Final Exam Information

- 8:30-11:15 AM, Tuesday, Dec 12th
- Location: vary, see Canvas
- Format:
  - 10-15 Multiple choice conceptual questions + 4-5 written problems
  - 8:30-11:00 to work on exam; 11:00-11:15 to scan/upload exam to Canvas
- Week 14 extra practice: relevant questions at the end of chapters 16, 33, and 35
- TA Office Hours for Exam Review Questions
  - Dec 4th & 5th: 5-8pm; Dec 8th: 10-12am & 12-2pm; Dec 11th: 10-12am & 2-4pm

Interesting lecture by Prof. Dierker (PHYS 157 section 103)

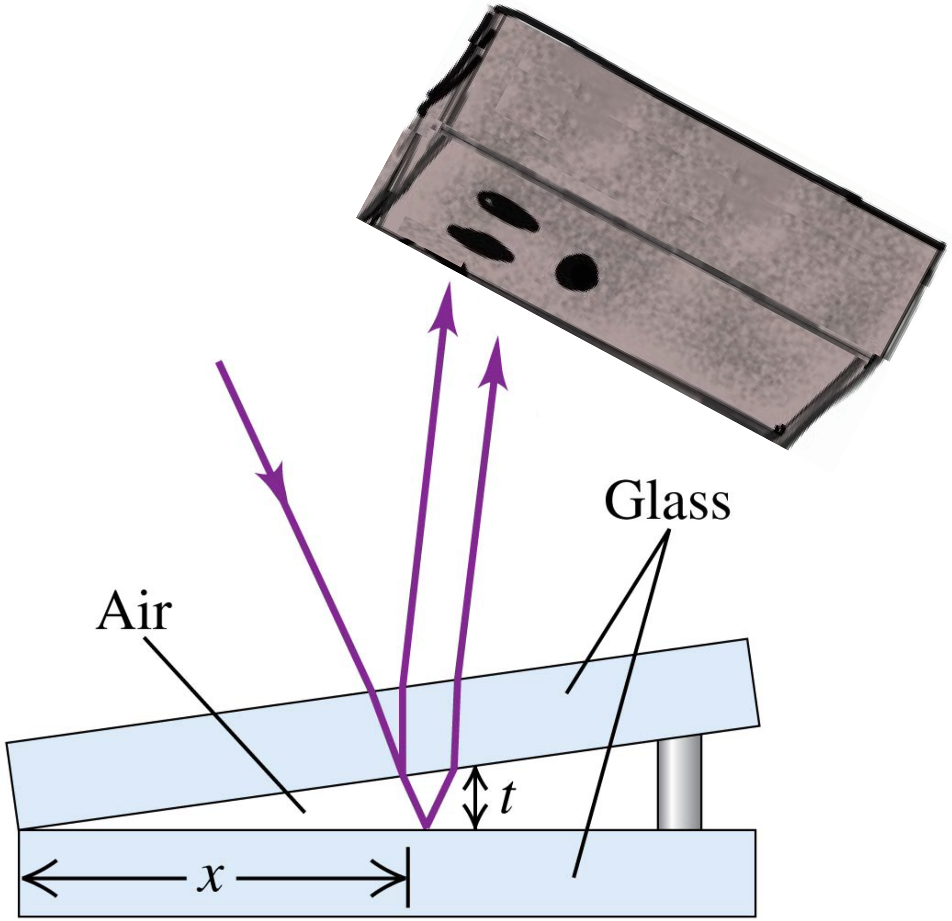
- Tuesday, Dec 7th at 2:00 pm (Hebb 100)
- Title: "Einstein's Gravity, Black Holes, and Oscillations of Space Time"
- Our section cannot make it since we have 1 class less than Tu/Th.
- The material is not on the exam, but it is going to be interesting!

Lecture 37.

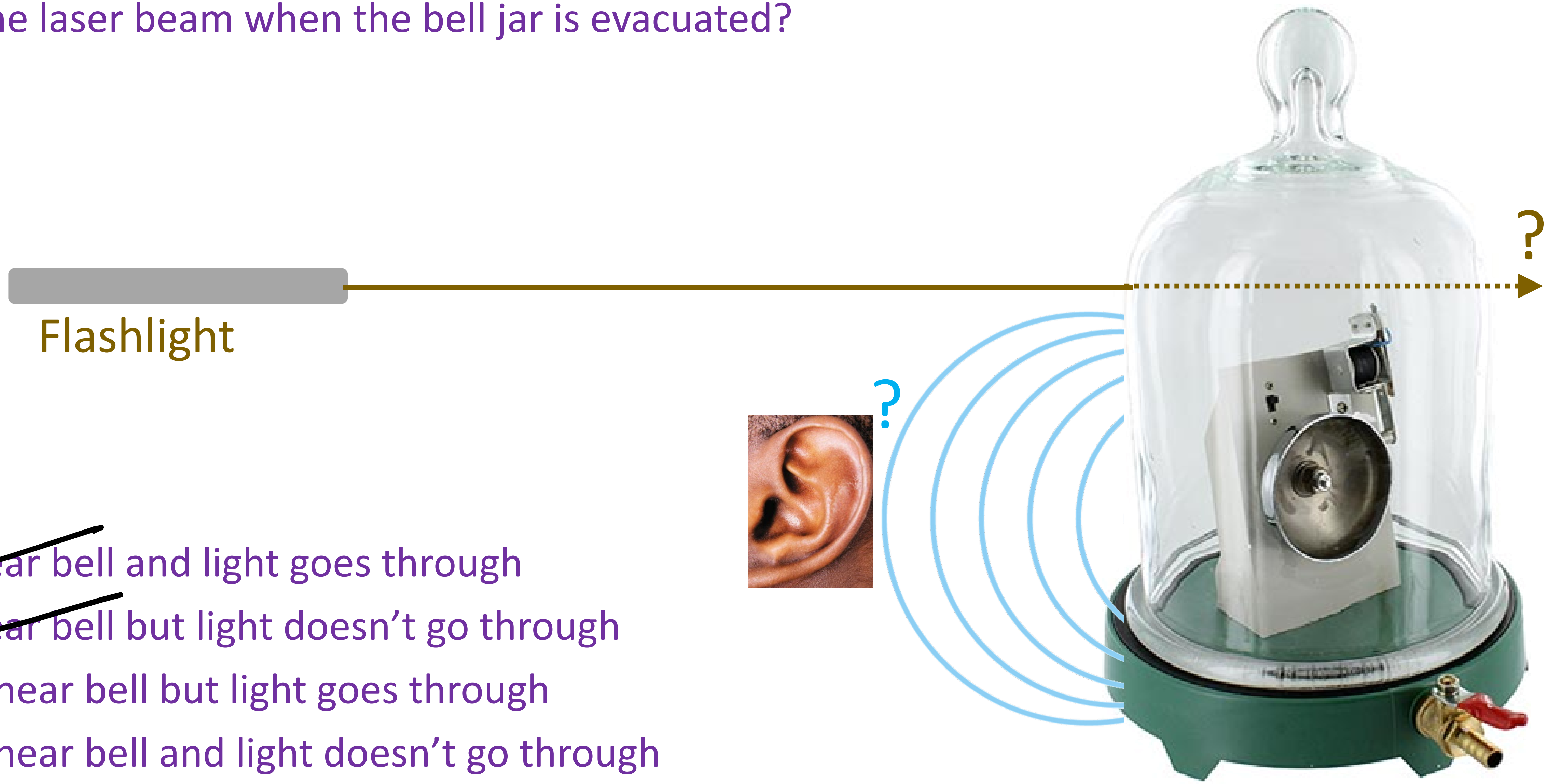
Light as electromagnetic wave.

Reflection and refraction.

Interference in thin films.



Q: You place a ringing bell inside a bell jar that can be evacuated. You also shine a laser beam from a laser pointer through the bell jar. What happens to the sound from the bell and to the laser beam when the bell jar is evacuated?



A. ~~Still hear~~ bell and light goes through
B. ~~Still hear~~ bell but light doesn't go through
C. Don't hear bell but light goes through
D. Don't hear bell and light doesn't go through
E. The bell jar explodes!!!!

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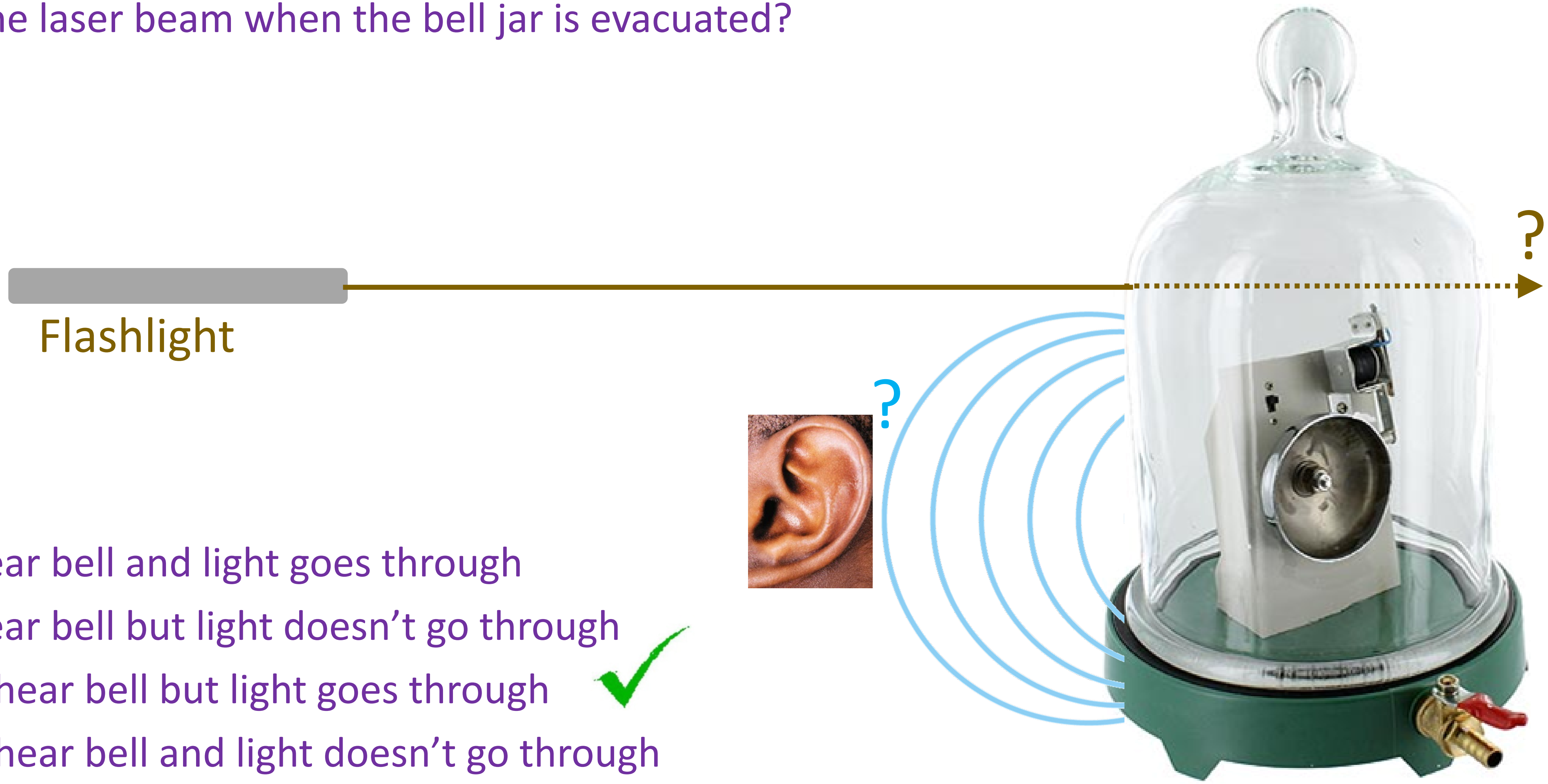
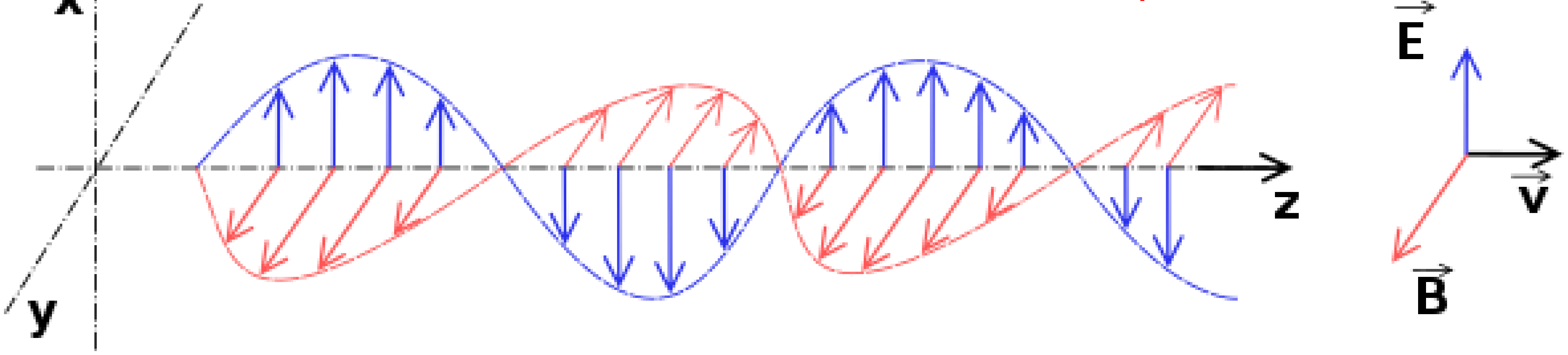


A. Still hear bell and light goes through
B. Still hear bell but light doesn't go through
C. Don't hear bell but light goes through ✓
D. Don't hear bell and light doesn't go through
E. The bell jar explodes!!!!

Light Waves

- Sound waves are mechanical waves (displacements of atoms in a material) and can only exist in a material (air, water, etc.) and not in a vacuum
- Light waves correspond to transverse displacements of the electric and magnetic fields that permeate all space, including vacuum
  - ➢ Light waves can propagate in a vacuum as well a material

- Speed of light in vacuum: $c = 3 \times 10^8\ m/s$



- We will only study the wave properties of light
- You will study its electromagnetics properties in PHYS 158

Light Waves in a Material

- The speed of light in vacuum is $v_0 \equiv c = 3 \times 10^8\, m/s$
- Light travels more slowly in any material than in vacuum (Q: why? Can you explain?)
- The index of refraction, n, of a material is the ratio of the speed of light in vacuum, c, to that in the material, v:

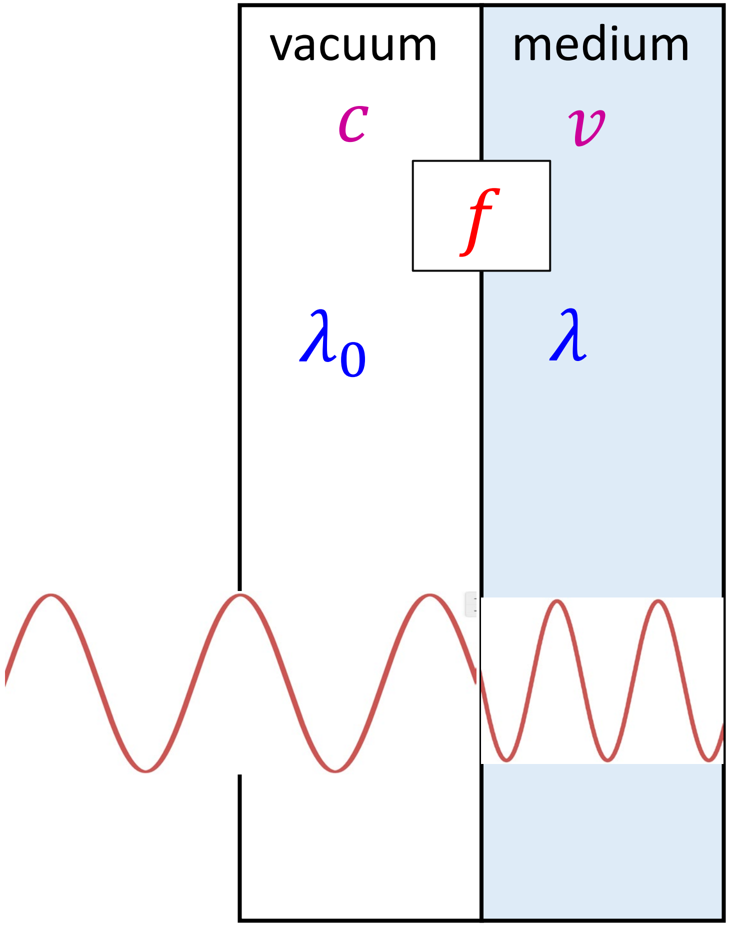
$$\boxed{n = c/v} \qquad \boxed{v = c/n}$$

Index of Refraction of Various Materials

Material	n
Vacuum	1
Air	1.003
Ice (H_2O)	1.309
Water (H_2O) at 20 °C	1.333
Glycerine at 20 °C	1.473
Crown glass	1.52
Rock salt (NaCl)	1.544
Quartz (SiO_2)	1.544
Diamond (C)	2.417

Note: Index of refraction depends on the wavelength of the light. These values are for yellow light ($\lambda_0 = 589\, nm$).

Light Waves in a Material and in Vacuum



- Important: Frequency of light wave, f, does not change as it propagates from one material to another

- What can we say about the wavelength?

- Since $f\lambda = v$, we have:

$$\lambda_1 n_1 = \lambda_2 n_2$$

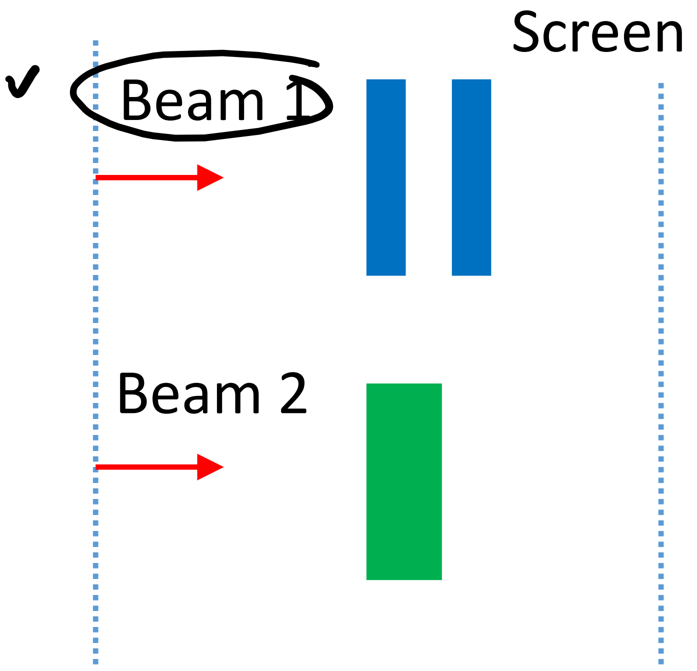
$$f = \frac{c}{\lambda_0} = \frac{v}{\lambda} \quad \Longrightarrow \quad \boxed{\lambda = \lambda_0 \frac{v}{c} = \frac{\lambda_0}{n}}$$

- The wavelength of light is always shorter in a medium than in vacuum!

- When a wave passes from one material into another material, it:
  - gets "squeezed" (the wavelength gets shorter) if the refraction index increases, and
  - gets "stretched" (the wavelength gets longer) if the refraction index decreases

$$\boxed{n = c/v}$$

Q: Two laser beams are turned on simultaneously at $t = 0$. Laser beam 1 goes through two separate 1 cm thick pieces of blue glass, each with an index of refraction of $n_b = 1.25$. Laser beam 2 goes through a single 2 cm thick piece of green glass with an index of refraction of $n_g = 1.5$. There is a screen on the other side of the glass. Do both beams arrive at the screen at the same time?



t_b 2 cm, n_b ? t_g 2 cm n_g

$n_g > n_b \rightarrow v_g < v_b$

$$t_b - t_g = \frac{\Delta s}{c/n_b} - \frac{\Delta s}{c/n_g} = \frac{\Delta s}{c}(n_b - n_g)$$

A. Yes, they both arrive at the same time
B. Beam 1 arrives $17 \times 10^{-12} s$ before beam 2
C. Beam 1 arrives $17 \times 10^{-12} s$ after beam 2
D. Beam 1 arrives $8.5 \times 10^{-12} s$ before beam 2
E. Beam 1 arrives $8.5 \times 10^{-12} s$ after beam 2

$$t = \frac{\Delta s}{v}$$

$$v = \frac{c}{n}$$

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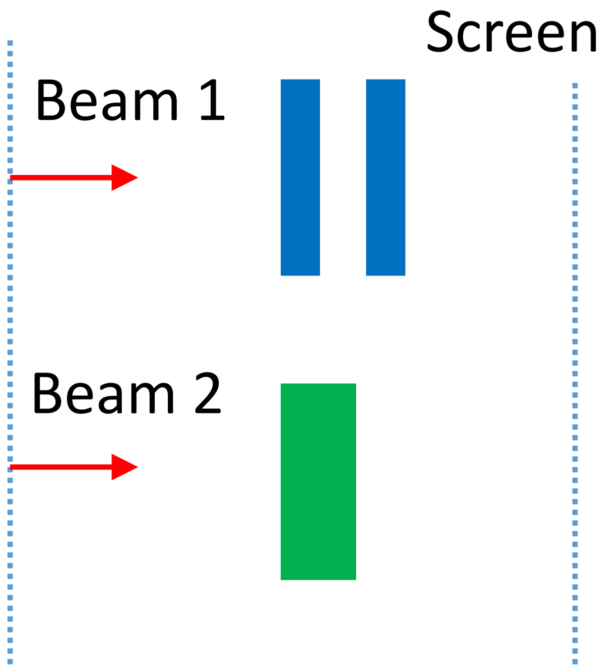

$$\Delta x_b = \Delta x_g = 2\ cm \equiv \Delta x$$

$$\Delta t = t_b - t_g = \frac{\Delta x}{v_b} - \frac{\Delta x}{v_g} = \frac{\Delta x}{c}\left(n_b - n_g\right)$$

$$= \frac{0.02}{3\times10^8}(-0.25) = -16.7 \times 10^{-12} s$$

A. Yes, they both arrive at the same time
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$t_b < t_g$ so beam 1 arrives first

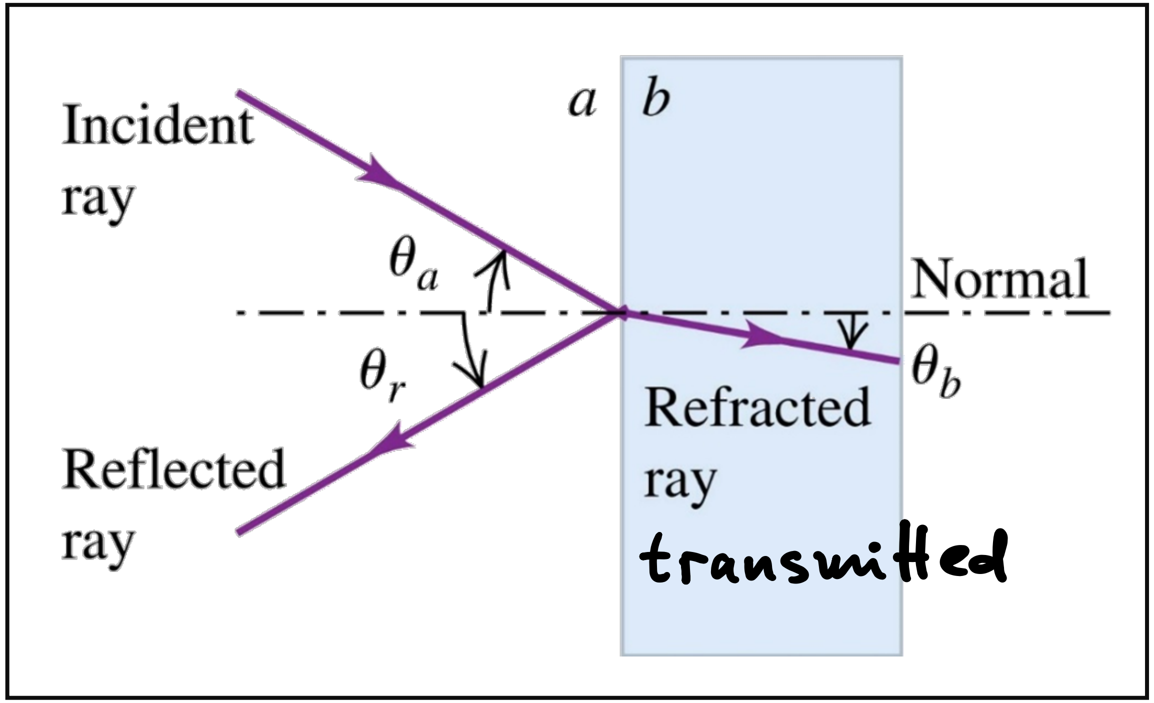
Light Waves Incident on a Material Interface

- A light wave (or "ray") incident on an interface separating two transparent materials is partly reflected and partly transmitted (also called "refracted")
- Transmission is NOT absorption, absorption here is assumed to be zero!
- The angle of reflection, θ_r, is always equal the angle of incidence, θ_a:

$$\boxed{\theta_a = \theta_r}$$

- The angle of refraction, θ_b, is related to the angle of incidence, θ_a, by Snell's Law:

$$\boxed{n_a \sin\theta_a = n_b \sin\theta_b}$$

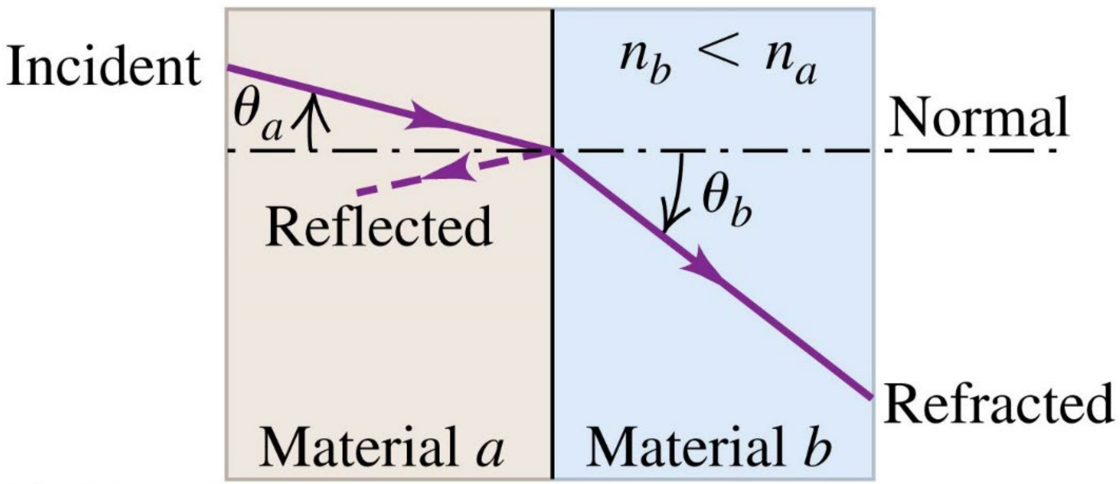


Note that all angles are measured **from the normal**

Light Waves Incident on a Material Interface

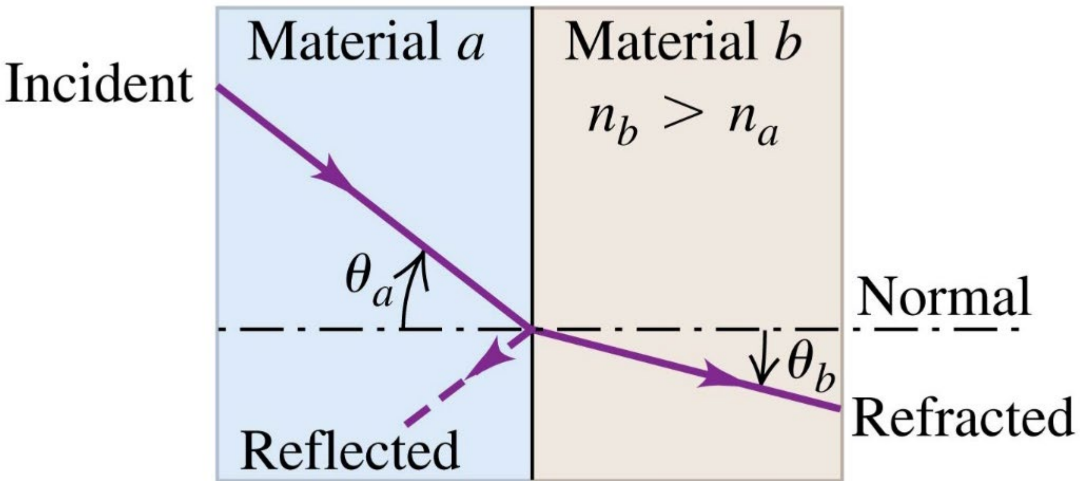
$$\boxed{n_a \sin\theta_a = n_b \sin\theta_b}$$

$n_a > n_b$



Light entering a material with a smaller index bends away from the normal

$n_a < n_b$

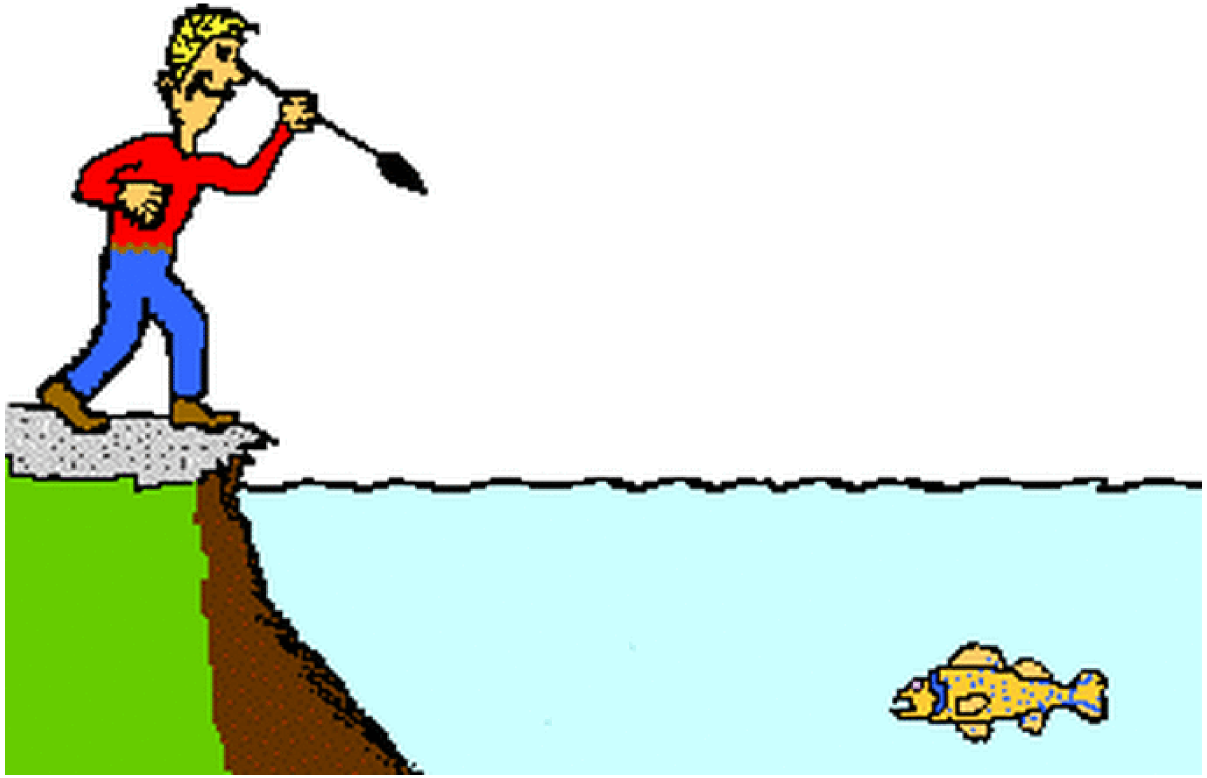


Light entering a material with a larger index bends toward the normal

$$\boxed{\theta_a = \theta_r}$$

- n is larger $\Rightarrow$ $\sin\theta$ is smaller

Q: You are standing on the dock and trying to spear a fish in the water. To make sure you have lunch, where should you throw your spear? $n_{air} = 1.003$ and $n_{water} = 1.33$.



A. Closer than where you see the fish
B. Straight at where you see the fish
C. Farther away than where you see the fish
D. Just toss in an underwater explosive and be done with it

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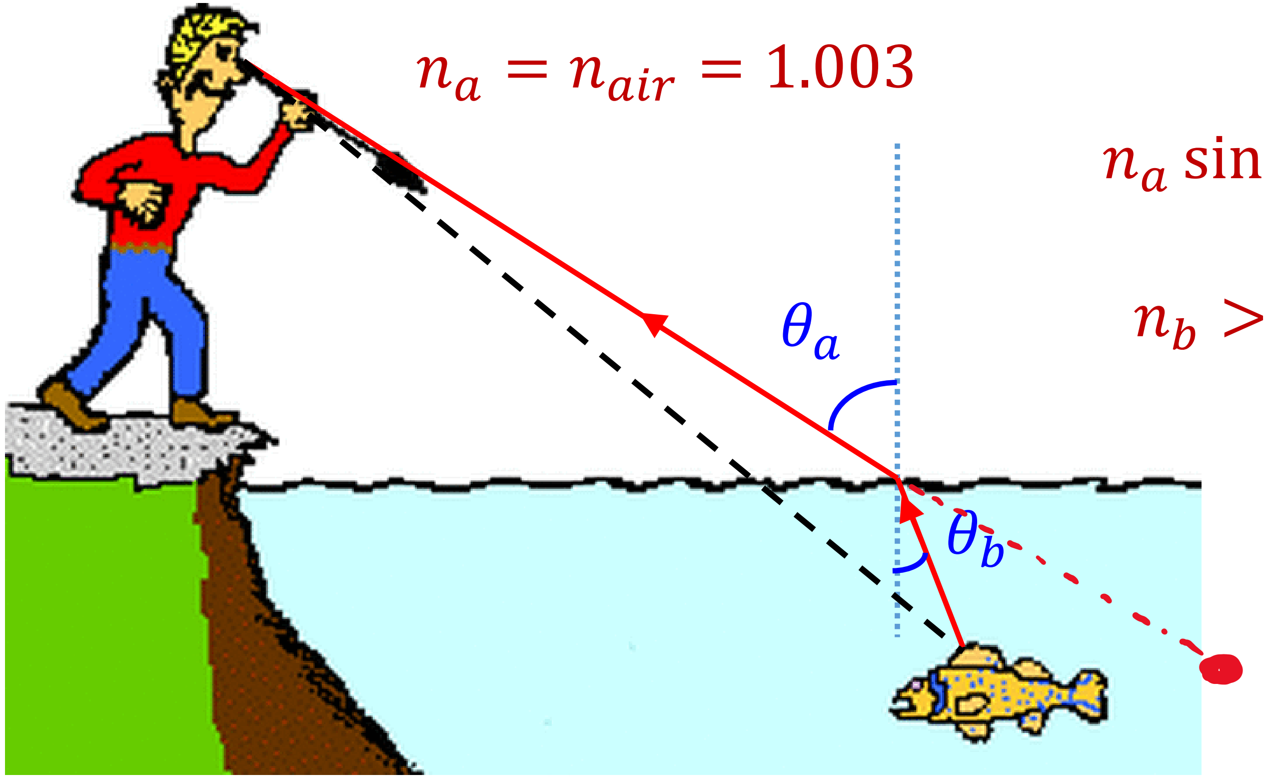


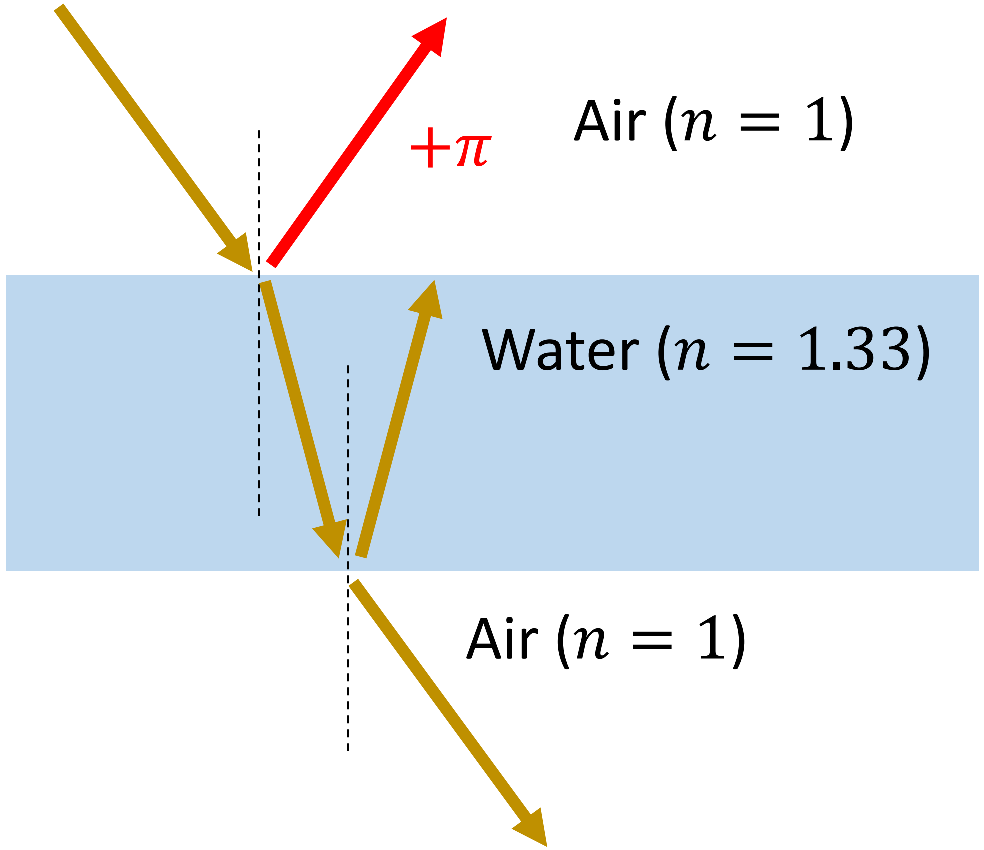
$$n_a \sin\theta_a = n_b \sin\theta_b$$

$$n_b > n_a \Rightarrow \theta_b < \theta_a$$

$$n_b = n_{water} = 1.33$$

A. Closer than where you see the fish ✓
B. Straight at where you see the fish
C. Farther away than where you see the fish
D. Just toss in an underwater explosive and be done with it

Phase shifts during reflection of light waves



- Reflection at a boundary to medium with higher index of refraction:

  π phase shift

- Reflection at boundary to medium with lower index of refraction:

  no phase shift

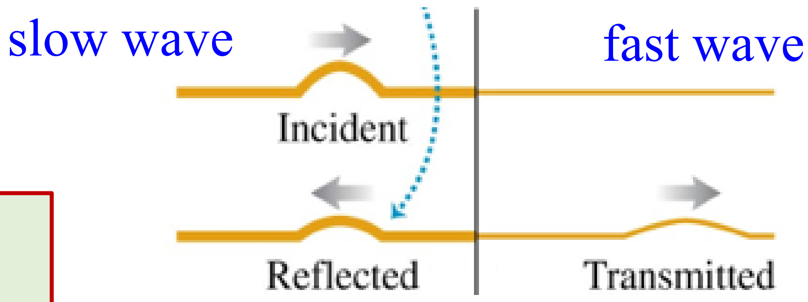
- Never ever phase shifts for transmitted rays

- The reflection phase shifts are included in the interference equation

Analogy with ropes (extra, not on the exam)

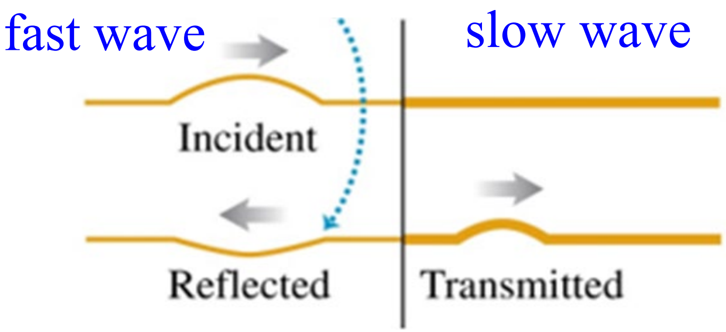
- Reflection of a mechanical wave at a boundary between two ropes

(like an open-end reflection)



$$v = \sqrt{\frac{T}{\mu}}$$

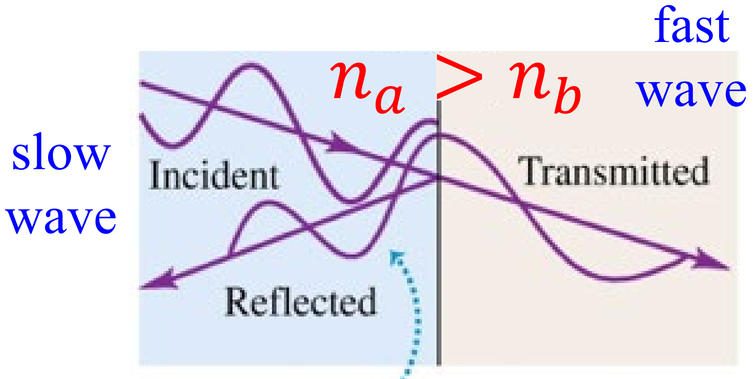
(like a closed-end reflection)



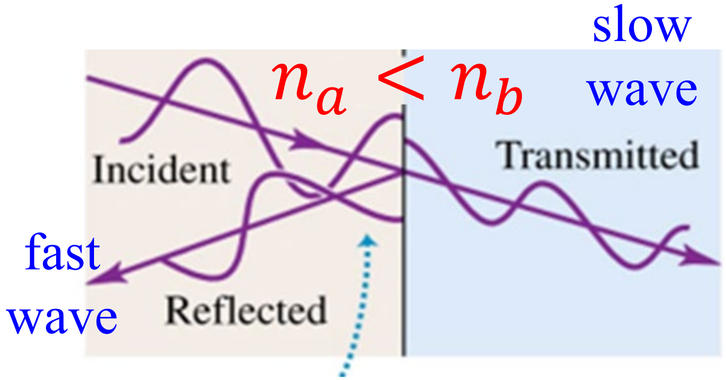
No phase shift

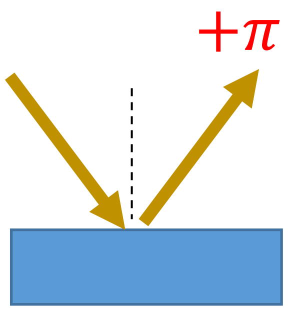
Half-cycle (180^o) phase shift for reflected wave !!

- Reflection of a light wave at a boundary between two media



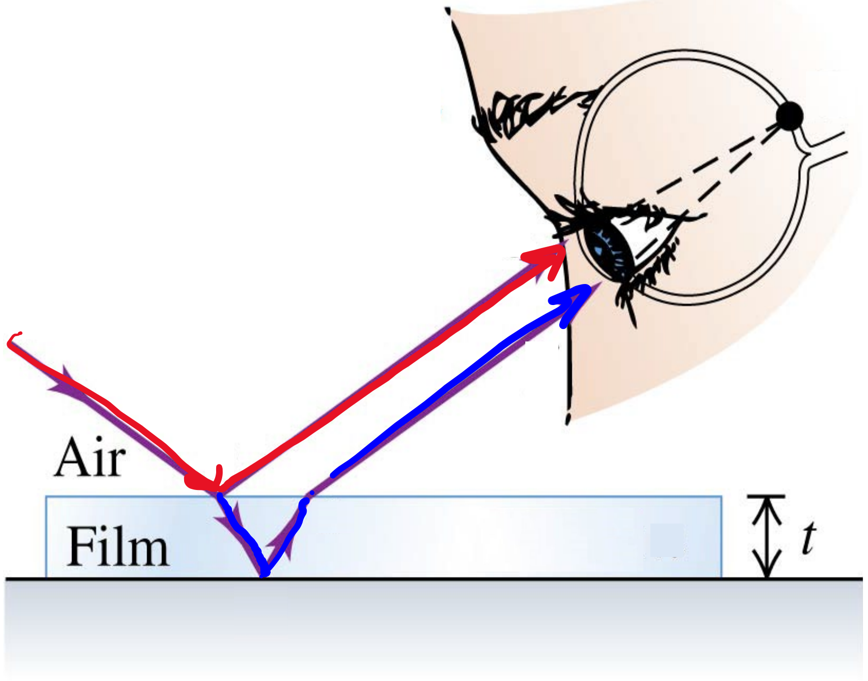
$$v = \frac{c}{n}$$





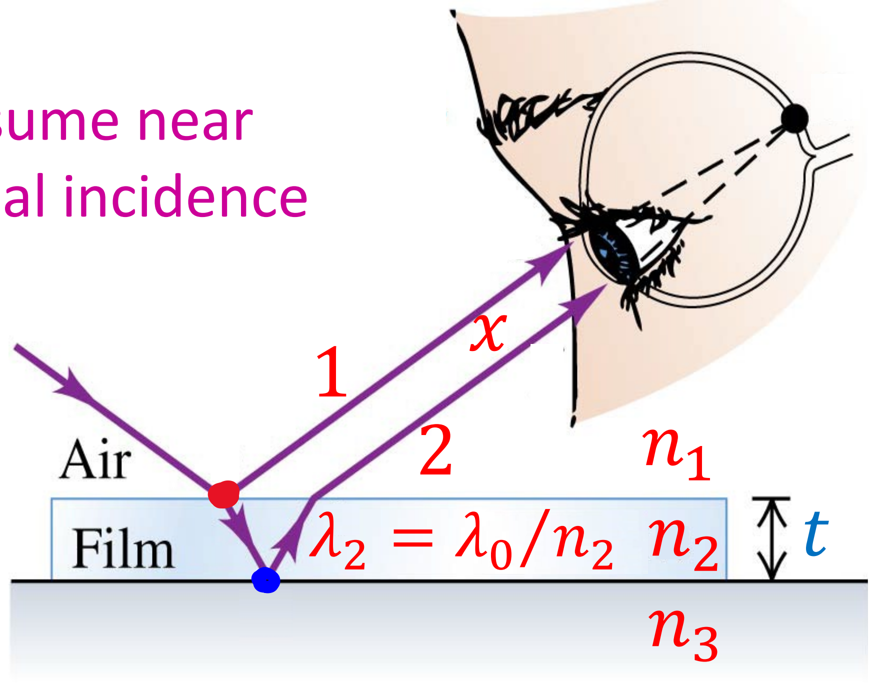
Interference in Thin Films

- Light reflected from the upper and lower surfaces of a film come together in the eye and undergo interference
- Here we include the phases possibly acquired during reflection



- Some colors interfere constructively and others destructively, creating the color bands we see

Interference in Thin Films



- Wave 1: $\arg_1 = \cancel{k_1 x} - \cancel{\omega t} + \boxed{\Delta\phi_1}$ 0 or π
- Wave 2: $\arg_2 = k_2 \cdot 2t + \cancel{k_1 x} - \cancel{\omega t} + \boxed{\Delta\phi_2}$
- Extra path length in film: $k_2 \cdot 2t = (2\pi/\lambda_2)2t$
- Phase difference:

$$\arg_2 - \arg_1 = (2\pi/\lambda_2)2t + \Delta\phi_1 - \Delta\phi_2$$

- If neither or both of the reflected waves have a half-cycle phase shift:

  Constructive interference: $2t = m\lambda_2$ $\quad (m = 0, 1, 2, \dots)$

  Destructive interference: $2t = \left(m + \frac{1}{2}\right)\lambda_2$ $\quad (m = 0, 1, 2, \dots)$

- If only one of the reflected waves has a half-cycle phase shift:

  Constructive interference: $2t = \left(m + \frac{1}{2}\right)\lambda_2$ $\quad (m = 0, 1, 2, \dots)$

  Destructive interference: $2t = m\lambda_2$ $\quad (m = 0, 1, 2, \dots)$

Q: An air wedge separates two glass plates as shown. Light of wavelength λ (in air) strikes the upper plate at normal incidence. Considering only the two reflected waves, 1 and 2, you will see a bright fringe if the air wedge has thickness, t, equal to:

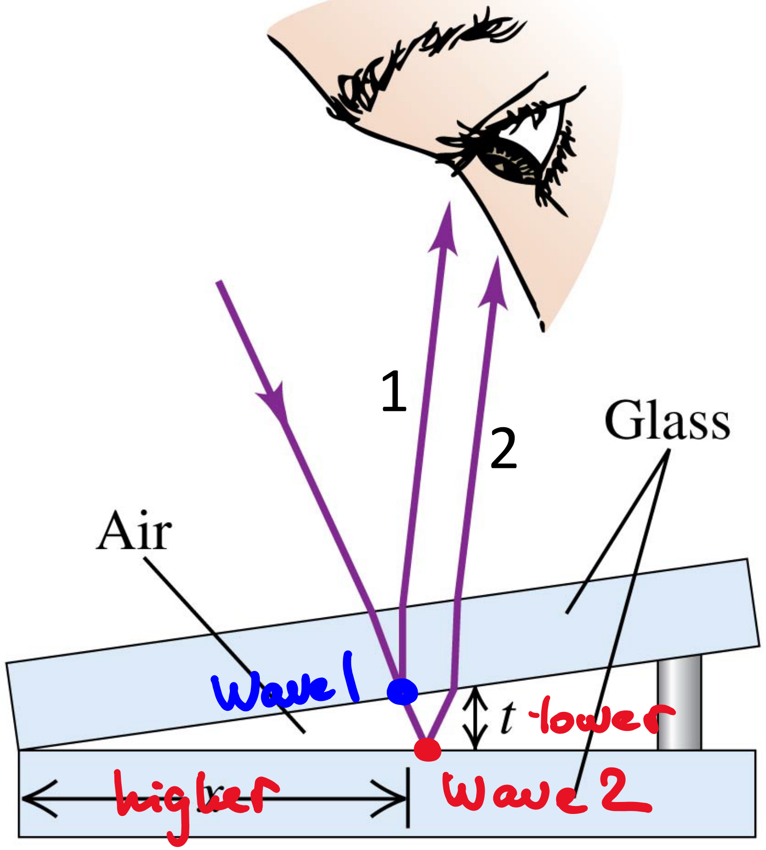
$$n_{air} = 1.0$$
$$n_{glass} = 1.3$$

wave 1 = $\cancel{\Delta\phi_1} = 0$

wave 2 = $k \cdot 2t + \Delta\phi_2$ = π

$$2t = \left(m + \tfrac{1}{2}\right)\lambda$$

A. $\lambda/2$
B. $3\lambda/4$
C. λ
D. either A or C
E. any of A, B, or C



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$n_{air} = 1.0$
$n_{glass} = 1.3$

- Phase difference $= (2\pi/\lambda) \cdot 2t + \Delta\phi_1 - \Delta\phi_2$

For wave 1, $n_g > n_a$ (reflection happens in optically heavy medium), so $\Delta\phi_1 = 0$

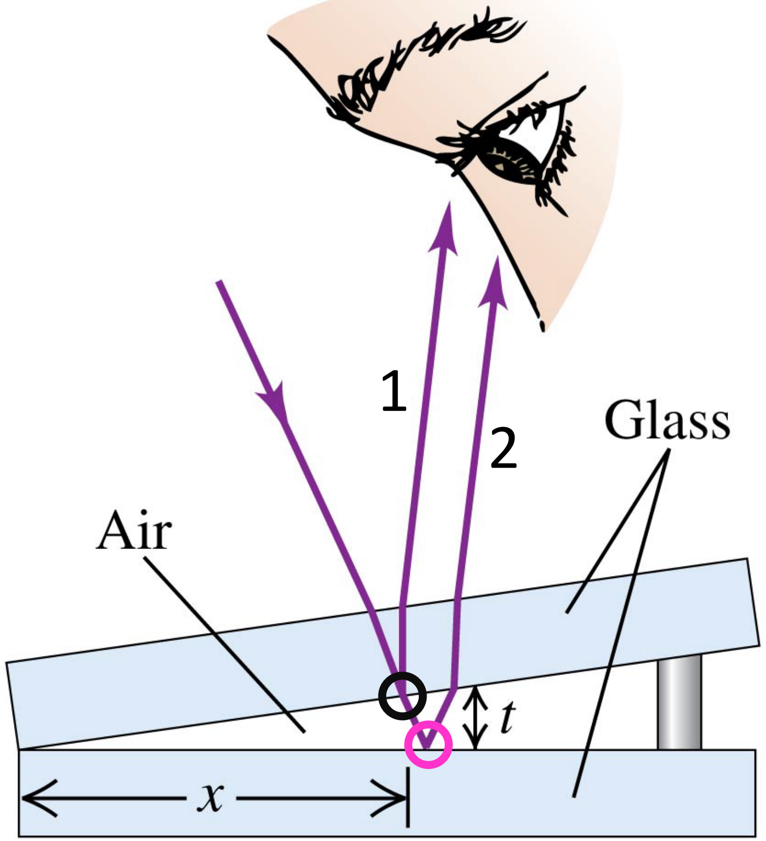
For wave 2, $n_a < n_g$ (reflection happens in optically light medium), so $\Delta\phi_2 = \pi$

- Bright fringe => Constructive Interference:

Phase difference $= (2\pi/\lambda) \cdot 2t - \pi = 2\pi \cdot m$

$\Longrightarrow t = \frac{(2m+1)}{4}\lambda \quad (m = 0, \pm 1, \pm 2, \ldots)$

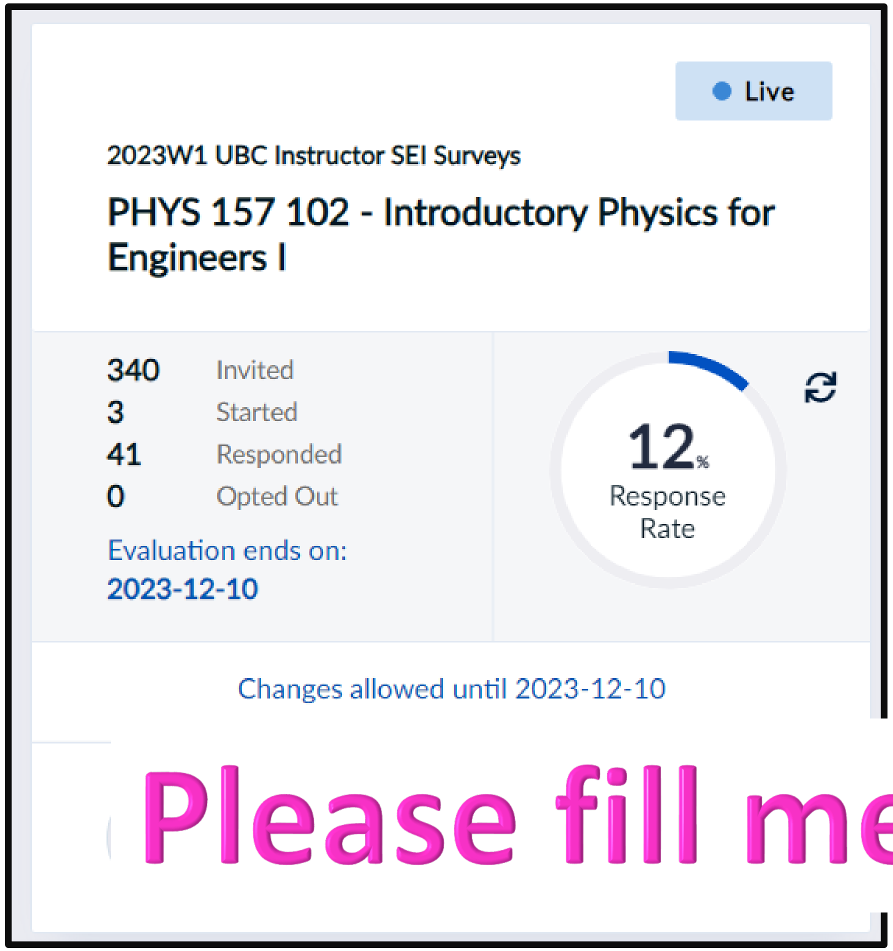
A. $\lambda/2$
B. $3\lambda/4$ ✓
C. λ
D. either A or C
E. any of A, B, or C



Summary of the material covered today:

- Light is a wave, with a speed in vacuum $c = 3 \times 10^8 m/s$
- Refractive index, and how it changes the speed of light in a medium and its wavelength
- Reflection and refraction at an interface of two materials with different n. Snell's law (how angle of refraction depends on n)
- Reflected wave acquires a phase π (= shifts by half an oscillation cycle) when it is reflected back from a material with a higher n
- How this extra phase shift is applied to the discussion of interference in thin films (where two beams reflected from the two differend sides of the film interfere with each other)

Student Experience of Instruction (SEI) Survey



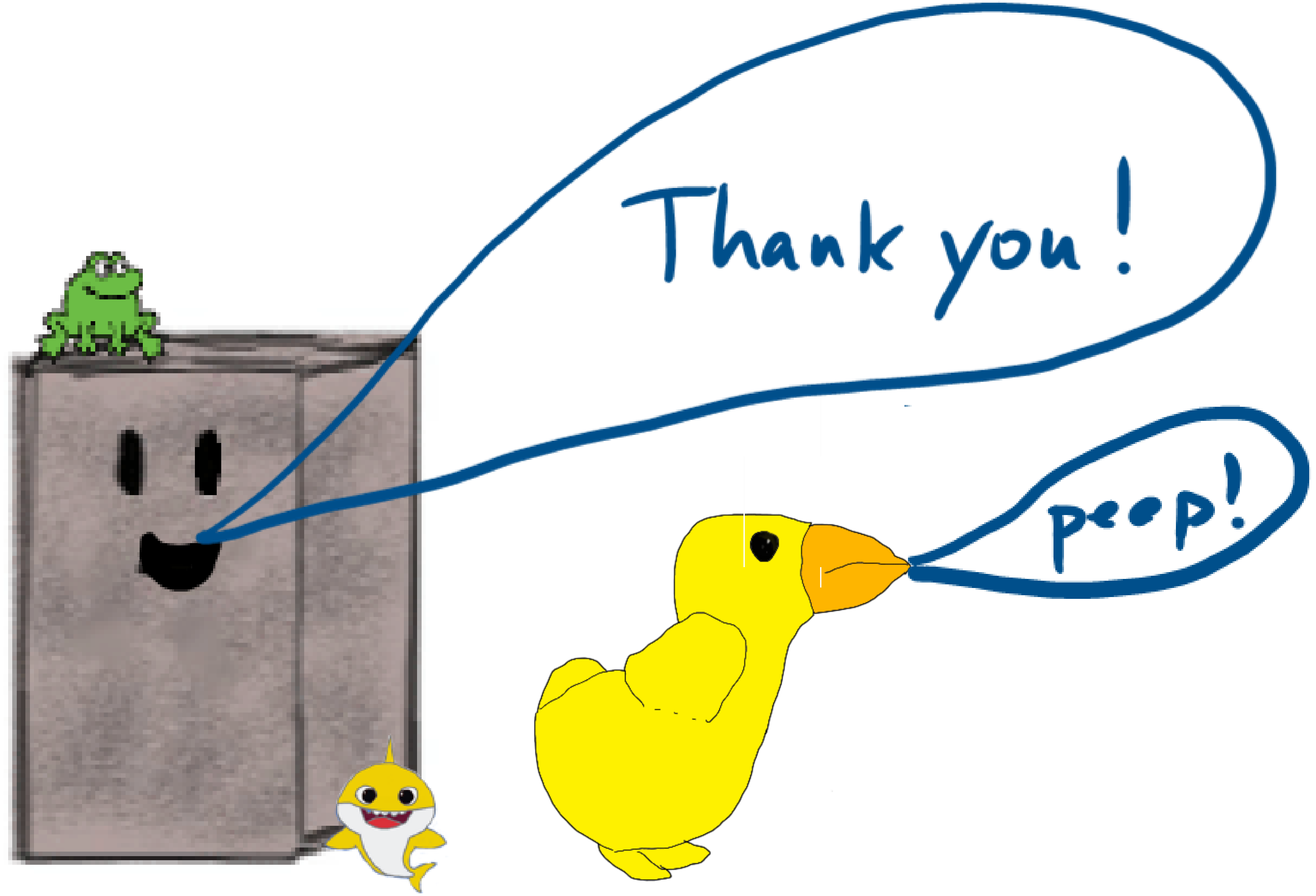
Please fill me out!

- If you are not one of those 41 well-organized people – please do it today!

I hope that this course will stay with you for a while –

– at least in some aspects!

Credits: Kyle Wong


Thank you!
peep!