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.

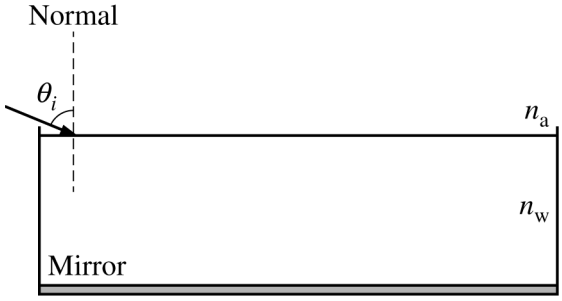
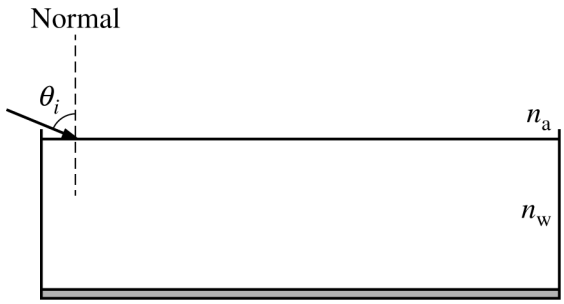


Figure 1

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.



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

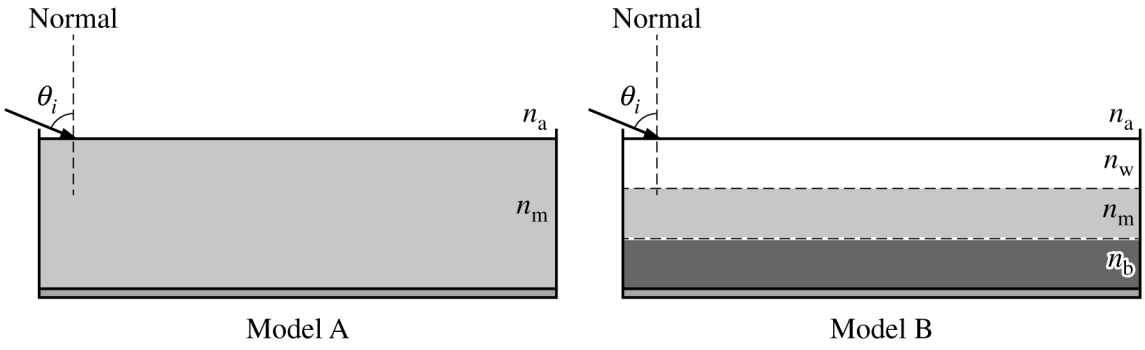

Figure 2

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.

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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.

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.

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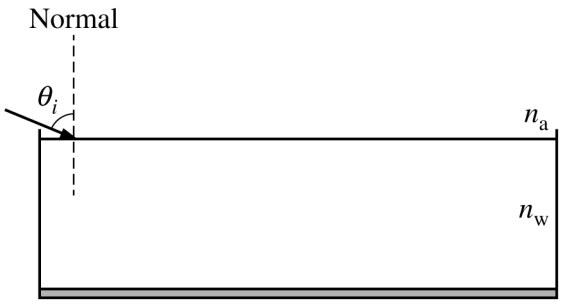
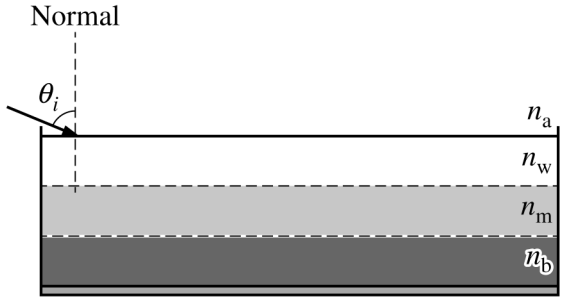
Continue your response to **QUESTION 1** on this page.



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.

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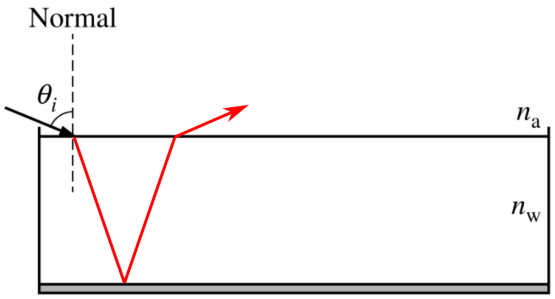
Question 1: Short Answer — 10 points

(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 $\lambda = \frac{v}{f}$.

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