Suppose \( \theta_f = 90^\circ \)

\[
\sin \theta_c = \frac{n_i}{n_o}
\]

\( \eta_1 \sin \theta_1 = \eta_2 \sin 90^\circ \)

\( \theta_i \geq \theta_c \) gives no refracted light—only reflected light

\( \rightarrow \) total internal reflection

Fiber optics

Laser surgery
Endoscopic surgery

Thin lenses

Lens eqn

\[
\frac{1}{o} + \frac{1}{i} = \frac{1}{f}
\]

Object distance
Image distance
Focal length

Thickness of lens is small compared to \( d, e, i, o, f \).

Ray diagram is often used in analysis

Parallel ray
Central ray
Focal ray

Do convex lens diagram
Sign Conventions

<table>
<thead>
<tr>
<th>$f$</th>
<th>$0$</th>
<th>$i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>convex lens</td>
<td>$+$</td>
<td></td>
</tr>
<tr>
<td>diverging lens</td>
<td>$-$</td>
<td></td>
</tr>
<tr>
<td>real object</td>
<td>$+$</td>
<td></td>
</tr>
<tr>
<td>virtual object</td>
<td>$-$</td>
<td></td>
</tr>
<tr>
<td>real image</td>
<td>$+$</td>
<td></td>
</tr>
<tr>
<td>virtual image</td>
<td>$-$</td>
<td></td>
</tr>
</tbody>
</table>

Magnification

Triangle ABC is similar to triangle DEC

\[ M = \frac{h'}{h} = -\frac{i}{o} \]

"-" means inverted image
"+" would mean an upright image

Examples

Object 2mm high 100 cm from converging lens of focal length 20 cm

Where and how large is image?

\[ \frac{1}{100} + \frac{1}{i} = \frac{1}{20} \]
\[ i = +25 \text{ cm} \]

\[ M = -\frac{h'}{h} = -\frac{\frac{25}{100}}{25} = -0.25 \]

Image is real, inverted and \((2 \text{ mm}) \times (-2.5) = 0.5 \text{ mm high}\)
f is > Converging lens

- rays converge
- thicker in middle

f is < Diverging lens

- rays
- "rays

Show how rays go in diagrams

Tricky part up Thin lens eqn is the Sign Convention to do homework problems on this one or else!

Real/Virtual image/object Conventions

An image is virtual if the rays diverge from it

An image is real if rays converge toward it

(can project on a screen!)

An object is virtual when rays converge toward it
(on to the "image" side of a thin lens)

An object is real when rays diverge from it.
Suppose object is 15 cm from same lens?

\[ \frac{1}{d} + \frac{1}{i} = \frac{1}{f} \]

\[ \frac{1}{15} + \frac{1}{i} = \frac{1}{20} \]

\[ i = -60 \]

Image is virtual erect

\[ m = \frac{-60}{15} = 4 \]

4x larger than object

\[ (4)(2 \text{ cm}) = 8 \text{ mm} \]

Eye Examples

Compound systems - optical instruments

⇒ image of first lens is the object of the 2nd lens

Magnification

Natural rays from object diverge. When they \( d \) is small enough, your eye can no longer compare → Near point

\( \theta' \) larger than \( \theta \) because object is closer

\[ a \cdot d > f \quad M = \frac{\theta'}{\theta} \approx \frac{d}{f} \]

⇒ Allows one to magnifying glass
Object is 50 cm to left of lens 1. What is final position, size, and nature of final image?

**Lens 1**

\[
\frac{1}{o} + \frac{1}{i} = \frac{1}{f} \quad \frac{1}{50} + \frac{1}{i} = \frac{1}{40}
\]

\[i = 200 \text{ cm}\]

\[M_1 = -\frac{200}{+50} = -4\]

**Lens 2**

\[o = +20 \text{ cm}\]

\[
\frac{1}{20} + \frac{1}{i} = \frac{1}{10}
\]

\[i = +20 \text{ cm}\]

\[M_2 = -\frac{20}{+20} = -1\]

**Lens 3**

Object is 12 cm to right of lens 3.

Counts as virtual object

\[-\frac{1}{12} + \frac{1}{i} = -\frac{1}{3}\]

\[i = -4 \text{ cm}\]

\[M_3 = -\frac{-4 \text{ cm}}{-12 \text{ cm}} = -\frac{1}{3}\]

\[\text{inverted virtual}\]

\[\frac{4}{3} \times \text{size of original object}\]

\[M_{total} = M_1 \times M_2 \times M_3 = (-4)(-1)(-\frac{1}{3}) = -\frac{4}{3}\]
Ray diagrams for thin lenses