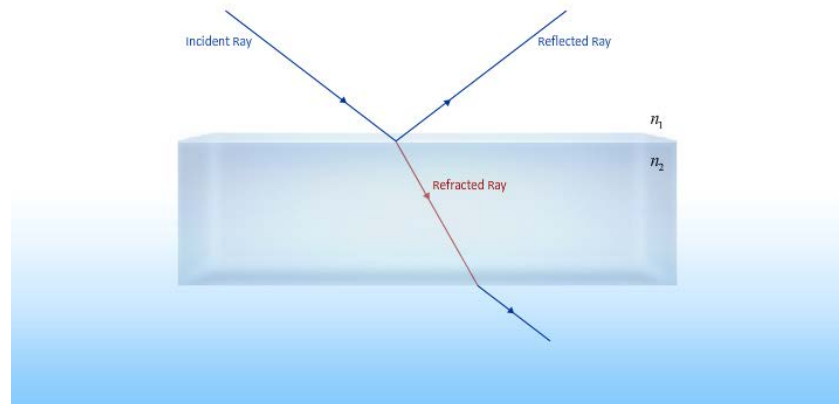


Physics 212

Lecture 25

REFLECTION and REFRACTION



Your Comments

Could you explain the difference between ϵ_0 and μ_0 ? They are making me really confused...

I know that the speed of light is a constant, but if ϵ_0 changes to ϵ , and μ_0 changes to μ , then doesn't the speed of propagation change?

What is the purpose of not unlocking the exam 3 study videos yet? I would like to be able to work ahead and start studying over the weekend because I know that I have several exams that are all that week.

checkpoint 1a seems like it belongs in 225. Good try 212!

Can we go over polarization due to refraction and Brewster's angle, especially why the light reflected becomes horizontally polarized. This is a tough concept

I was fine until the polarization slide came up. And then all hell broke loose...

I was wondering if the mirrors material would be on exam 3 since it is the day before the exam. I was also curious because the last time I encountered that material, it reflected poorly on my grade. Get it? Reflected? Mirrors.

End-of-Term and Exam Stuff

*There will be NO CLASS on Tuesday, May 5th

* - **Final Exam dates are scheduled:** 5/12, 1:30-4:30pm (combined) and 5/14, 7:00-10:00pm (conflict). You will be automatically signed up for the combined exam; if you want to instead take the conflict you must sign up in the gradebook. Please email shunk@illinois.edu if you have a double conflict.

Exam 3: Wed. April 29th at 7:00

- Covers material in Lectures 17 – 25 (Today's material)
- Sign up in Gradebook for Conflict Exam at 5:15pm
- Link in Gradebook if you have a double-conflict

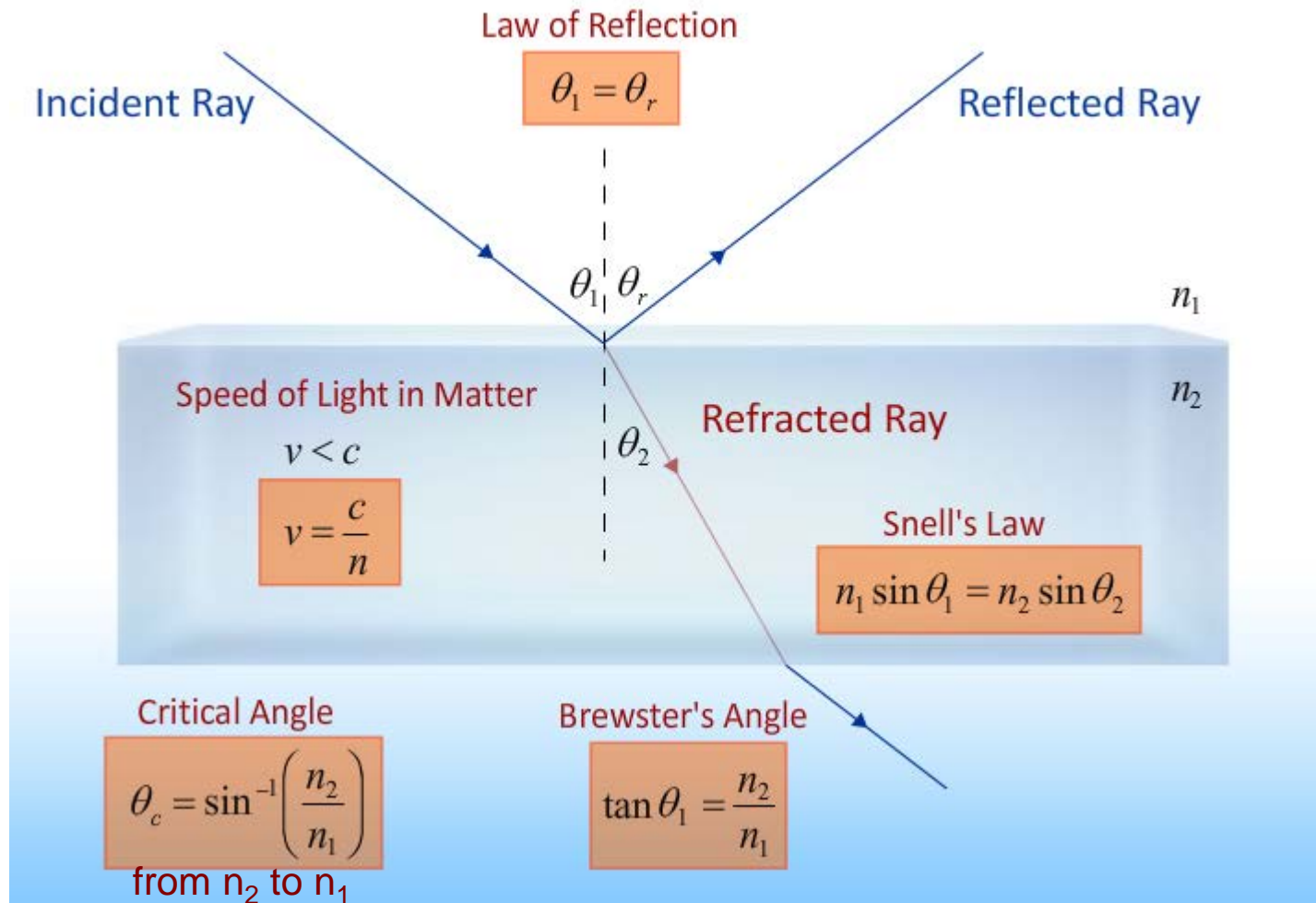
Exam Preparation:

- Study HW, Discussion, Checkpoints
- Old Exams are a good way to assess what you need to know
- Video Solutions of Spring 2013 Hour Exam 3

Extra Office Hours next week:

- (see website for schedule and rooms)

Let's Start with a Summary:



The speed of light in a medium
is slower than in empty space:

Speed of Light

$$v = \frac{1}{\sqrt{\mu\epsilon}} < \frac{1}{\sqrt{\mu_0\epsilon_0}}$$

Index of Refraction

$$n \equiv \frac{c}{v} = \frac{\sqrt{\mu\epsilon}}{\sqrt{\mu_0\epsilon_0}} \approx \sqrt{\frac{\epsilon}{\epsilon_0}} \approx \sqrt{K} \quad \kappa \text{ is the dielectric constant}$$

Examples for Visible Light

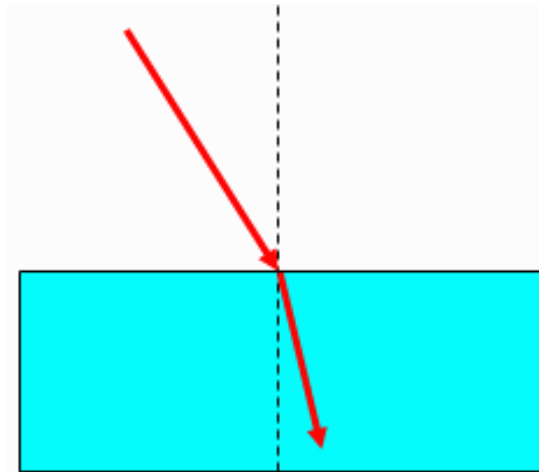
$$n_{\text{air}} = 1.0 \quad n_{\text{glass}} = 1.5 \quad n_{\text{diamond}} = 2.4$$

$$v_{\text{medium}} = c / n_{\text{medium}}$$

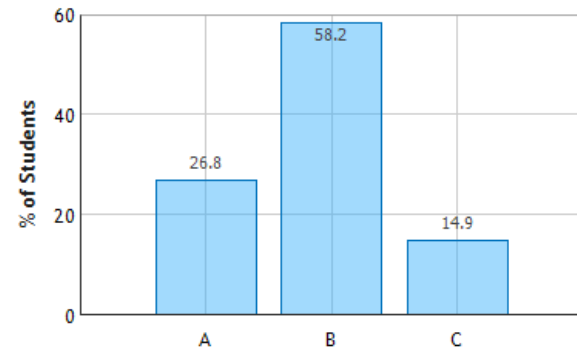
Checkpoint 1a



2) A ray of light passes from air into water with an angle of incidence of 30 degrees.



Light Passing from Air into Water: Question 1 (N = 776)

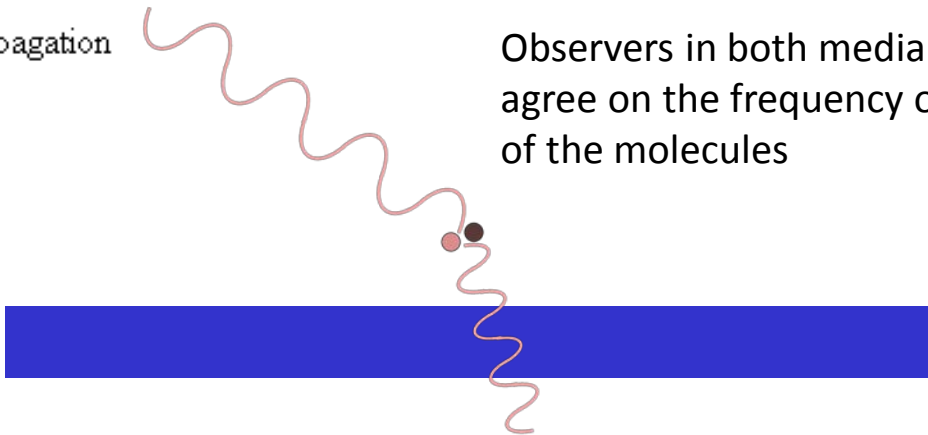


Which of the following quantities does not change as the light enters the water. Mark all correct answers.

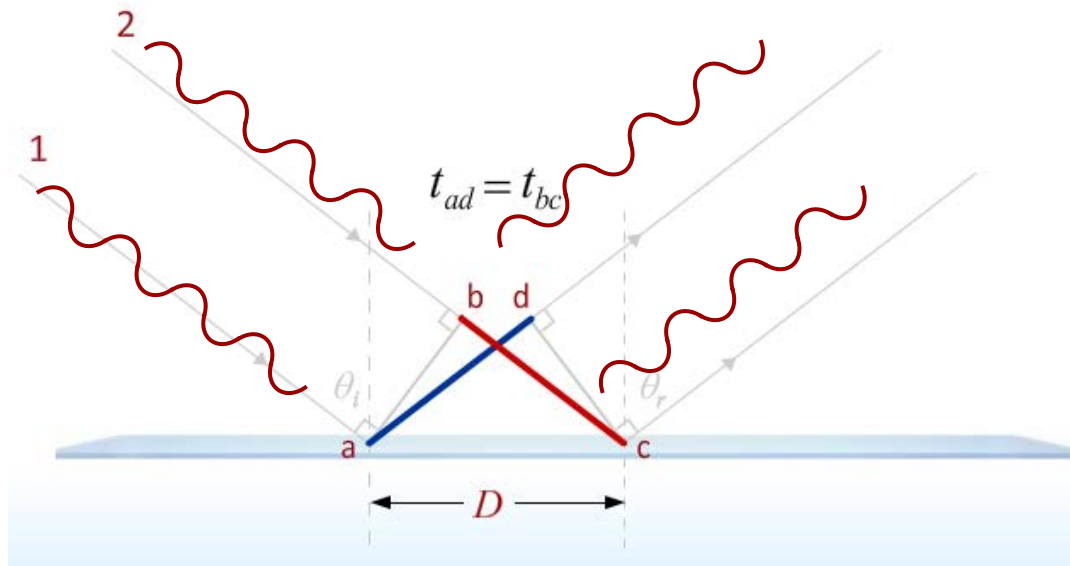
- A wavelength
- ☒ B frequency
- C speed of propagation

What about the wave must be the same on either side?

Observers in both media must agree on the frequency of vibration of the molecules

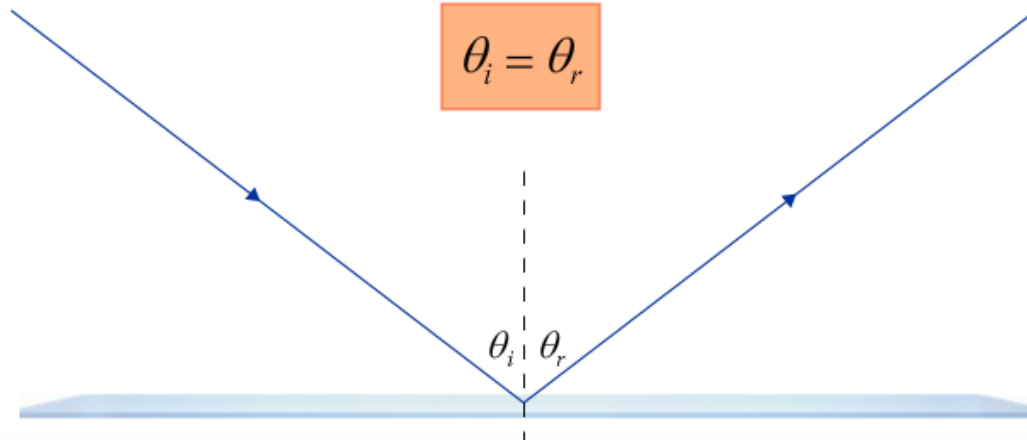


Reflection

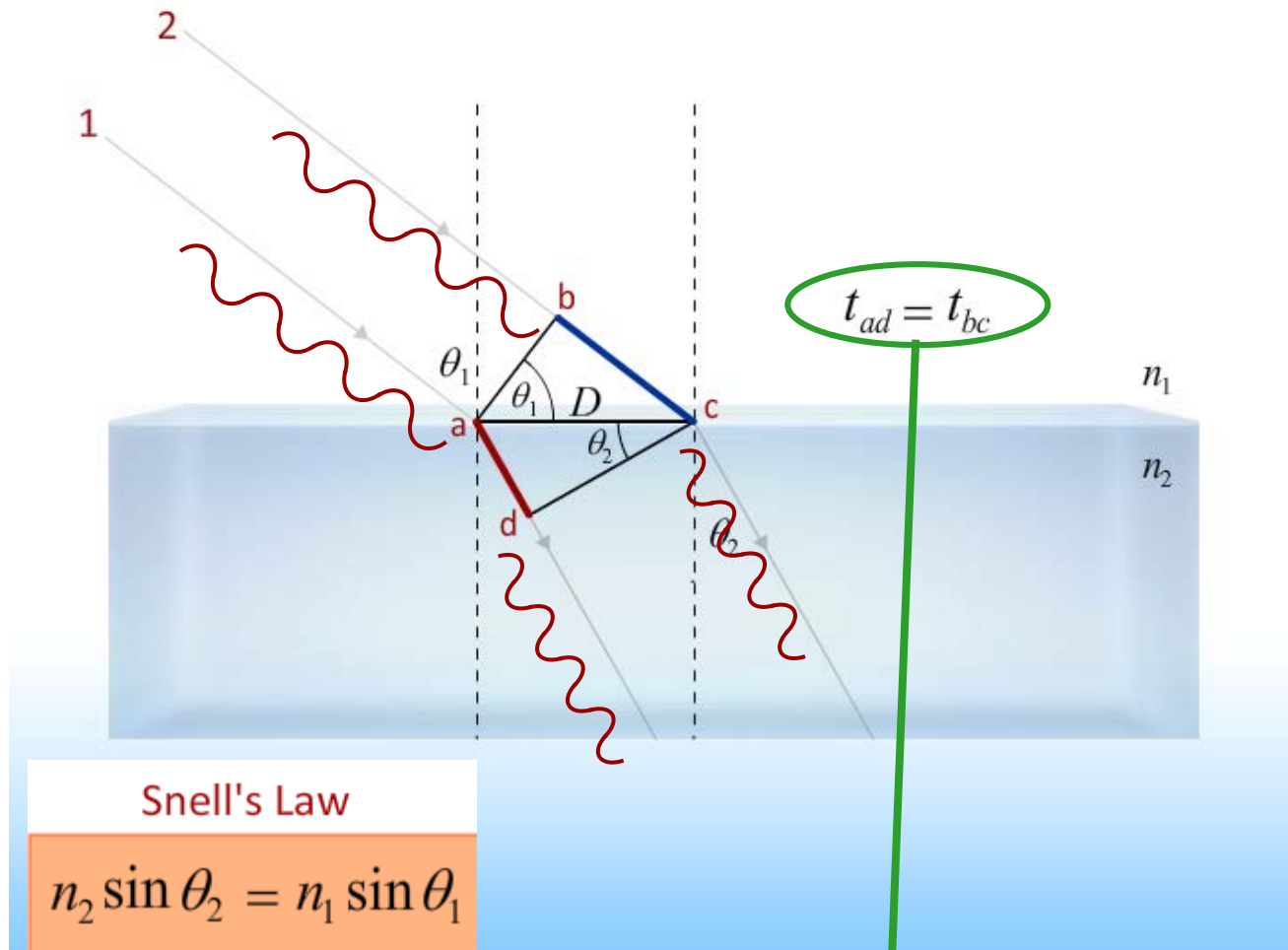


Law of Reflection

$$\theta_i = \theta_r$$



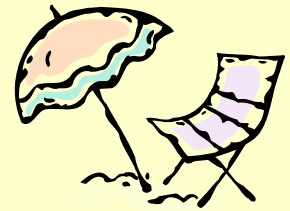
Refraction: Snell's Law



$$\frac{D \sin \theta_2}{c/n_2} = \frac{D \sin \theta_1}{c/n_1} \rightarrow n_2 \sin \theta_2 = n_1 \sin \theta_1$$

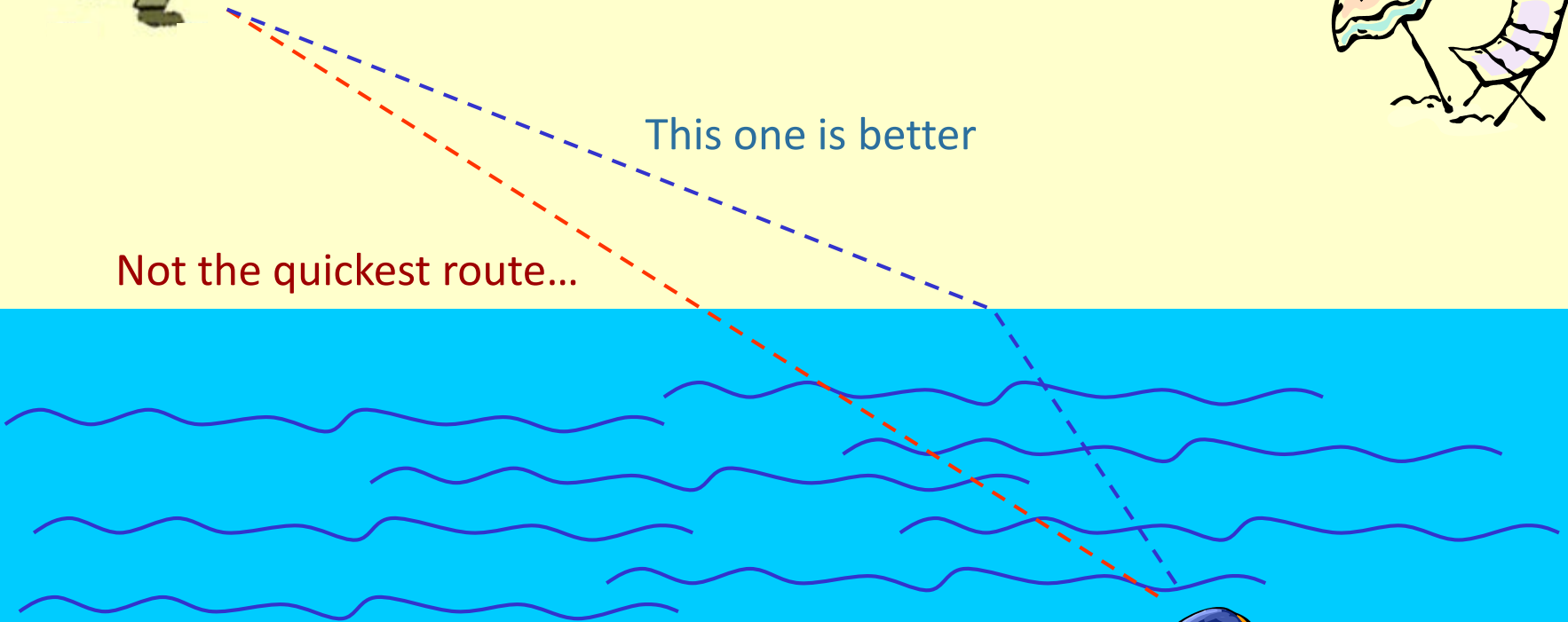
Think of a Day at the Beach

What's the fastest path to the ball knowing you can run faster than you can swim?

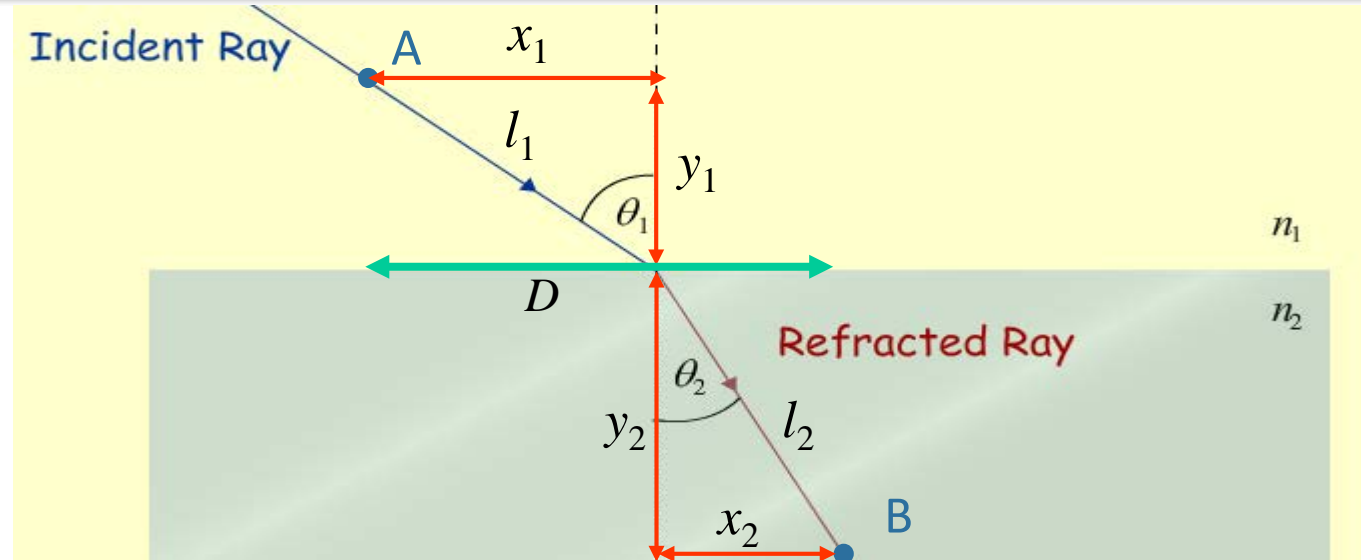


This one is better

Not the quickest route...



Same Principle
works for Light!



Time from A to B :

$$t = \frac{l_1}{v_1} + \frac{l_2}{v_2} = \frac{\sqrt{x_1^2 + y_1^2}}{v_1} + \frac{\sqrt{x_2^2 + y_2^2}}{v_2}$$

To find minimum time,
differentiate t wrt x_1 and set $= 0$

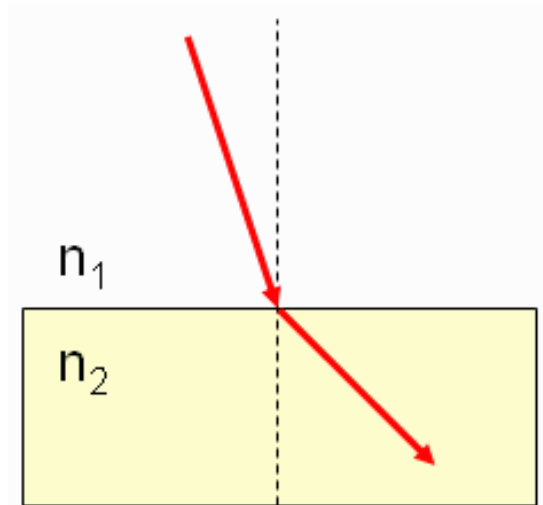
$$\frac{dt}{dx_1} = \frac{x_1}{v_1 \sqrt{x_1^2 + y_1^2}} + \frac{x_2}{v_2 \sqrt{x_2^2 + y_2^2}} \frac{dx_2}{dx_1}$$

How is x_2 related to x_1 ? $x_2 = D - x_1 \rightarrow \frac{dx_2}{dx_1} = -1$

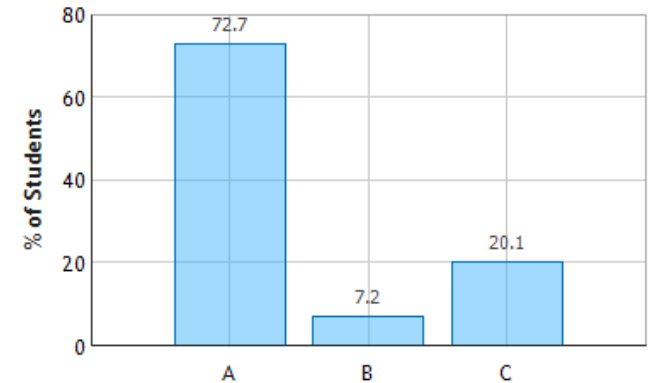
Setting $\frac{dt}{dx_1} = 0 \rightarrow \frac{x_1}{v_1 l_1} - \frac{x_2}{v_2 l_2} = 0 \rightarrow \frac{\sin \theta_1}{v_1} = \frac{\sin \theta_2}{v_2} \xrightarrow{v = c/n} n_1 \sin \theta_1 = n_2 \sin \theta_2$

CheckPoint 2a

☐ The path of light is bent as passes from medium 1 to medium 2.



Reflection and Refraction at a Surface:
Question 1 (N = 805)



Compare the indexes of refraction in the two mediums.

☒ A $n_1 > n_2$

☐ B $n_1 = n_2$

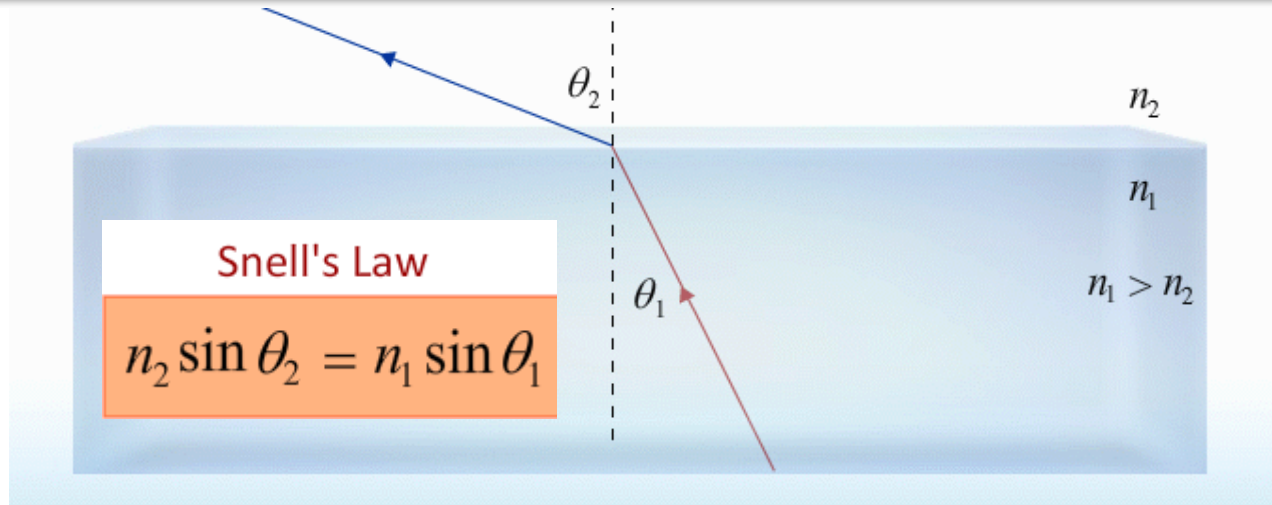
☐ C $n_1 < n_2$

Snell's Law:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

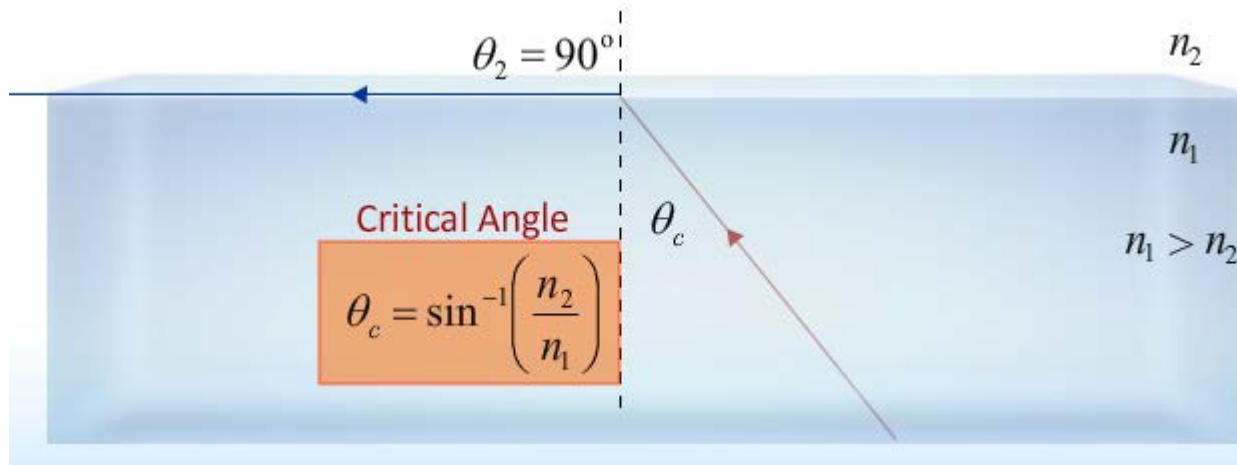
n decreases $\Rightarrow \theta$ increases

Total Internal Reflection

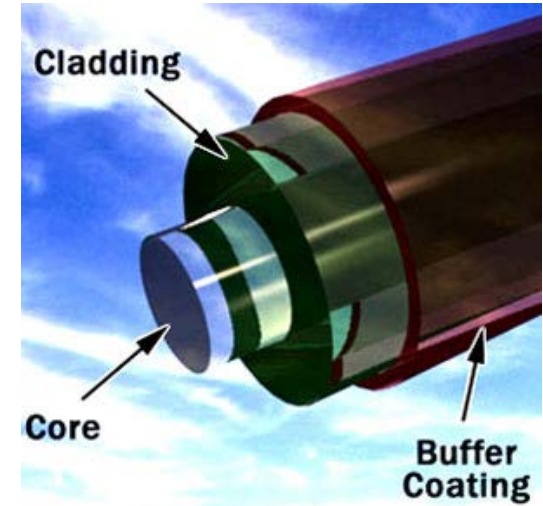


NOTE: $n_1 > n_2$ implies $\theta_2 > \theta_1$

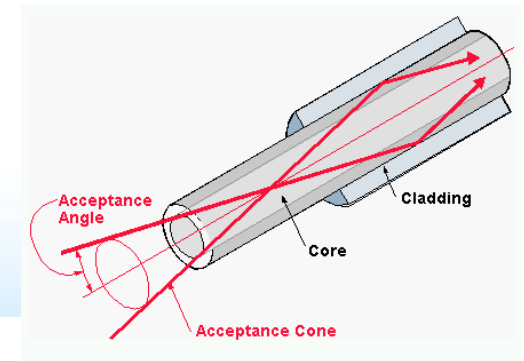
BUT: θ_2 has max value = 90° !



$\theta_1 > \theta_c \rightarrow$ Total Internal Reflection

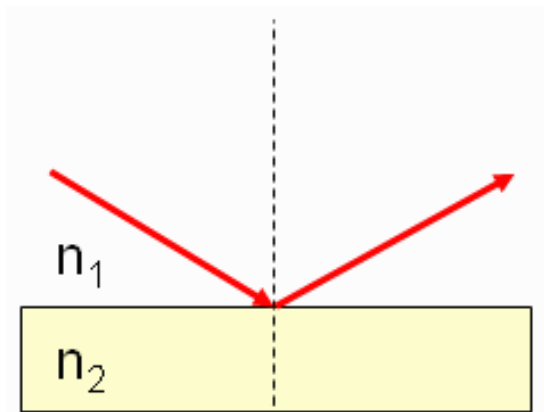


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CheckPoint 2b

A light ray travels in a medium with n_1 and completely reflects from the surface of a medium with n_2 .



The critical angle depends on:

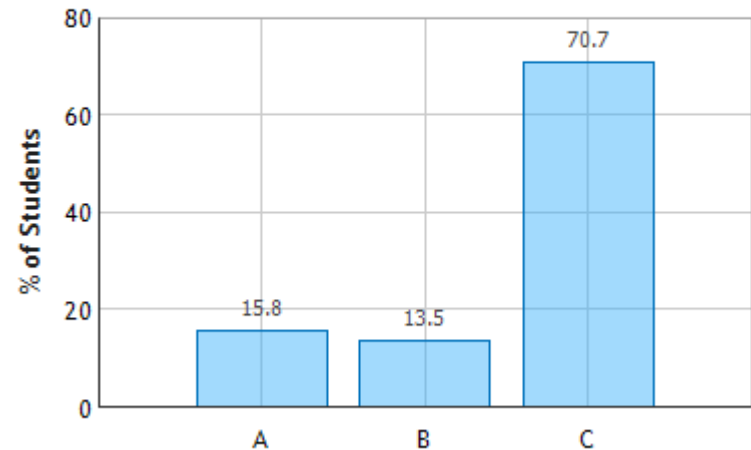
- A n_1 only
- B n_2 only
- C both n_1 and n_2**

Critical Angle

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

θ_c depends on both n_2 and n_1

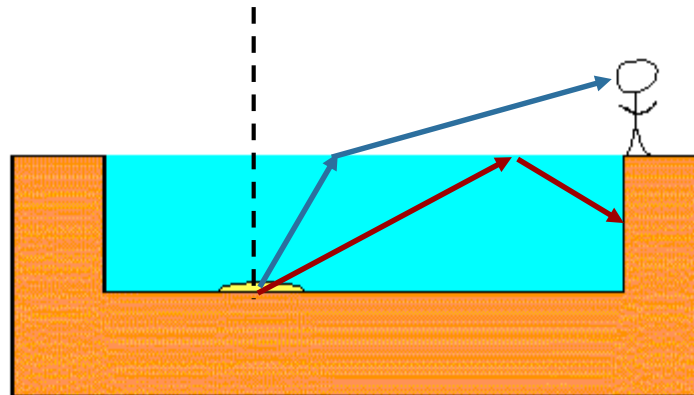
Reflection and Refraction at a Surface:
Question 3 (N = 805)



CheckPoint 3



A light is shining at the bottom of a swimming pool (shown in yellow in the figure). A person is standing at the edge of the pool.

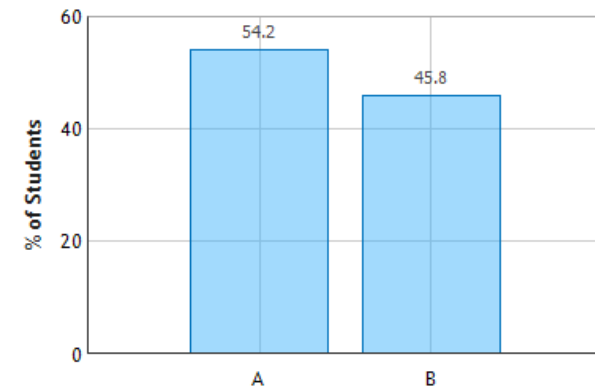


Can the person standing on the edge of the pool be prevented from seeing the light by total internal reflection at the water-air surface?

A. Yes ☒ B. No

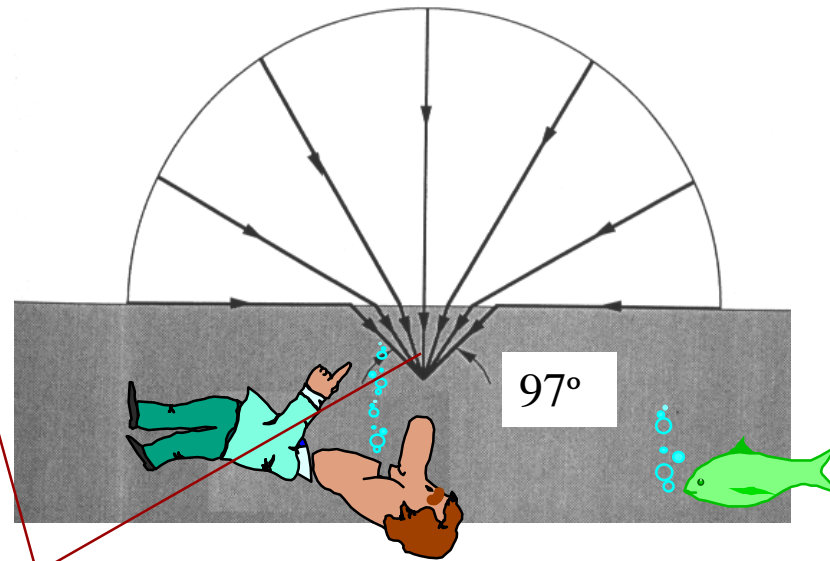
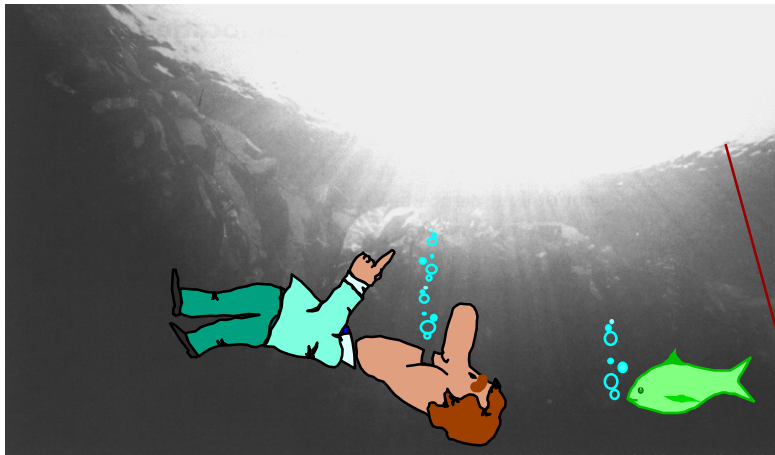
This light is random in the sense that it is radially emitted. If one of those rays makes an angle of ~ 36 degrees (the critical angle) with the plane normal to the plane parallel to the water-air interface, then those rays will be completely reflected and thus hidden from sight from the person looking at the pool. However, all of the rays making an angle slightly different than ~ 36 degrees will not be completely reflected, and will thus possibly be in the person's line of sight, if even slightly due to reduced intensity.

Swimming Pool: Question 1 (N = 806)



Example: Refraction at Water/Air Interface

Diver's illusion

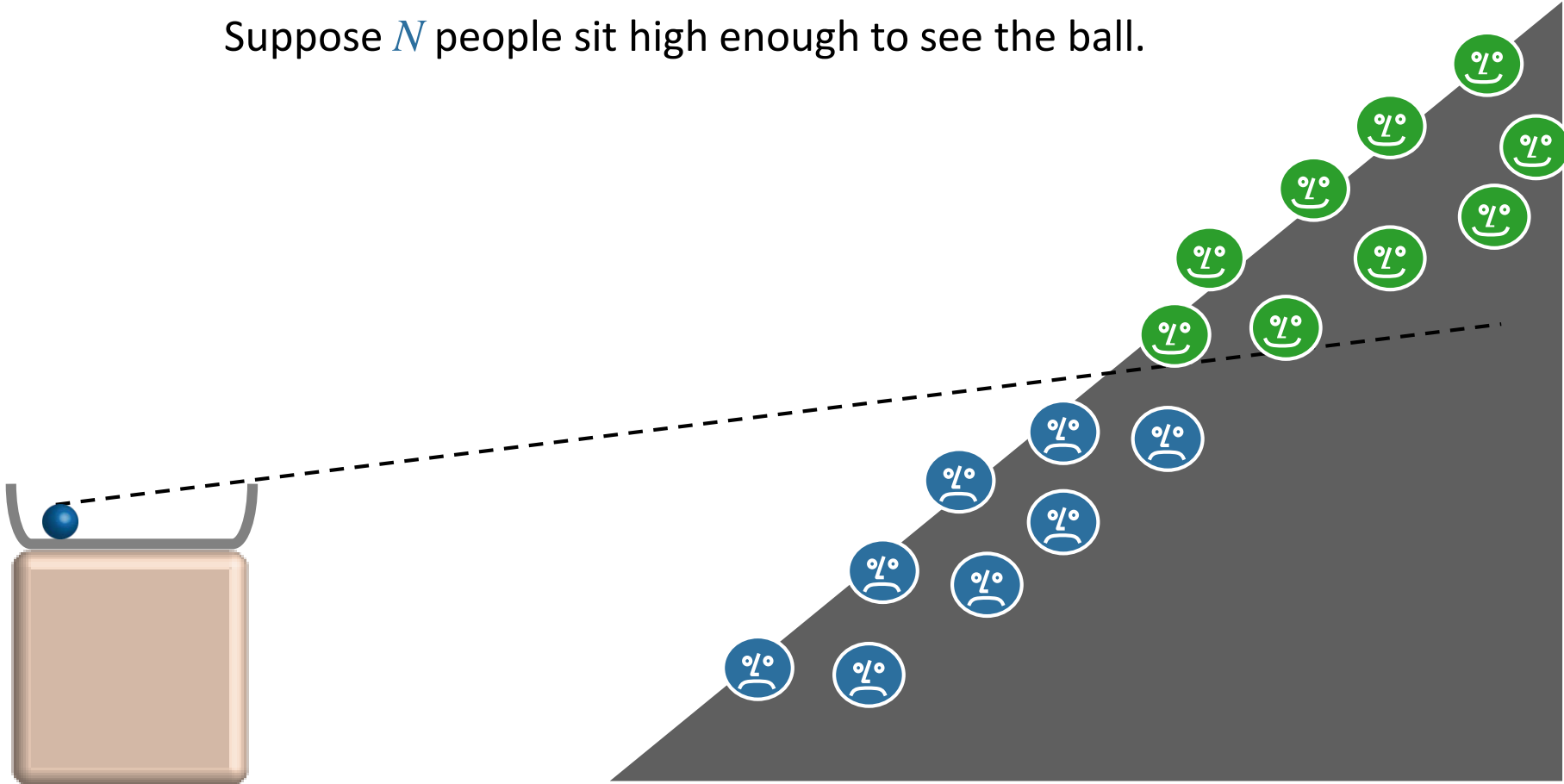


Diver sees all of horizon
refracted into a 97° cone

$$\theta_1 = 90^\circ \quad \rightarrow \quad \sin \theta_2 = \frac{n_1}{n_2} \sin 90^\circ = \frac{n_1}{n_2} = \frac{1}{1.33} \quad \rightarrow \quad \theta_2 = 48.5^\circ$$

A ball sits in the bottom of an otherwise empty tub at the front of the room.

Suppose N people sit high enough to see the ball.

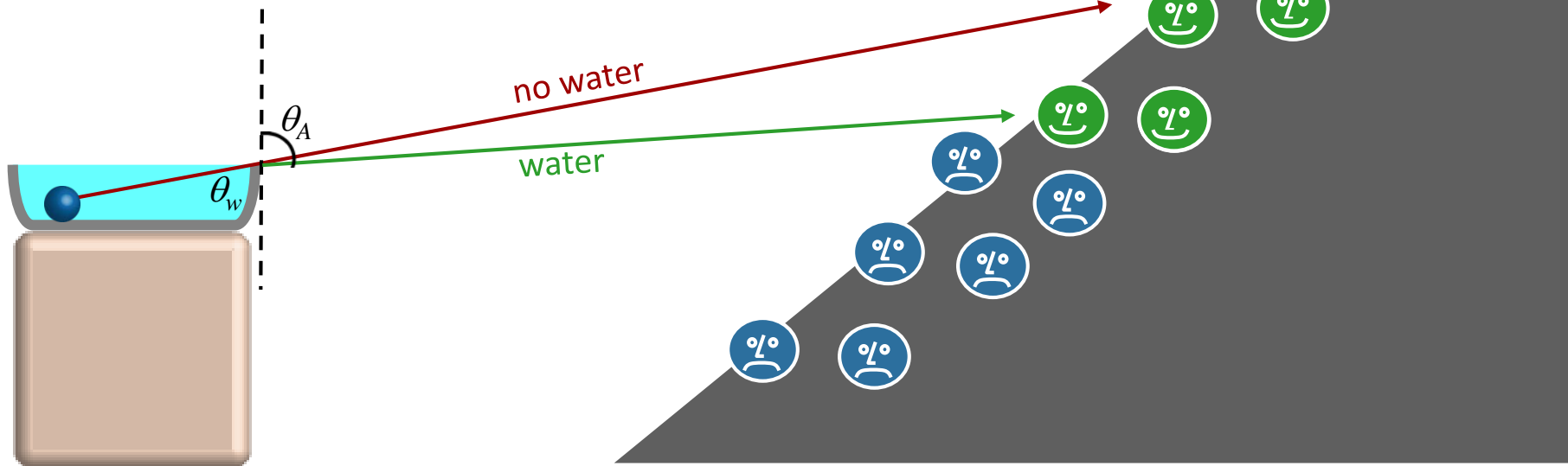


A ball sits in the bottom of an otherwise empty tub at the front of the room.
Suppose N people sit high enough to see the ball.

Suppose I fill the tub with water but the ball doesn't move.

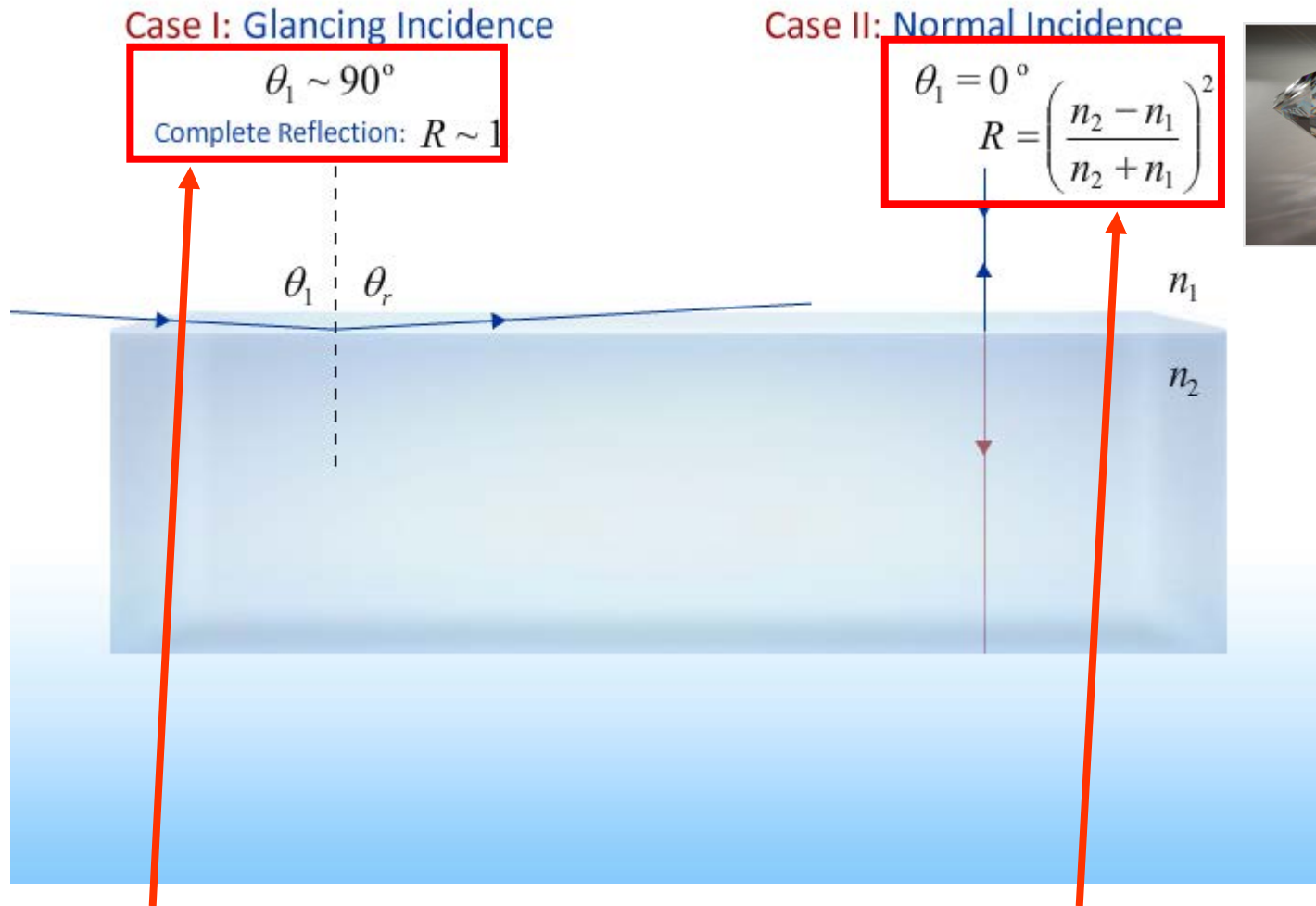
Will more or less people see the ball?

- A) More people will see the ball
- B) Same # will see the ball
- C) Less people will see the ball



Snell's Law: ray bent away from normal going from water to air

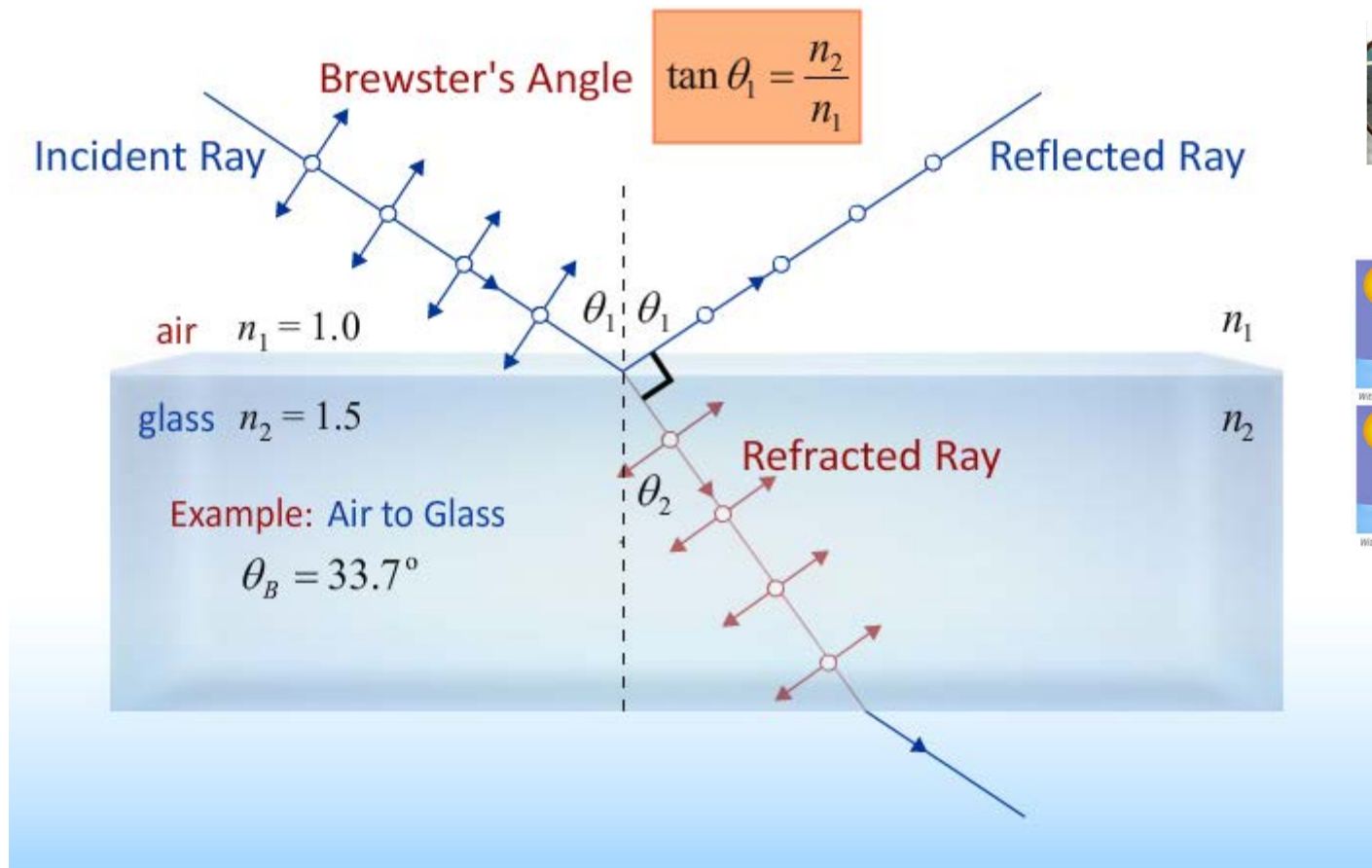
Intensity



Anything looks like a mirror
if light is just glancing off it.

If two materials have the same n
then its hard to tell them apart.

Polarization

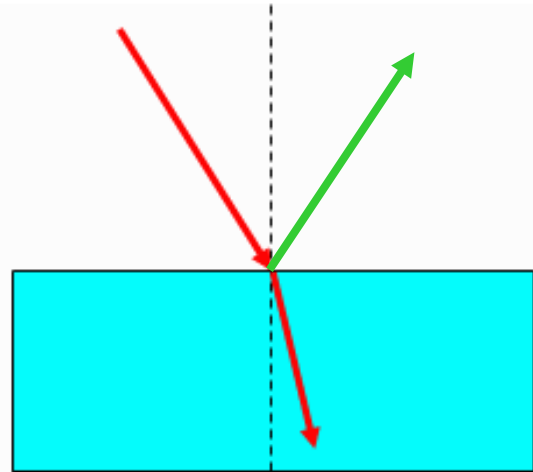


$$\theta_1 + \theta_2 = 90^\circ \quad \longrightarrow \quad \sin \theta_2 = \sin(90^\circ - \theta_1) = \cos \theta_1$$

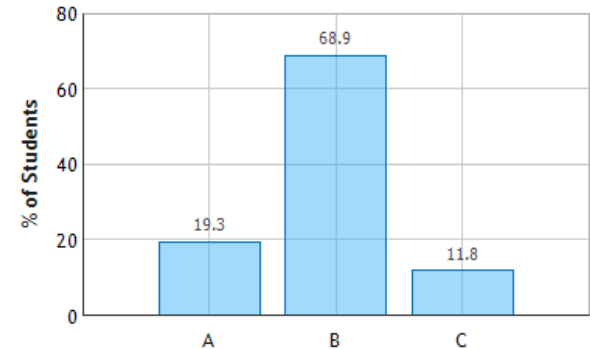
$$\text{Snell's Law: } n_2 \sin \theta_2 = n_2 \cos \theta_1 = n_1 \sin \theta_1 \quad \longrightarrow \quad \tan \theta_1 = \frac{n_2}{n_1}$$

CheckPoint 1b

A ray of light passes from air into water with an angle of incidence of 30 degrees.

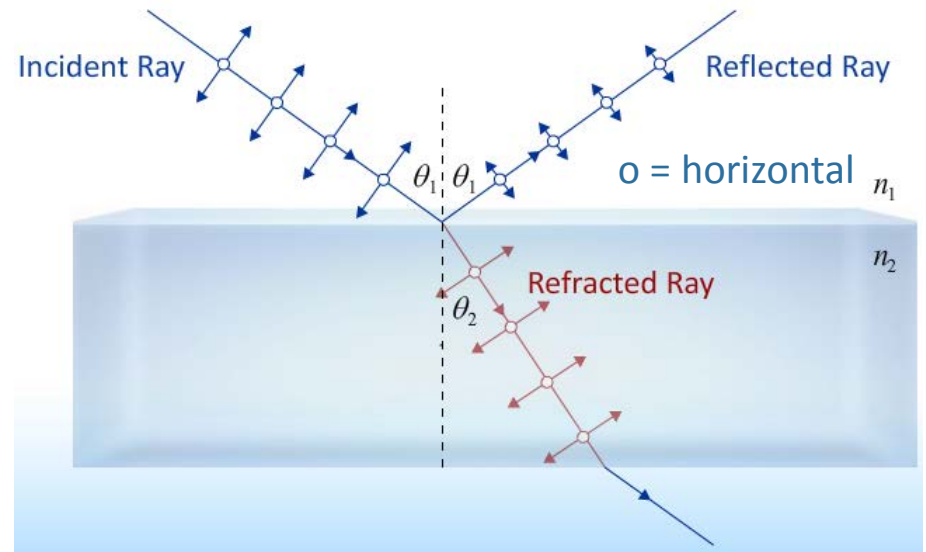


Light Passing from Air into Water: Question 3 (N = 779)



Some of the light also reflects off the surface of the water. If the incident light is initially unpolarized, the reflected light will be

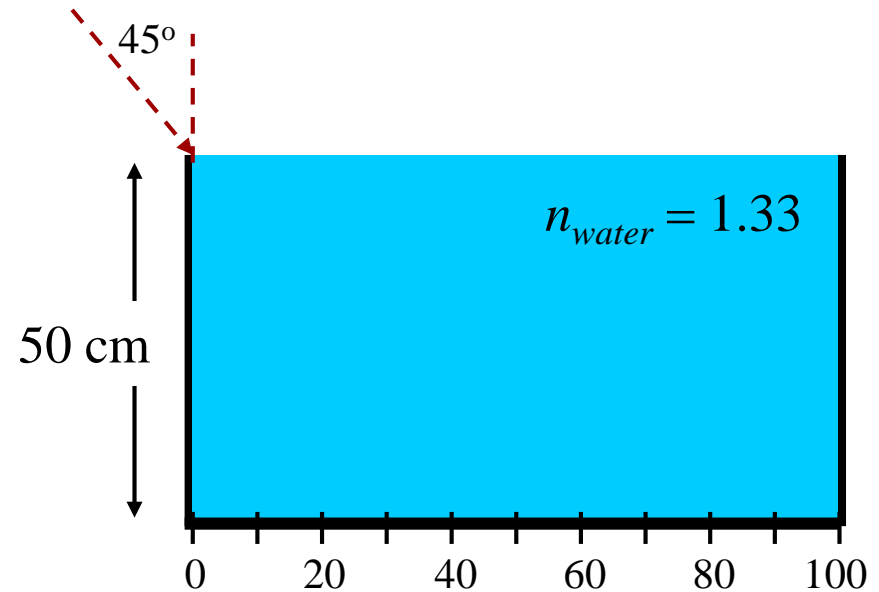
- A unpolarized
- B somewhat horizontally polarized**
- C somewhat vertically polarized



Exercise

A meter stick lies at the bottom of a rectangular water tank of height 50cm. You look into the tank at an angle of 45° relative to vertical along a line that skims the top edge of the tank.

What is the smallest number on the ruler that you can see?



Conceptual Analysis:

- Light is refracted at the surface of the water

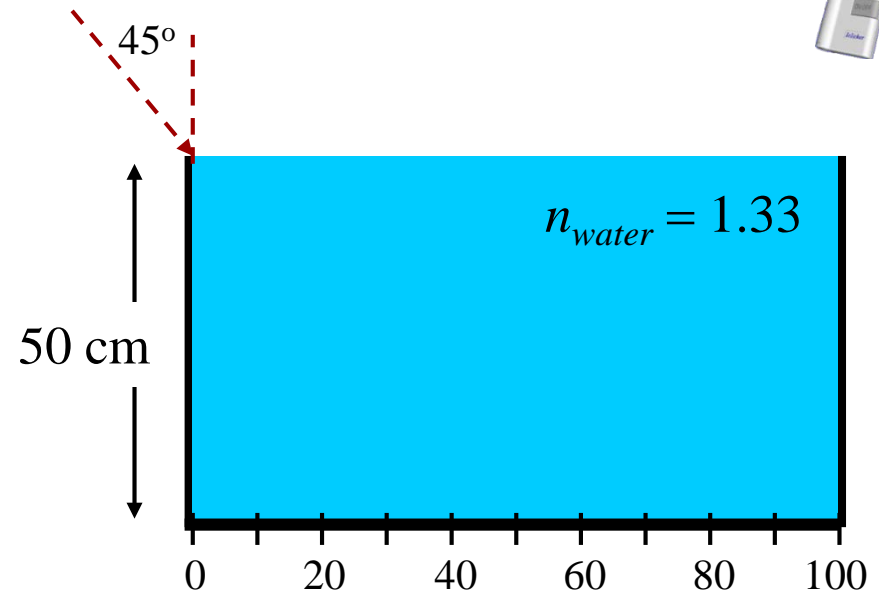
Strategy:

- Determine the angle of refraction in the water and extrapolate this to the bottom of the tank.

Exercise

A meter stick lies at the bottom of a rectangular water tank of height 50cm. You look into the tank at an angle of 45° relative to vertical along a line that skims the top edge of the tank.

What is the smallest number on the ruler that you can see?



If you shine a laser into the tank at an angle of 45° , what is the refracted angle θ_R in the water ?

A) $\theta_R = 28.3^\circ$

B) $\theta_R = 32.1^\circ$

C) $\theta_R = 38.7^\circ$

Snell's Law: $n_{air} \sin(45) = n_{water} \sin(\theta_R)$

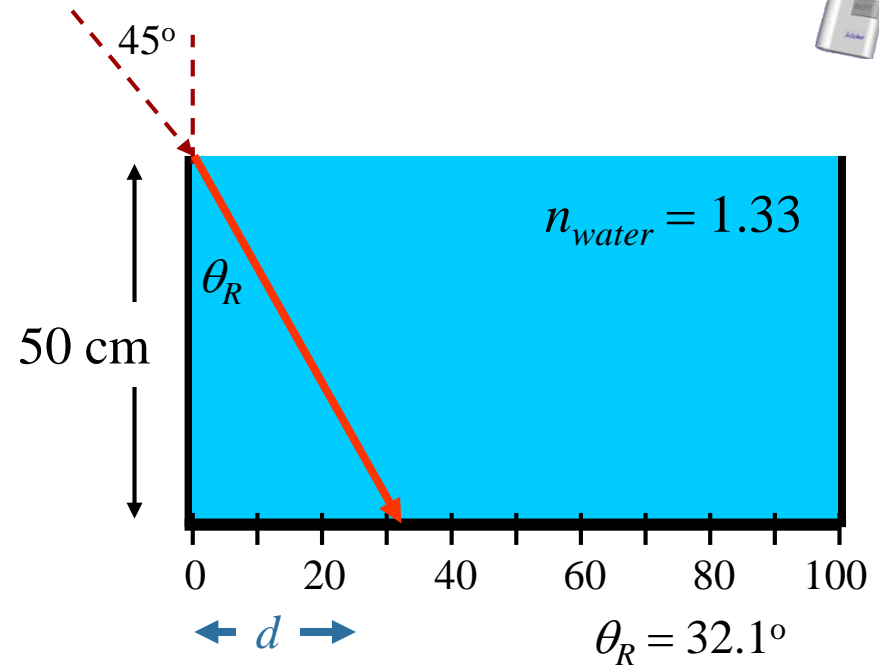
→ $\sin(\theta_R) = n_{air} \sin(45) / n_{water} = 0.532$

→ $\theta_R = \sin^{-1}(0.532) = 32.1^\circ$

Exercise

A meter stick lies at the bottom of a rectangular water tank of height 50cm. You look into the tank at an angle of 45° relative to vertical along a line that skims the top edge of the tank.

What is the smallest number on the ruler that you can see?



What number on the ruler does the laser beam hit?

A) 31.4 cm

B) 37.6 cm

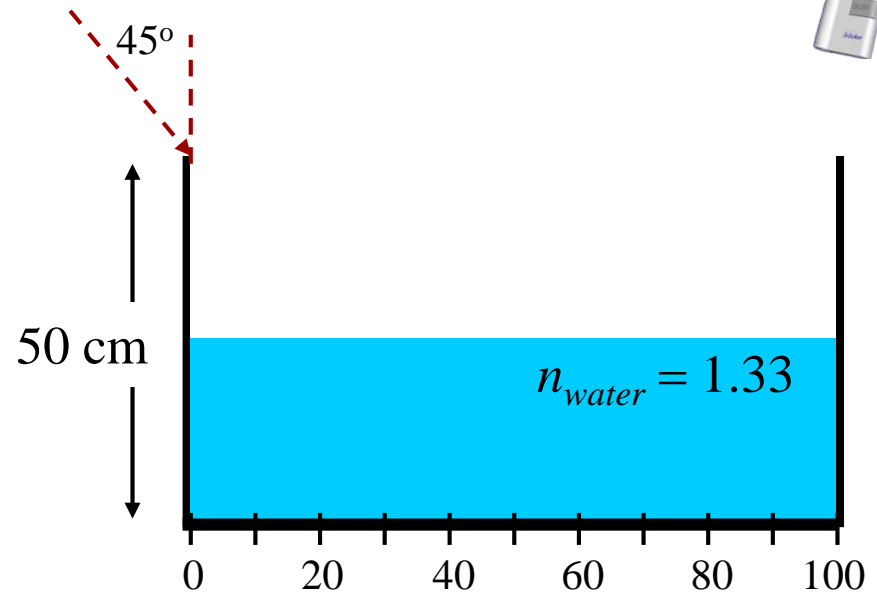
C) 44.1 cm

$$\tan(\theta_R) = d/50$$

$$\rightarrow d = \tan(32.1) \times 50\text{cm} = 31.4\text{cm}$$

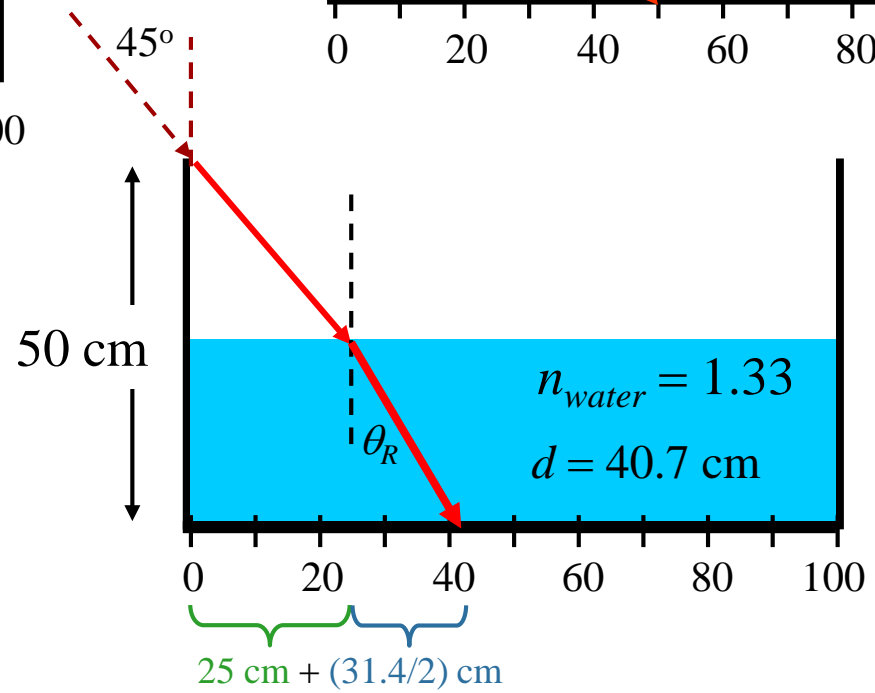
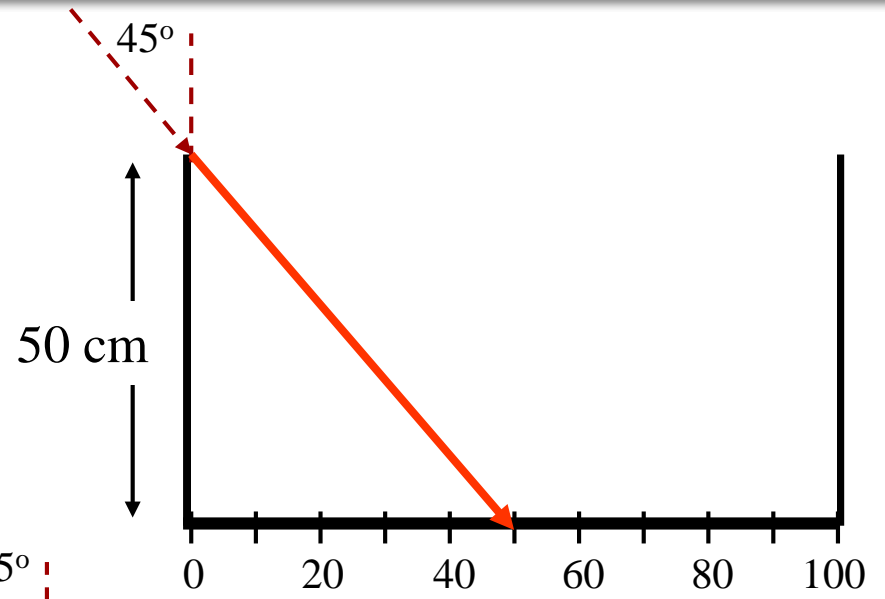
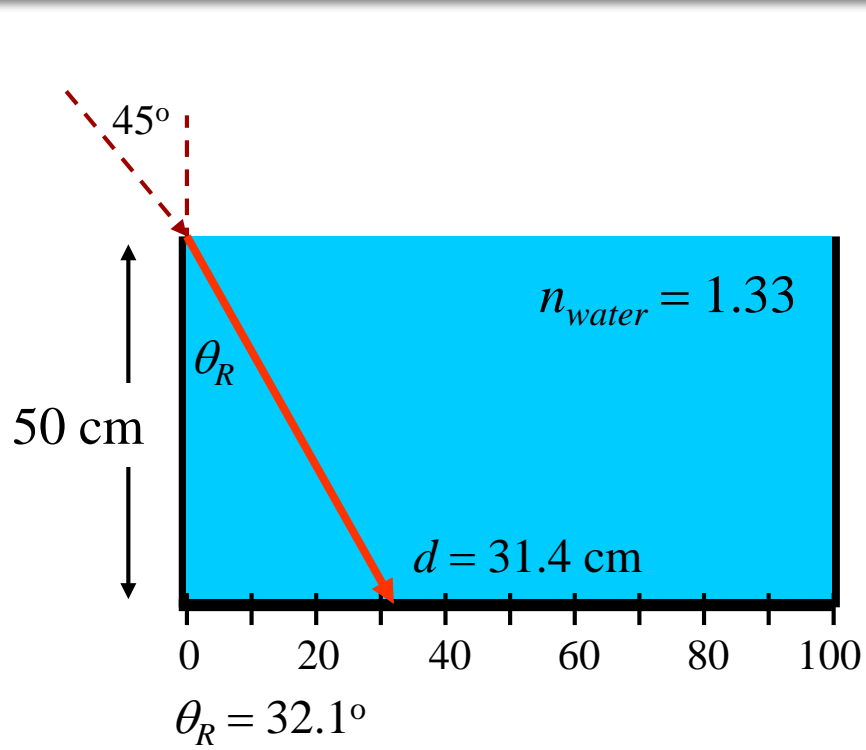
Follow-Up

A meter stick lies at the bottom of a rectangular water tank of height 50cm. You look into the tank at an angle of 45° relative to vertical along a line that skims the top edge of the tank.



If the tank were half full of water, what number would the laser hit?
(When full, it hit at 31.4 cm)

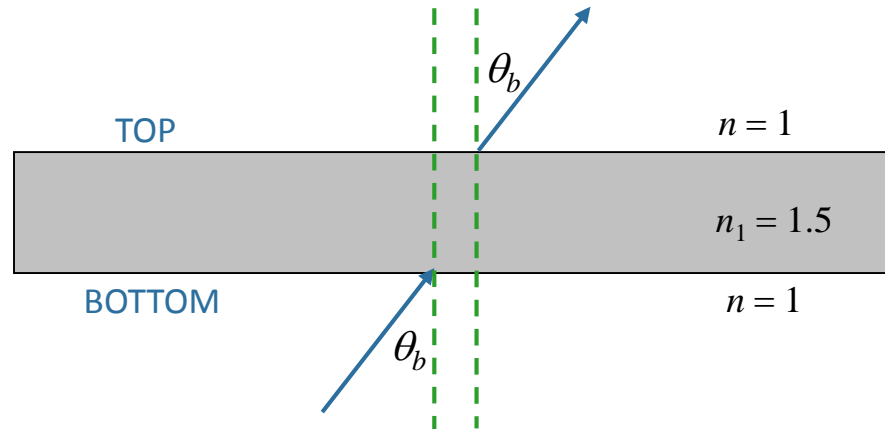
- A) 25 cm B) 31.4 cm C) 32.0 cm **D) 40.7 cm** E) 44.2 cm



More Practice



A monochromatic ray enters a slab with $n_1 = 1.5$ at an angle θ_b as shown.



- A) Total internal reflection at the top occurs for all angles θ_b , such that $\sin \theta_b < 2/3$
- B) Total internal reflection at the top occurs for all angles θ_b , such that $\sin \theta_b > 2/3$
- C) There is no angle θ_b ($0 < \theta_b < 90^\circ$) such that total internal reflection occurs at top.

Snell's law:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$



$n \sin \theta$ is "conserved"

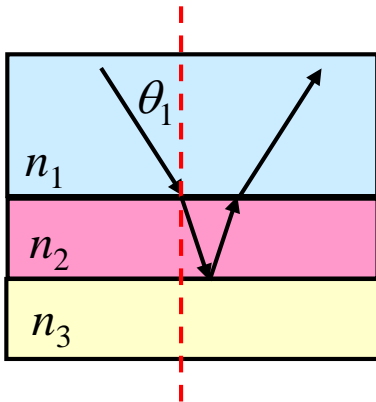


Ray exits to air with same angle as it entered!

Follow-Up



A ray of light moves through a medium with index of refraction n_1 and is incident upon a second material (n_2) at angle θ_1 as shown. This ray is then totally reflected at the interface with a third material (n_3). Which statement must be true?

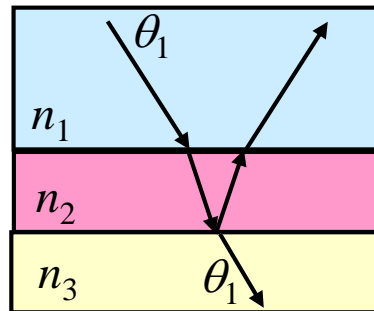


A) $n_3 < n_1$

B) $n_1 < n_3 \leq n_2$

C) $n_3 \geq n_2$

If $n_1 = n_3$



Want larger angle of refraction in n_3



$n_3 < n_1$