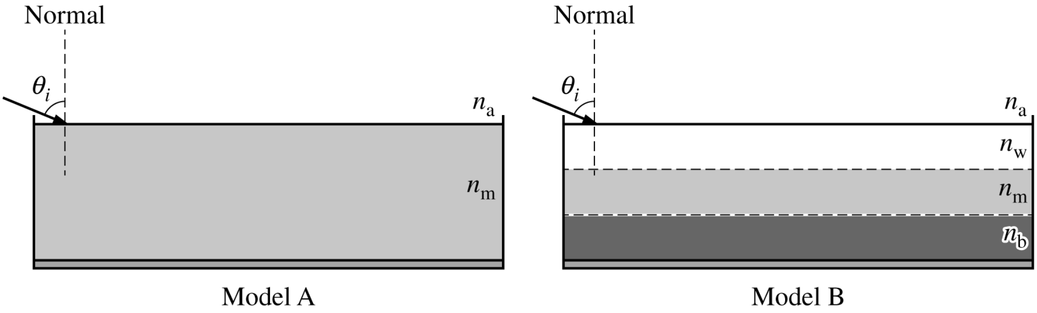


Figure 2

Question 1

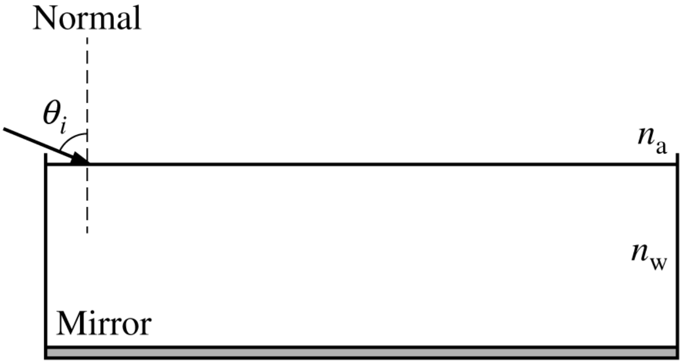


Figure 1

Question 1

2023 ▪ Q1

(10 points, suggested time 20 minutes)
A rectangular tank with a mirrored bottom is filled with water (index of refraction n_w). A beam of light passes from air (index of refraction n_a) into the water at angle θ_i from the normal, as shown in Figure 1. Index of refraction n_w is greater than index of refraction n_a.
[Figure 1: A rectangular tank of water with a mirrored bottom, labeled "Mirror" along the bottom. A dashed vertical line labeled "Normal" is drawn at the point where a beam enters the top surface of the water at angle θ_i from the normal. The region above the water surface is labeled n_a; the region inside the tank (the water) is labeled n_w.]

(b) Sugar is then added to the water, resulting in a mixture that has a different index of refraction than water. A student considers two models, Model A and Model B, for how the sugar mixes with the water. The models are shown in Figure 2.

Question 1

Model A: The sugar is uniformly mixed throughout the water, resulting in a mixture with index of refraction n_m such that $n_m > n_w$.
Model B: Layers are formed of varying concentrations of sugar in the water. There are three distinct layers of equal volume. The top layer is only water (index of refraction n_w). The middle layer has the same concentration of sugar in the water as in Model A (index of refraction n_m). The bottom layer has the highest concentration of sugar (index of refraction n_b).
[Figure 2: Two diagrams side by side, each a rectangular tank with a mirrored bottom and a valve/beam entering at angle θ_i from the "Normal." Model A: a single shaded region labeled n_m inside the tank below the surface labeled n_a (air above), with the beam entering at θ_i. Model B: three horizontal layers inside the tank, from top to bottom labeled n_w (top layer, unshaded), n_m (middle layer, lightly shaded), and n_b

Question 1

(bottom layer, densely shaded/hatched), with air (n_a) above and the beam entering at θ_i.]

Consider Model A. Briefly describe how the observed wavelength of light changes, if at all, as the beam travels from air into the mixture.

Question 1

2023 ▪ Q1

(10 points, suggested time 20 minutes)

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[Figure 1: A rectangular tank of water with a mirrored bottom, labeled "Mirror" along the bottom. A dashed vertical line labeled "Normal" is drawn at the point where a beam enters the top surface of the water at angle θ_i from the normal. The region above the water surface is labeled n_a; the region inside the tank (the water) is labeled n_w.]

Question 1

(c)(i) Relevant angles between the beam and the normal for the various layers present in models A and B are defined in the following table.

Model A		**Model B**	
θ_i	Incident angle of the beam in air	θ_i	Incident angle of the beam in air
θ_1	Angle the beam makes with the normal in the mixture in Model A	θ_2	Angle the beam makes with the normal in the top layer in Model B
		θ_3	Angle the beam makes with the normal in the middle layer in Model B
		θ_4	Angle the beam makes with the normal in the bottom layer in Model B

Question 1

Determine an expression for θ_4 in terms of θ_i, n_a, and n_b.
(c)(ii) Rank the angles from greatest to least, with 1 being greatest. If two angles are the same value, give them the same ranking.

______ θ_1 ______ θ_2 ______ θ_3 ______ θ_4

Briefly explain your reasoning using appropriate physics principles and/or mathematical models.

Question 1

2023 ▪ Q1

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[Figure 1: A rectangular tank of water with a mirrored bottom, labeled "Mirror" along the bottom. A dashed vertical line labeled "Normal" is drawn at the point where a beam enters the top surface of the water at angle θ_i from the normal. The region above the water surface is labeled n_a; the region inside the tank (the water) is labeled n_w.]

(d) [Figure: Three diagrams. "Original Tank" — a rectangular water tank with a mirrored bottom, beam entering at θ_i from the Normal, region above labeled n_a, water labeled n_w. "Model A" — same tank with a single mixture layer labeled n_m. "Model B" — same tank with three layers labeled n_w (top), n_m (middle), n_b (bottom).]

Question 1

For the original tank filled with water, the beam is observed to exit the surface of the water a horizontal distance d_w from the entry point. For models A and B, the horizontal distances are d_A and d_B, respectively.
Determine whether d_A and d_B are each greater than, less than, or equal to d_w. It is NOT necessary to compare d_A to d_B. Briefly justify your answer.

Solution 1

(a) Mark scheme

- Sketch: the beam refracts at the water surface toward the normal (since $n_w > n_a$), so it travels in a straight line from the entry point down to the mirrored bottom at an angle from the normal that is LESS than θ_i. It reflects off the mirror and travels back up along a path that is the mirror image of the incoming path, symmetric about the vertical line through the point of reflection on the mirror, exiting the water surface (parallel to, but horizontally displaced from, the entry ray). Point 1: straight-line path from entry point to the bottom with refraction angle $< \theta_i$. Point 2: continuous path symmetric about the vertical axis through the point where the beam hits the mirror.

Solution 1

(b)

Mark scheme

- As light travels from one medium into a medium with a higher index of refraction (the sugar mixture, $n_m > n_w$), the speed of light decreases while the frequency of the light remains the same. Therefore, by $\lambda = v/f$, the wavelength of the light decreases. Point earned for indicating the wavelength decreases with no incorrect statements.

Solution 1

(c)(i)

Mark scheme

- Applying Snell's law across each boundary and combining (since $n_1 \sin\theta_1 = n_2 \sin\theta_2$ at every interface): $n_a \sin\theta_i = n_w \sin\theta_2 = n_m \sin\theta_3 = n_b \sin\theta_4$. Using only the air and bottom-layer boundary: $n_a \sin\theta_i = n_b \sin\theta_4$, so $\sin\theta_4 = \dfrac{n_a}{n_b}\sin\theta_i$, i.e. $\theta_4 = \sin^{-1}\left(\dfrac{n_a}{n_b}\sin\theta_i\right)$. Full credit for a correct Snell's-law application across the two media boundaries (air to bottom layer directly is acceptable).

Solution 1

(c)(ii) Mark scheme

- Ranking from greatest (1) to least (4): θ_2 is rank 1 (greatest), θ_1 and θ_3 are tied at rank 2, θ_4 is rank 3 (least). Explanation: θ_2 has the greatest value because water (top layer, Model B) has the lowest index of refraction of the layers. θ_1 and θ_3 are equal because each is in a layer with the same index of refraction (n_m), but the angles are smaller than θ_2 because the index of refraction is larger in this layer. θ_4 has the smallest value because the bottom layer (n_b) has the highest index of refraction (larger index of refraction bends the ray more toward the normal, i.e. smaller angle). Four points: (1) θ_4 alone is the smallest angle; (1) θ_2 alone is the largest angle; (1) $\theta_1 = \theta_3$; (1) explanation correctly relates index of refraction to angle size (higher index $\rightarrow$ smaller angle from normal).

Solution 1

(d) Mark scheme

- Both horizontal distances d_A and d_B are less than d_w (the original all-water horizontal distance). The light rays for all scenarios enter from air, but in Models A and B the light rays enter a medium (or media) with an index of refraction greater than that of water. Therefore the light rays bend more toward the normal in Models A and B than in the original all-water tank. Bending more toward the normal results in a shorter horizontal distance traveled before the beam reaches the mirrored bottom and exits. Two points: (1) both $d_A, d_B < d_w$ with an attempt at a relevant explanation; (1) correctly indicating the horizontal distance decreases as refraction toward the normal increases.

Question 1

2022 ▪ Q1

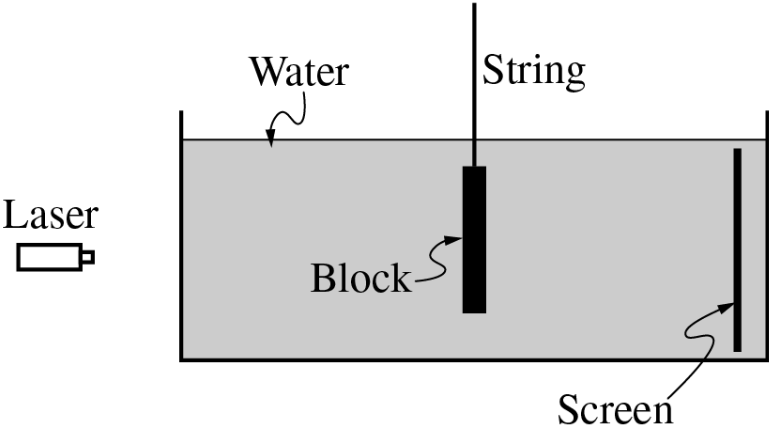
Students are investigating electromagnetic wave phenomena in transparent media. They use a string to support a stationary thin, rectangular block of mass m_b, volume V_b, and density ρ_b. The block has two narrow slits in its center and is submerged in a glass tank containing water with density ρ_w, as shown above.
[Diagram: A rectangular glass tank of water, viewed from the side. A string hangs from the top of the tank down to a thin rectangular block suspended in the water; the block has two narrow slits in its center. A laser is aimed horizontally at the block from outside the left wall of the tank. A screen is shown near the bottom right, inside the tank.]
(a)(i) On the dot below, which represents the block, draw and label the forces that are exerted on the block. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.

Question 1

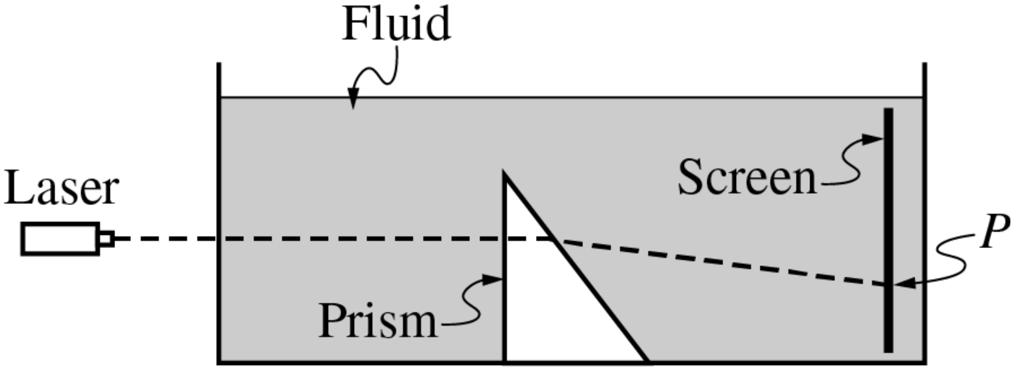
[A single dot is shown, representing the block, for the student to draw force vectors on.]
(a)(ii) Derive an expression for the force exerted on the block by the string in terms of the given quantities and physical constants, as appropriate.

Question 1

Question 1



Question 1



Question 1

2022 ▪ Q1

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(b) A monochromatic laser beam is incident perpendicular to the wall of the tank. The beam passes through the slits in the block. An interference pattern is formed on the screen inside the tank. The water is then replaced with a clear fluid with a greater index of refraction than that of water. In a coherent, paragraph-length response,

Question 1

describe how the greater index of refraction of the new fluid affects the interference pattern. Explain your reasoning in terms of speed, frequency, and wavelength of the light.

Question 1

2022 ▪ Q1

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[Diagram: A rectangular glass tank of water, viewed from the side. A string hangs from the top of the tank down to a thin rectangular block suspended in the water; the block has two narrow slits in its center. A laser is aimed horizontally at the block from outside the left wall of the tank. A screen is shown near the bottom right, inside the tank.]

(c) [Diagram: The same tank, now containing a fluid instead of water, with a triangular prism placed in it in place of the block. A laser enters from the left, perpendicular to the tank wall, and its path is shown as a dotted line traveling through

Question 1

the fluid to the prism; after passing through the prism the beam is refracted and travels (dotted line) to a screen on the right, striking it at a labeled point P.]
The block is replaced by a triangular prism, as shown above. The path of the beam is indicated by the dotted line, and the beam reaches the screen at point P. The fluid is then removed from the tank, and the prism is surrounded by air. Predict whether the beam will reach the side of the tank above point P, at point P, or below point P when the prism is surrounded by air. Support your answer using physics principles.

Solution 1

(a)(i)

Mark scheme

- Free-body diagram on the dot representing the block, with exactly three labeled force arrows starting at the dot: $F_{buoyant}$ (upward, from the surrounding fluid), $F_{tension}$ (upward, from the string), and $F_{gravity}$ (downward, weight of the block). Full credit requires all three forces correctly drawn and labeled with no extraneous forces (e.g. no friction, no normal force).

Solution 1

(a)(ii) Mark scheme

- Apply Newton's second law to the submerged block, which is in equilibrium (zero net force), consistent with the part (a)(i) diagram: $\Sigma F = ma = 0 \Rightarrow F_T + F_B - F_g = 0 \Rightarrow F_T = F_g - F_B$ (1 point: correct application of Newton's laws consistent with the diagram, indicating zero net force). Substitute the buoyant force $F_B = \rho_w V_b g$ (weight of displaced fluid) and gravitational force $F_g = m_b g$: $F_T = m_b g - \rho_w V_b g$ (1 point: correct substitution of the buoyant force into a solution consistent with the previous equation). A correct final answer with no supporting work earns both points.

Solution 1

(b) Mark scheme

- Paragraph-length response earning 5 points for addressing each of the following in a coherent argument: (1) the speed of light in the new fluid is less than in water because the new fluid has a greater index of refraction ($v = c/n$, so larger n gives smaller v); (2) the frequency of the light does not change when it enters a new medium; (3) since $v = f\lambda$ and f is constant while v decreases, the wavelength λ must decrease; (4) using the double-slit relation $m\lambda = d\sin\theta$, a smaller wavelength gives a smaller angular separation between bright fringes for the same slit spacing d, so the fringe separation decreases; (5) an overall logical, relevant, and internally consistent argument that follows the paragraph-response guidelines. Model response: "The speed of light in the new fluid is less than the speed of

Solution 1

light in water because the fluid has a greater index of refraction. This means that the wavelength of the light in the beam will be smaller because the frequency does not change. Since the wavelength is smaller, the angular separation of the bright fringes will decrease, as described by the equation $m\lambda = d\sin\theta$."

Solution 1

(c)

Mark scheme

- (1 point) Explicitly indicate that the amount of refraction at the fluid-prism interface depends on the ratio (or, acceptably, the difference) of the indices of refraction of the two materials. (1 point) Correctly relate a larger angle of refraction to the beam hitting the screen below point P. Model response: "The beam refracts more when the air is present because the difference between the indices of refraction between the prism and the surrounding medium is greater. So, the beam hits the screen below point P."

Question 4

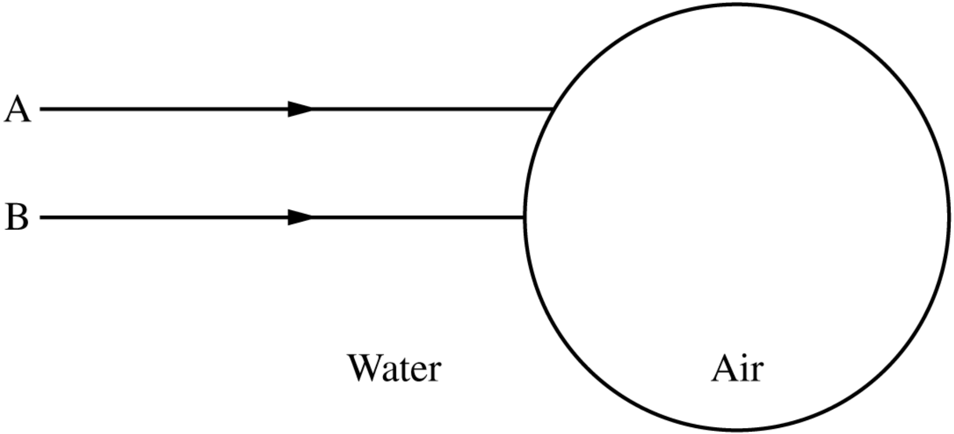
2019 ▪ Q4

A student notices many air bubbles rising through the water in a large fish tank at an aquarium.

(a) In the figure below, the circle represents one such air bubble, and two incoming rays of light, A and B, are shown. Ray B points toward the center of the circle. On the diagram, draw the paths of rays A and B as they go through the bubble and back into the water. Your diagram should clearly show what happens to the rays at each interface.

[Figure: A large circle labeled "Air" on the right side, with "Water" labeled to its left outside the circle. Two horizontal rays labeled A (upper) and B (lower) enter from the left and strike the circle's boundary; ray B is aimed at the center of the circle. Arrowheads show the rays traveling rightward toward the circle.]

Question 4



Question 4

2019 ▪ Q4

A student notices many air bubbles rising through the water in a large fish tank at an aquarium.

(b) The bubble has a volume V_1, the air inside it has density ρ_A, and the water around it has density ρ_W. The bubble starts at rest and has a speed v_f when it has risen a height h. Assume that the change in the bubble's volume is negligible. Derive an expression for the mechanical energy dissipated by drag forces as the bubble rises this distance. Express your answer in terms of the given quantities and fundamental constants, as appropriate.

Question 4

2019 ▪ Q4

A student notices many air bubbles rising through the water in a large fish tank at an aquarium.

(c)(i) At a particular instant, one bubble is 4.5 m below the water's surface. The surface of the water is at sea level, and the density of the water is 1000 kg/m^3. Determine the absolute pressure in the bubble at this location.

(c)(ii) The bubble has a volume V_1 when it is 4.5 m below the water's surface. Assume that the temperature of the air in the bubble remains constant as it rises. In terms of V_1, calculate the volume of the bubble when it is just below the surface of the water.

(c)(iii) If the air in the bubble cooled as it rose, the volume of the bubble would be less than the value calculated in part (c)(ii). Use physics principles to briefly explain why.

Solution 4

(a) Mark scheme

- Ray B is aimed at the center of the circular bubble, so it strikes the water–air interface along the normal (radial direction) and passes straight through undeviated, continuing in a straight line through the bubble and back into the water on the far side (1 pt for ray B going straight through). Ray A strikes the first interface at an angle to the normal and bends away from the normal as it refracts from water into air (light speeds up going into the lower-index medium, air) (1 pt for ray A bending away from the normal entering the air from the water). At the second interface, as ray A exits the air bubble back into the water, it bends the opposite way relative to the normal there (toward the normal, since it is now going from a lower-index medium, air, into a higher-index medium, water)

Solution 4

compared to how it refracted at the first interface (1 pt for ray A bending the opposite direction relative to the normal on exiting compared to entering).

Solution 4

(b) Mark scheme

- Apply the work-energy theorem to the rising bubble:
  $\Delta K = W_{net} = |W_b| - |W_g| - |W_{diss}|$, where W_b is the work done by the buoyant force, $|W_g|$ is the magnitude of the work done against gravity, and $|W_{diss}|$ is the mechanical energy dissipated by drag (1 pt for a valid application of the work-energy theorem). The buoyant force equals the weight of displaced water, $\rho_W V_1 g$, so the work it does over height h is $W_b = \rho_W V_1 gh$ (1 pt for finding the work done by the buoyant force). Substituting $\Delta K = \frac{1}{2}\rho_A V_1 v_f^2$ (starting from rest) and $|W_g| = \rho_A V_1 gh$ (weight of the bubble's air) with consistent relative signs: $\frac{1}{2}\rho_A V_1 v_f^2 = \rho_W V_1 gh - \rho_A V_1 gh - |W_{diss}|$, so

Solution 4

$|W_{diss}| = \rho_W V_1 gh - \rho_A V_1 gh - \frac{1}{2}\rho_A V_1 v_f^2$ (1 pt for correct substitution into an equation with consistent relative signs for the terms).

Solution 4

(c)(i)

Mark scheme

- $P_{4.5\text{m}} = P_{atm} + \rho_W g d = (1.0 \times 10^5 \text{ Pa}) + (1000 \text{ kg/m}^3)(9.8 \text{ m/s}^2)(4.5 \text{ m})$. $P_{4.5\text{m}} = 1.44 \times 10^5$ Pa (or 1.45×10^5 Pa using $g = 10 \text{ m/s}^2$). (1 pt for a correct answer with units.)

Solution 4

(c)(ii)

Mark scheme

- Applying the ideal gas law at constant temperature between the two locations (so PV is constant): $P_{4.5\mathrm{m}} V_1 = P_{atm} V_{surface}$, giving $V_{surface} = P_{4.5\mathrm{m}} V_1 / P_{atm}$ (1 pt for applying the ideal gas law at two locations to determine the new bubble volume). Substituting the pressure from part (c)(i): $V_{surface} = (1.44 \times 10^5 \text{ Pa})\, V_1/(1 \times 10^5 \text{ Pa}) = 1.44\, V_1$ (or $1.45\, V_1$ using $g = 10 \text{ m/s}^2$) (1 pt for substituting pressures consistent with part (i)).

Solution 4

(c)(iii) Mark scheme

- By the ideal gas law, $P_{4.5\text{m}} V_1 / T_1 = P_{atm} V_{surface} / T_{surface}$, so $V_{surface} = P_{4.5\text{m}} V_1 T_{surface} / (P_{atm} T_1)$; the pressures are the same as before, but now $T_{surface} < T_1$ (the air cooled), so the volume at the surface comes out smaller than the constant-temperature value found in part (c)(ii). (Equivalent microscopic explanation: as the bubble cools, its air molecules move slower and exert less outward force on the bubble's inner surface; the resulting unbalanced inward force from the water causes the bubble to expand less than — i.e., contract relative to — the constant-temperature case.) Full credit for a correct explanation, whether qualitative or quantitative, macroscopic or microscopic. (1 pt.)

Question 3

2017 ▪ Q3

[Diagram: An optical bench setup shown in 3D perspective. From left to right along a ruled track: a vertical screen with a ruled scale at the left end, a convex lens (drawn as an ellipse/ring) mounted upright in the middle, and a light box with a plate on its hidden side at the right end. A callout points from the light box to a small square labeled "Plate on Hidden Side of Box" showing an arrow and a bar-with-circle cutout shape. Labels: "Screen", "Convex Lens", "Light Box with Plate".]
Some students are asked to determine the focal length of a convex lens. They have the equipment shown above, which includes a waterproof light box with a plate on one side, a lens, and a screen. The box has a bright light inside, and the plate on the side has shapes cut out of it through which the light shines to create a bright object. This particular plate has a cutout that is a vertical arrow and a horizontal bar with a circle at one end. In the view shown above, the circle is near the right edge of the plate.

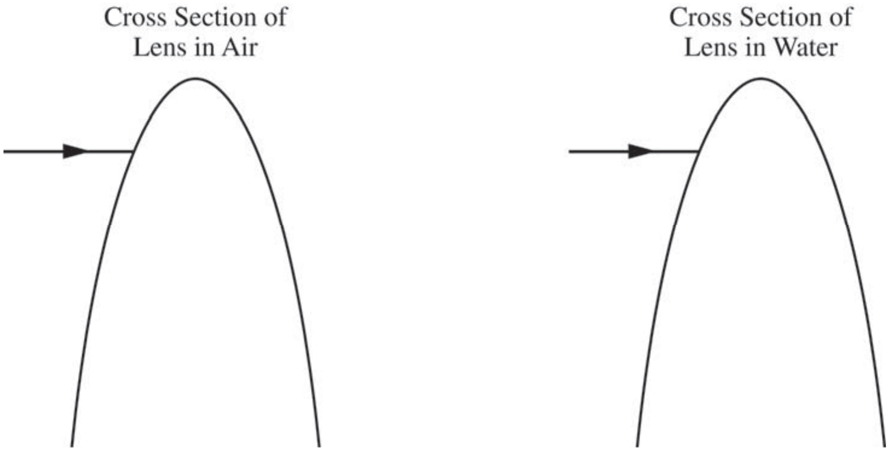
Question 3

With the screen and light box on opposite sides of the lens, the box is aligned so that the plate is 20 cm from the center of the lens, and an image of the arrow and bar is formed on the screen. The students find that the image is clear on the screen when the screen is 30 cm from the center of the lens.

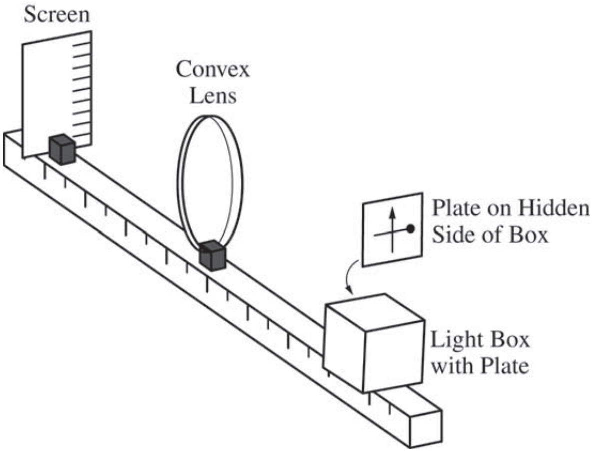
(a) On the figure below, sketch how the image on the screen appears to the students.

[Figure: A blank rectangular screen outline with a ruled scale down its right edge (tick marks), for the student to sketch the observed image.]

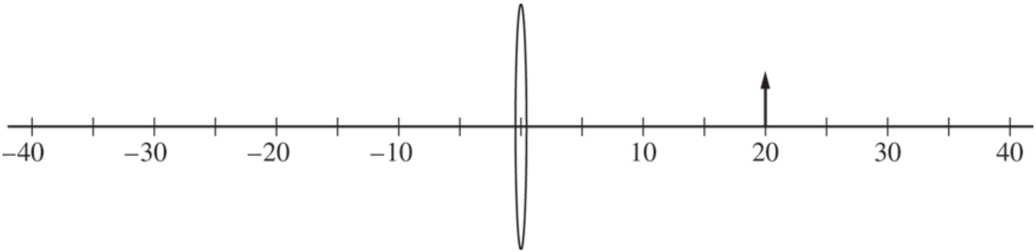
Question 3



Question 3


Screen
Convex Lens
Plate on Hidden Side of Box
Light Box with Plate

Question 3



Question 3

2017 ▪ Q3

[Diagram: An optical bench setup shown in 3D perspective. From left to right along a ruled track: a vertical screen with a ruled scale at the left end, a convex lens (drawn as an ellipse/ring) mounted upright in the middle, and a light box with a plate on its hidden side at the right end. A callout points from the light box to a small square labeled "Plate on Hidden Side of Box" showing an arrow and a bar-with-circle cutout shape. Labels: "Screen", "Convex Lens", "Light Box with Plate".]

Some students are asked to determine the focal length of a convex lens. They have the equipment shown above, which includes a waterproof light box with a plate on one side, a lens, and a screen. The box has a bright light inside, and the plate on the side has shapes cut out of it through which the light shines to create a bright object. This particular plate has a cutout that is a vertical arrow and a horizontal bar with a circle at one end. In the view shown above, the circle is near the right edge of the plate.

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(b)(i) Calculate the focal length of the lens.

(b)(ii) Calculate the magnitude of the magnification of the image.

Question 3

2017 ▪ Q3

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Question 3

With the screen and light box on opposite sides of the lens, the box is aligned so that the plate is 20 cm from the center of the lens, and an image of the arrow and bar is formed on the screen. The students find that the image is clear on the screen when the screen is 30 cm from the center of the lens.

(c)(i) In the side view below, the arrow represents the bright object created by the plate. Draw a ray diagram on the figure below that is consistent with your calculations in parts (b)(i) and (ii). Show at least two rays, as well as the location and orientation of the image.

[Figure: A horizontal optical axis numbered from -40 to 40 in increments of 10, with a thin convex lens drawn vertically at the origin (position 0) and an upward-pointing arrow (the object) at position 20 on the axis, representing the object placed 20 cm from the lens.]

Question 3

(c)(ii) Explain how your diagram is consistent with your calculated focal length and magnification in parts (b)(i) and (ii).

Question 3

2017 ▪ Q3

[Diagram: An optical bench setup shown in 3D perspective. From left to right along a ruled track: a vertical screen with a ruled scale at the left end, a convex lens (drawn as an ellipse/ring) mounted upright in the middle, and a light box with a plate on its hidden side at the right end. A callout points from the light box to a small square labeled "Plate on Hidden Side of Box" showing an arrow and a bar-with-circle cutout shape. Labels: "Screen", "Convex Lens", "Light Box with Plate".]

Some students are asked to determine the focal length of a convex lens. They have the equipment shown above, which includes a waterproof light box with a plate on one side, a lens, and a screen. The box has a bright light inside, and the plate on the side has shapes cut out of it through which the light shines to create a bright object. This particular plate has a cutout that is a vertical arrow and a horizontal bar with a circle at one end. In the view shown above, the circle is near the right edge of the plate.

Question 3

With the screen and light box on opposite sides of the lens, the box is aligned so that the plate is 20 cm from the center of the lens, and an image of the arrow and bar is formed on the screen. The students find that the image is clear on the screen when the screen is 30 cm from the center of the lens.

(d)(i) The entire apparatus is now submerged in water, whose index of refraction is greater than that of air but less than that of the lens.

The figures below show cross sections of the top portion of the convex lens in air and the convex lens in water. An incident ray is shown in both cases. On each figure, draw the ray as it passes through the lens and back into the air or water.

[Figure: Two side-by-side diagrams, each showing the cross section of the top (curved) portion of a convex (plano-convex-like, rounded-top) lens shape. The left diagram is labeled "Cross Section of Lens in Air" with a horizontal incident ray arrow approaching the curved surface from the left. The right diagram is labeled "Cross Section of Lens

Question 3

in Water" with an identical horizontal incident ray arrow approaching the curved surface from the left. Both lens outlines are otherwise identical and unshaded.]
(d)(ii) Describe how the focal length of the lens and the position and size of the image formed by the lens when it is in the water compare to when the lens is in air. Explain how the rays drawn in the figures in part (d)(i) support your answer.

Solution 3

(a)

Mark scheme

- Sketch the image on the screen. 2 points:
- 1 pt for the arrow drawn upside down (inverted) relative to the object.
- 1 pt for the bar/circle drawn left-to-right reversed relative to the object, or consistent with an (incorrect) upright arrow.

Solution 3

(b)(i) Mark scheme

- $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{20\text{ cm}} + \frac{1}{30\text{ cm}}$
- $f = 12$ cm.
- 1 pt for correctly showing this calculation and a correct answer with units.

Solution 3

(b)(ii)

Mark scheme

- $M = d_i/d_o = 30\text{ cm}/20\text{ cm}$
- $M = 1.5.$
- 1 pt for correctly showing the magnification calculation (with or without sign) and a correct answer.

Solution 3

(c)(i)

Mark scheme

- Ray diagram consistent with the calculated focal length ($f = 12$ cm): draw at least two rays from the tip of the object (at position $+20$) through the lens, showing them converge on the far side to form an inverted image (around position -30, height $\approx 1.5\times$ the object, pointing downward). 1 pt for two reasonably correctly drawn rays consistent with the calculated focal length, including the inverted image.

Solution 3

(c)(ii)

Mark scheme

- Explain the ray diagram. 2 points:
- 1 pt for a correct explanation of how the drawn rays relate to the focal length.
- 1 pt for a correct explanation of how the image relates to the magnification.
- Example: The horizontal ray from the object bends to cross the axis at 12 cm from the middle of the lens, which is the focal length. The image arrow is about 1.5 times the height of the object, which is the magnification.

Solution 3

(d)(i) Mark scheme

- Draw the refracted ray at the top surface of the plano-convex lens, for the lens in air and again for the lens in water. 2 points:
- 1 pt for showing the downward refraction of the ray at the lens surface when in air (i.e., bending toward the normal entering the lens / away from the normal leaving the lens).
- 1 pt for showing the ray refracted by the lens in water at a greater angle to the normal than the corresponding angle for the lens in air — i.e., less bending (this point can be earned even if the first point was not; scoring is relative to whatever was drawn for the lens in air).

Solution 3

(d)(ii) Mark scheme

- Compare the focal length/image in water vs. air, using the rays drawn in (d)(i). 3 points:
- 1 pt for describing a greater focal length when the lens is in water (or a comparison consistent with the student's own part (d)(i)).
- 1 pt for describing a larger image distance and image size (or a comparison consistent with (d)(i)).
- 1 pt for describing how the rays drawn in (d)(i) support these descriptions.

Solution 3

- Example: The rays do not bend as much passing from water to glass as they do passing from air to glass (and vice versa). This means parallel rays entering the lens converge at a farther distance, so the focal length is longer. Rays from an object also converge farther from the lens, so the new image is farther away and larger.

Question 2

2016 ▪ Q2

A student is given a glass block that has been specially treated so that the path of light can be seen as the light travels through the glass. The student is asked to design an experiment to measure the index of refraction of the glass. The light source available in the laboratory is a hydrogen lamp that emits red light of a known wavelength.

(a) A linear graph is to be used to determine the index of refraction of the glass. Indicate the quantities that should be graphed and describe how the graph could be used to determine the index of refraction of the glass.

Question 2

2016 ▪ Q2

A student is given a glass block that has been specially treated so that the path of light can be seen as the light travels through the glass. The student is asked to design an experiment to measure the index of refraction of the glass. The light source available in the laboratory is a hydrogen lamp that emits red light of a known wavelength.

(b) Outline an experimental procedure that could gather the necessary data. Include sufficient detail so that another student could follow your procedure. In addition to the glass block and the hydrogen lamp, the equipment in a typical classroom laboratory is available.

Question 2

2016 ▪ Q2

A student is given a glass block that has been specially treated so that the path of light can be seen as the light travels through the glass. The student is asked to design an experiment to measure the index of refraction of the glass. The light source available in the laboratory is a hydrogen lamp that emits red light of a known wavelength.

(c) Predict how the path of the light will change as it enters the glass. Support your prediction using a qualitative comparison of the speed of light in glass and the speed of light in air.

Question 2

2016 ▪ Q2

A student is given a glass block that has been specially treated so that the path of light can be seen as the light travels through the glass. The student is asked to design an experiment to measure the index of refraction of the glass. The light source available in the laboratory is a hydrogen lamp that emits red light of a known wavelength.

(d) Describe the process(es) by which red light from the lamp is produced by hydrogen atoms that are initially in the ground state. Draw and label an energy level diagram that supports the atomic process(es) you describe.

Solution 2

(a) Mark scheme

- Graph sin $\theta 1$ (the angle of incidence, measured in air) on one axis versus sin $\theta 2$ (the angle of refraction, measured in the glass) on the other axis — plot the SINES of the angles, not the raw angles. By Snell's law, n1 sin $\theta 1$ = n2 sin $\theta 2$. Because medium 1 is air, n1 = 1, so sin $\theta 1$ = n2 sin $\theta 2$, meaning a graph of sin $\theta 1$ (vertical axis) vs. sin $\theta 2$ (horizontal axis) is a straight line through the origin whose SLOPE equals n2, the index of refraction of the glass. Full credit needs (1) graphing angles or functions of angles on the axes, (2) plotting the sines of the angles while indicating/implying that the index of refraction of air is 1, and (3) indicating a method (e.g., slope = n2) to determine the glass's index of refraction that is consistent with the graph described.

Solution 2

(b) Mark scheme

- Procedure: Place an aperture or slit in front of the hydrogen lamp so that a single, narrow, well-defined beam of light strikes the glass block (a beam is needed so the entry/exit points and ray paths are unambiguous). Place the glass block on a sheet of paper on the lab table and trace its outline, marking the point where the beam enters the glass and drawing the normal (perpendicular) line to the surface at that point. Direct the beam at the glass block at a chosen angle of incidence and trace the incident ray and the refracted ray inside the glass on the paper. Using a protractor, measure the angle of incidence $\theta 1$ between the incident ray and the normal (in air) and the angle of refraction $\theta 2$ between the refracted ray and the normal (in glass) at the boundary. Repeat this procedure for at least

Solution 2

three (or more) different angles of incidence, recording each ($\theta 1$, $\theta 2$) pair, to obtain enough data points to plot the graph from part (a). Full credit needs (1) indicating the light must be formed into a beam entering the glass, (2) describing a method for measuring angles with a protractor (or equivalent) in both media at the boundary, (3) using angles measured with respect to the normal, and (4) repeating the measurement at three or more different incidence angles.

Solution 2

(c)

Mark scheme

- As the light ray crosses the boundary from air into the glass, it bends TOWARD the normal. This occurs because the speed of light in glass is slower than the speed of light in air (glass is optically denser / has a higher index of refraction); when light slows down entering a medium, its path bends toward the normal at the boundary. Full credit needs (1) indicating the ray bends toward the normal going from air to glass and (2) indicating the speed of light is slower in glass than in air (or an answer consistent with the stated bending direction).

Solution 2

(d) Mark scheme

- Hydrogen atoms in the ground state absorb energy from the electricity delivered to the lamp, which excites the atoms from the ground state up to a higher (excited) energy level. The atoms then spontaneously drop back down to a lower energy level, emitting a photon whose energy equals the difference between the two levels; red light corresponds to a transition whose energy difference equals the energy of a red photon. Energy-level diagram: draw several horizontal lines representing discrete allowed energy levels, with the lowest line labeled 'Ground state'; draw an upward arrow from the ground state to a higher level labeled 'Energy absorption' (showing excitation from the lowest level), and a downward arrow from a higher level to a lower level labeled 'Photon emission' (showing the

Solution 2

atom dropping down and emitting a photon). Full credit needs (1) an appropriate energy-level diagram showing absorption starting from the lowest (ground) level and showing emission, (2) indicating a hydrogen atom can be excited from the ground state to a higher energy state by absorbing energy, and (3) indicating that transitions to lower energy levels cause emission of photons.

Question 1

2015 ▪ Q1

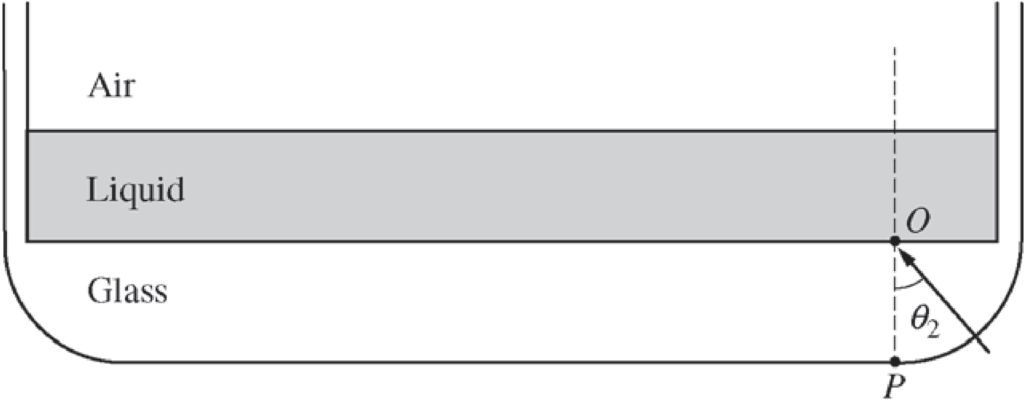
[Figure: Cross section of a drinking glass filled with a thin layer of liquid. From top to bottom: a layer labeled "Air", then a shaded layer labeled "Liquid", then a layer labeled "Glass". The bottom right corner of the glass is a circular arc centered at point O, which is marked at the liquid-glass boundary directly above the arc's center. A vertical dashed line rises from O. Point P is marked on the flat bottom (outer) surface of the glass, directly below O. An arrow representing a light beam comes from the lower right, aimed at O, making angle θ_1 with the vertical dashed line at O.]
The figure above shows a cross section of a drinking glass (index of refraction 1.52) filled with a thin layer of liquid (index of refraction 1.33). The bottom corners of the glass are circular arcs, with the bottom right arc centered at point O. A monochromatic light source placed to the right of point P shines a beam aimed at point O at an angle of incidence θ. The flat bottom surface of the glass containing

Question 1

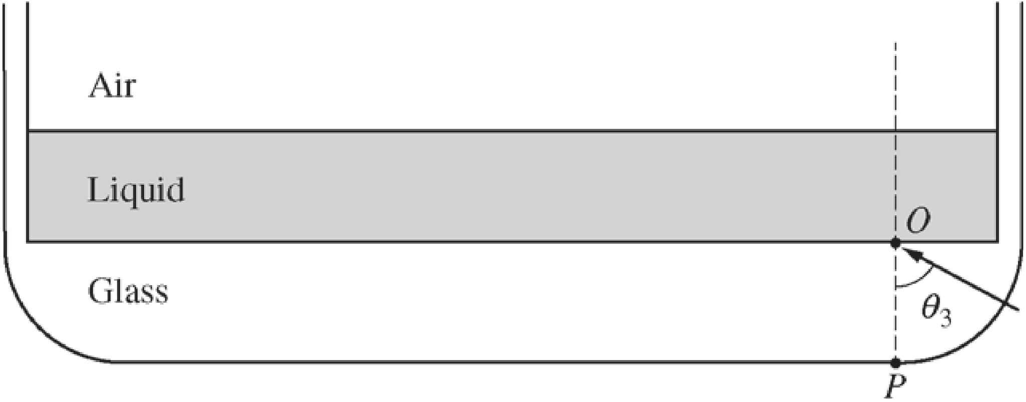
point P is frosted so that bright spots appear where light from the beam strikes the bottom surface and does not reflect. When $\theta = \theta_1$, two bright spots appear on the bottom surface of the glass. The spot closer to point P will be referred to as X; the spot farther from P will be referred to as Y. The location of spot X and that of spot Y both change as θ is increased.

(a) In a coherent paragraph-length answer, describe the processes involved in the formation of spots X and Y when $\theta = \theta_1$. Include an explanation of why spot Y is located farther from point P than spot X is and what factors affect the brightness of the spots.

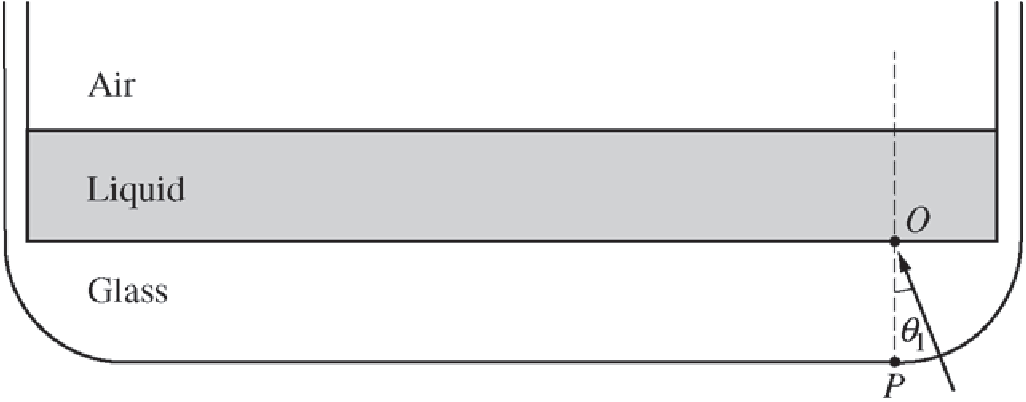
Question 1



Question 1



Question 1



Question 1

2015 ▪ Q1

[Figure: Cross section of a drinking glass filled with a thin layer of liquid. From top to bottom: a layer labeled "Air", then a shaded layer labeled "Liquid", then a layer labeled "Glass". The bottom right corner of the glass is a circular arc centered at point O, which is marked at the liquid-glass boundary directly above the arc's center. A vertical dashed line rises from O. Point P is marked on the flat bottom (outer) surface of the glass, directly below O. An arrow representing a light beam comes from the lower right, aimed at O, making angle θ_1 with the vertical dashed line at O.]

The figure above shows a cross section of a drinking glass (index of refraction 1.52) filled with a thin layer of liquid (index of refraction 1.33). The bottom corners of the glass are circular arcs, with the bottom right arc centered at point O. A monochromatic light source placed to the right of point P shines a beam aimed at point O at an angle of incidence θ. The flat bottom surface of the glass containing point P is frosted so that bright spots appear where

Question 1

light from the beam strikes the bottom surface and does not reflect. When $\theta = \theta_1$, two bright spots appear on the bottom surface of the glass. The spot closer to point P will be referred to as X; the spot farther from P will be referred to as Y. The location of spot X and that of spot Y both change as θ is increased.

(b)(i) When θ is increased to θ_2, one of the spots becomes brighter than it was before, due to total internal reflection.

[Figure: Same cross-section diagram as above (Air / Liquid / Glass layers, arc centered at O, point P below), but the incident beam now makes angle θ_2 with the vertical dashed line at O.]

On the figure below, draw a ray diagram that clearly and accurately shows the formation of spots X and Y when $\theta = \theta_2$.

(b)(ii) Which spot, X or Y, becomes brighter than it was before due to total internal reflection? Explain your reasoning.

Question 1

2015 ▪ Q1

[Figure: Cross section of a drinking glass filled with a thin layer of liquid. From top to bottom: a layer labeled "Air", then a shaded layer labeled "Liquid", then a layer labeled "Glass". The bottom right corner of the glass is a circular arc centered at point O, which is marked at the liquid-glass boundary directly above the arc's center. A vertical dashed line rises from O. Point P is marked on the flat bottom (outer) surface of the glass, directly below O. An arrow representing a light beam comes from the lower right, aimed at O, making angle θ_1 with the vertical dashed line at O.]

The figure above shows a cross section of a drinking glass (index of refraction 1.52) filled with a thin layer of liquid (index of refraction 1.33). The bottom corners of the glass are circular arcs, with the bottom right arc centered at point O. A monochromatic light source placed to the right of point P shines a beam aimed at point O at an angle of incidence θ. The flat bottom surface of the glass containing point P is frosted so that bright spots appear where

Question 1

light from the beam strikes the bottom surface and does not reflect. When $\theta = \theta_1$, two bright spots appear on the bottom surface of the glass. The spot closer to point P will be referred to as X; the spot farther from P will be referred to as Y. The location of spot X and that of spot Y both change as θ is increased.

(c)(i) When θ is further increased to θ_3, one of the spots disappears entirely.
[Figure: Same cross-section diagram as above (Air / Liquid / Glass layers, arc centered at O, point P below), but the incident beam now makes angle θ_3 with the vertical dashed line at O.]
On the figure below, draw a ray diagram that clearly and accurately shows the formation of the remaining spot, X or Y, when $\theta = \theta_3$.
(c)(ii) Indicate which spot, X or Y, disappears. Explain your reasoning in terms of total internal reflection.

Solution 1

(a) Mark scheme

- Full credit requires five points. (1) Explain that the light forming spot X reflects at the glass-liquid interface. (2) Explain that the light forming spot Y is refracted both as it leaves the glass into the liquid and as it re-enters the glass (the direction of refraction need not be correct). (3) Explain that Y's light is then reflected at the liquid-air interface before returning through the liquid and glass to P. (4) Explain, in terms of the geometry of the longer path, why Y lands farther from point P than X. (5) Explain that at each interface some light reflects and some is transmitted/refracted, so the brightness of each spot depends on how the light is divided between reflection and transmission/refraction at every interface

Solution 1

along its path. A diagram may support the reasoning but cannot replace the written explanation.

Solution 1

(b)(i)

Mark scheme

- A ray diagram is expected (drawn on the given Air/Liquid/Glass figure at angle theta_2). Full credit needs: (1) a reasonably accurate ray path for spot X — light reflecting at the glass-liquid interface and reaching P as X; (2) a reasonably accurate ray path for spot Y — light refracting as it leaves the glass into the liquid, refracting again re-entering the glass, and reflecting at the liquid-air interface, with correct refraction directions and no rays drawn out into the air. Grade a written description of the two paths against these two criteria.

Solution 1

(b)(ii)

Mark scheme

- Spot Y becomes brighter than before. At theta_2, part of the light that would otherwise be transmitted out through the liquid-air interface now undergoes total internal reflection there instead, so more of the beam's energy stays in the path that reaches spot Y — explain the answer in terms of this redistribution of energy between the with-TIR and without-TIR cases, not just the conclusion 'Y is brighter.'

Solution 1

(c)(i)

Mark scheme

- A ray diagram is expected at angle theta_3: draw the ray totally internally reflecting at the glass-liquid interface and reaching spot X, with NO ray drawn crossing into the liquid layer or air (one point is deducted for any ray drawn above the glass-liquid interface, since at theta_3 all the light is totally internally reflected back down).

Solution 1

(c)(ii)

Mark scheme

- Spot Y disappears. At theta_3 the angle of incidence at the glass-liquid interface exceeds the critical angle for that interface, so total internal reflection occurs there: all the light reflects back down toward X and none is transmitted into the liquid to eventually form spot Y.