2023

AP® Physics 2: Algebra-Based

Sample Student Responses and Scoring Commentary

Inside:

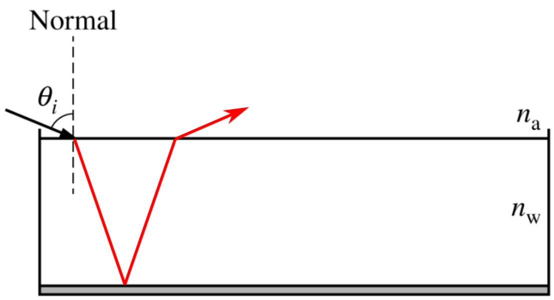
Free-Response Question 1

- ☑ Scoring Guidelines
- ☑ Student Samples
- ☑ Scoring Commentary

Question 1: Short Answer — 10 points

(a)	For drawing a straight-line path from the entry point to the bottom of the tank with an angle from the normal that is less than θ_i	**1 point**
	For drawing a continuous path that is symmetric about a vertical axis that intersects the mirror at the location where the beam of light is incident upon the mirror	**1 point**

Example Response



Total for part (a) — 2 points

(b)	For indicating that the wavelength of light decreases without any incorrect statements	**1 point**

Example Response

As light travels from one medium to a medium that has a higher index of refraction, the speed of light decreases and the frequency of the light remains the same. Therefore, the wavelength of the light decreases, as described by the equation $\lambda = \dfrac{v}{f}$.

Total for part (b) — 1 point

(c)(i)	For a correct application of Snell's law for two media boundaries	**1 point**

Scoring Note: If a test taker correctly applies Snell's law for air and the bottom layer, this point can be earned.

Example Response

$$\theta_4 = \sin^{-1}\left(\frac{n_a}{n_b}\sin\theta_i\right) \text{ OR } \sin\theta_4 = \frac{n_a}{n_b}\sin\theta_i$$

Example Solution

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$
$$n_a \sin\theta_i = n_w \sin\theta_2 = n_m \sin\theta_3 = n_b \sin\theta_4$$

$$n_a \sin\theta_i = n_b \sin\theta_4$$
$$\sin\theta_4 = \frac{n_a}{n_b}\sin\theta_i$$
$$\theta_4 = \sin^{-1}\left(\frac{n_a}{n_b}\sin\theta_i\right)$$

(c)(ii) For indicating that θ_4 alone is the smallest angle		**1 point**
For indicating that θ_2 alone is the largest angle		**1 point**
For indicating that $\theta_1 = \theta_3$		**1 point**
For an explanation that correctly relates the index of refraction to an angle		**1 point**

Example Response

__2__ θ_1 __1__ θ_2 __2__ θ_3 __3__ θ_4

θ_2 has the greatest value because water has the lowest index of refraction. θ_1 and θ_3 are equal because each is in the same layer with the same index of refraction, 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 has the highest index of refraction.

Total for part (c) 5 points

(d) For indicating that both d_A and d_B are less than d_w, with an attempt at a relevant explanation		**1 point**
For correctly indicating that the horizontal distance traveled decreases with increasing refraction toward the normal		**1 point**

Example Response

Horizontal distances d_A and d_B are less than d_w. The light rays for all scenarios are entering from air. However, in models A and B, the light rays enter a medium with an index of refraction that is greater than that of water. Therefore, the light rays bend more toward the normal in models A and B than in the original tank. Bending more toward the normal results in a shorter horizontal distance traveled.

Total for part (d) 2 points

Total for question 1 10 points

Question 1

Begin your response to **QUESTION 1** on this page.

PHYSICS 2

SECTION II

Time—1 hour and 30 minutes

4 Questions

Directions: Questions 1 and 4 are short free-response questions that require about 20 minutes each to answer and are worth 10 points each. Questions 2 and 3 are long free-response questions that require about 25 minutes each to answer and are worth 12 points each. Show your work for each part in the space provided after that part.

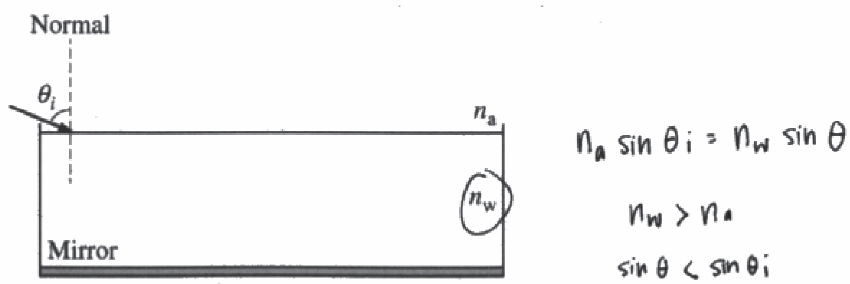
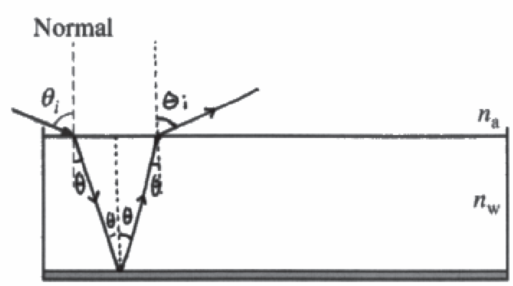


Figure 1

1. (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.

(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

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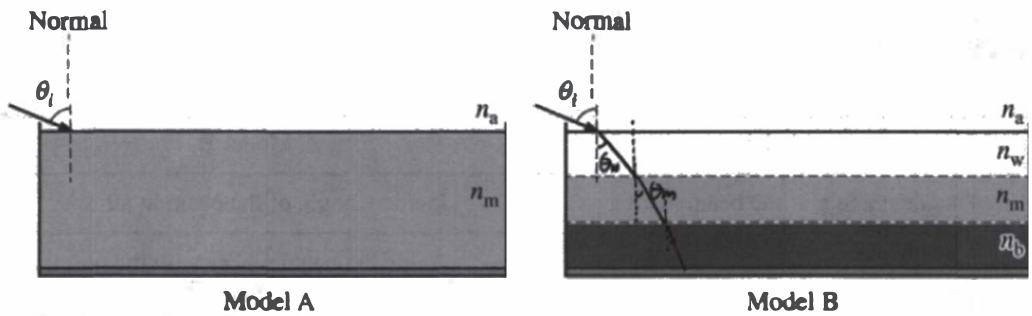


Figure 2

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 water. The models are shown in Figure 2.

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 as the mixture in Model A (index of refraction n_m). The bottom layer has the highest concentration of sugar (index of refraction n_b).

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

As light enters the mixture, the observed wavelength decreases. Because n_m is larger than n_a, wavelength in the mixture is smaller than that in air as frequency remains constant.

GO ON TO THE NEXT PAGE.

Question 1

Continue your response to QUESTION 1 on this page.

(c) 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

i. Determine an expression for θ_4 in terms of θ_i, n_a, and n_b.

$$n_a \sin\theta_i = n_w \sin\theta_2 = n_m \sin\theta_3 = n_b \sin\theta_4$$

$$\sin\theta_4 = \frac{n_a \sin\theta_i}{n_b} \rightarrow \therefore \theta_4 = \sin^{-1}\left(\frac{n_a \sin\theta_i}{n_b}\right)$$

$$\theta_4 = \sin^{-1}\left(\sin\theta_i \cdot \frac{n_a}{n_b}\right.$$

ii. Rank the angles from greatest to least, with 1 being greatest. If two angles are the same value, give them the same ranking.

2 θ_1 1 θ_2 2 θ_3 3 θ_4

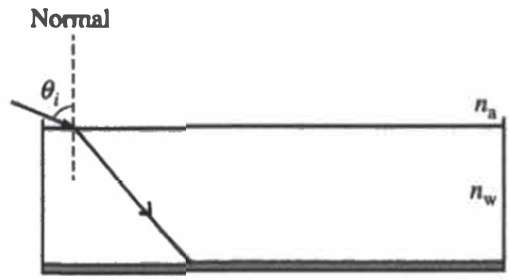
Briefly explain your reasoning using appropriate physics principles and/or mathematical models.

According to Snell's Law, in model B, $n_a \sin\theta_i = n_w \sin\theta_2 = n_m \sin\theta_3 = n_b \sin\theta_4$.

In model A, $n_a \sin\theta_i = n_m \sin\theta_1$. As $n_a < n_w < n_m < n_b$, θ_2 from $n_w \sin\theta_2$ has the greatest value. When comparing θ_1 and θ_3, ~~both~~ $n_m \sin\theta_1 = n_m \sin\theta_3 = n_a \sin\theta_i$, therefore $n_m \sin\theta_1 = n_m \sin\theta_3$. As $\sin\theta_1 = \sin\theta_3$, $\theta_1 = \theta_3$. As ~~tat~~ n_b is the largest, θ_4 from $n_b \sin\theta_4$ is smallest.

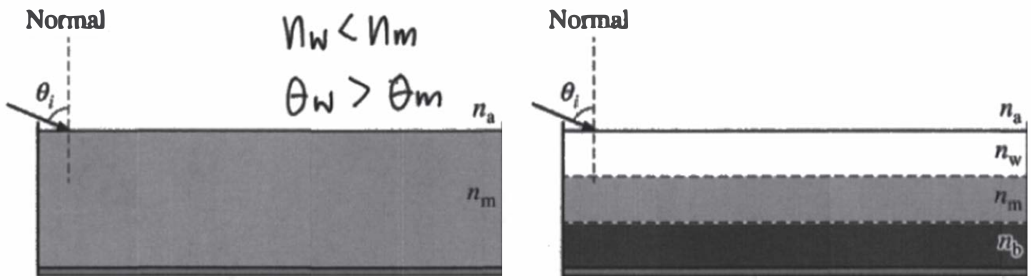
Question 1

Continue your response to QUESTION 1 on this page.



Original Tank

$n_a \sin\theta_i = n_w \sin\theta_w$



Model A Model B

$n_w < n_m$

$\theta_w > \theta_m$

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.

(d) 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.

Comparing d_A and d_w, d_A is less than d_w. Because $n_w < n_m$, angle of refraction in water is larger than that in model A. As the angle of refraction and reflection on mirror and therefore horizontal distance is larger, $d_w > d_A$.

d_B is also less than d_w. While both angles of refraction in water are the same, in model B, as the beam enters different liquids with higher indexes of refraction, the angles of refraction reduce. Therefore, the angle of reflection when hitting the mirror is less as well, resulting in a smaller d_B.

GO ON TO THE NEXT PAGE.

Question 1

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PHYSICS 2

SECTION II

Time—1 hour and 30 minutes

4 Questions

Directions: Questions 1 and 4 are short free-response questions that require about 20 minutes each to answer and are worth 10 points each. Questions 2 and 3 are long free-response questions that require about 25 minutes each to answer and are worth 12 points each. Show your work for each part in the space provided after that part.

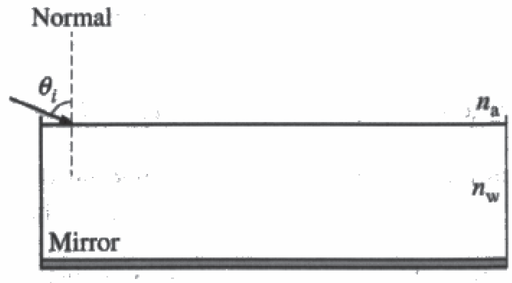
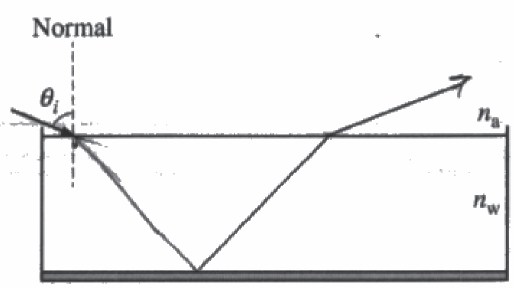


Figure 1

1. (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.

(a) On the following diagram, sketch the entire path of the beam as the beam enters, travels through, and then exits the water.



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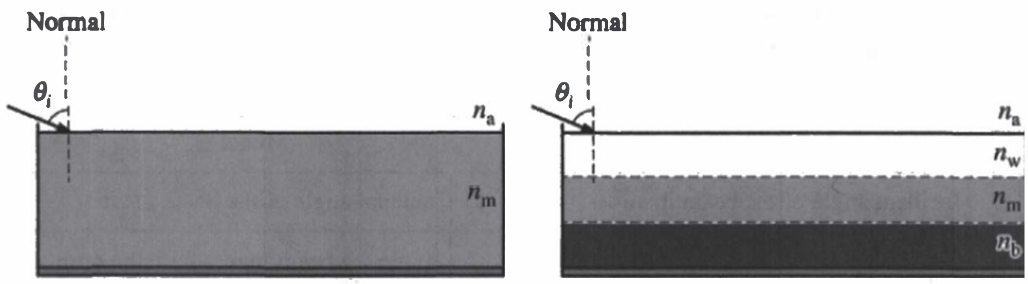
Question 1

Continue your response to **QUESTION 1** on this page.



Model A Model B

Figure 2

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 water. The models are shown in Figure 2.

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 as the mixture in Model A (index of refraction n_m). The bottom layer has the highest concentration of sugar (index of refraction n_b).

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

As the beam travels from air into the mixture, the magnitude of the wavelength stays the same but shifts directions.

Question 1

Continue your response to **QUESTION 1** on this page.

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

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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

i. Determine an expression for θ_4 in terms of θ_i, n_a, and n_b.

$$n_a \sin\theta_i = n_b \sin\theta_4$$

$$\sin\theta_4 = \frac{n_a \sin\theta_i}{n_b}$$

$$\theta_4 = \sin^{-1}\left(\frac{n_a \sin\theta_i}{n_b}\right)$$

ii. Rank the angles from greatest to least, with 1 being greatest. If two angles are the same value, give them the same ranking.

1 θ_1 2 θ_2 3 θ_3 4 θ_4

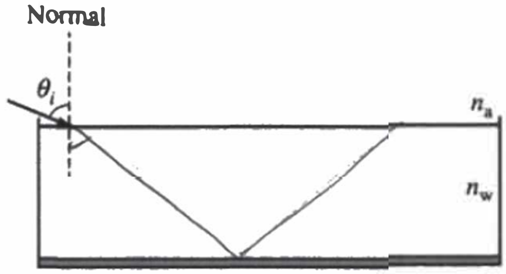
Briefly explain your reasoning using appropriate physics principles and/or mathematical models.

~~[illegible]~~

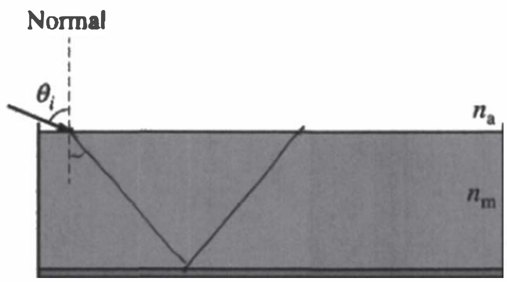
According to $n_1 \sin\theta_1 = n_2 \sin\theta_2$, as the index of refraction increases, the angle has to decrease and the light is ~~[illegible]~~ entering mixtures with the greater index of refractions ~~[illegible]~~. So its angle must be decreasing.

Question 1

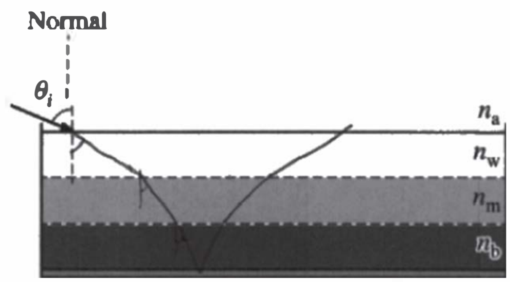
Continue your response to QUESTION 1 on this page.



Original Tank



Model A



Model B

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.

(d) 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.

Both d_A an d_B are less than d_w because tanks A and B are filled with substances with greater index of refractions or a mixture of equal to and greater index of refractions, so the angle decreases, leading to an exit point closer to the entry point.

Question 1

Begin your response to **QUESTION 1** on this page.

PHYSICS 2

SECTION II

Time—1 hour and 30 minutes

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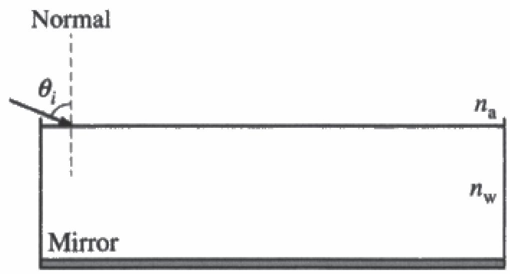
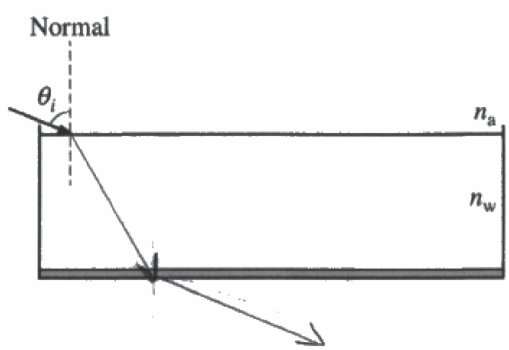


Figure 1

1. (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.

(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

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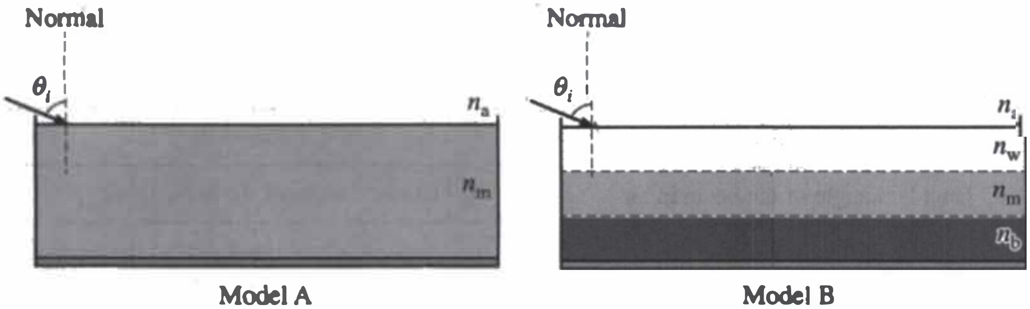

Figure 2

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 water. The models are shown in Figure 2.

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 as the mixture in Model A (index of refraction n_m). The bottom layer has the highest concentration of sugar (index of refraction n_b).

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

The wavelength will change when going from air to the mixture. The wavelength will increase, this is because the light will travel slower in the mixture creating a smaller frequency, increasing wavelength.

GO ON TO THE NEXT PAGE.

Question 1

Continue your response to **QUESTION 1** on this page.

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

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		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

i. Determine an expression for θ_4 in terms of θ_i, n_a, and n_b.

$n_a \sin\theta_i = n_b \sin\theta_4$

ii. Rank the angles from greatest to least, with 1 being greatest. If two angles are the same value, give them the same ranking.

1 θ_1 2 θ_2 3 θ_3 4 θ_4

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

θ_1 has the largest angle because it travels the fastest, as the index of refraction changes, so does the speed, resulting in the rankings above. Making θ_1 the greatest, and θ_4 the smallest

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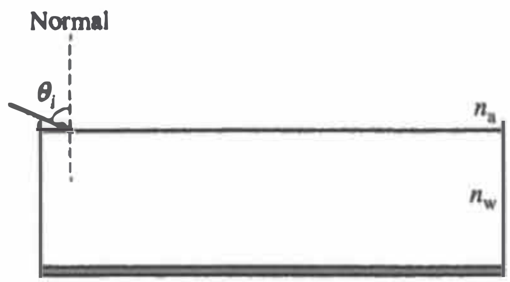
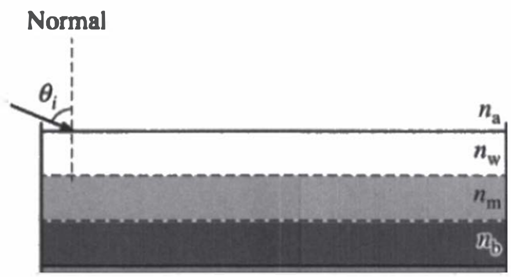
Question 1

Continue your response to QUESTION 1 on this page.



Original Tank

Model A



Model B

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.

(d) 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.

d_A and d_B are equal to dw. For the distance does not change but at the speed the light travels does.

Question 1

Note: Student samples are quoted verbatim and may contain spelling and grammatical errors.

Overview

The responses were expected to demonstrate the ability to:

- Relate the refraction of light passing from one medium to another to the indices of refraction of the two media.
- Relate the index of refraction of a medium and the wavelength of the light in the medium.
- Use Snell's law at an interface between two optical media, including demonstrating an understanding of the correct normal line.
- Apply Snell's law for multiple sequential interfaces between optical media and rank the resulting angles of refraction at each interface.
- Predict path changes for a beam of light entering and exiting a tank filled with layers of liquids of varying indices of refraction.

Sample: 1A
Score: 10

Part (a) earned 2 points. The first point was earned for showing a straight-line path from the point of entry into the water toward the mirror with an angle of refraction that is less than θ_i. The second point was earned for showing that the total path is symmetric about a vertical line through the reflection point. Part (b) earned 1 point for stating that the wavelength of the light in the sugar-water mixture decreases compared to the wavelength of the light in air, with no incorrect statements. Part (c) earned 5 points. The first point was earned for correctly applying Snell's law at multiple surfaces. The second point was earned for correctly ranking θ_4 as the smallest angle. The third point was earned for correctly ranking θ_2 as the largest angle. The fourth point was earned for correctly indicating that θ_1 and θ_3 are equal. The fifth point was earned for correctly relating a greater index of refraction to a smaller angle of refraction. Part (d) earned 2 points. The first point was earned for correctly stating that both d_A and d_B will be less than d_W. The second point was earned for correctly connecting greater refraction toward the normal to shorter horizontal distances between the light beam's entry and exit points.

Question 1 (continued)

Sample: 1B
Score: 7

Part (a) earned 2 points. The first point was earned for correctly showing a straight-line path from the point of entry into the water to the mirror with an angle of refraction that is less than θ_i. The second point was earned for showing that the total path is reasonably symmetric about a vertical line through the reflection point. Part (b) earned no points because the response incorrectly states that the wavelength stays the same in the new substance. Part (c) earned | 3 points. The first point was earned for correctly relating the indexes of refraction and angles of refraction for the top and bottom layers. This relationship cannot be arrived at without correctly applying Snell's law at multiple surfaces. Although it may be unclear in the first line whether the subscript on the first angle is an i or a 1, the rest of the work makes it clear that the subscript is correct. The second point was earned for correctly ranking θ_4 as the smallest angle. The third point was not earned because the response does not rank θ_2 as the largest angle. The fourth point was not earned because the response does not indicate that θ_1 and θ_3 are equal. The fifth point was earned for correctly relating a higher index of refraction to a smaller angle of refraction. Part (d) earned 2 points. The first point was earned for correctly stating that both d_A and d_B will be less than d_W. The second point was earned for correctly connecting higher indexes of refraction to shorter horizontal distances between the light beam's entry and exit points.

Sample: 1C
Score: 3

Part (a) earned 1 point for correctly showing a refracted path in the water with an angle of refraction less than θ_i. The second point was not earned because the path does not reflect off the mirror. Part (b) earned no points because the response incorrectly states that the wavelength will increase in the sugar-water mixture. Part (c) earned 2 points. The first point was earned for indicating a correct relationship between θ_4, θ_i, n_a and n_b that could only be arrived at by applying Snell's law at multiple surfaces. The second point was earned for correctly ranking θ_4 as the smallest angle. The third point was not earned because the response does not rank θ_2 as the largest angle. The fourth point was not earned because the response does not indicate that θ_1 and θ_3 are equal. The fifth point was not earned because, although the explanation does mention both indexes of refraction and both angles, the response does not link the value of the index of refraction to the value of the angle. Part (d) earned no points because the response incorrectly states that both d_A and d_B are greater than d_W, and the explanation does not involve refraction.