Refraction

The speed of light in vacuum is: \( c = 3 \times 10^8 \text{ m/s} \)

But if light passes through a different medium (e.g., water, glass) it travels slower.

E.g.: Speed of light through diamond is: \( 1.2 \times 10^8 \text{ m/s} \)

Every medium has an Index of Refraction \((n)\):

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

...which measures the speed of light in that medium, \( v \), compared to \( c \).
### Table 26–2: Index of Refraction for Common Substances

<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>Diamond</td>
<td>2.42</td>
</tr>
<tr>
<td>Flint glass</td>
<td>1.66</td>
</tr>
<tr>
<td>Crown glass</td>
<td>1.52</td>
</tr>
<tr>
<td>Fused quartz (glass)</td>
<td>1.46</td>
</tr>
<tr>
<td>Ice</td>
<td>1.31</td>
</tr>
<tr>
<td><strong>LIQUIDS</strong></td>
<td></td>
</tr>
<tr>
<td>Benzene</td>
<td>1.50</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>1.36</td>
</tr>
<tr>
<td>Water</td>
<td>1.33</td>
</tr>
<tr>
<td><strong>GASES</strong></td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>1.00045</td>
</tr>
<tr>
<td>Air</td>
<td>1.000293</td>
</tr>
</tbody>
</table>

**Index of Refraction (n):**

$$n = \frac{c}{v}$$
Refraction: Snell’s Law

When light enters a new medium, its speed changes. This causes it to bend (refract). The angle of incidence ($\theta_1$) does not equal the angle of refraction ($\theta_2$). Instead they are related by:

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

Where $n_1$, $n_2$ = Indices of refraction.

(A portion of the light is reflected and obeys the law of reflection: $\theta_i = \theta_r$)
Properties of refraction:

1. Light entering a more dense medium bends Toward the normal.
2. Light entering a less dense medium bends Away from the normal.

“Toward” & “Away” mean with respect to the original path of the light.

(There is no change in angle if light strikes along the normal or if $n$ is the same for both media.)
1.) Does $\theta_1 = \theta_2$?

2.) Where does the gold coin appear: A, B or C???
Total Internal Reflection

Light can also *speed up* if it enters a medium of *lower* index of refraction *(n)*.

It will be bent *away from* the normal.

Also, some of the beam will be reflected back into the original medium.

As the angle of incidence *(θ₁)* increases, the angle of *refraction* *(θ₂)* approaches 90°!
(a) Small angle of incidence
(b) Larger angle of incidence
Figure 26-25C

(c) Refracted beam parallel to interface

No light enters medium 2!!!
Total Internal Reflection

Light entering a **less dense medium** it will bend _away from_ the normal.

At some **critical angle** ($\theta_c$) the _entire beam_ is reflected.

This is called:

**Total Internal Reflection**

---

**Snell’s Law**

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

---

(c) Refracted beam parallel to interface
If light enters a new medium, it will **refract**. The angle of refraction depends on the **index of refraction** \((n)\) of each medium.

Snell's Law

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]
Each layer in Earth’s Atmosphere has a different temperature and different density, and thus different index of refraction: $n$.

This causes an interesting optical effect.... Mirages.
Sometimes we see an image below an object....
An ‘Inferior Mirage’
Superior Mirage stretches out the tops of mountains.
Another type of mirage is called Fata Morgana.
Where will the light come out?
A prism refracts light *towards its base*. 

Where will the light come out?

A

B

C

D

[Diagram showing light refracting towards the base of a prism]

A prism refracts light *towards its base*. 

A

B

C

D

[Diagram showing light refracting towards the base of a prism]
Converging (Convex) Lenses

Two prisms with their bases together bring light to the optic axis.

Change the shape a little and you have....

A lens!

If the middle is thicker (convex), then the lens converges light to a focus.
Diverging (Concave) Lenses

...are similar to two prisms with their *points* together. They cause light to diverge.
A Convex Lens Converges parallel light

A Concave Lens Diverges Parallel Light
Like mirrors, lenses produce images.

$d_o$, $d_i$, & $f$ have same meaning.
The Thin-Lens Equation

If a lens is thin, then we can use:

\[
\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}
\]

**Thin-Lens Equation**

\[
m = -\frac{d_i}{d_o}
\]

**Magnification, \( m \)**

These are the same equations as with mirrors!

But there are sign conventions...
## Sign conventions for LENSES and MIRRORS

<table>
<thead>
<tr>
<th>Quantity</th>
<th>+</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$</td>
<td>convex lens</td>
<td>concave lens</td>
</tr>
<tr>
<td>$m$</td>
<td>upright</td>
<td>inverted</td>
</tr>
<tr>
<td>$d_i$</td>
<td>real</td>
<td>virtual</td>
</tr>
<tr>
<td>$f$</td>
<td>concave mirror</td>
<td>convex mirror</td>
</tr>
</tbody>
</table>
Ray Tracing for Lenses

The three principal rays for lenses are similar to those for mirrors. Before hitting the lens:

- The $F$ ray goes through a focus
- The $P$ ray is Parallel to optic axis
- The $M$ ray goes through lens midpoint.

Start these rays at the *tip of the object*, and let them pass through the lens.
Convex Lens

$P$ ray

$M$ ray

$F$ ray
Principal Rays

After passing through the lens,

- The $F$ ray: goes parallel to the optic axis.
- The $P$ ray: targets the focus.
- The $M$ ray: is not deflected*

The image is found at the intersection of these rays.

*Assuming the lens is “thin”
Convex Lens

$P$ ray

$M$ ray

$F$ ray
Demo: thick lens

This image is inverted
(and “Real” ... because light actually goes there.)
Convex Lens: What if the object is inside $F$?

(b) Object between $F$ and the lens
(b) Object between $F$ and the lens

Image is Upright and Magnified
...... a magnifying glass!
Concave Lenses Make Light *Diverge*

But they still can form an **Image**...
Image is smaller and virtual
### TABLE 26–3 Imaging Characteristics of Concave and Convex Lenses

<table>
<thead>
<tr>
<th>CONCAVE LENS</th>
<th>Convex Lens</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Object location</strong></td>
<td><strong>Image orientation</strong></td>
</tr>
<tr>
<td>Arbitrary</td>
<td>Upright</td>
</tr>
<tr>
<td><strong>Concave Lens</strong></td>
<td><strong>Image orientation</strong></td>
</tr>
<tr>
<td><strong>Object location</strong></td>
<td><strong>Beyond F</strong></td>
</tr>
<tr>
<td><strong>Just beyond F</strong></td>
<td><strong>Inverted</strong></td>
</tr>
<tr>
<td><strong>Just inside F</strong></td>
<td><strong>Upright</strong></td>
</tr>
<tr>
<td><strong>Between lens and F</strong></td>
<td><strong>Upright</strong></td>
</tr>
</tbody>
</table>

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For \( f = +20 \text{ cm.} \) (+ means convex)

\[
\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{+20 \text{ cm}}
\]

<table>
<thead>
<tr>
<th>( d_o )</th>
<th>( d_i )</th>
<th>( m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-2.2</td>
<td>1.1</td>
</tr>
<tr>
<td>5</td>
<td>-6.6</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-20</td>
<td></td>
</tr>
<tr>
<td>19.9</td>
<td>-3900</td>
<td>195</td>
</tr>
<tr>
<td>25</td>
<td>+100</td>
<td>-4</td>
</tr>
<tr>
<td>50</td>
<td>33</td>
<td>-0.6</td>
</tr>
<tr>
<td>100</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>20.4</td>
<td>-0.02</td>
</tr>
</tbody>
</table>