PHYS 262

George Mason University

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Chapter 33: The Nature and Propagation of Light

- The nature of light
- Reflection and Refraction
- Total internal reflection
- Dispersion
- Polarization
- Huygens’ principle
The Nature of Light

Light is a propagating **electromagnetic waves**
The Nature of Light

But, as we will learn (later), light can also be characterized as discrete packets of energy called photons.

Also, as we will learn (later), light travels in vacuum at the same speed:

\[ c = 2.99792458 \times 10^8 \text{ m/s} \]

and it is the universal speed limit for all physical processes.
Sources of Light

- Thermal Radiation: E&M radiation from accelerating charges due to thermal motion.
  - Mixture of many $\lambda$'s
  - Bluer with higher $T$
Sources of Light

- Electrical Discharges thru diluted Ionized Gases (will study this later)
  - Lights are in a selected set of wavelengths
  - e.g. sodium vapor lamps (street lamps), neon signs, fluorescent lamps
Sources of Light

- Lasers
  - Coherent
  - Monochromatic (single frequency)

- Light Emitting Diodes (LEDs)
  - Semiconductor device
  - Electroluminescence
  - Narrow range of frequencies
  - Very low power consumption
Propagation of Light: Waves and Wave Fronts

Propagating waves are usually visualized as a sequence of expanding wave fronts in space.

Wave front: the locus of points where the wave has the same phasic relation, e.g. crests, troughs.
Waves, Wave Fronts, and Rays

When wave fronts are planar (source is sufficiently far away), rays are perpendicular to the wave fronts and parallel to each other.

Rays are always \textit{perpendicular} to the wave fronts.

A ray indicates the direction of travel of the wave.
The Study of Light: Optics

- Geometric (or Rays) Optics:
  - In most daily situations, light (rays) travel in a *straight* line in a *uniform* medium.
  - At the boundary between two materials (air & glass), a ray’s direction might change.
  - Wave characteristics of light are not important.

Geometric Optics is the study of the propagation of light with the assumption that rays are *straight* lines in a *fixed* direction through an *uniform* medium.
The Study of Light: Optics

- Condition for Rays Optics:
  \[ L >> \lambda \]

  Relevant system size >> wavelength

  In this approximation, wave characteristic of light is not important and rays model of light gives accurate predictions.

  (Visible light: \( \lambda \approx 500 \text{ nm} \ll L \) \( \rightarrow \) Rays Optics works well with typical optical instruments: mirror, lens, cameras, telescopes, …)

- Physical (Wave) Optics (Ch.35-36):
  The study of light when wave properties of light are important (diffraction and interference).
  \[ L \approx \lambda \]
When light hits a boundary, typically a part of it will be reflected & a part of it will be refracted.
Reflection

- **Specular Reflection**
  - Reflection from a smooth surface
  - Reflected rays are parallel

- **Diffused Reflection**
  - Reflection from a rough surface
  - Reflected rays are in various directions
Law of Reflection

\[ \theta_r \text{(angle of reflection)} = \theta_a \text{(angle of incidence)} \]
Law of Reflection (general interface)
Example 33.3 (Retroreflector)

Reflected ray goes back in the same direction as incident ray independent of incident angel $\theta$!

YouTube video of retroreflector: https://www.youtube.com/watch?reload=9&v=S4vYq31cpyc
Index of Refraction $n$:

- In materials, light interacts with atoms/molecules and travels *slower* than it can in vacuum, e.g.,
  \[ v_{water} \approx \frac{3}{4} c \]

- The optical property of transparent materials is called the **Index of Refraction**:
  \[ n \equiv \frac{c}{v_{\text{material}}} \quad \text{(Table 33.1)} \]

- Since $v_{\text{material}} < c$ always, $n > 1$!
### Index of Refraction \((n)\)

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

<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 ((\text{H}_2\text{O}))</td>
<td>1.309</td>
</tr>
<tr>
<td>Fluorite ((\text{CaF}_2))</td>
<td>1.434</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>1.49</td>
</tr>
<tr>
<td>Rock salt ((\text{NaCl}))</td>
<td>1.544</td>
</tr>
<tr>
<td>Quartz ((\text{SiO}_2))</td>
<td>1.544</td>
</tr>
<tr>
<td>Zircon ((\text{ZrO}_2\cdot\text{SiO}_2))</td>
<td>1.923</td>
</tr>
<tr>
<td>Diamond ((\text{C}))</td>
<td>2.417</td>
</tr>
<tr>
<td>Fabulite ((\text{SrTiO}_3))</td>
<td>2.409</td>
</tr>
<tr>
<td>Rutile ((\text{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>
<tr>
<td><strong>Liquids at 20°C</strong></td>
<td></td>
</tr>
<tr>
<td>Methanol ((\text{CH}_3\text{OH}))</td>
<td>1.329</td>
</tr>
<tr>
<td>Water ((\text{H}_2\text{O}))</td>
<td>1.333</td>
</tr>
<tr>
<td>Ethanol ((\text{C}_2\text{H}_5\text{OH}))</td>
<td>1.36</td>
</tr>
<tr>
<td>Carbon tetrachloride ((\text{CCl}_4))</td>
<td>1.460</td>
</tr>
<tr>
<td>Turpentine</td>
<td>1.472</td>
</tr>
<tr>
<td>Glycerine</td>
<td>1.473</td>
</tr>
<tr>
<td>Benzene</td>
<td>1.501</td>
</tr>
<tr>
<td>Carbon disulfide ((\text{CS}_2))</td>
<td>1.628</td>
</tr>
</tbody>
</table>
Index of Refraction and Wave Aspects of Light

Note: frequency of the EM wave is dictated by the oscillations of the charge and the timing of this oscillation can’t change for an observer in either medium $a$ or $b$.

$f$ does not change across media!
Recall for a EM wave, we have: \( v = f \lambda \)

So, in the two medium, we have:

\[ v_a = f \lambda_a \quad \text{and} \quad v_b = f \lambda_b \]

Dividing these two equations, we have:

\[
\frac{v_a}{v_b} = \frac{f \lambda_a}{f \lambda_b} = \frac{\lambda_a}{\lambda_b} \quad \Rightarrow \quad \frac{\lambda_a}{\lambda_b} = \frac{c/n_a}{c/n_b} \quad \Rightarrow \quad \frac{\lambda_a}{\lambda_b} = \frac{n_b}{n_a}
\]

So, the wavelength of a light must change in different medium accordingly,

\[ n_a \lambda_a = n_b \lambda_b \]

With one medium being a \textit{vacuum}, we have \( \lambda_n = \lambda/n \)
Law of Refraction (Snell’s Law)

\[ n_a \sin \theta_a = n_b \sin \theta_b \]
Snell’s Law (3 cases)

Recall

\[ n = \frac{c}{v} \]

\[ n_a \sin \theta_a = n_b \sin \theta_b \]

A ray entering a material of larger index of refraction bends toward the normal.

A ray entering a material of smaller index of refraction bends away from the normal.
Total Internal Reflection

- Light moves from a medium with a larger $n$ to one with a smaller $n$.

- As the angle of incidence becomes more and more acute, the light ceases to be transmitted, only reflected.
Total Internal Reflection

- Critical Angle $\theta_{crit}$ is determined by the borderline case (ray 3).

\[ n_a \sin \theta_{crit} = n_b \sin 90^\circ \]  \hspace{1cm} \text{(from Snell’s Law)}

\[
\sin \theta_{crit} = \frac{n_b}{n_a}
\]  \hspace{1cm} \text{(only valid for } n_a > n_b)
Applications of Internal Reflection

(a) Total internal reflection in a Porro prism

(b) Binoculars use Porro prism reflect the light to each eyepiece

The light is trapped in the rod if all the angles of incidence (such as $\alpha$, $\beta$, and $\gamma$) exceed the critical angle.

If the incident beam is oriented as shown, total internal reflection occurs on the 45° faces (because, for a glass–air interface, $\theta_{\text{crit}} = 41.1°$).
Dispersion

- The index of refraction $n$ is usually a property of the medium but equally important, it also varies with the frequency $f$ of light $\rightarrow$ dispersion.
- $n$ typically increases with increasing $f$. 
Physical Observable Consequence of Dispersion

- The Visible Spectrum of White Light

According to Snell’s Law, angle of refraction depends on \( n \),

\[
\sin \theta_a = n \sin \theta_{blue} \quad \text{and} \quad n \sin \theta_{red}
\]

\( \theta_{blue} < \theta_{red} \)

\( n > n \)
Dispersion by a Prism