The Nature and Propagation of Light

Chapter 33
November 20, 2012
Reminders....

- Our final exam will be on Friday December 7th at 12:30 pm in this room.
- The final exam is cumulative and will cover all topics from the semester evenly.
- There is a sample final exam on my web site for you to take a look at.
- If you have three finals on December 7th, please see me after class on the 11/27 to discuss the possibilities for a makeup.
Overview of the next few classes

- Following our introduction of the wave equation for E&M fields in the last chapter, we will now embark on the study of the optical properties of various surfaces and interfaces.

- This discussion will then be followed by the introduction of the concepts of Geometrical Optics.

- Then we will conclude our discussion of light with an introduction to the principals of interference and diffraction.
Learning Goals

- What is a light ray and how is it related to a wave front.
- The laws that govern reflection and refraction.
- The circumstances governing “total internal reflection”
- How to make polarized light out of ordinary light.
- What is Huygen’s Principle?
Wave Fronts and Light Rays

Wave Fronts
(move at the velocity of propagation of the wave in the medium)

Rays (are always perpendicular to the wave fronts that they are associated with.)
The ratio of the velocity of light in vacuum divided by the velocity of light in the medium is called the "index of refraction" of the medium.

\[ \frac{C}{v} = n \equiv \text{index of refraction} \]

\( n \) of vacuum is 1 and all other indices are \( > 1 \).

\( n_{\text{H}_2\text{O}} = 1.33 \); \( n_{\text{air}} = 1.0003 \); \( n_{\text{Diamond}} = 2.42 \)

• Remember for all wave phenomenon
  \( v_{\text{propagation}} = \lambda f \)

  with the \( v_{\text{propagation}} = \frac{\lambda}{n} \) for a given substance.

\( \frac{v_{\text{propagation}}}{\text{H}_2\text{O}} = \frac{2.997 \times 10^8 \text{ m/s}}{1.33} = 2.28 \times 10^8 \text{ m/s} \)
Reflection and Refraction of light at a boundary between materials
Reflection by a Plane Mirror

"Incident" Ray \text{\textcolor{red}{Ein}} \quad \text{\textcolor{red}{Out}} \quad "Outgoing" Ray \text{\textcolor{red}{Ray}}

At a plane surface ... the angle of incidence of the incoming ray with the "normal" to the surface \textcolor{red}{equals} the angle of reflection of the outgoing ray with the same normal.

This law is the result of conservation of momentum in the scattering of the light ray at this flat surface. (The same law governs the scattering of the balls in a game of pool.)
Using this result and the principles of geometrical optics we can find the location of the images being formed.

These similar triangles give \( d_i = d_o \)

These similar triangles show that \( h_i = h_o \)

The image is behind the mirror and it is "up right". The images are "seen" in a mirror are "VIRTUAL IMAGES"
Laws of Reflection and Refraction

- The incident, reflected and refracted rays and the normal to the surface all lie in the same plane.
- The angle of reflection is equal to the angle of incidence (as measured with respect to the normal to the surface.)
- For monochromatic light, the ratio of the sines of the angle of incidence and refraction is equal to the inverse ratio of the indices of refraction.
$n_a \sin \theta_a = n_b \sin \theta_b$  \hspace{1cm} \text{(law of refraction)} \hspace{1cm} (33.4)
Typical indices of refraction

<table>
<thead>
<tr>
<th>Substance</th>
<th>Index of Refraction, $n$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solids</strong></td>
<td></td>
</tr>
<tr>
<td>Ice (H$_2$O)</td>
<td>1.309</td>
</tr>
<tr>
<td>Fluorite (CaF$_2$)</td>
<td>1.434</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>1.49</td>
</tr>
<tr>
<td>Rock salt (NaCl)</td>
<td>1.544</td>
</tr>
<tr>
<td>Quartz (SiO$_2$)</td>
<td>1.544</td>
</tr>
<tr>
<td>Zircon (ZrO$_2$·SiO$_2$)</td>
<td>1.923</td>
</tr>
<tr>
<td>Diamond (C)</td>
<td>2.417</td>
</tr>
<tr>
<td>Fabulite (SrTiO$_3$)</td>
<td>2.409</td>
</tr>
<tr>
<td>Rutile (TiO$_2$)</td>
<td>2.62</td>
</tr>
<tr>
<td><strong>Glasses (typical values)</strong></td>
<td></td>
</tr>
<tr>
<td>Crown</td>
<td>1.52</td>
</tr>
<tr>
<td>Light flint</td>
<td>1.58</td>
</tr>
<tr>
<td>Medium flint</td>
<td>1.62</td>
</tr>
<tr>
<td>Dense flint</td>
<td>1.66</td>
</tr>
<tr>
<td>Lanthanum flint</td>
<td>1.80</td>
</tr>
</tbody>
</table>

Table 33.1  Index of Refraction for Yellow Sodium Light ($\lambda_0 = 589$ nm)

Copyright © 2004 Pearson Education, Inc., publishing as Addison Wesley.
Now we want to move on to consider what happens when light passes through a transparent medium with an index of refraction, \( n \).

![Diagram of light refraction at an interface]

**SNEILL'S LAW OF REFRACTION**

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

where \( n_1 \) is index of refraction of medium 1 and \( n_2 \) is index of refraction of medium 2.

**Note:** All angles here are measured relative to the normal to the surface.
Refraction, an example.

**Example**

Air

30°

Water

**A)** Find angle of reflected and refracted rays relative to the normal.

**B)** What is the velocity of light in water?
The Solution

Part A)

\[ \theta_i = 60^\circ \]

\[ \theta_r = 60^\circ \text{ to normal!} \]

\[ \text{Ejected} \]

\[ \text{Reflected} \]

\[ \frac{1.00 \sin 60^\circ}{1.33 \sin \theta_r} = \frac{1.00 \sin 60^\circ}{1.33} \]

\[ \sin \theta_r = \frac{1.00}{1.33} \sin 60^\circ \]

\[ = \left( \frac{1.00}{1.33} \right) \cdot 0.866 \]

\[ = 0.65 \]

\[ \theta_r = 40.6^\circ \]

Part B)

\[ n_{H_2O} = 1.33 = \frac{c}{V_{H_2O}} \]

\[ \text{So} \]

\[ V_{H_2O} = \frac{c}{1.33} = \frac{3 \times 10^8}{1.33} = 2.25 \times 10^8 \text{ m}^3 \]
Light ray is "trapped" by internal reflections if $\alpha$, $\beta$, and $\gamma$ exceed the critical angle.

Total Internal Reflection

**Critical Angle** when TIR occurs

$$n_1 \sin \Theta_i = n_2 \sin 90^\circ = n_2$$

$$\Rightarrow \sin \Theta_i = \frac{n_2}{n_1} < 1$$

**Air/Water**

$n_{\text{Air}} = 1$; $n_{\text{H}_2\text{O}} = 1.33$

$$\sin \Theta_i = \frac{1}{1.33} = 0.751; \Theta_i = 48.8^\circ$$

**Air/Plastic**

$n_{\text{Air}} = 1$; $n_{\text{Plastic}} = 1.45$

$$\sin \Theta_i = \frac{1}{1.45} = 0.68; \Theta_i = 43.6^\circ$$
Dispersion of light

Index of refraction (n)

1.7

Silicate flint glass

1.6

Borate flint glass

Quartz

1.5

Silicate crown glass

Fused quartz

Fluorite

Wavelength in vacuum (nm)

400 500 600 700

White light

Deviation of yellow light

Measure of dispersion

Copyright © 2004 Pearson Education, Inc., publishing as Addison Wesley.
Physics 208

17
Polarization of Light

The direction of the polarization of a light ray is given by the direction of the electric field vector in that wave.
Polarization of Light by reflection at a surface

1. If natural light is incident at the polarizing angle …

2. … then the reflected light is 100% polarized perpendicular to the plane of incidence …

3. … and the transmitted light is partially polarized parallel to the place of incidence.
Huygen’s Principle

\[ r = vt \]
Huygen’s Principle and Snell’s Law

(a) Material $a$ | $n_a$ | $S$ | $n_b$ | Material $b$

(b) Material $a$ | $v_{at}$ | $O$ | $v_{bt}$ | Material $b$