Chapter 10: Refraction

What is refraction?

Refraction: The phenomenon that occurs at the boundary of two translucent substances. Because light travels at different speeds in different media, it will slightly change direction ("bend") when it goes from one medium to another.

Medium: Substance/material through which light travels.

Index of refraction (n): Factor by which the speed of light is decreased in a given medium, compared to the speed of light in a vacuum.

Note: $n = \frac{c}{v}$ where n: index of refraction of medium
c: speed of light in a vacuum ⇔ fastest (3.0×10⁸ m/s)
v: speed of light in medium slower

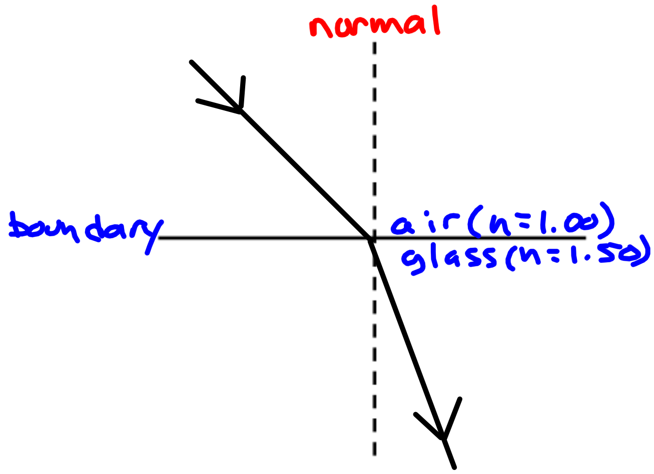
n always ≥ 1 (+ no units)

Some indexes of refraction:

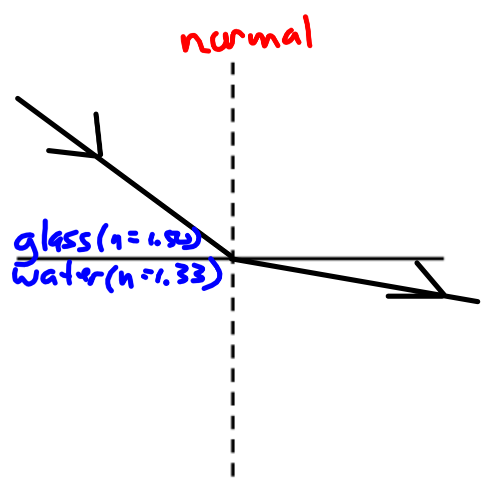
Vacuum:	1.00 (Exactly!)
Air:	1.00029 (Basically 1.00) * know n = 1.00 for air
Crystal:	2.00
Glass:	1.50
Water:	1.33
Ice:	1.31

*write n with 2 decimals

From lower index to higher index: Light bens towards the normal.



From higher index to lower index: light bends away from the normal.

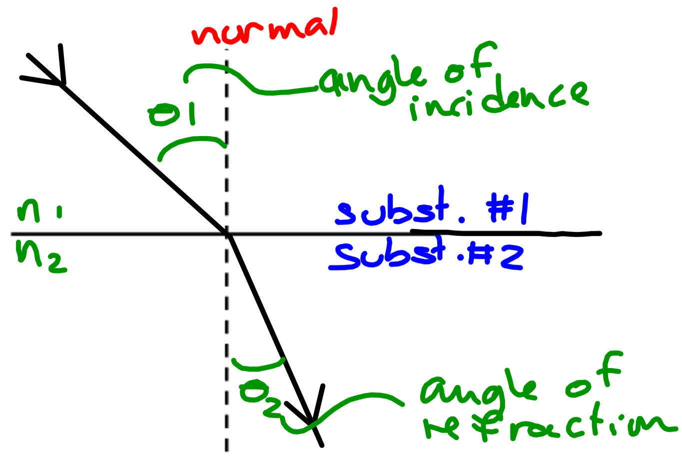


Law of Refraction (Snell's Law)

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

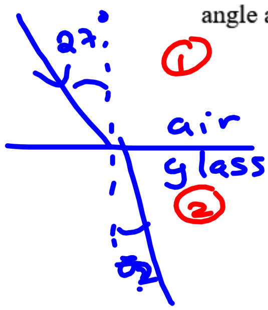
1 – substance #1
2 – substance #2

* always measure angles from the normal



Examples:

1. A light ray traveling through air enters glass ($n = 1.50$) at an angle of 27 °. What is the angle at which the light ray travels through the glass?



$n_1 = 1.00$
$\theta_1 = 27°$
$n_2 = 1.50$
$\theta_2 = ?$

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

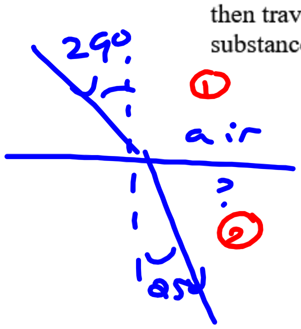
$\sin\theta_2 = \dfrac{n_1 \sin\theta_1}{n_2}$

$\theta_2 = \sin^{-1}\left(\dfrac{n_1 \sin\theta_1}{n_2}\right)$

$= \sin^{-1}\left(\dfrac{1.00 \sin 27°}{1.50}\right)$

$\theta_2 = 18°$

2. A light ray travels through air at an angle of 29 ° enters an unidentified substance where it then travels at an angle of 25 °. What is the index of refraction of the unidentified substance?



$n_1 = 1.00$
$\theta_1 = 29°$
$n_2 = ?$
$\theta_2 = 25°$

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

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

$n_2 = \dfrac{(1.00)(\sin 29)}{\sin 25°}$

$n_2 = 1.15$

* if you get $n < 1$, go back and find your mistake.

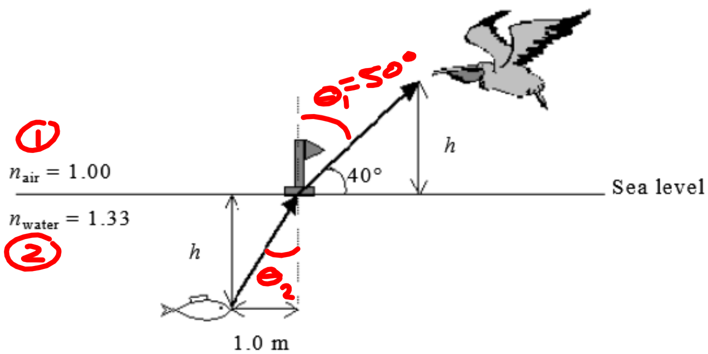
3. Since the refractive index of water is 1.33, what is the speed of light in water?

$n = \frac{c}{v} \rightarrow v = \frac{c}{n}$

$= \frac{3.0 \times 10^8 \text{ m/s}}{1.33}$

$v = 2.26 \times 10^8 \text{ m/s}$

4. A pelican is flying above sea level in search of its next snack. It sees a fish at an angle of 40° to the horizontal, as shown below. The fish is located 1.0 m away, horizontally, from the buoy. The height of the pelican above the water is equal to the depth of the fish.



What is the height of the pelican above sea level?

① $n_1 = 1.00$

~~$\theta_1 = 50°$~~ (from normal)

$n_2 = 1.33$

$\theta_2 = ?$

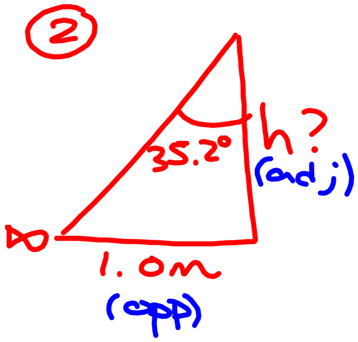
$n_1 \sin\theta_1 = n_2 \sin\theta_2$

$\theta_2 = \sin^{-1}\left(\frac{n_1 \sin\theta_1}{n_2}\right)$

$= \sin^{-1}\left(\frac{1.00 \sin 50°}{1.33}\right)$

$\theta_2 = 35.2°$

②

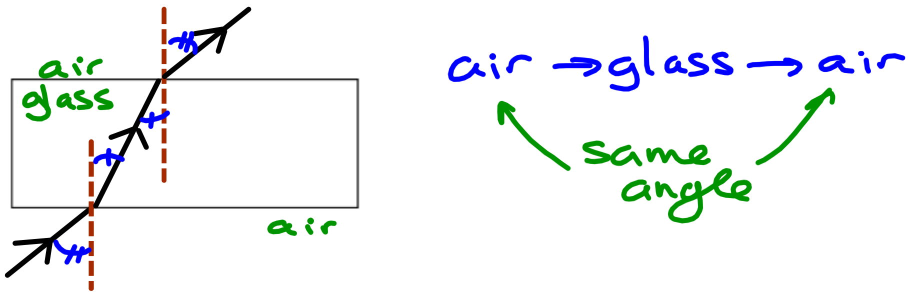


$\tan 35.2° = \frac{1.0\text{m}}{h}$

$h = \frac{1.0\text{m}}{\tan 35.2°}$

$h = 1.4\text{m}$

Light Through a Medium with Parallel Sides



Critical Angle and Total Internal Reflection

Critical angle (θ_c): Maximum angle for which refraction will occur

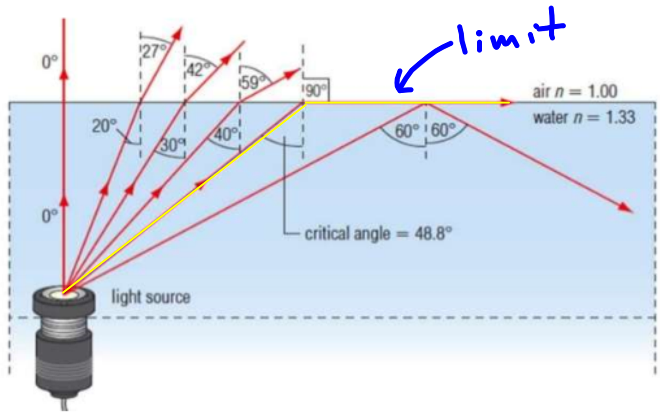
limit

Minimum angle for which total internal reflection will occur

Depends on both medium involved

Only happens when light goes from a medium with higher index of refraction to one with a lower index of refraction.

When the incident ray hits the surface at an angle greater or equal to the critical angle, all the light is reflected. When this occurs inside a closed medium, this is called **total internal reflection**.

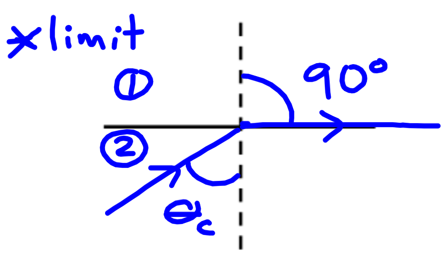


How to find the critical angle

For a problem:

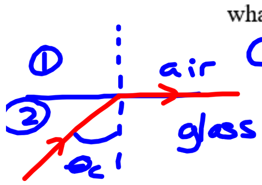
→ when the angle of refraction is 90 °.

In the lab:



Examples:

1. A light ray inside a glass block ($n = 1.50$) hits the surface as if it was to enter in air. For what angle of incidence will ~~total internal reflection occur~~?



① Find θ_c (limit)

$n_1 = 1.00$
$\theta_1 = 90°$
$n_2 = 1.50$
$\theta_c = \theta_2 = ?$

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

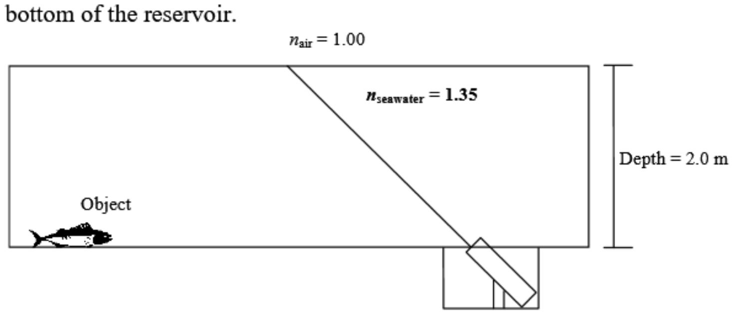
$\theta_2 = \sin^{-1}\left(\frac{n_1 \sin\theta_1}{n_2}\right)$

$= \sin^{-1}\left(\frac{(1.00)\sin 90°}{1.50}\right)$

$\theta_2 = 41.8°$

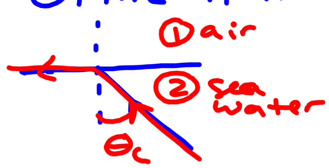
② Ans: we get total internal reflection for incident angles > 41.8°

2. An adjustable laser is attached to the bottom of a reservoir containing seawater (***n*** =**1.35**). The laser is adjusted so that the reflected light illuminates an object (the fish) placed on the bottom of the reservoir.



What minimum distance must there be between the laser light source and the object so that the ray of light does not exit the surface of the seawater?

① Find limit (θ_c)



$n_1 = 1.00$
$\theta_1 = 90°$
$n_2 = 1.35$
$\theta_c = \theta_2 = ?$

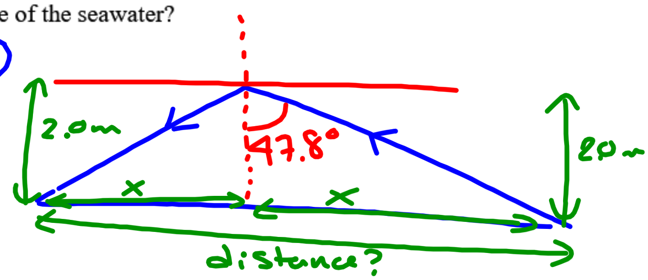
$n_1 \sin\theta_1 = n_2 \sin\theta_2$

$\theta_2 = \sin^{-1}\left(\frac{n_1 \sin\theta_1}{n_2}\right)$

$= \sin^{-1}\left(\frac{1.00 \sin 90°}{1.35}\right)$

$\theta_2 = 47.8°$
(critical angle)

②



$\tan 47.8° = \frac{x}{2.0m}$

$x = 2.0m \tan 47.8°$
$= 2.2m$

distance $= 2(2.2m)$
$= 4.4m$

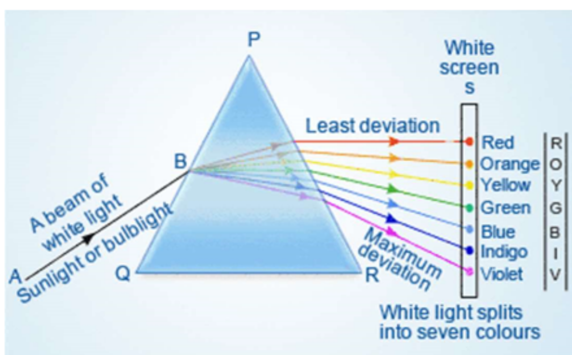
Colour and index of refraction

White light is composed of all the different colours (wavelengths) of light. For each colour, the medium (glass or water) has a slightly different index of refraction.

Index of refraction of a type of glass

color	Wavelength (nm)	n
Red	660	1.520
orange	610	1.522
yellow	580	1.523
green	550	1.526
blue	470	1.531
violet	410	1.538

This is why sending white light through a prism produces a "rainbow". The different colours of light are each refracted at a slightly different angle, causing the colours to "separate" into a rainbow.



Lenses

Lenses are made of transparent materials that have an index of refraction greater than the index of refraction of air (usually plastic or glass).

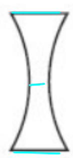
Because light enters and leaves the lens at an angle, it changes direction. By changing the shape of the lens, we can control exactly how the light will be deviated.

Some uses of lenses:

- Eyeglasses
- Microscope
- Telescope
- Overhead projector

Types of lenses

Diverging Lenses (Concave)



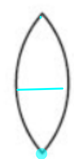
Biconcave

Planoconcave

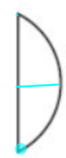
Diverging meniscus
(negative meniscus)

center of lens is thinner than edges

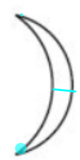
Converging Lenses (Convex)



Biconvex



Planoconvex



Converging meniscus
(positive meniscus)

center of lens is thicker than edges

Note: When light travels through a lens, it changes direction twice: once when it enters the lens, and once when it leaves the lens.

Parts of a lens

Principal Axis: same as for reflection

Optical Center (O): geometrical center of a lens

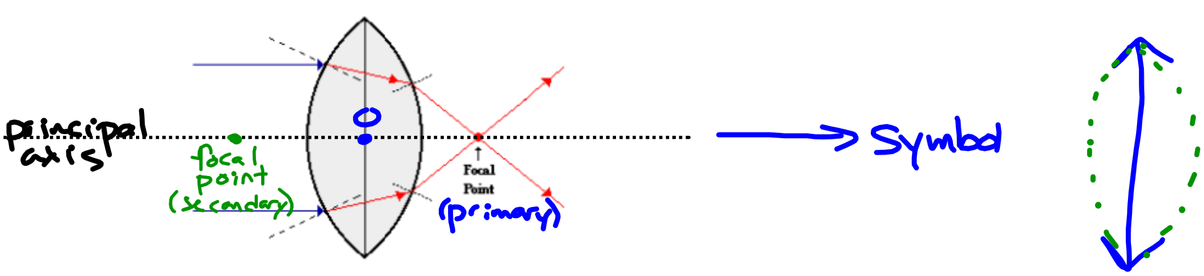
Primary Focus (F): *converging lens: where the refracted rays (initially parallel) converge
*diverging lens: where the refracted rays (initially parallel) appear to diverge from

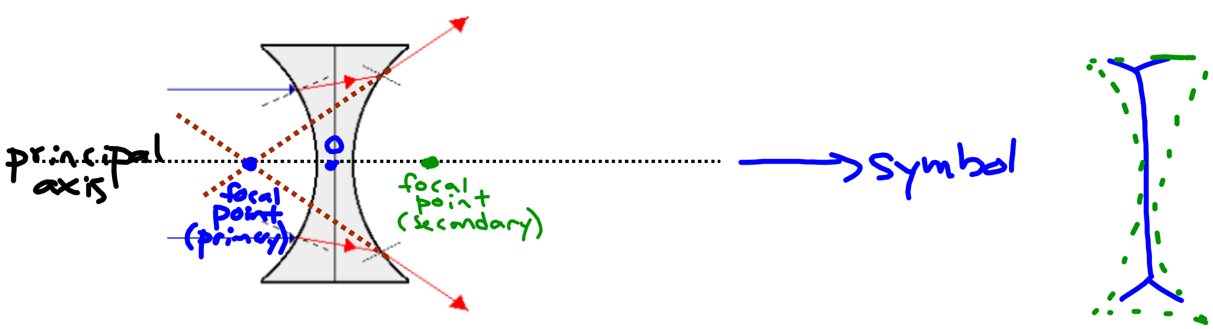
↑ focal point

Secondary Focus (F'): *on the other side of the lens (depends where the light is coming from)
*for symmetrical lenses, same distance from lense as primary

↑ focal point

How light is refracted as it travels through a lens.





<u>Drawing the ~~principal rays~~ going through a lens</u>

<u>3 principal rays:</u>

(1) Through the ~~optical center~~: The refracted ray comes out ~~undeviated~~

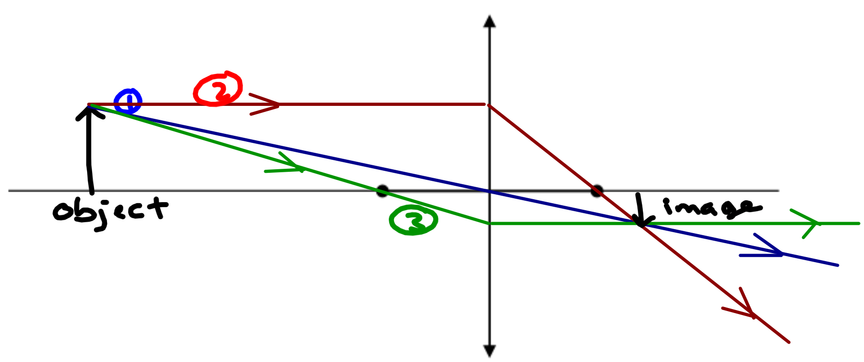
(2) ~~Parallel~~ to principal axis: *~~Converging~~ (convex) lens* ← primary
The ray is refracted ~~through the focal point~~

~~Diverging~~ (concave) lens ← primary
The ray is refracted "~~as if~~" it came ~~from the focal point~~

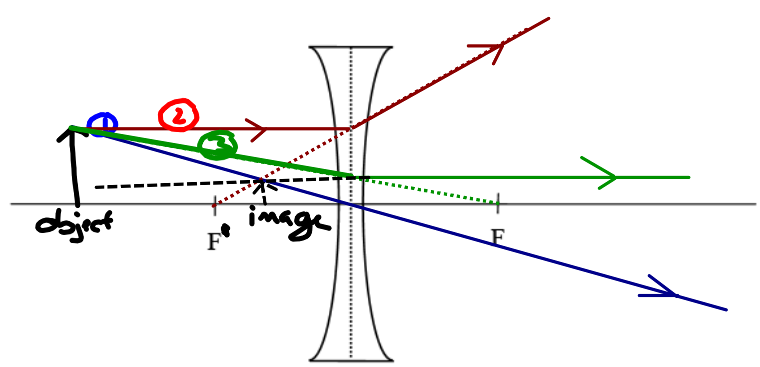
secondary
(3) ~~Through the focus~~: The ray is refracted ~~parallel~~ to the principal axis
Or "as if" from
(*~~Converging~~ lens*)

secondary
~~As if TO focus~~ on o~~ther side~~: The ray is refracted ~~parallel~~ to the principal axis
(*~~Diverging~~ lens*)

Convex (converging lens)



Concave (diverging lens)



Images Formed by Lenses

Images formed by DIVERGING lenses (concave)

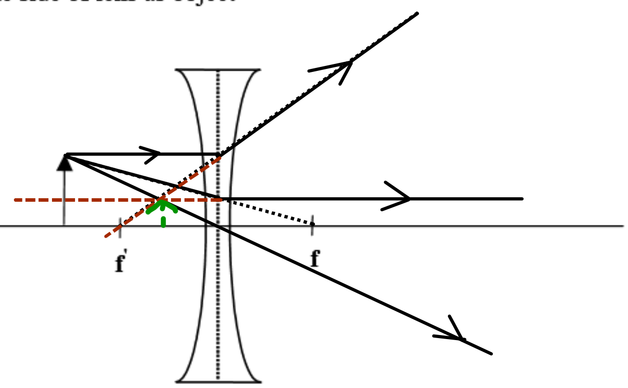
↳ rays always diverge!

Always

- Virtual
- Upright
- Smaller than image
- Located between F and C
- Same side of lens as object

(same as diverging mirror)

Example:



Images formed by CONVERGING lenses (convex) = converging mirror!

Object \ Image	Real or Virtual?	Upright or Inverted?	Smaller or bigger than object?	Where?
Far beyond 2F	Real	Inverted	Smaller	At F
Beyond 2F	Real	Inverted	Smaller	Between F and 2F
At 2F	Real	Inverted	Same size	At 2F
Between 2F and F	Real	Inverted	Larger	Beyond 2F
At F	NO IMAGE			
Between F and O	Virtual	Upright	Larger	Same side of lens as object

* real images are always inverted!

* Screen = real image = inverted

Example:

1.

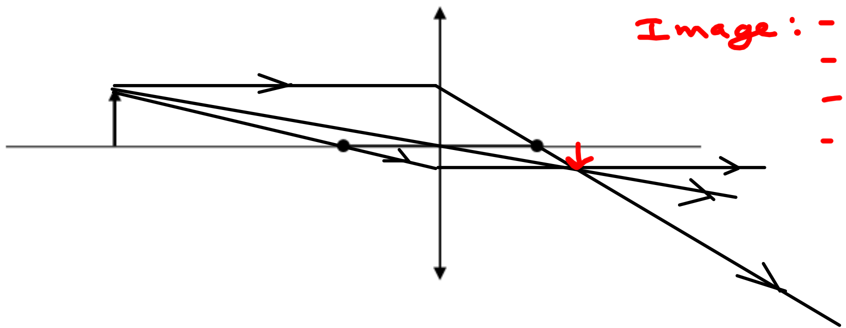


Image: - real
- inverted
- smaller
- between F and 2F

2.

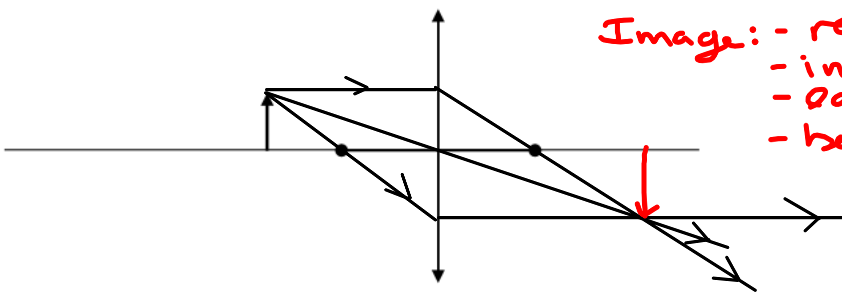
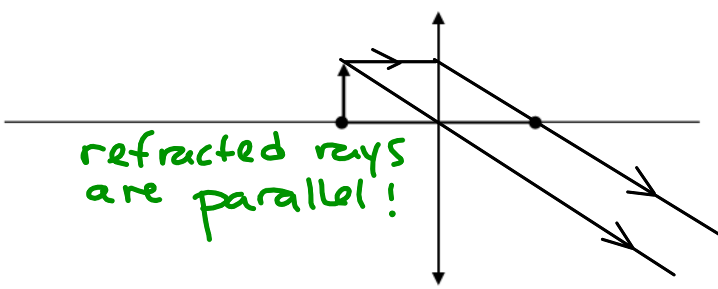


Image: - real
- inverted
- larger
- beyond 2F

3.

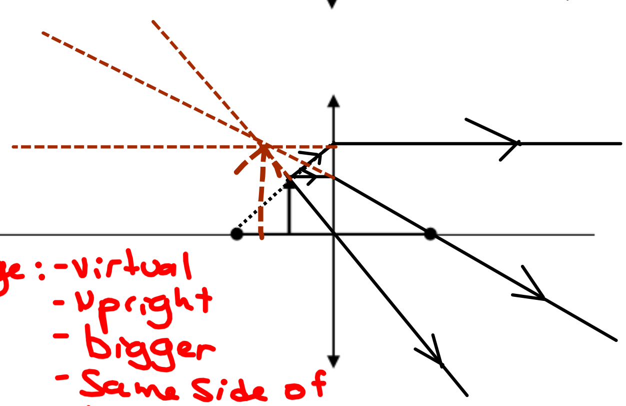


refracted rays are parallel!

NO IMAGE!

4.

* magnifying glass!



refracted rays diverge!

Image: - virtual
- upright
- bigger
- same side of lens as object

Locating images using formulas (lenses)

Just as for mirrors, for lenses we have:

M $\quad h_o$ $\quad h_i$ $\quad d_o$ $\quad d_i$

d_i ⊕ → real image
d_i ⊖ → virtual image

The meaning of positive and negative signs is the same as for mirrors.

f: focal length of the lens (distance between focal point and vertex)

Note: If f is positive, the lens is converging (convex). = converging mirror (concave)

If f is negative, the lens is diverging (concave). = diverging mirror (convex)

* Distances are always measured from the optical center of the lens.

$$M = -\frac{d_i}{d_o} \qquad M = \frac{h_i}{h_o} \qquad \frac{h_i}{h_o} = -\frac{d_i}{d_o} \qquad \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

Examples:

1. A candle is placed in front of a concave lens of focal length 12.0 cm. How far from the lens should this candle be placed so that its image is 4 times smaller than the candle?

$f = ⊖$

$f = -12.0\text{ cm}$

$M = +\frac{1}{4}$

(diverging lens always makes upright images)

① $M = -\frac{d_i}{d_o}$

$d_i = -Md_o$

$d_i = -\left(\frac{1}{4}\right)d_o$

$d_i = -\frac{d_o}{4}$

② $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$

$\frac{1}{-12.0\text{ cm}} = \frac{1}{d_o} + \frac{1}{-\frac{d_o}{4}}$

$\frac{1}{-12.0\text{ cm}} = \frac{1}{d_o} - \frac{4}{d_o}$

$\frac{1}{-12.0\text{ cm}} = -\frac{3}{d_o}$

$d_o = 36.0\text{ cm}$

2. A manufacturer of slide projectors wants to produce images 1.5 m in height on a screen that is placed 5.0 m from the lens of the projector. If the height of the slides is 30 mm, calculate the focal length of the lens.

screen → real = inverted

$d_o = ?$

$h_o = 0.03\text{ m}$

$d_i = 5.0\text{ m}$

$h_i = -1.5\text{ m}$

screen = real = inverted

① $\frac{h_i}{h_o} = -\frac{d_i}{d_o}$

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

$= -\frac{(5.0\text{ m})(0.03\text{ m})}{-1.5\text{ m}}$

$d_o = 0.1\text{ m}$

② $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$

$\frac{1}{f} = \frac{1}{0.1\text{ m}} + \frac{1}{5.0\text{ m}}$

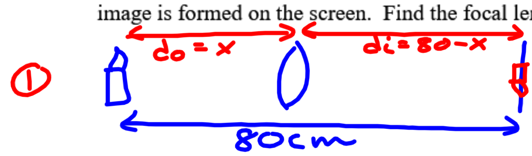
$\frac{1}{f} = \frac{5}{0.5\text{ m}} + \frac{0.1}{0.5\text{ m}}$

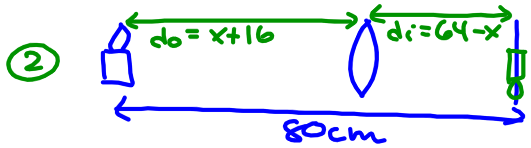
$\frac{1}{f} = \frac{5.1}{0.5\text{ m}}$

$f = \frac{0.5\text{ m}}{5.1}$

$f = 0.098\text{ m}$

3. An object and a screen are fixed at a distance of 80 cm apart. A convex lens forms an image of the object on the screen. The lens is then moved 16 cm closer to the screen, and a new image is formed on the screen. Find the focal length of the lens.





$80 - (x+16)$
$80 - x - 16$
$64 - x$

f is same for both!

Set-up ①

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

$$\boxed{\frac{1}{f} = \frac{1}{x} + \frac{1}{80-x}}$$

Set-up ②

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

$$\boxed{\frac{1}{f} = \frac{1}{x+16} + \frac{1}{64-x}}$$

System

$$\frac{1}{x} + \frac{1}{80-x} = \frac{1}{x+16} + \frac{1}{64-x}$$

$$\frac{80-x+x}{x(80-x)} = \frac{64-x+x+16}{(x+16)(64-x)}$$

$$\frac{80}{x(80-x)} = \frac{80}{(x+16)(64-x)}$$

$$80(x+16)(64-x) = 80(80-x)x$$

$$64x - x^2 + 1024 - 16x = 80x - x^2$$

$$1024 = 80x - x^2 - 64x + x^2 + 16x$$

$$1024 = 32x$$

$$x = \frac{1024}{32}$$

$$x = 32\text{ cm}$$

Find f

$$\frac{1}{f} = \frac{1}{x} + \frac{1}{80-x}$$

$$\frac{1}{f} = \frac{1}{32\text{cm}} + \frac{1}{48\text{cm}}$$

$$\frac{1}{f} = \frac{48}{1536\text{cm}} + \frac{32}{1536\text{cm}}$$

$$\frac{1}{f} = \frac{80}{1536\text{cm}}$$

$$f = \frac{1536\text{cm}}{80}$$

$$\boxed{f = 19.2\text{ cm}}$$