https://finalexams.rutgers.edu/
May 10, 12PM – 3 PM, Busch (PLH A-Q, SEC210 R-Z)

34 multiple choice questions
22 questions on material not covered on exams 1 and 2
12 on material covered on exams 1 and 2
Exam topics do include waves, but NOT fluids

Course evaluations online:
https://sakai.rutgers.edu/portal/site/sirs

COME DOWN AND PLAY WITH THE DEMOS
Tank: look at Queen through the top surface – squished
Look at Ten from low angle through top and then through side

Congrats on 4/4 to: Ballance, Briski, Cheng, Cho, Huang, Kamara, Kanagala, Lai, Laya, McKeown, Meer, Polito, Raghuraman, Rondel, Stephen, Sun, Thuel, Tian, Zimmerman
Simple “linearly polarized” electromagnetic wave

Direction of propagation and wavelength (or frequency) = \( \vec{k} \)
Amplitude of the oscillating E field: intensity \( I = \text{power/area} \)
Direction of the oscillating E field = “polarization”

\[
E_y(x, y, z, t) = E_m \sin(kx - \omega t)
\]
\[
B_z(x, y, z, t) = B_m \sin(kx - \omega t)
\]
\[
\lambda = \frac{2\pi}{k} ; \quad \omega = ck
\]
How does light behave at the interface between two materials?
REFLECTION – back into the first material
REFRACTION – onward into the second material

Ray representation of wave:
Line shows direction of propagation
Optional: Spacing of wavefronts indicates wavelength
How does light behave at the interface between two materials?

REFLECTION – back into the first material

“Incident ray” hits the interface at a point
Construct the “normal to the surface” at that point
Determine the “angle of incidence” $\phi$

Reflected ray is in the same plane as incident ray and normal, makes same angle $\phi$ with the normal = “angle of reflection”

FOG DEMOS with mirrors!
Point object is source of light = straight rays

Observer assumes that light arriving from point object has traveled in a straight line
Locate the object by detecting two or more rays and finding where they intersect

If light has been bent, apparent position is different from true position
In a plane mirror the light seems to come from an object on the other side.

For an extended object, image of each point on object follows the rule “Straight to the mirror and equal distance on other side”

\[ i = p \]

Cool candle demo!
How does light behave at the interface between two materials?

**REFLECTION** – back into the first material

**REFRACTION** – onward into the second material

<table>
<thead>
<tr>
<th>Air</th>
<th>Water</th>
<th>Glass or Crystal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air</td>
<td></td>
</tr>
</tbody>
</table>

4/19/17 Phys 272
Angle of incidence $\theta_1$
Angle of reflection $\theta_1'$
Angle of refraction $\theta_2$

**LAW OF REFLECTION**

$$\theta_1' = \theta_1 \quad \text{(reflection).}$$

**LAW OF REFRACTION?**
How is $\theta_2$ related to $\theta_1$?
In general, $\theta_2 \neq \theta_1$ (bent!)
Bending depends on the 2nd material

FOG DEMO with crystal

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*Fig. 33-16 (Continued) (b) A ray representation of (a). The angles of incidence ($\theta_1$), reflection ($\theta_1'$), and refraction ($\theta_2$) are marked.*
Index of refraction $n$

Property of a material
Ratio of the speed of light in vacuum to speed of light in material
a number greater than or equal to 1 = $n$
Wave speed in the material = $c/n$
### 33.8: Reflection and Refraction:

Table 33-1

<table>
<thead>
<tr>
<th>Medium</th>
<th>Index</th>
<th>Medium</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>Exactly 1</td>
<td>Typical crown glass</td>
<td>1.52</td>
</tr>
<tr>
<td>Air (STP) (^b)</td>
<td>1.00029</td>
<td>Sodium chloride</td>
<td>1.54</td>
</tr>
<tr>
<td>Water (20°C)</td>
<td>1.33</td>
<td>Polystyrene</td>
<td>1.55</td>
</tr>
<tr>
<td>Acetone</td>
<td>1.36</td>
<td>Carbon disulfide</td>
<td>1.63</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>1.36</td>
<td>Heavy flint glass</td>
<td>1.65</td>
</tr>
<tr>
<td>Sugar solution (30%)</td>
<td>1.38</td>
<td>Sapphire</td>
<td>1.77</td>
</tr>
<tr>
<td>Fused quartz</td>
<td>1.46</td>
<td>Heaviest flint glass</td>
<td>1.89</td>
</tr>
<tr>
<td>Sugar solution (80%)</td>
<td>1.49</td>
<td>Diamond</td>
<td>2.42</td>
</tr>
</tbody>
</table>

\(^a\)For a wavelength of 589 nm (yellow sodium light).

\(^b\)STP means “standard temperature (0°C) and pressure (1 atm).”
Index of refraction

Property of a material
Ratio of the speed of light in vacuum to speed of light in material
a number greater than or equal to 1
Wave speed in the material = $c/n$

Wave along the normal direction
Frequency doesn’t change so wavelength changes (decreases from lower $n$ (air) to higher $n$ (water))
Index of refraction

Property of a material
Ratio of the speed of light in vacuum to speed of light in material
a number greater than or equal to 1
Wave speed in the material = c/n

Wave along the normal direction
Frequency doesn’t change so wavelength changes
(decreases from lower n (air) to higher n (water))

Wave with $\theta_i > 0$
Change in wave speed results in **bending** of wave as it crosses the interface
(wavelength changes as above)
Law of refraction (Snell’s law)

\[ n_2 \sin \theta_2 = n_1 \sin \theta_1 \]

If the next index is greater, the ray is bent toward the normal.

If the next index is less, the ray is bent away from the normal.
Reflected ray from first interface is the incident ray for the second interface
The glass causes the ray of light to get displaced parallel to itself.
Demo: glass block and laser
i-clicker:

When light goes from one medium to another, its frequency doesn’t change. Suppose light goes from air $n=1$ into water $n=1.33$

a) Its speed will stay the same  
b) Its wavelength will stay the same  
c) Its speed will increase  
d) Its wavelength will decrease
i-clicker:

When light goes from one medium to another, its frequency doesn’t change. Suppose light goes from air $n=1$ into water $n=1.33$

a) Its speed will stay the same
b) Its wavelength will stay the same
c) Its speed will increase
d) Its wavelength will decrease
What happens if $n_1 = n_2$?

Fig. 33-16 (Continued) (b) A ray representation of (a). The angles of incidence ($\theta_1$), reflection ($\theta'_1$), and refraction ($\theta_2$) are marked.
What happens if $n_1 = n_2$?

Answer: NOTHING – it is as if both materials were the same and there was no interface: light goes through without bending, no reflection

$n$ of air = 1.0
$n$ of pyrex glass = 1.474
$n$ of Wesson vegetable oil = 1.474

DEMO
33.9: Total Internal Reflection

For angles of incidence larger than \( \theta_c \), such as for rays \( f \) and \( g \), there is no refracted ray and all the light is reflected; this effect is called **total internal reflection**.

For the critical angle, \( n_1 \sin \theta_c = n_2 \sin 90^\circ \),

\[
\theta_c = \sin^{-1} \frac{n_2}{n_1} \quad \text{(critical angle)}.
\]

**DEMO:** light pipe and optical fibers

FOG DEMO with crystal
Reflected light: what happens to the polarization?

In general, it changes

At a special angle of incidence

Reflected light is polarized as shown

Brewster angle

\[ \theta_B = \tan^{-1} \frac{n_2}{n_1} \]

Polaroid sunglasses are polarizing sheets that block this polarization – reduce glare from water
Point object is source of light = straight rays

Observer assumes that light arriving from point object has traveled in a straight line
Locate the object by detecting two or more rays and finding where they intersect

If light has been bent, apparent position is different from true position
Light from submerged object
Apparent depth of submerged objects

\[ y' = \frac{\tan \theta_2}{\tan \theta_1} \]

\[ y \approx \frac{\sin \theta_2}{\sin \theta_1} \]

\[ y = \frac{y}{n_2 / n_1} \]

Fish is deeper than it looks

y: true depth of fish
y’: apparent depth

Approximation is good for \( \theta \) small (close to normal)
Object is lower than it looks

Position of object in air viewed from underwater

\[ y' = \frac{\tan \theta_1}{\tan \theta_2} \]

\[ y \approx \frac{\sin \theta_1}{\sin \theta_2} y = \frac{n_2}{n_1} y \]

Approximation is good for \( \theta \) small (close to normal)

\( y \): true height of object

\( y' \): apparent height

Object is lower than it looks
i-clicker:
A swimmer under water looks up at the diving board, which is at a height y above water surface. What apparent height y' will swimmer perceive?

a) \( y' < y \)
b) \( y' = y \)
c) \( y' > y \)
i-clicker:
A swimmer under water looks up at the diving board, which is at a height $y$ above water surface. What apparent height $y'$ will swimmer perceive?

a) $y' < y$
b) $y' = y$
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33.8: Chromatic Dispersion:

The index of refraction $n$ encountered by light in any medium except vacuum depends on the wavelength of the light.

The dependence of $n$ on wavelength implies that when a light beam consists of rays of different wavelengths, the rays will be refracted at different angles by a surface; that is, the light will be spread out by the refraction.

This spreading of light is called chromatic dispersion.
**Chromatic Dispersion:** Glass prism separates white light into colors

**Fig. 33-19** Chromatic dispersion of white light. The blue component is bent more than the red component. 
(a) Passing from air to glass, the blue component ends up with the smaller angle of refraction. 
(b) Passing from glass to air, the blue component ends up with the greater angle of refraction. Each dotted line represents the direction in which the light would continue to travel if it were not bent by the refraction.