Physics 30
Electromagnetic Radiation - Optics

Jad Chehimi

May 19, 2021

Unfinished!

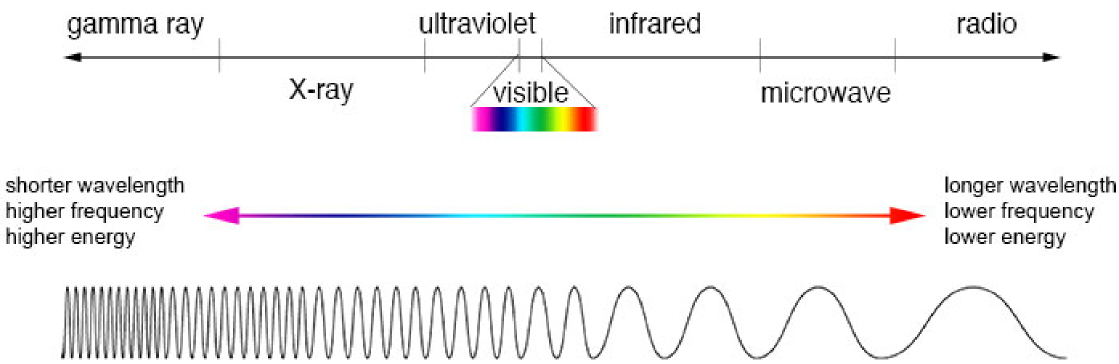
Contents

Terms

- **Monochromatic Light**: Light of one colour
- **Medium**: the material the wave is travelling in
- **Refraction**: a change in the direction of a light wave due to a change in its speed as it passes from one medium to another
- **Refractive Index**: a ratio comparing the speed of light in a vacuum to the measured speed of light in a given material ($n = \frac{c}{v}$)

Electromagnetic Spectrum

Figure 1: "Cosmic" rays on the left of gamma



- ALL EMR travels at the speed of light. ($c = 3.00 \times 10^{8}\ \frac{\text{m}}{\text{s}}$)
- Memorize the visible spectrum wavelength range
  - 400 nm to 750 nm
  - 400×10^{-9} m to 750×10^{-9} m

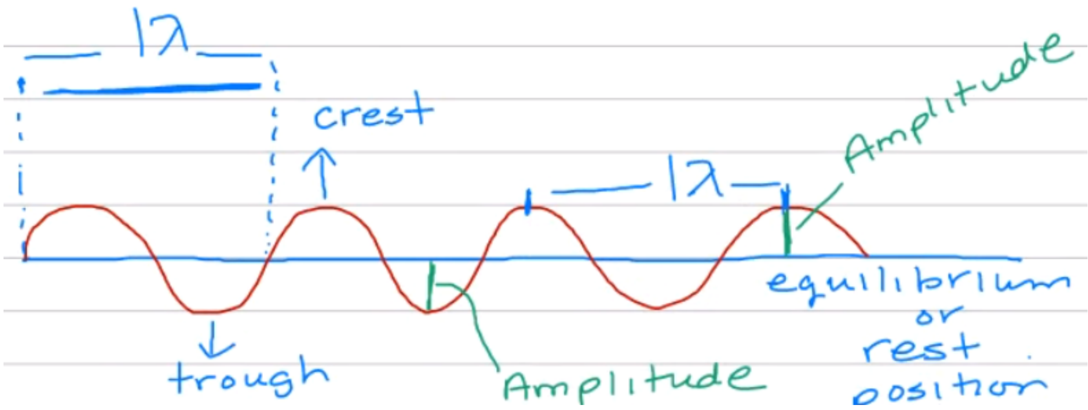
Universal Wave Equation

$$v = f\lambda$$

- v = speed ($\frac{\text{m}}{\text{s}}$)
- f = frequency (Hz)
- λ = wavelength (m) (often given in nanometers, 100 nm $= 100 \times 10^{-9}$ m)

Speed of light: $c = f\lambda$

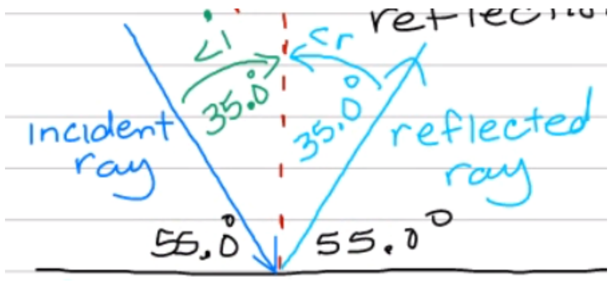
Transverse Wave



- **Crest**: peak of wave
- **Trough**: depression of wave
- **Amplitude**: the maximum displacement from the equilibrium position

Law of Reflection

$$\angle I = \angle R$$



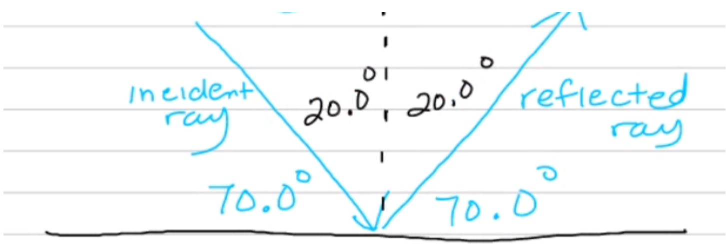
- $\angle I$: **Angle of Incidence**

  Measured from the light ray to the normal
- $\angle R$: **Angle of Reflection**

  Measured from reflected ray to normal
- **Normal**
  - Perpendicular to the surface
  - Broken/dotted line
  - Drawn from where the incident ray contacts the mirror surface

Example

A light ray strikes a flat mirror at an angle of 70.0° to the mirror surface. What is the angle of reflection? What is the angle between the incident ray and the reflected ray?



$\angle r = 20.0^\circ$

40.0° = the angle betwee the incident ray and the refected ray.

Refraction

The bending of a wave when entering a new medium at an angle.

- n: Index of Refraction (air is $n = 1.00$)
- When a light ray travels from a lower n-value medium to a greater n-value medium, the light ray will bend toward the normal

Snell's Law

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

Use to calculate the new angle in a different medium/n value.

$$\frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2} = \frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2}$$

Frequency

Frequency is unaffected by medium.

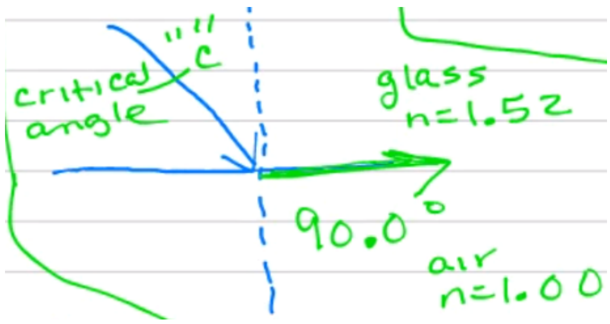
Frequency can only be changed at the source.

Critical Angle

For any two mediums, the critical angle is the angle of the incident angle for which the angle of refraction is 90°.

Two conditions must be met for a critical angle.

- The light must travel from a greater n-value to a lesser n-value
- The angle of refraction must be 90.0°



Total Internal Reflection

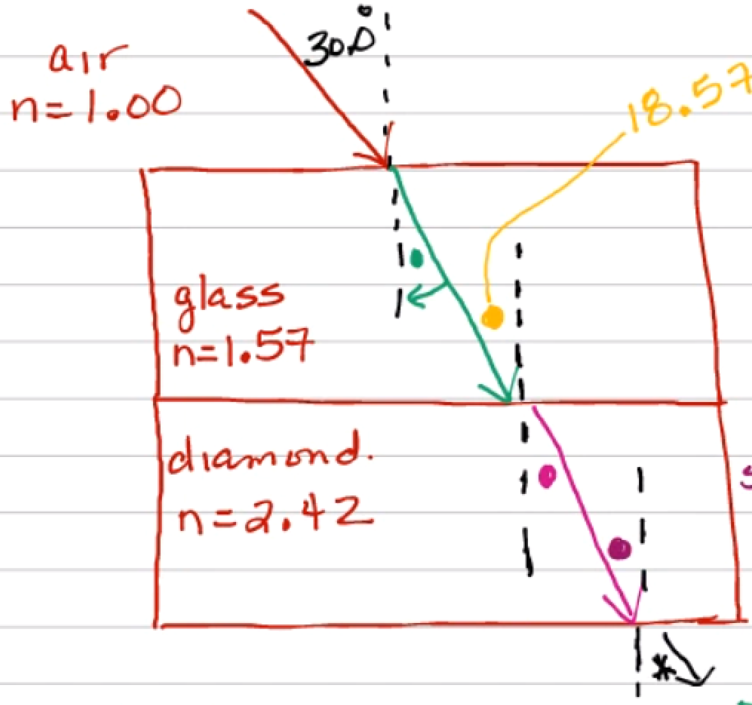
Reflection of all incident light back into a medium of higher refractive index due to the inability to refract light back at an angle beyond the maximum angle of 90°.

If the angle of incidence is greater than the critical value, then the ray will reflect instead of refract. (therefore, staying inside the medium)

Trying to calculate this angle with Snell's Law will error.

Examples

Parallelogram



$$\frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2}$$

$$\sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2}$$

$$\sin\theta_2 = \frac{2.42 \times \sin 11.9°}{1.00}$$

$$\theta_2 = 30.0°$$

n=1.00
air

Calculate the angle the light leaves the diamond with

$$\frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2}$$

$$\sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2}$$

$$\sin\theta_2 = \frac{1.00 \times \sin 30.0°}{1.57}$$

$$\theta_2 = \angle R = 18.57050303°$$

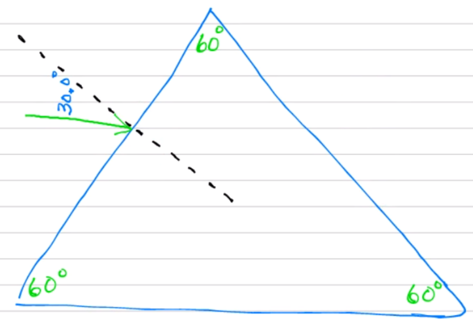
$$\frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2}$$

$$\sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2} = \frac{1.57 \times \sin 18.57}{2.42}$$

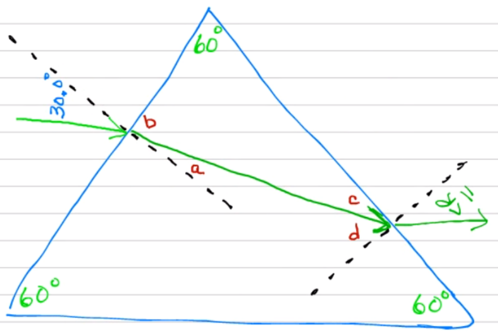
$$\theta_2 = 11.92385513°$$

Equilateral Triangle

Angle of incidence = 30.0°
nglass = 1.52
Equilateral Triangle
Refraction in a Triangular Prism.



Calculate the angle the light ray leaves the PRISM with.



(a) $\frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2}$

$\sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2}$

$\sin\theta_2 = \frac{1.00 \times 30.0^\circ}{1.52}$

$\theta_2 = 19.2048975^\circ$

(b) We know the normal is $\perp$ to the surface

$\therefore\ 90^\circ - 19.2048975^\circ = $ "b"

$b = 70.7951025^\circ$

(c) The sum of the angles of a $\Delta = 180^\circ$

$180^\circ - 70.7951025^\circ - 60^\circ = c$

$\angle c = 49.2048975^\circ$

(d) The normal is $\perp$ to the surface.

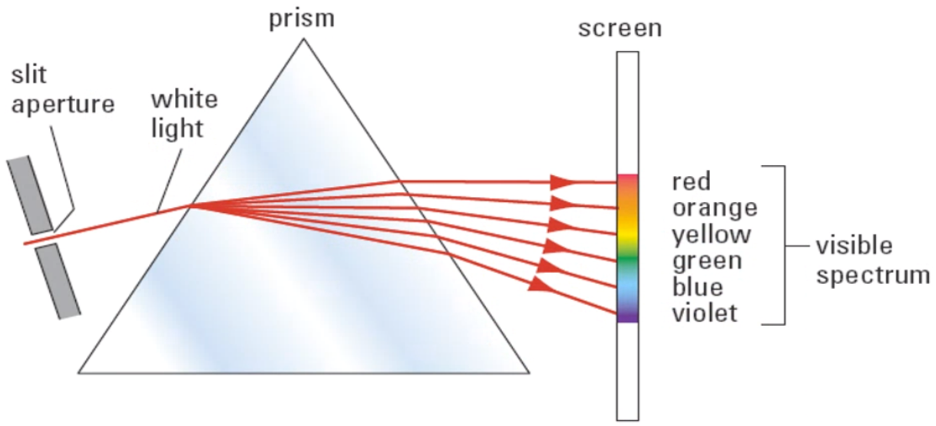
$\therefore\ 90^\circ - c = d$

$90^\circ - 49.2048975^\circ = 40.7951025^\circ$

$\angle d = 40.7951025^\circ$

$$\theta = 83.3^\circ$$

Dispersion



Separation of white light into its components.

The refraction of white light to form a spectrum of colours.

Spectrum: the bands of colours making up white light (red, orange, yellow, green, blue, violet)

In a rainbow, light from the sun enters a spherical raindrop and different colors are refracted at different angles.

Ray Diagrams for Lenses

- f: Focal length
- m: Magnification
- d_o: Object distance
- d_i: Image distance
- h_o: Object height
- h_i: Image height

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

$$\frac{h_i}{h_o} = \frac{-d_i}{d_o}$$

$$m = \frac{d_i}{d_o}$$

$$m = \frac{h_i}{h_o}$$

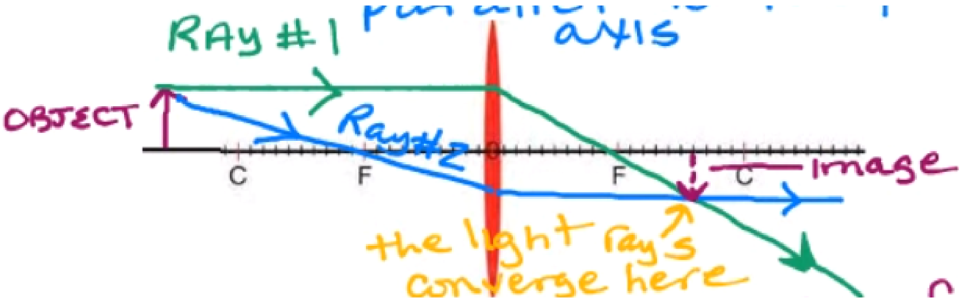
f is positive for convex lenses. f is negative for concave lenses.

Convex

- Ray 1 starts from the top of the object and travels parallel to the principal axis until the light ray strikes the midline of the lens
- Ray 1 then bends and travels down through F
- Ray 2 starts at the top of the object and travels down through F until the rayt strikes the midline of the lens
- Ray 2 then refracts and travels parallel to the principal axis
- The light rays converge at a point

Object Beyond C

aka. Converging Lens



The resulting image can be described as...

- **inverted** (upside down)
- **diminished** (smaller)
- located between F and C
- **real** (if the object and image are on opposite sides of the lens)

Example

A 3.00 cm tall object is placed 30.0 cm in front of a convex lens with a focal length of 10.0 cm. Calculate d_i, h_i and m.

$$\frac{hi}{ho} = \frac{-di}{do}$$

$$hi = \frac{ho \times -di}{do}$$

$$hi = \frac{3.00\,cm \times -15.0\,cm}{30.0\,cm}$$

$$hi = -1.50\,cm$$

The negative hi value tells me the image in inverted (upside down)

~~M = m = mag~~

$$\frac{1}{f} = \frac{1}{do} + \frac{1}{di}$$

f is positive for convex lenses

$$\frac{1}{di} = \frac{1}{f} - \frac{1}{do} = \frac{1}{10.0\,cm} - \frac{1}{30.0\,cm}$$

$$di = 15.0\,cm$$

(positive di tells me the image is real)

$$m = \frac{di}{do} = \frac{15.0\,cm}{30.0\,cm}$$

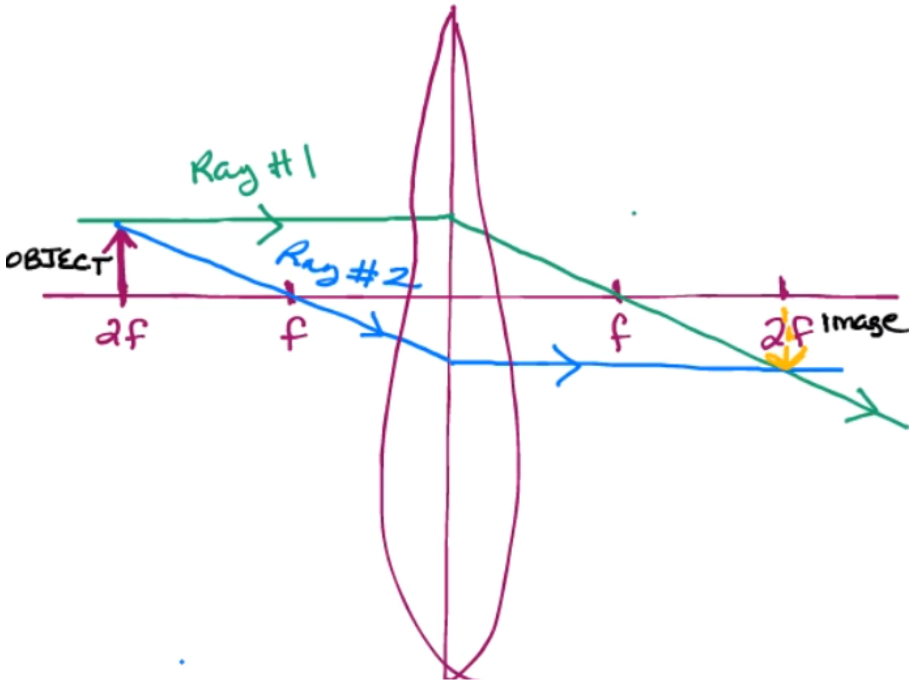
$$m = 0.500\,X$$

(diminished)

$$m = \frac{hi}{ho} = \frac{-1.50\,cm}{3.00\,cm}$$

$$m = -0.500\,X$$

Object At C



The resulting image can be described as...

- inverted
- same size
- located at C/2F
- real

Example

A 2.00 cm tall object is placed 20.0 cm in front of a convex lens with a focal length of 10.0 cm. Calculate d_i, h_i and m.

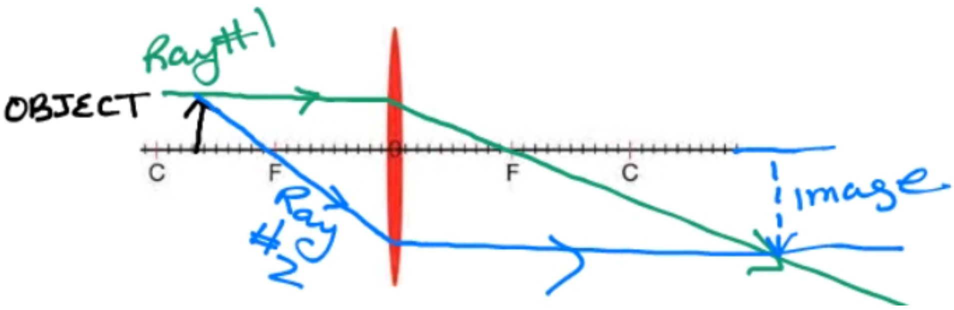
- $h_o = 2.00\,\text{cm}$
- $d_o = 20.0\,\text{cm}$
- $f = 10.0\,\text{cm}$

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$
$$\frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o}$$
$$\frac{1}{d_i} = \frac{1}{10.0\,\text{cm}} - \frac{1}{20.0\,\text{cm}}$$
$$d_i = 20.0\,\text{cm}$$

$$\frac{h_i}{h_o} = \frac{-d_i}{d_o}$$
$$h_i = \frac{h_o \times -d_i}{d_o}$$
$$h_i = \frac{2.00\,\text{cm} \times -20.0\,\text{cm}}{20.0\,\text{cm}}$$

$$m = \frac{d_i}{d_o}$$
$$m = \frac{20.0\,\text{cm}}{20.0\,\text{cm}} = 1$$

Object between C and F



The resulting image can be described as...

- inverted
- enlarged
- located beyond C/2F
- real

Object at F

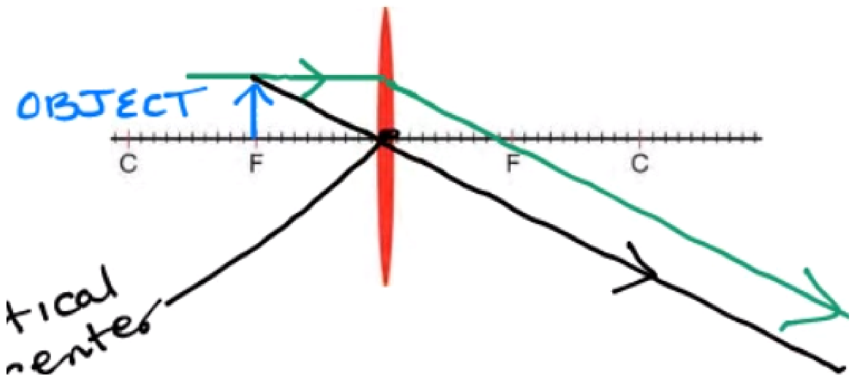
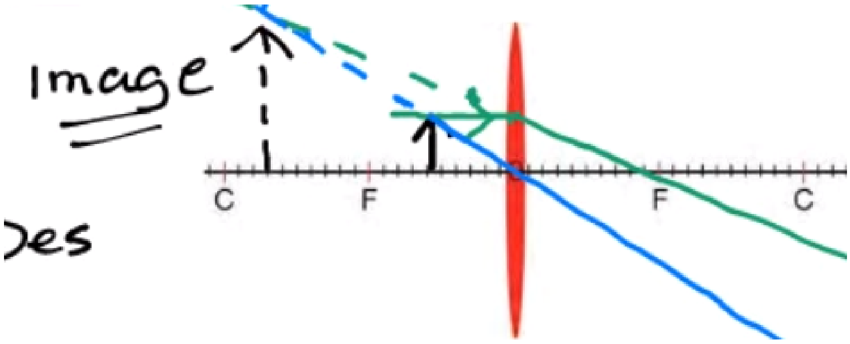


Figure 2: Ray 2 cannot be used because the object is sitting on the focal point (F). We must use Ray 3.

Ray 3 (is an imaginary ray that) starts from the top of the object and travels down through the optical center of the lens. This ray does not refract.

The rays end up running parallel to each other, so there is no image/image at infinity.

Convex, Object Inside F



The resulting image can be described as...

- **erect** (right side up)
- enlarged
- located beyond C/2F
- **virtual** (object and image on same side)

Example

A 4.00 cm tall object is 20.0 cm in front of a convex lens with a focal length of 40.0 cm. Calculate d_i, h_i and m.

- $h_o = 4.00\,\text{cm}$
- $d_o = 20.0\,\text{cm}$
- $f = 40.0\,\text{cm}$

$$\frac{1}{f} = \frac{1}{d_o} = \frac{1}{d_i}$$

$$\frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o}$$

$$\frac{1}{d_i} = \frac{1}{40.0\,\text{cm}} - \frac{1}{20.0\,\text{cm}}$$

$$d_i = -40.0\,\text{cm}$$

Negative d_i tells me the image is virtual.

$$\frac{h_i}{h_o} = \frac{-d_i}{d_o}$$

$$h_i = \frac{h_o \times -d_i}{d_o}$$

$$h_i = \frac{4.00\,\text{cm} \times -(-40.0\,\text{cm})}{20.0\,\text{cm}}$$

$$h_i = 8.00\,\text{cm}$$

Positive h_i means image is erect.

$$m = \frac{h_i}{h_o}$$

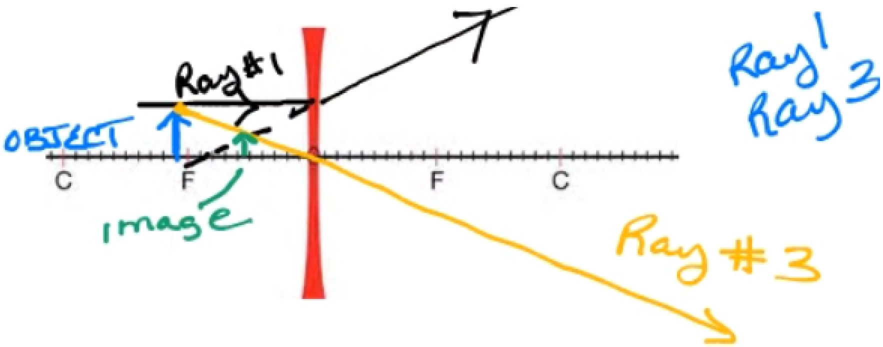
$$m = \frac{8.00\,\text{cm}}{4.00\,\text{cm}}$$

$$m = 2.00$$

Image will be 2.00X bigger than object.

Concave

- Diverging lens
- Ray 3 behaves as normal
- Ray 1 starts off straight and bends upward after the lens
- Use an imaginary line from point F to where ray 1 collides
- Ray 3 and the imaginary ray form the image



Concave lenses ALWAYS result in images described as...

- erect
- diminished
- virtual

Example

A 4.00 cm tall object is 15.0 cm in front of a concave lens with a focal length of 12.0 cm. Calculate d_i, h_i, and m.

- $h_o = 4.00\,\text{cm}$
- $d_o = 15.0\,\text{cm}$
- $f = -12.0\,\text{cm}$

$$\frac{1}{f} = \frac{1}{d_o} = \frac{1}{d_i}$$

$$\frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o}$$

$$\frac{1}{d_i} = \frac{1}{-12.0\,\text{cm}} - \frac{1}{15.0\,\text{cm}}$$

$d_i = -6.67\,\text{cm}$ (virtual)

$$\frac{h_i}{h_o} = \frac{-d_i}{d_o}$$

$$h_i = \frac{h_o \times -d_i}{d_o}$$

$$h_i = \frac{4.00\,\text{cm} \times -(-6.67\,\text{cm})}{15.0\,\text{cm}}$$

$h_i = 1.78\,\text{cm}$ (erect)

$$m = \frac{h_i}{h_o}$$

$$m = \frac{1.78\,\text{cm}}{4.00\,\text{cm}}$$

$m = 0.444$ (diminished)