Your questions/comments

“I'm always wrong when it comes to these questions”

“I'm really struggling with understanding a lot in the prelecture. How are the rays supposed to be drawn with they hit the lens? And how do the rays come out either convergent or divergent after hitting both sides of the lens?”

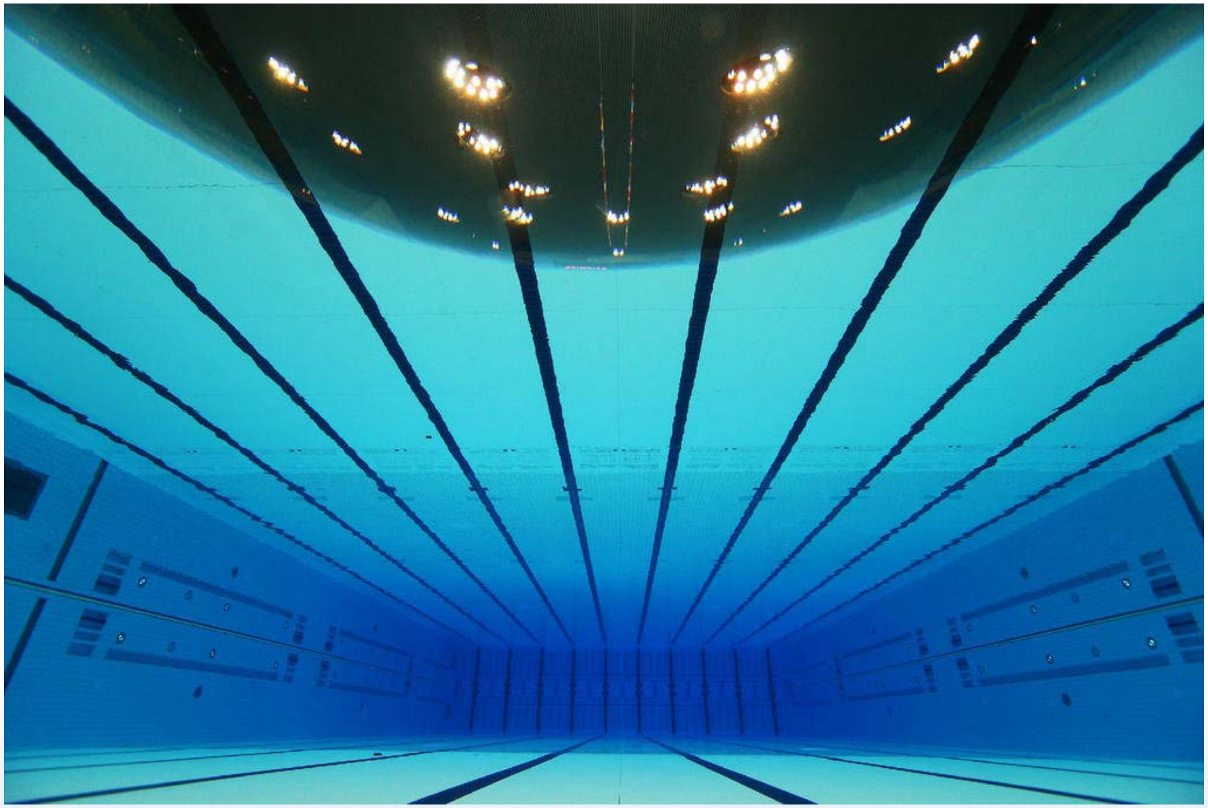
“If we can go over the half lens checkpoint, that'd be great!”

“are virtual images always upright and real always inverted?”

“Please review from Monday's lecture. I am very very confused. Please help!”

“I really despise mirrors.”

“I think in a past life Dr. Chemla could have been or passed off as a magician.”



Phys 102 – Lecture 19

Refraction & lenses

Today we will...

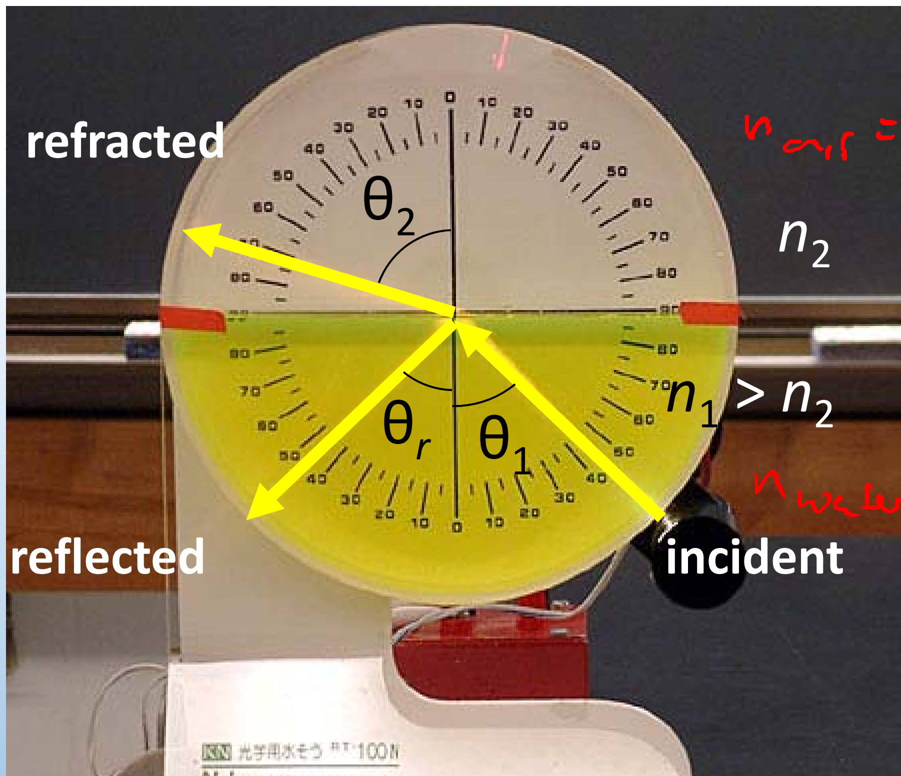
- Review refraction
  - Snell's law
- Learn applications of refraction
  - Total internal reflection
  - Converging & diverging lenses
- Learn how lenses produce images
  - Ray diagrams – principal rays
  - Lens & magnification equations

Review: Snell's Law

Light bends when traveling into material with different *n* $v = \frac{c}{n}$

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

$\sin\theta_2 > \sin\theta_1$



$n_{air} = 1.0$

$n_{water} = 1.33$

If $n_1 > n_2$ then $\theta_2 > \theta_1$

Light bends away from normal as it goes into a medium with lower *n*

Total internal reflection

From Snell's law, if $n_1 > n_2$ then $\theta_2 > \theta_1$

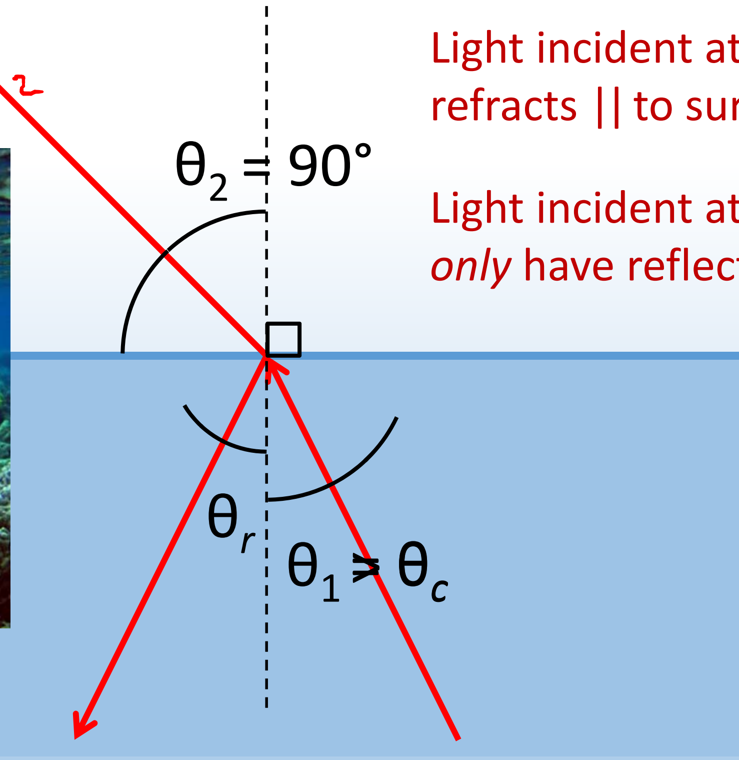
$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad n_1 \sin\theta_c = n_2 \sin 90^\circ$$

So, $\theta_c = \sin^{-1} \dfrac{n_2}{n_1}$

$\theta_1 > \theta_c$

$n_1 \sin\theta_1 > n_2$

$= n_2 \sin\theta_2$

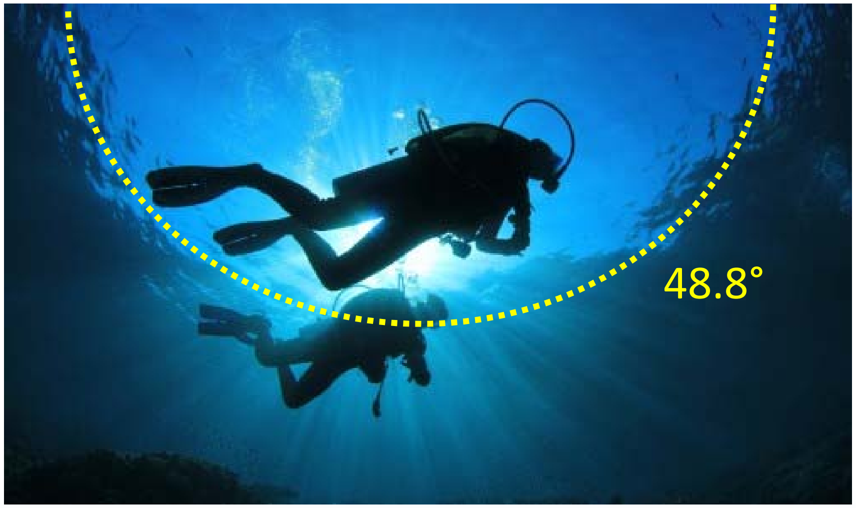


Light incident at *critical angle* $\theta_1 = \theta_c$ refracts || to surface ($\theta_2 = 90°$)

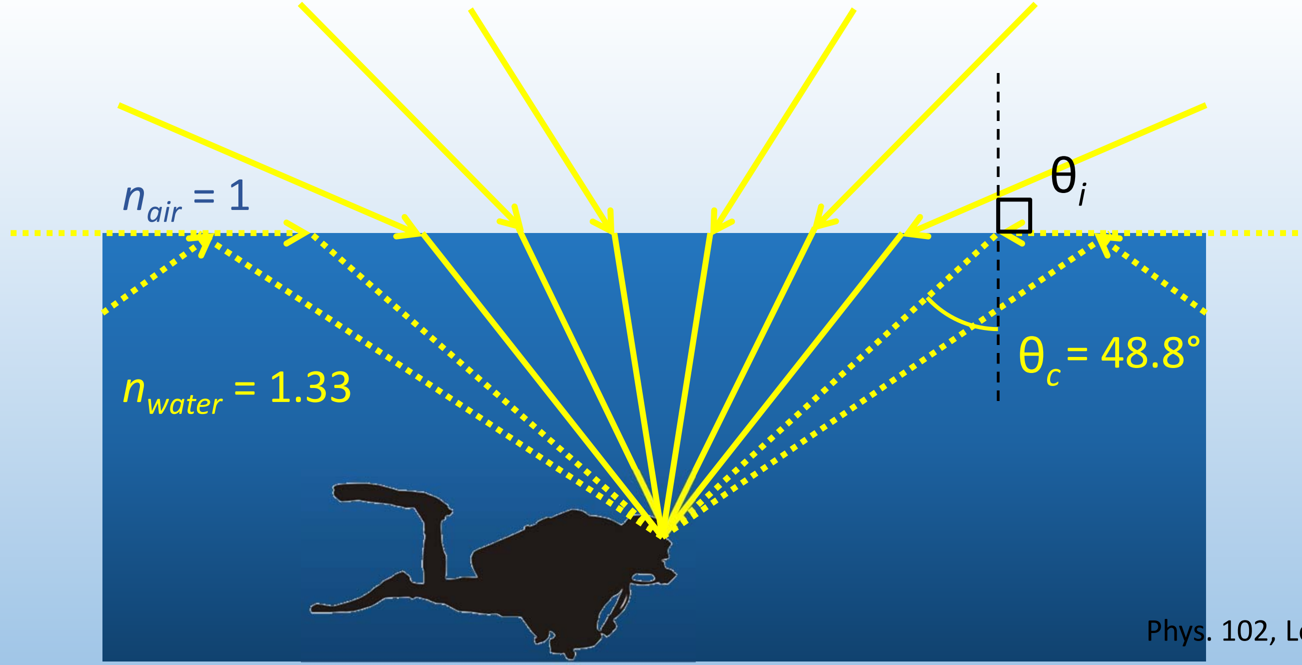
Light incident at angle $\theta_1 > \theta_c$ will *only* have reflection ($\theta_1 = \theta_r$)!

Calculation: underwater view

Explain why the diver sees a circle of light from outside surrounded by darkness

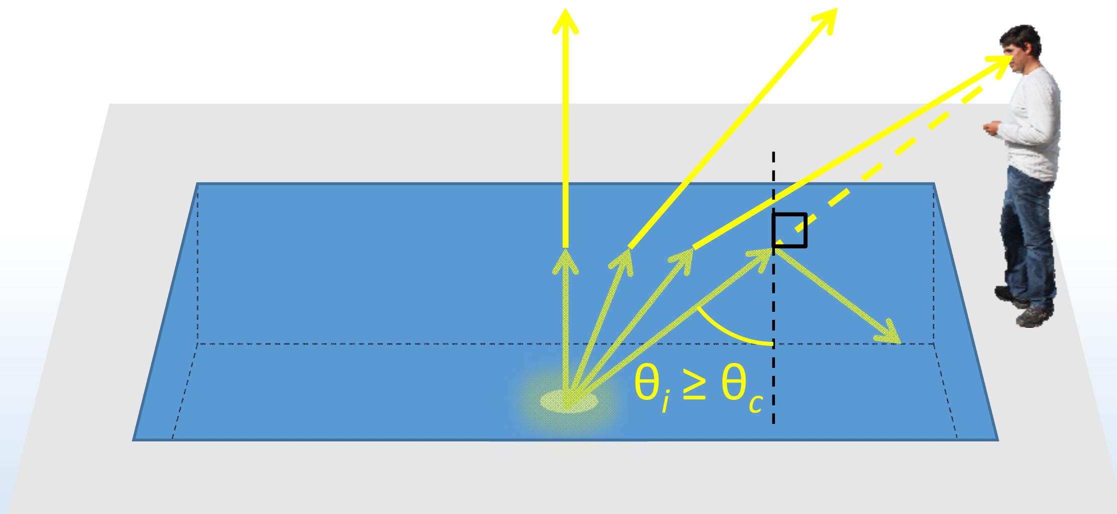


$$\theta_c = \sin^{-1}\frac{n_{air}}{n_{water}} = \sin^{-1}\frac{1}{1.33} = 48.8°$$



ACT: CheckPoint 1.1

Can the person standing on the edge of the pool be prevented from seeing the light by <u>total internal reflection</u>?



A. Yes

44%

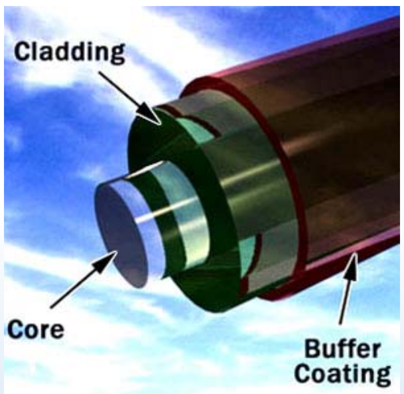
B. No

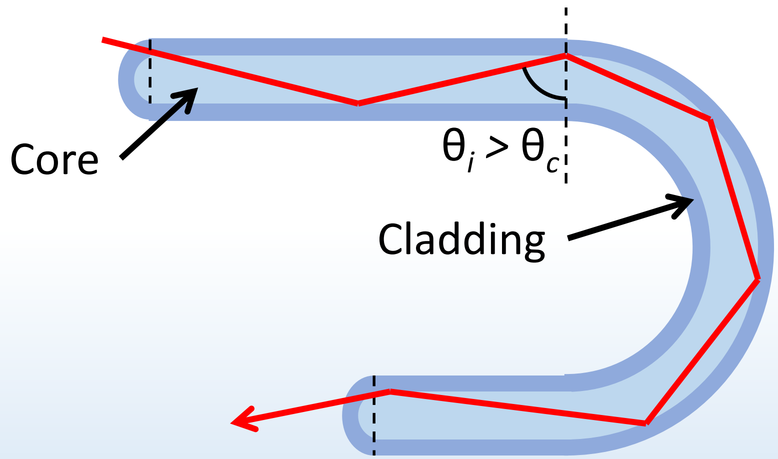
56%

Light emits rays in every direction. Some will be totally reflected back into the water, most will not.

Fiber Optics

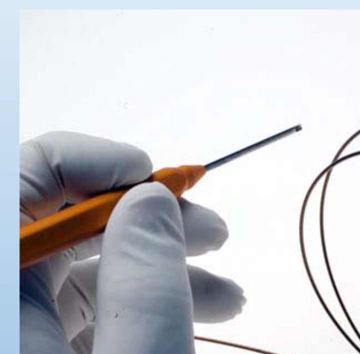
Optical fibers consist of “core” surrounded by “cladding” with $n_{cladding} < n_{core}$. Light hits core-cladding interface at $\theta_i > \theta_c$, undergoes total internal reflection and stays in the fiber.





Only works if $n_{cladding} < n_{core}$

- Telecommunication
- Arthroscopy
- Laser surgery

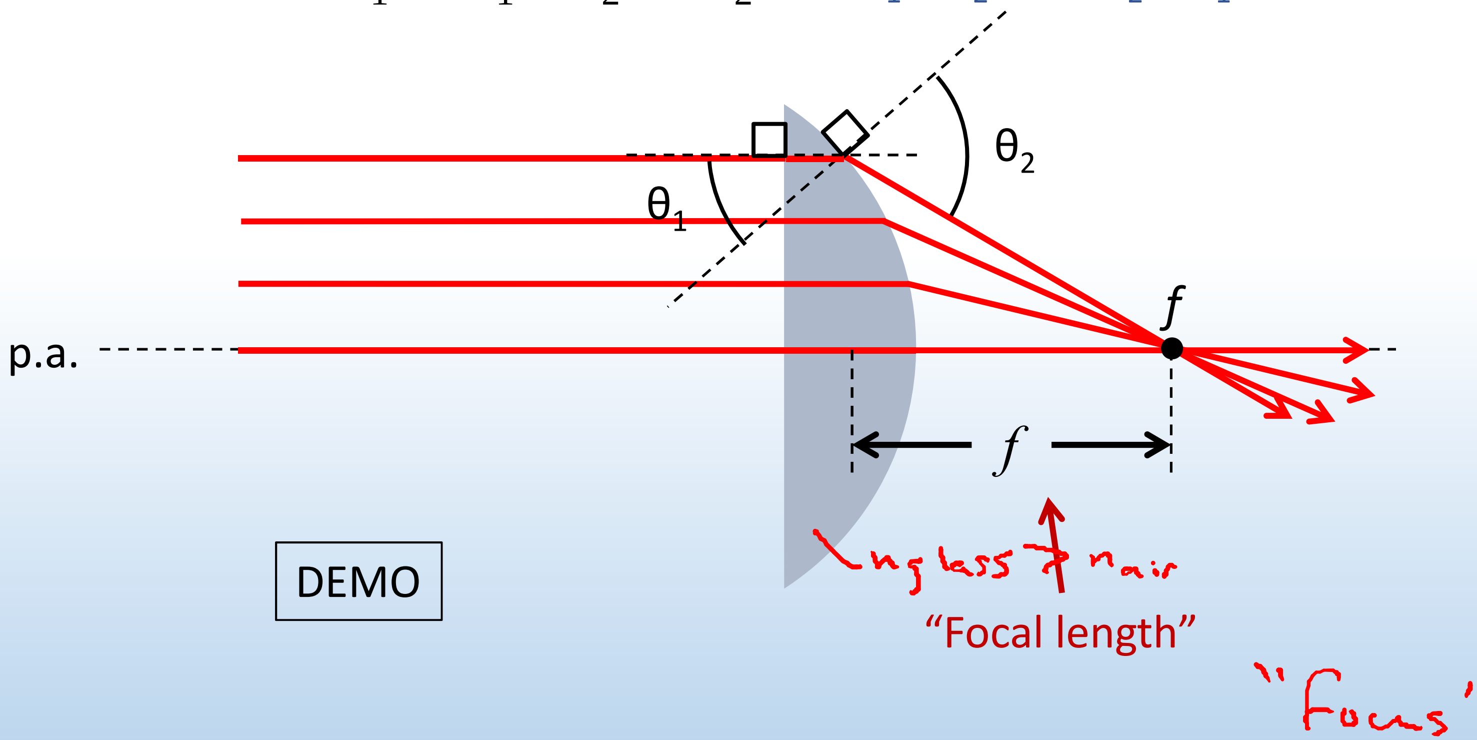


Converging lens

Lenses use refraction and curved surface(s) to bend light in useful ways

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

If $n_1 > n_2$ then $\theta_2 > \theta_1$

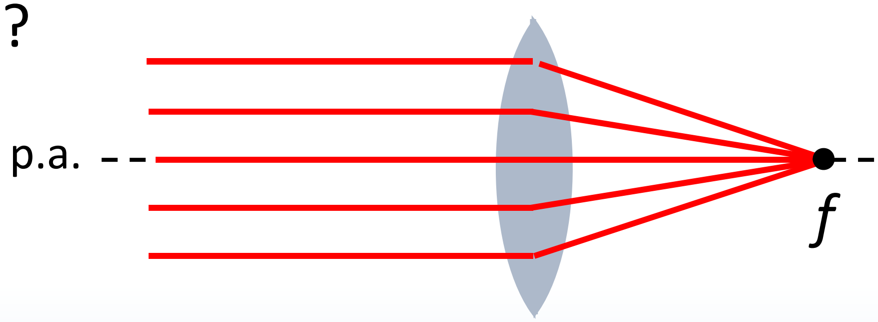


DEMO

Converging lens – rays || to p.a. refract through focal point *f* ***after*** lens

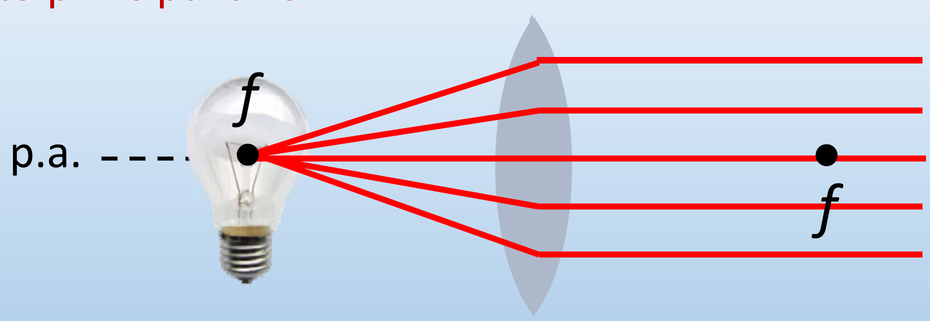
CheckPoint 2.1

A beacon in a lighthouse produces a parallel beam of light. The beacon consists of a bulb and a converging lens. Where should the bulb be placed?



All rays parallel to principal axis refract through focal point *f*

Reverse light – all rays passing through focal point *f* refract parallel to principal axis



68% A. At *f*

15% B. Inside *f*

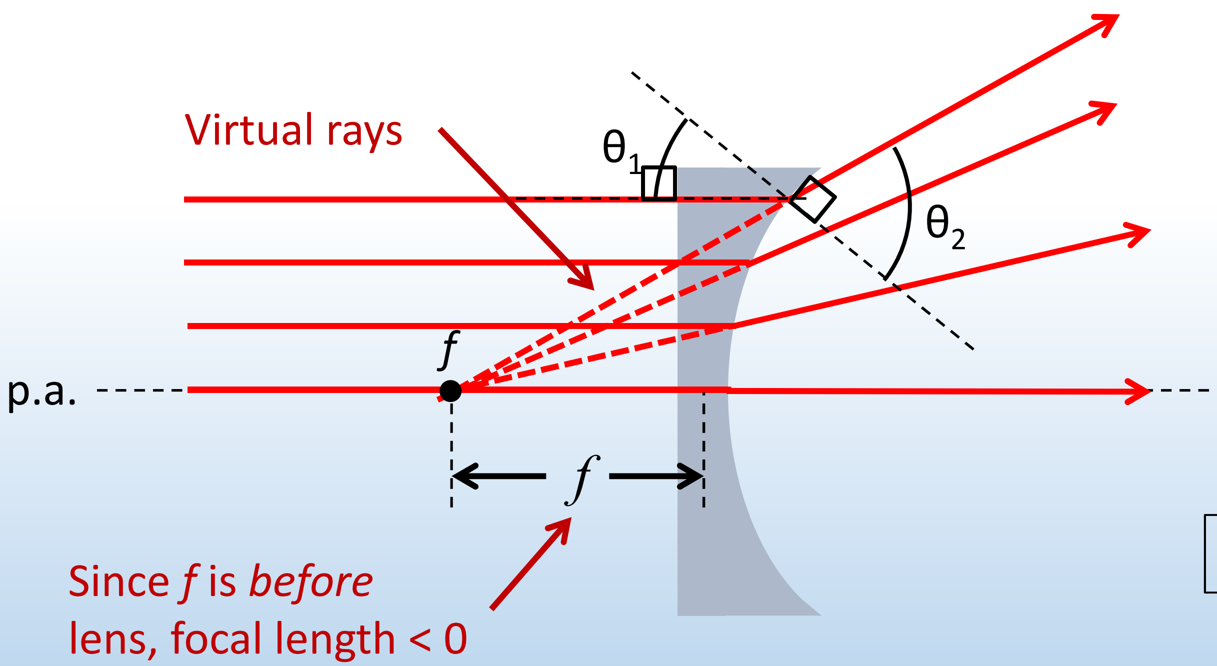
17% C. Outside *f*

Diverging lens

Lenses use refraction and curved surface(s) to bend light in useful ways

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

If $n_1 > n_2$ then $\theta_2 > \theta_1$



DEMO

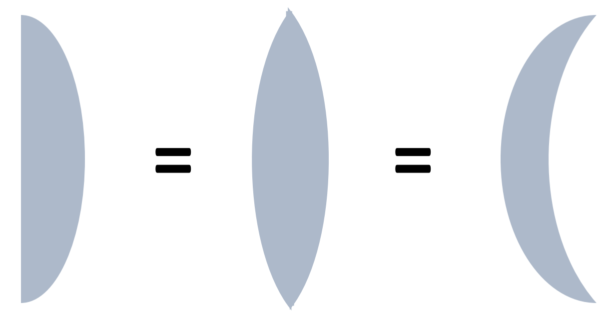
Diverging lens – rays || to p.a. reflect as if they originated from focal point *f* ***before*** lens

Converging & diverging lenses

Converging lens:

Rays parallel to p.a. converge on focal point after lens

Converging = thick in the middle

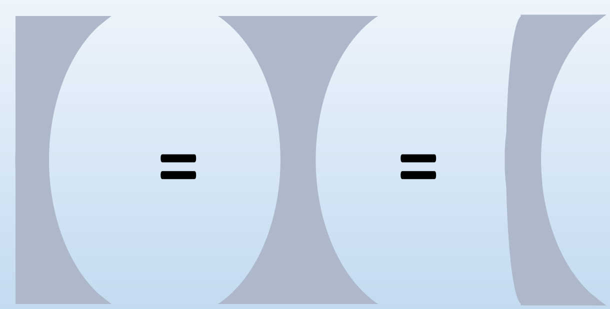


"Plano-convex" "Double convex" "Concave-convex"

Diverging lens:

Rays parallel to p.a. diverge as if originating from focal point before lens

Diverging = thin in the middle

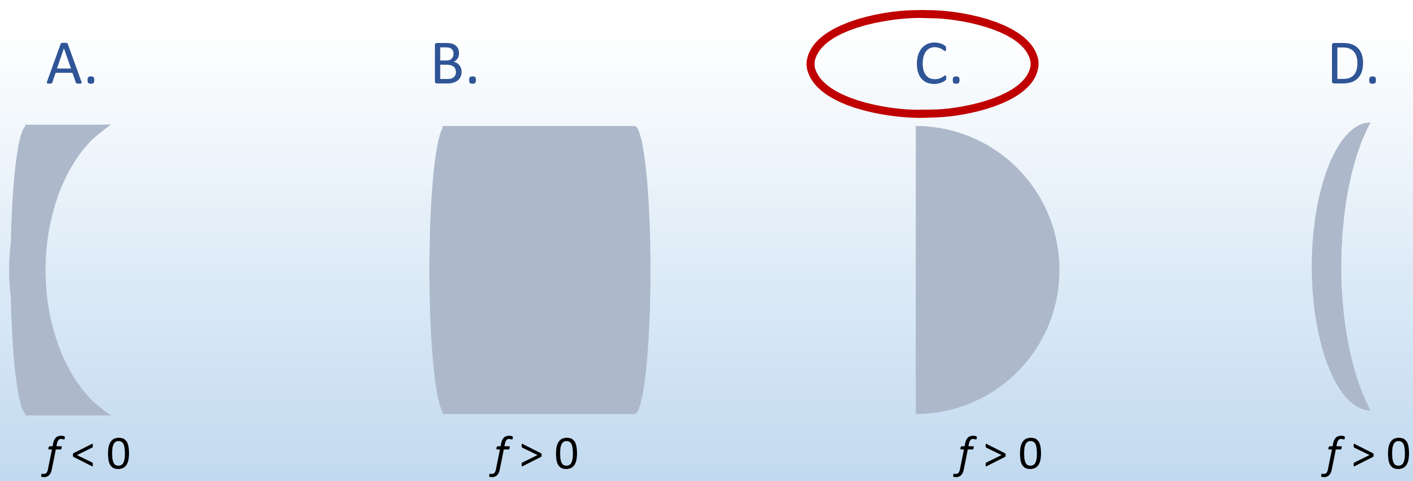


"Plano-concave" "Double concave" "Convex-concave"

ACT: Lens geometry

The following lenses are all made from the same material but have different geometry

Which lens has the shortest (positive) focal length?

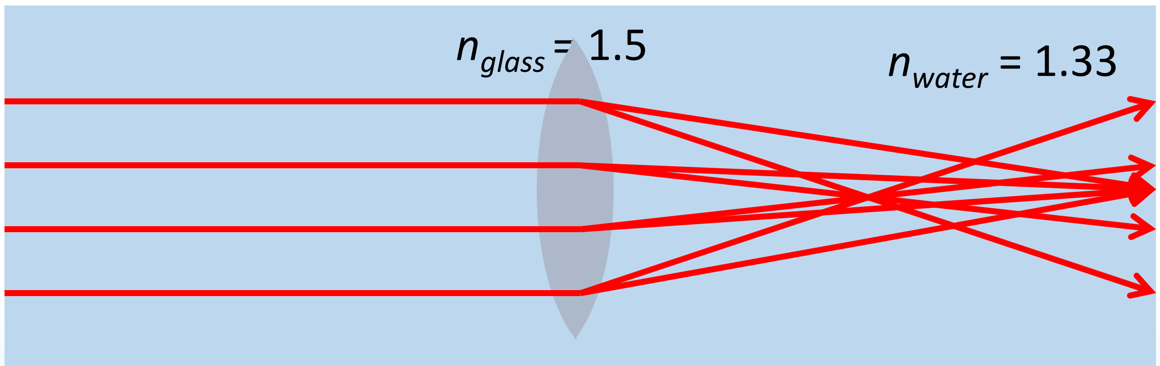


Converging/diverging = thick/thin in middle

More curved = more bending = shorter f

ACT: CheckPoint 3.1

A glass converging lens placed in air has focal length *f*.



Now the lens is placed in water. Its focal length:

32% A. Stays the same

51% B. Increases

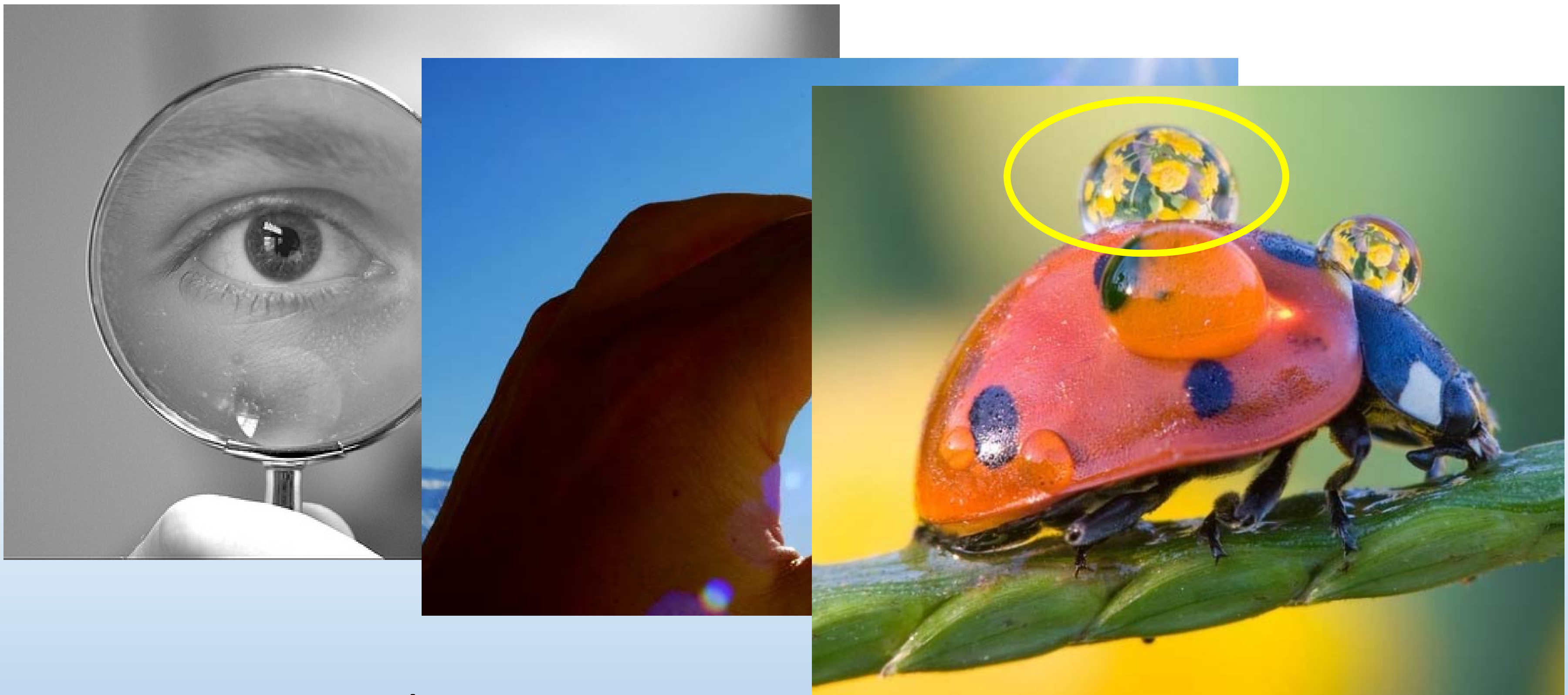
17% C. Decreases

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

Refraction depends on difference in *n*.
The closer n_{lens} and $n_{outside}$ are, the less bending and the larger *f*

Images & lenses

Like mirrors, lenses produce images of objects



Key approaches:

- Ray diagrams
- Thin lens & magnification equations

Principal rays – converging lens

Ray from object traveling:

1) parallel to principal axis, refracts through *f*
2) through *f*, refracts parallel to principal axis
3) through *C*, travels straight

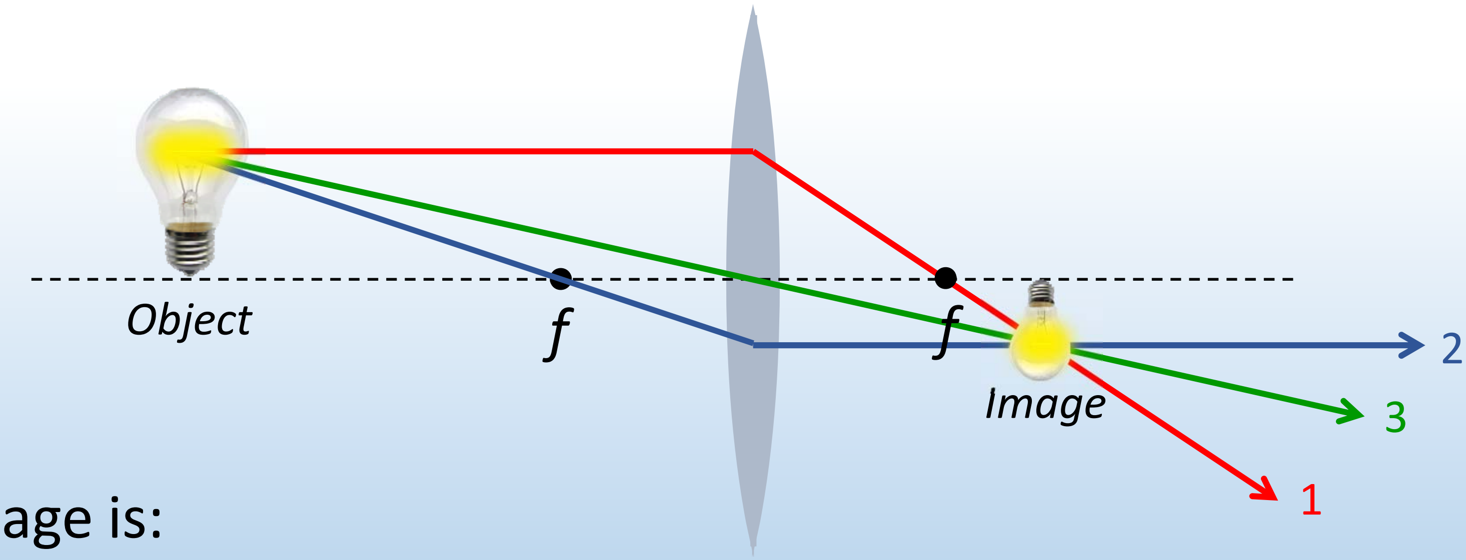


Image is:

Real (light rays cross)
Inverted (opposite direction as object)
Reduced (smaller than object)

Principal rays – diverging lens

Ray from object traveling:

1) parallel to principal axis, refracts through *f*
2) through *f*, refracts parallel to principal axis
3) through *C*, travels straight

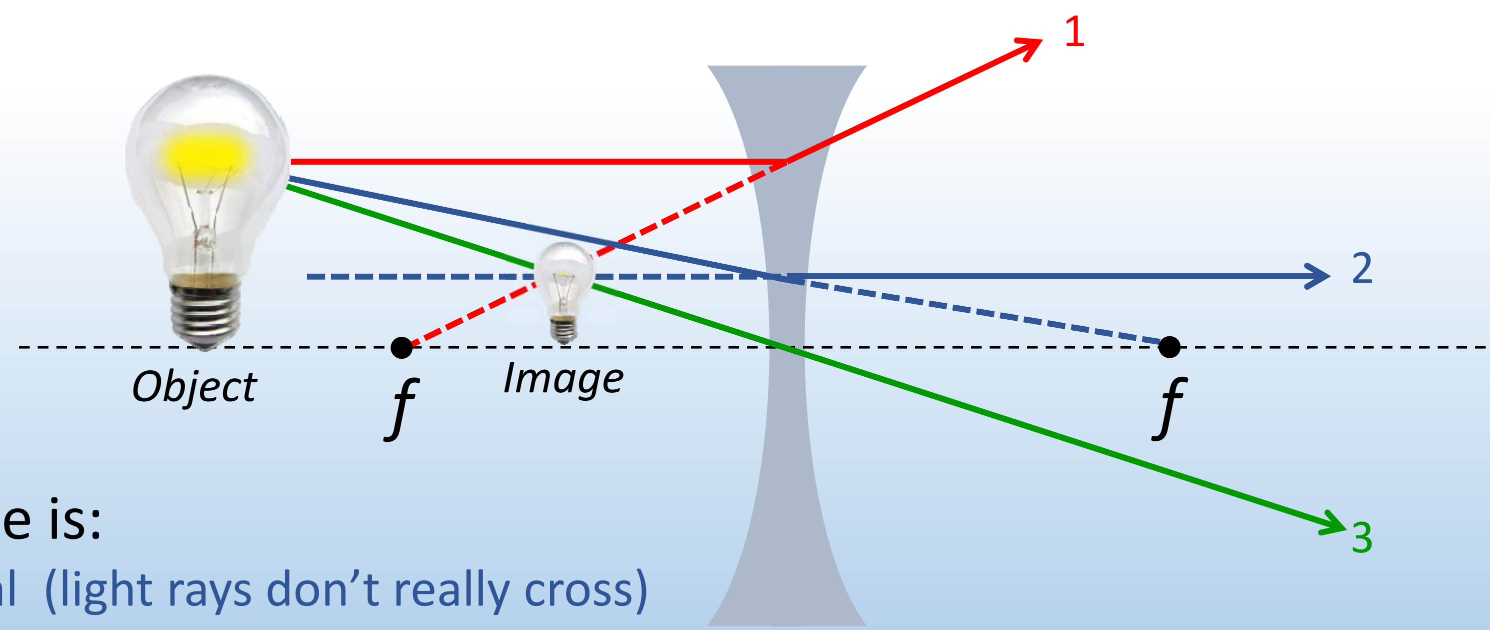


Image is:

Virtual (light rays don't really cross)

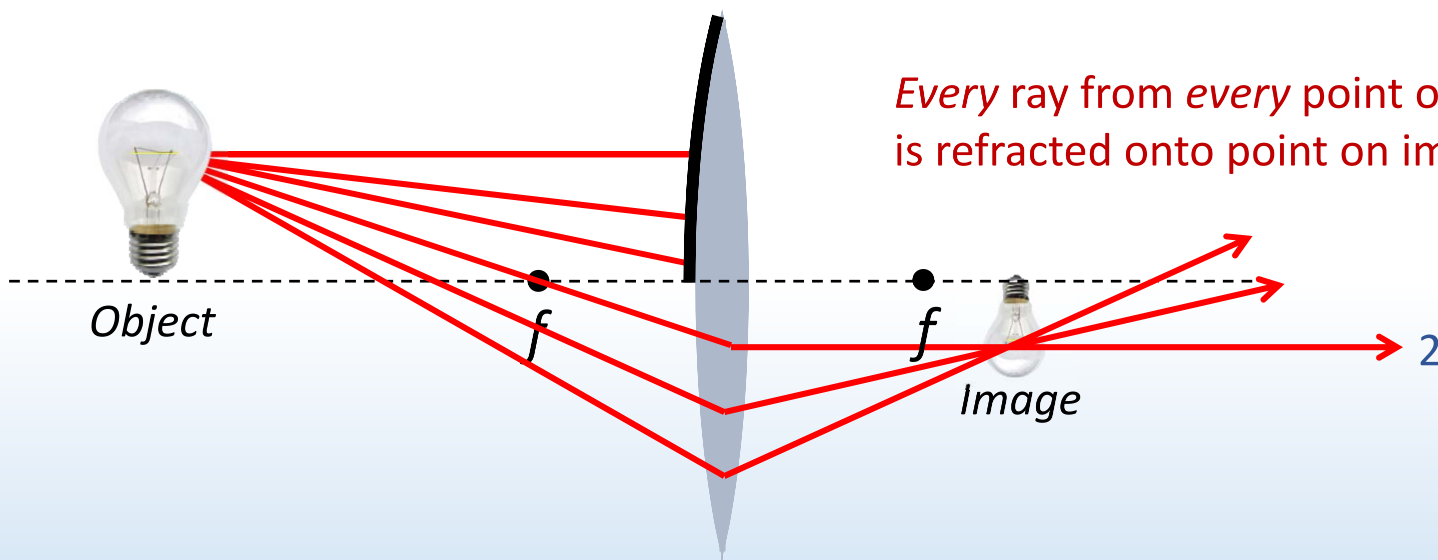
Upright (same direction as object)

Reduced (smaller than object)

ACT: CheckPoint 4.1

A converging lens produces a real image onto a screen. A piece of black tape is then placed over the upper half of the lens.

Every ray from *every* point on object is refracted onto point on image



½ the rays get through, so image is ½ as bright

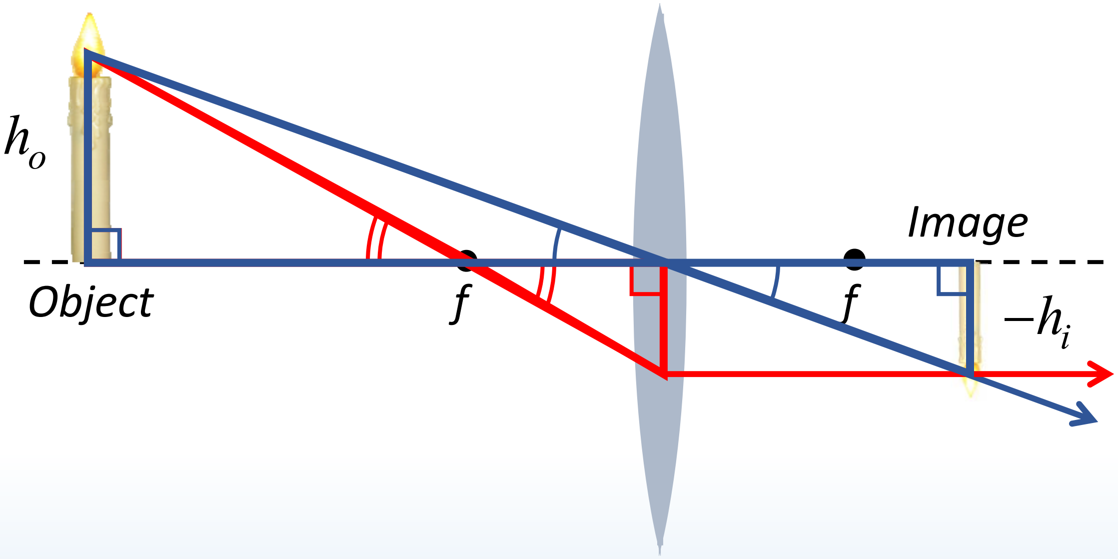
Which of the following is true:

22% A. Only the lower half of the object will show

27% B. Only the upper half of the object will show

51% C. The whole object will still show

Thin lens & magnification equations



Magnification

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

Thin lens equation

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

h_o h_o

f d_i

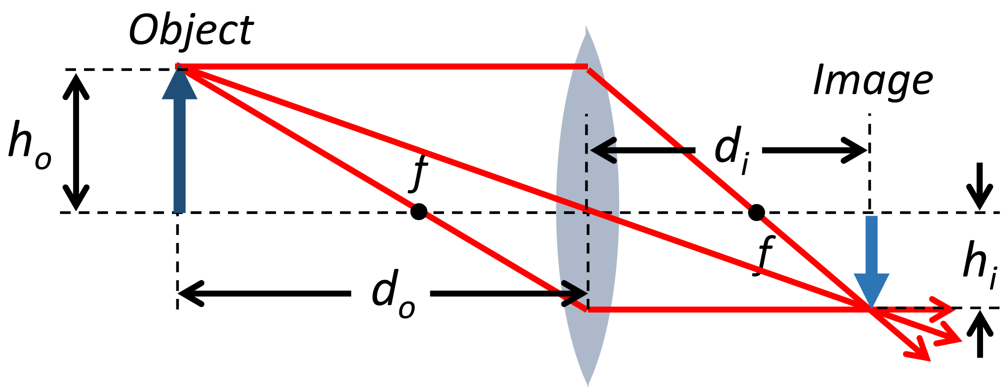
$d_o - f$ $-h_i$ d_o $-h_i$

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

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

Same as mirror equations!

Distance & magnification conventions



- d_o = distance object is from lens:
  - > 0: object before lens
  - < 0: object after lens
- h_o = height of object:
  - > 0: always
- d_i = distance image is from lens:
  - > 0: real image (after lens)
  - < 0: virtual image (before lens)
- h_i = height of image:
  - > 0: image is upright
  - < 0: image is inverted
- f = focal length lens:
  - > 0: converging lens
  - < 0: diverging lens
- $|m|$ = magnification:
  - < 1: image is reduced
  - > 1: image is enlarged

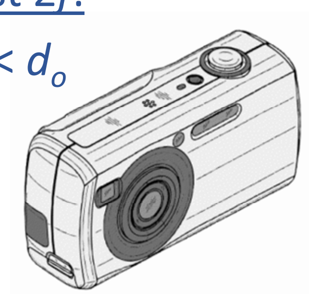
Note similarities to mirror conventions

3 cases for converging lens

Object is: / **Image is:**

Past $2f$:

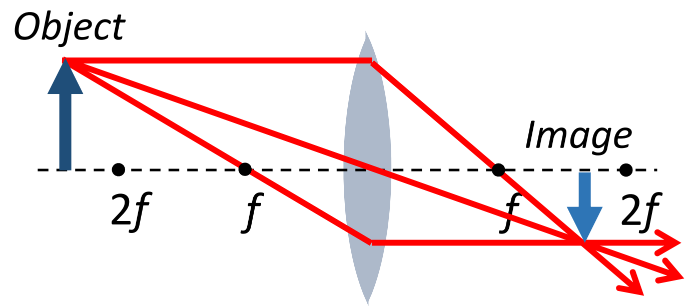
$2f < d_o$



Inverted: $h_i < 0$

Reduced: $m < 1$

Real: $d_i > 0$



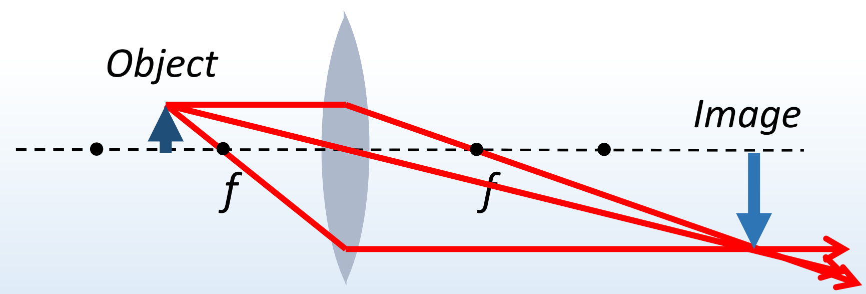
Between $2f$ & f:

$f < d_o < 2f$

Inverted: $h_i < 0$

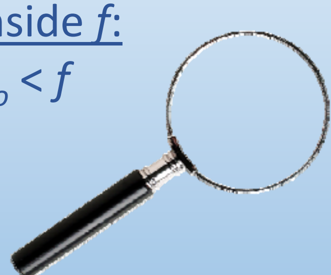
Enlarged: $m > 1$

Real: $d_i > 0$



Inside f:

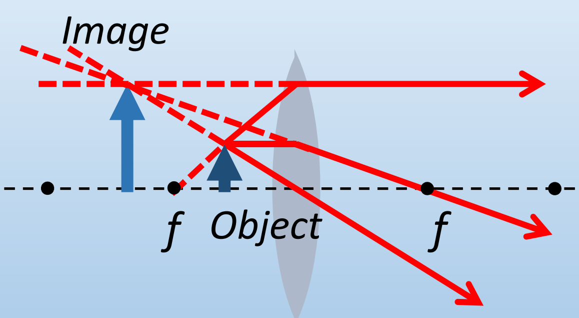
$d_o < f$



Upright: $h_i > 0$

Enlarged: $m > 1$

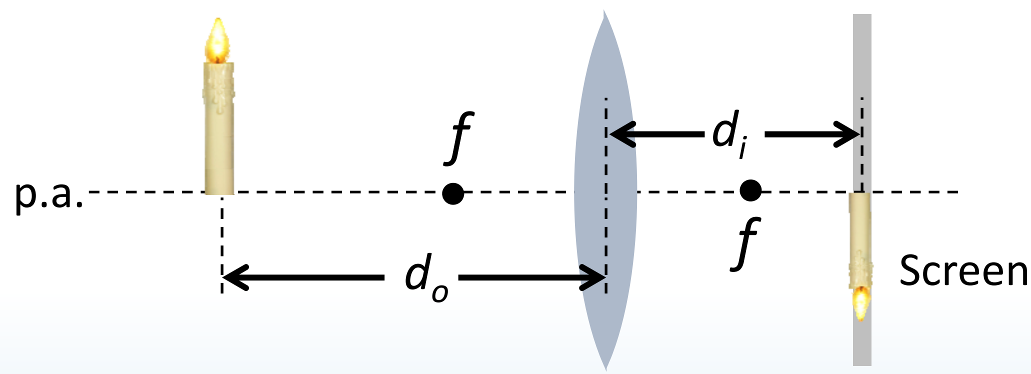
Virtual: $d_i < 0$



DEMO

ACT: Converging Lens

A candle is placed in front of a converging lens. The lens produces a well-focused image of the flame on a screen a distance d_i away.



If the candle is moved *farther* away from the lens, how should the screen be adjusted to keep a well-focused image?

A. Closer to lens
B. Further from lens
C. At the same place

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

If d_o increases, d_i must decrease

Calculation: diverging lens

A 6-cm tall candle is placed 12 cm in front of a *diverging* lens with a focal length $f = -6$ cm. Determine the image location, size, and whether it is upright or inverted

$$\frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o} = \frac{1}{-6} - \frac{1}{12} = -\frac{1}{4}$$

$$d_i = -4\,\text{cm}$$

Virtual image, before lens

$$m = -\frac{d_i}{d_o} = -\frac{-4}{12} = +\frac{1}{3}$$

Reduced image

$$h_i = m h_o = +2\,\text{cm}$$

Upright image

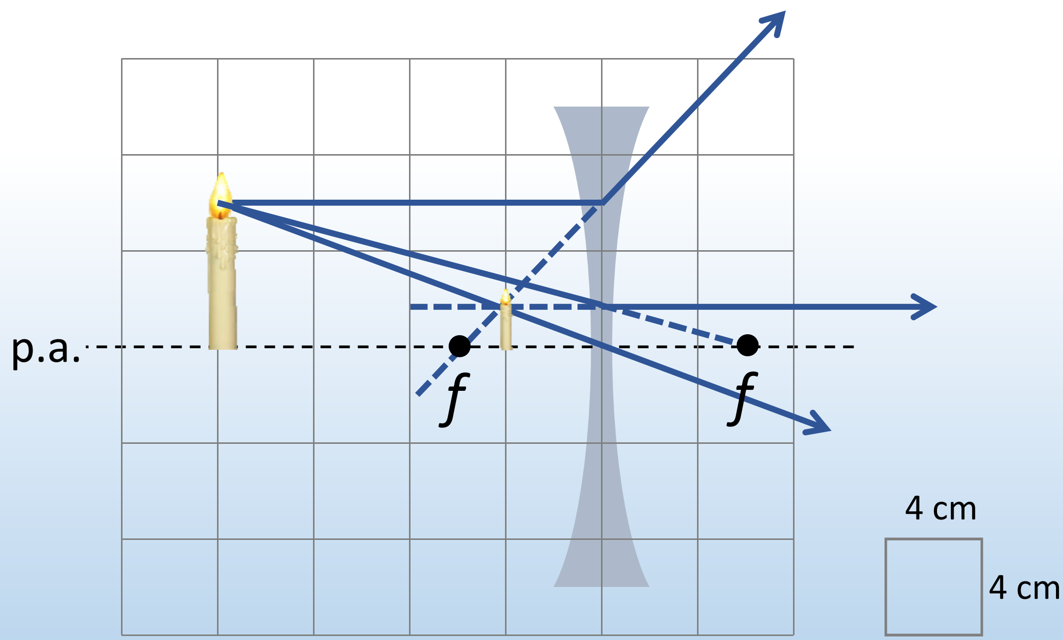
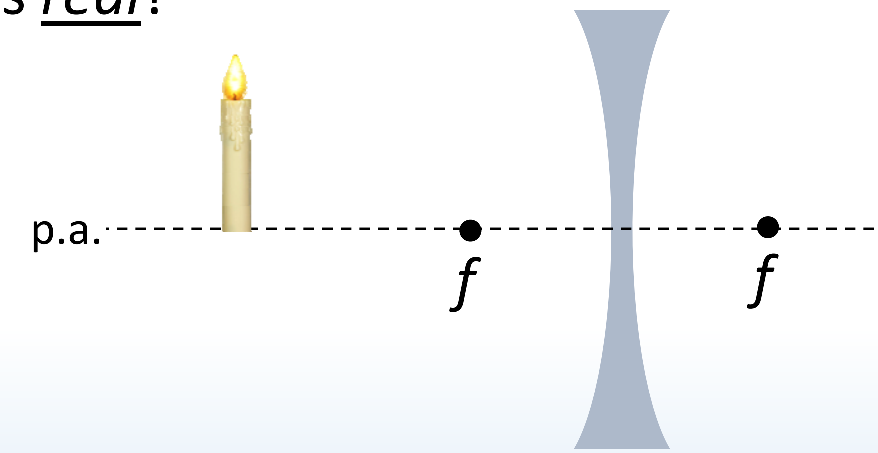


Diagram should agree!

ACT: Diverging Lenses

Where in front of a diverging lens should you place an object so the image is ***real***?



A. Closer to lens

B. Further from lens

C. Diverging lens can't create real image

Diverging lens: $f < 0$

Object in front of mirror: $d_o > 0$

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

$f < 0$ for diverging

$d_o > 0$

1 case for diverging lens:

$d_i < 0$ (virtual image) always!

Summary of today's lecture

- Total internal reflection
- Lenses – principal rays

  Parallel to p.a. –> refracts through *f*

  Through *f* -> refracts parallel to p.a.

  Through *C* -> straight through

- Thin lens & magnification equations

  Numerical answer consistent with ray diagram

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