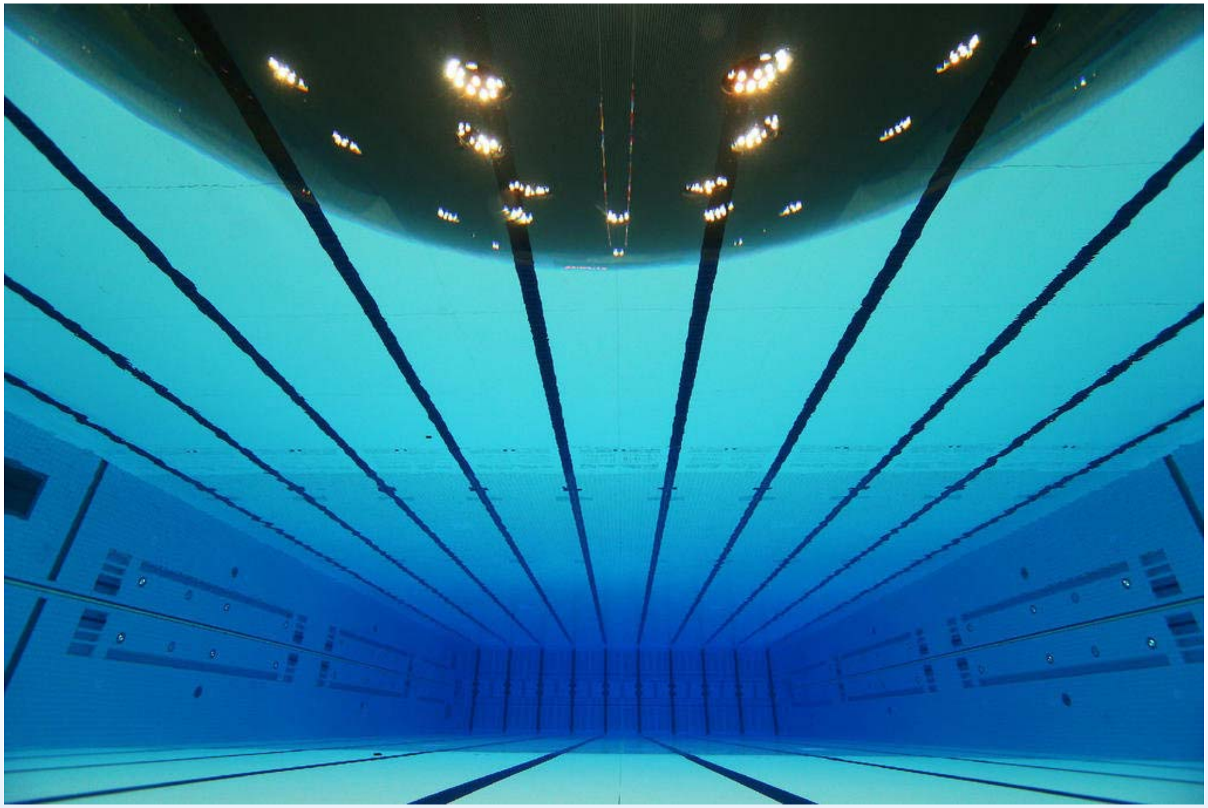


# Phys 102 – Lecture 19

**Refraction & lenses**

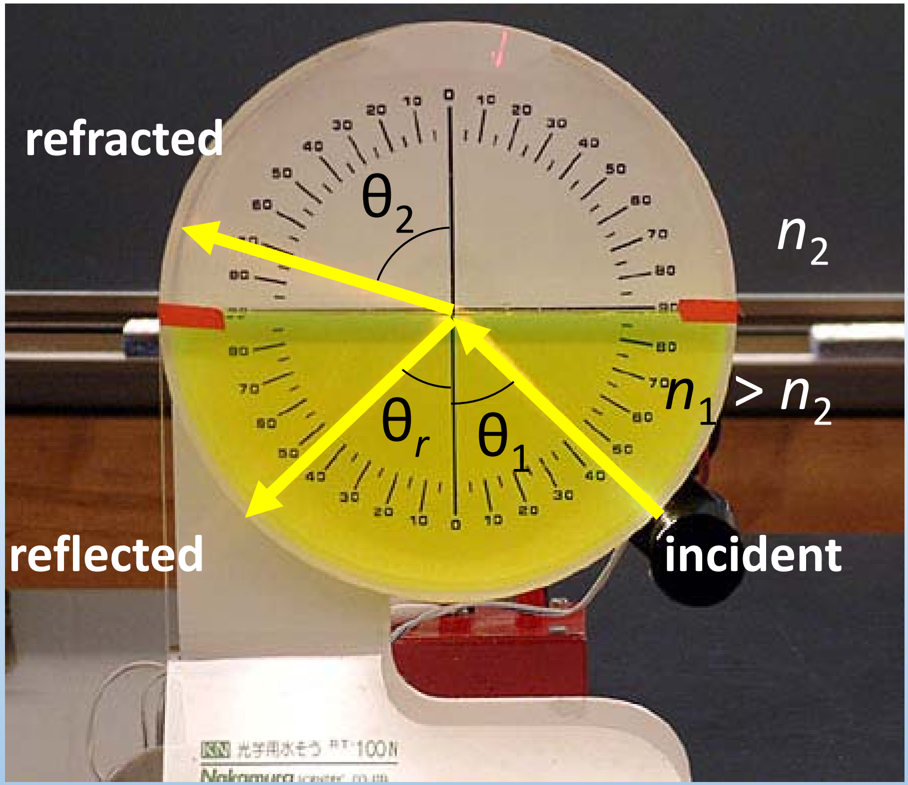
# *Today we will...*

- 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*

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




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

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

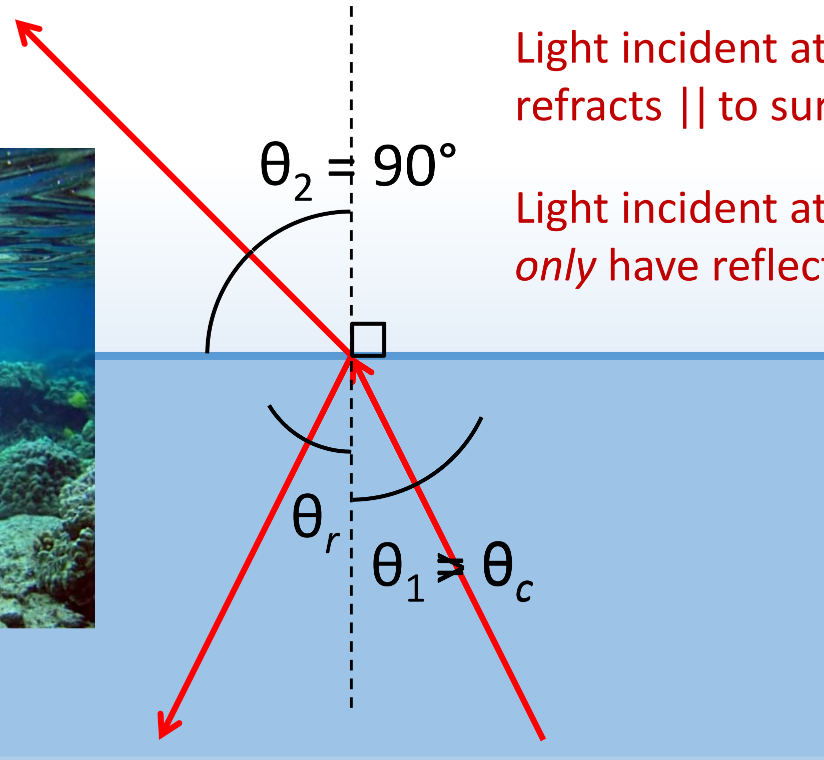
# *Total internal reflection*

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

$$n_1 \sin\theta_c = n_2 \sin 90^\circ \qquad \text{So,} \quad \theta_c = \sin^{-1}\frac{n_2}{n_1}$$

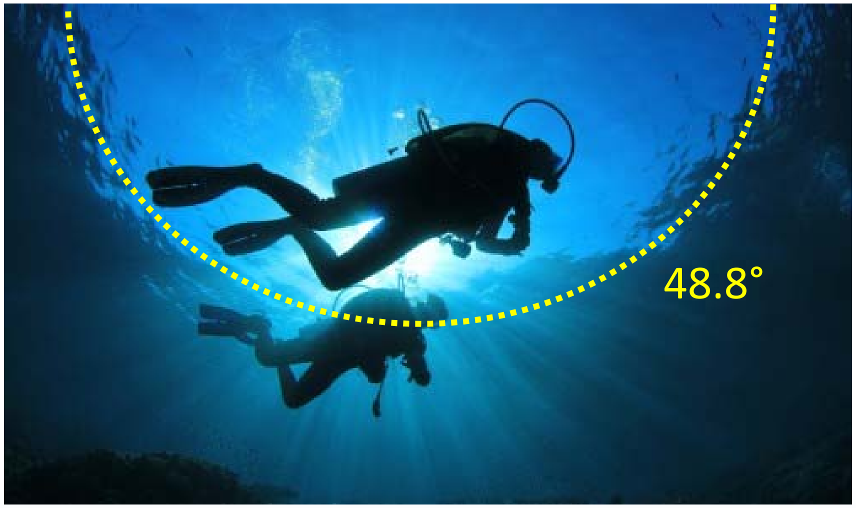
Light incident at *critical angle* $\theta_1 = \theta_c$ refracts || to surface ($\theta_2 = 90°$)

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

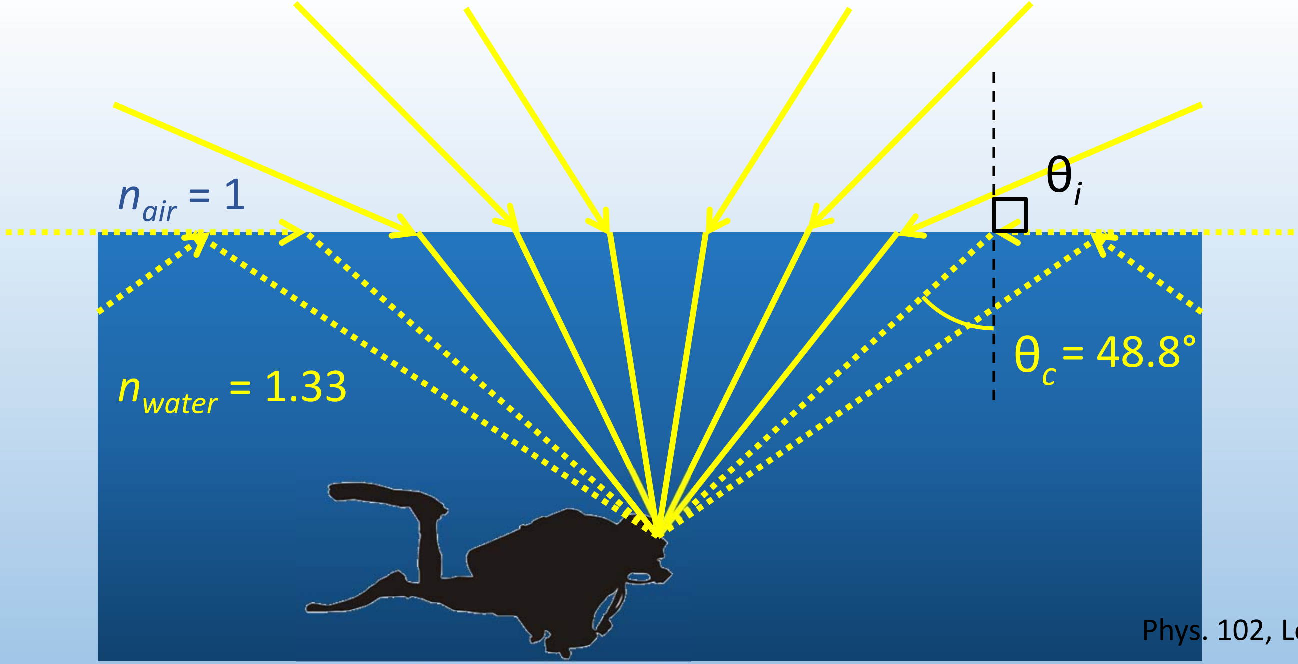


# Calculation: underwater view

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

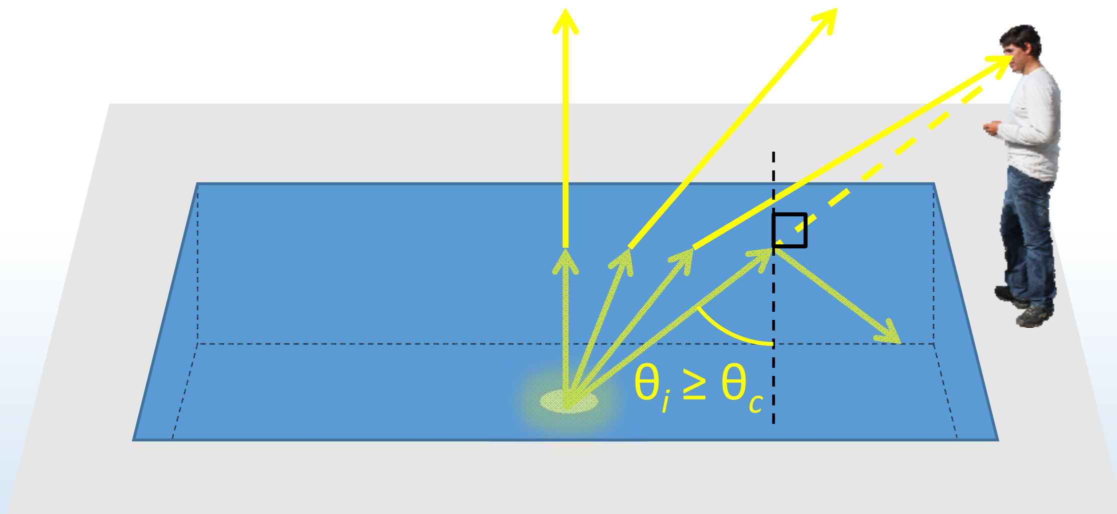



$$\theta_c = \sin^{-1}\frac{n_{air}}{n_{water}} = \sin^{-1}\frac{1}{1.33} = 48.8°$$



# ACT: CheckPoint 1.1

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




A. Yes

B. No

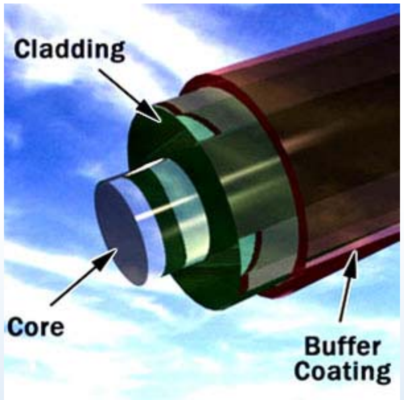
44%

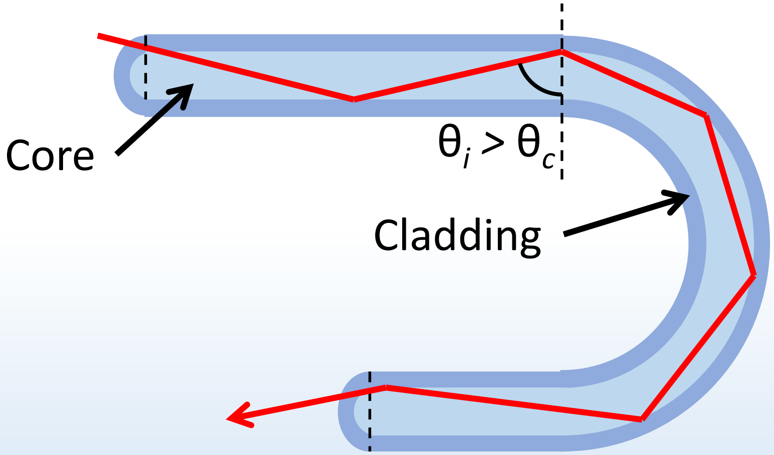
56%

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

# *Fiber Optics*

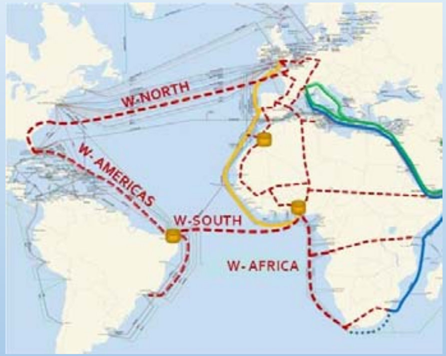
Optical fibers consist of "core" surrounded by "cladding" with $n_{cladding} < n_{core}$. Light hits core-cladding interface at $\theta_i > \theta_c$, undergoes total internal reflection and stays in the fiber.

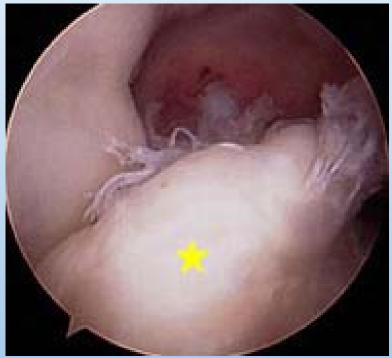


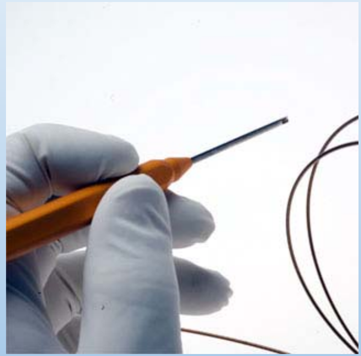




Only works if $n_{cladding} < n_{core}$

- Telecommunication
- Arthroscopy
- Laser surgery



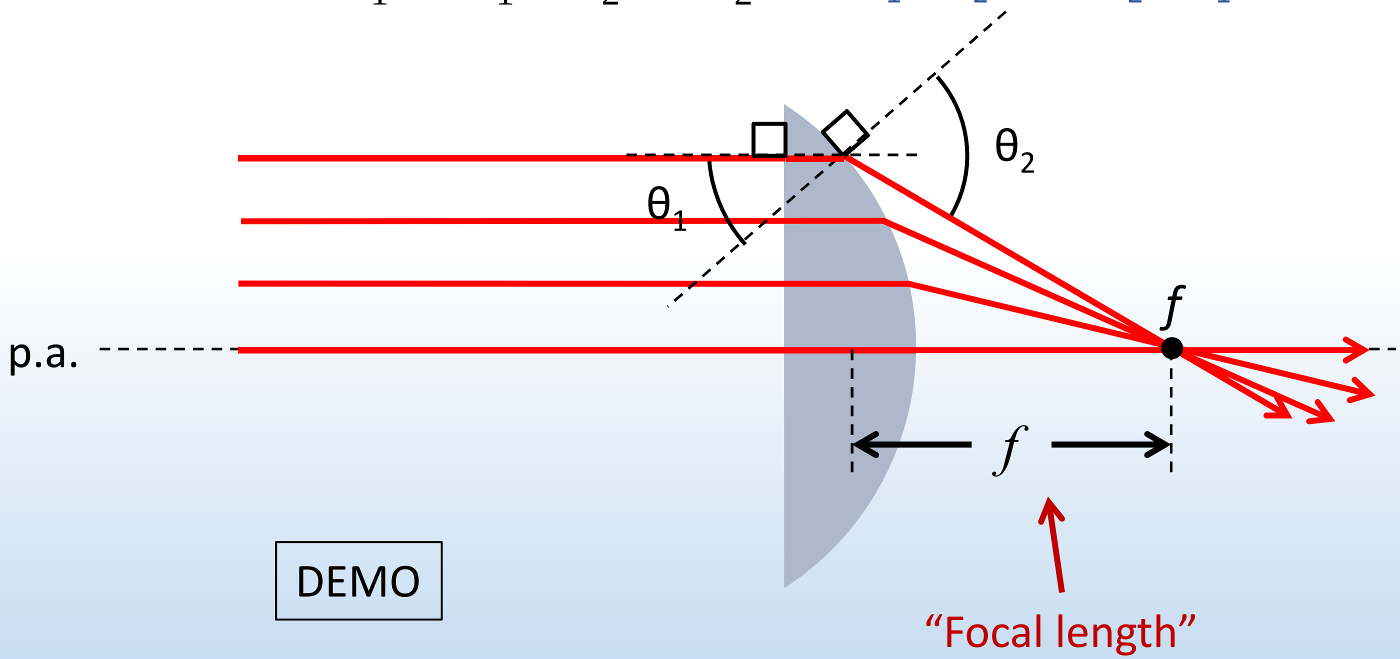


# *Converging lens*

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 $\theta_2 > \theta_1$

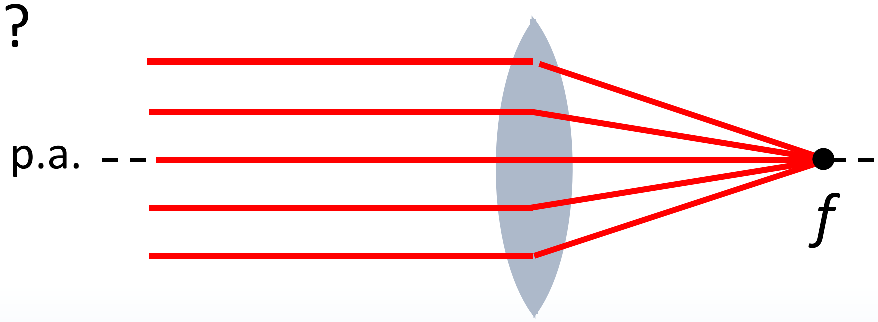



DEMO

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?



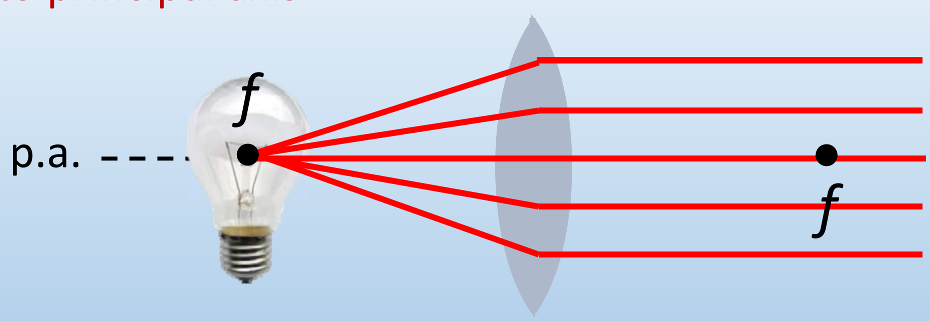

All rays parallel to principal axis refract through focal point *f*

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*

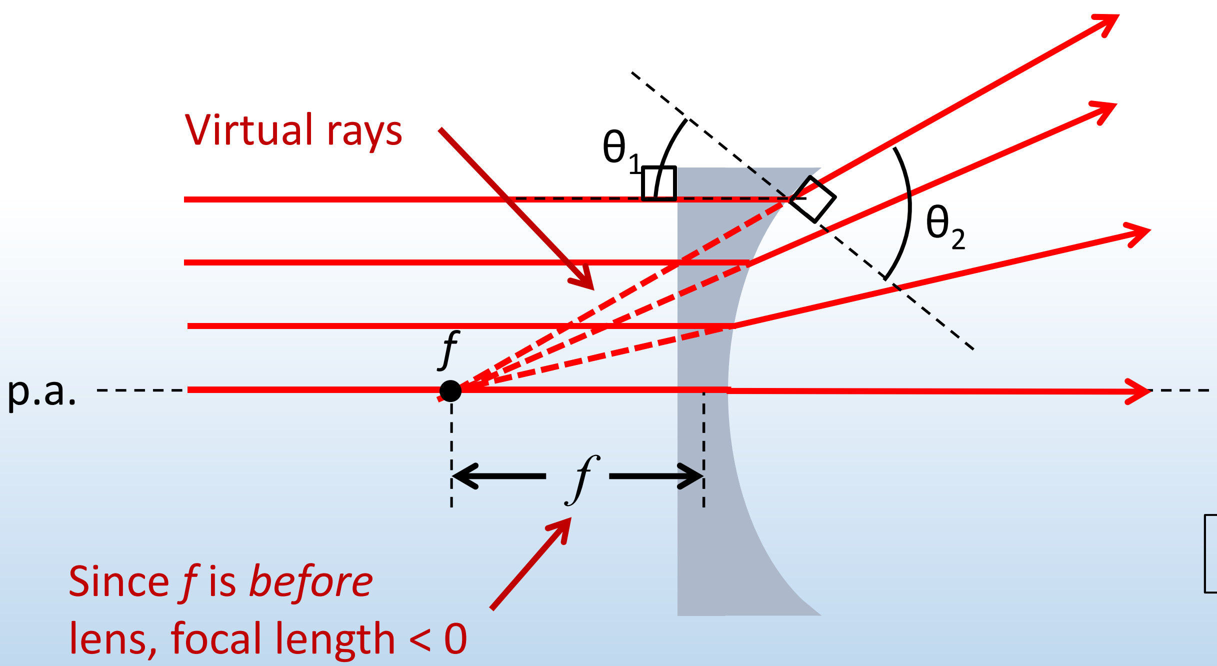


# *Diverging lens*

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

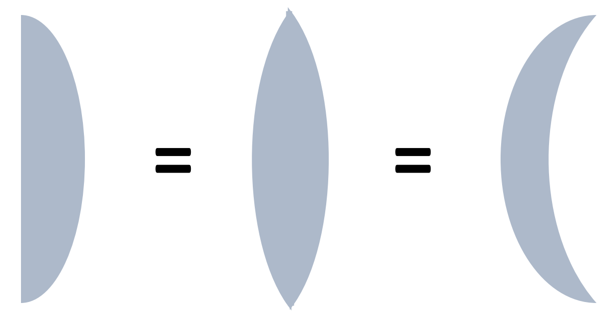
Diverging lens – rays || to p.a. reflect as if they originated from focal point *f* ***before*** lens

# *Converging & diverging lenses*

Converging lens:

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

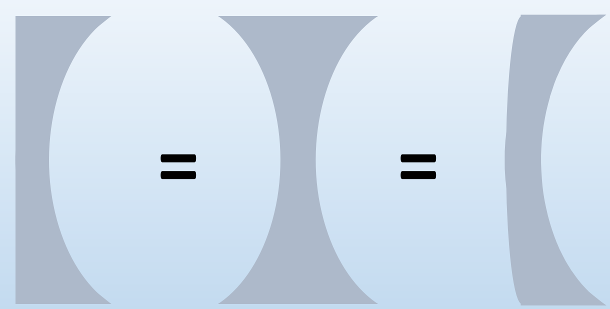
Converging = thick in the middle




Diverging lens:

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

Diverging = thin in the middle



# *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?

A. B. C. D.

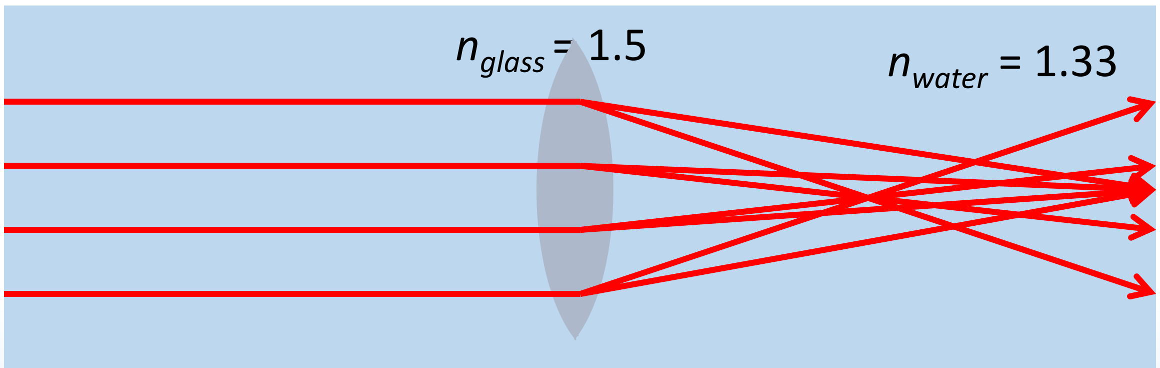
$f < 0$ $f > 0$ $f > 0$ $f > 0$

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

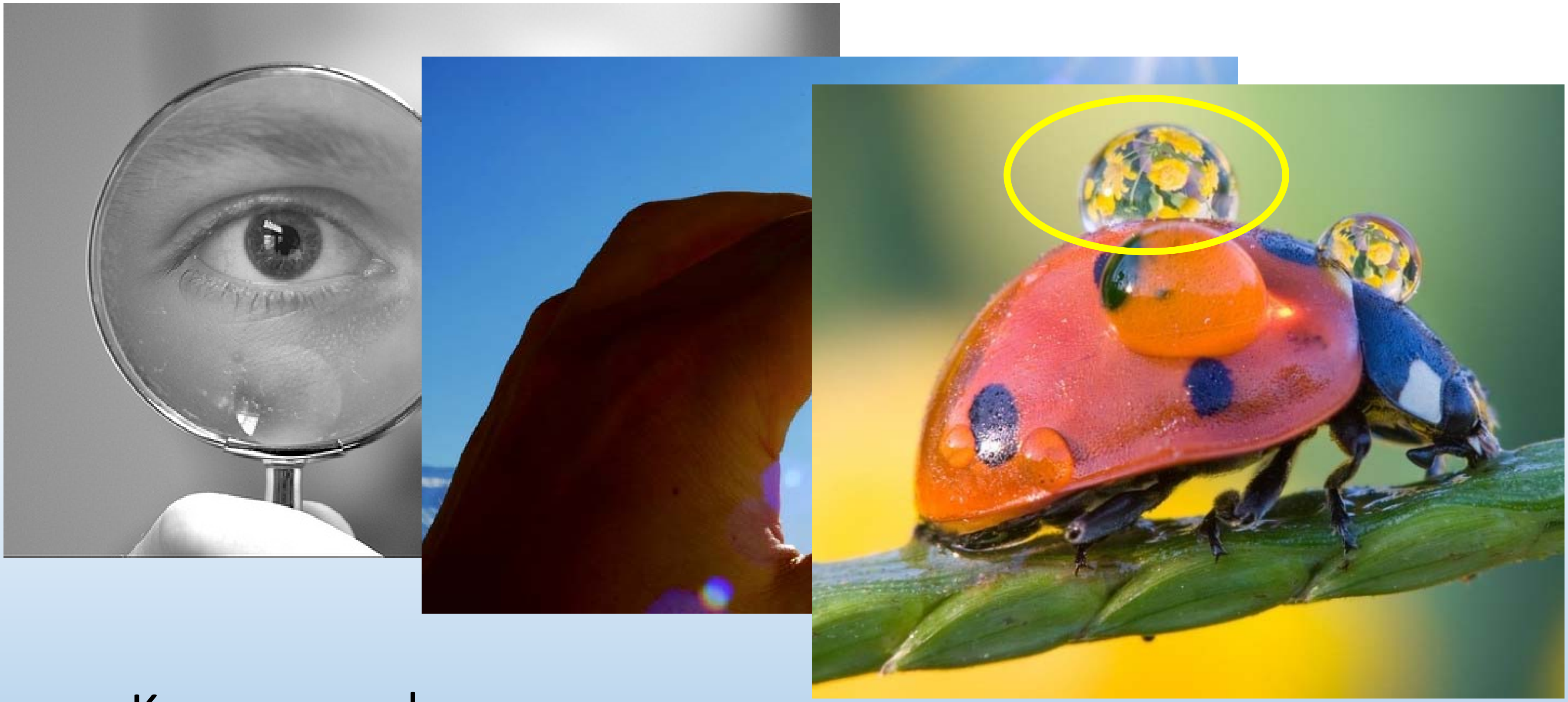
51% B. Increases

17% C. Decreases

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

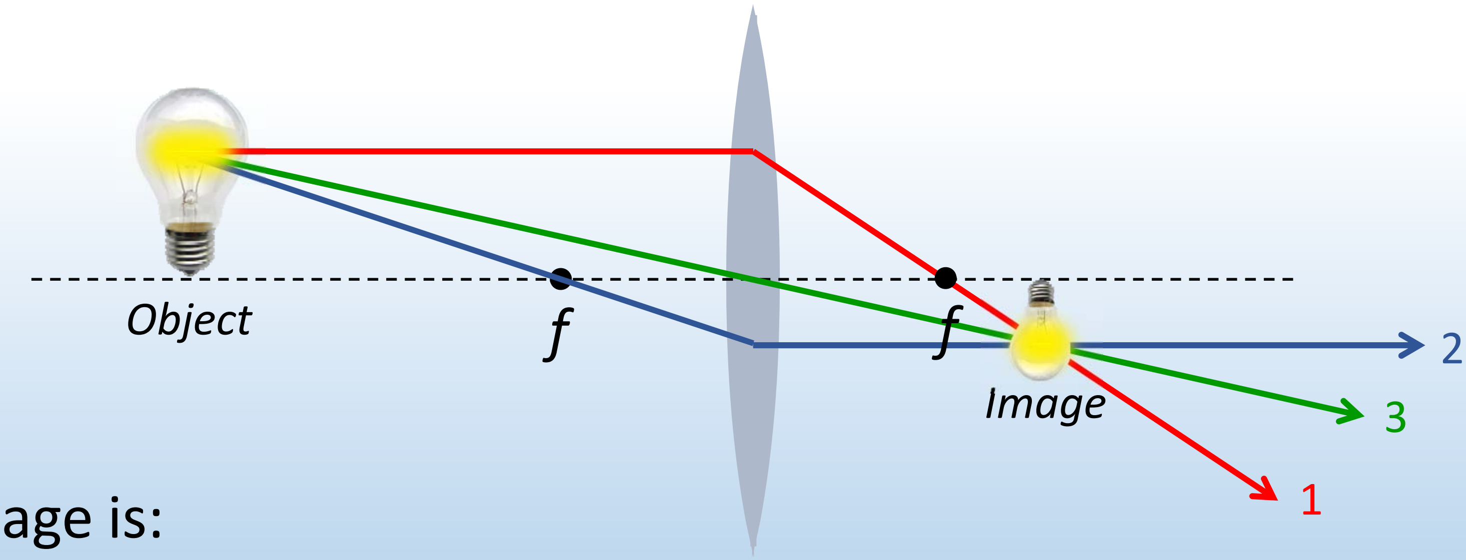



Image is:

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

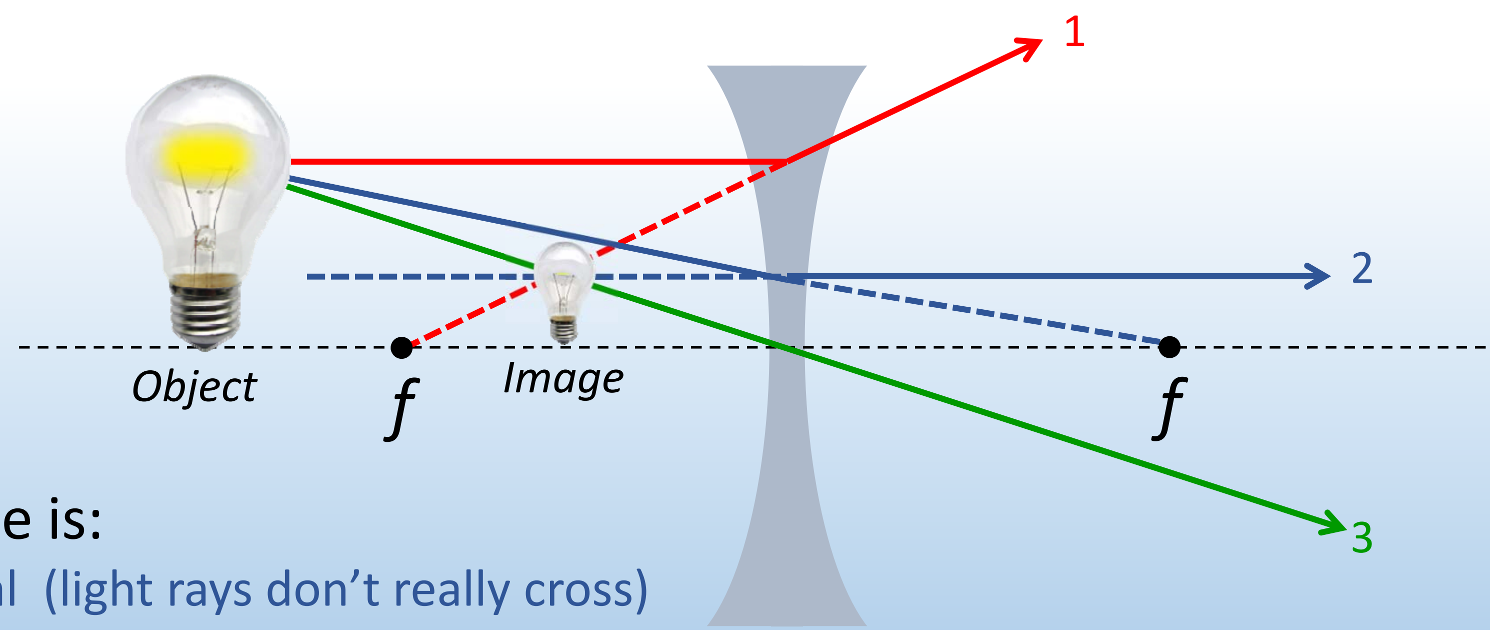



Image is:

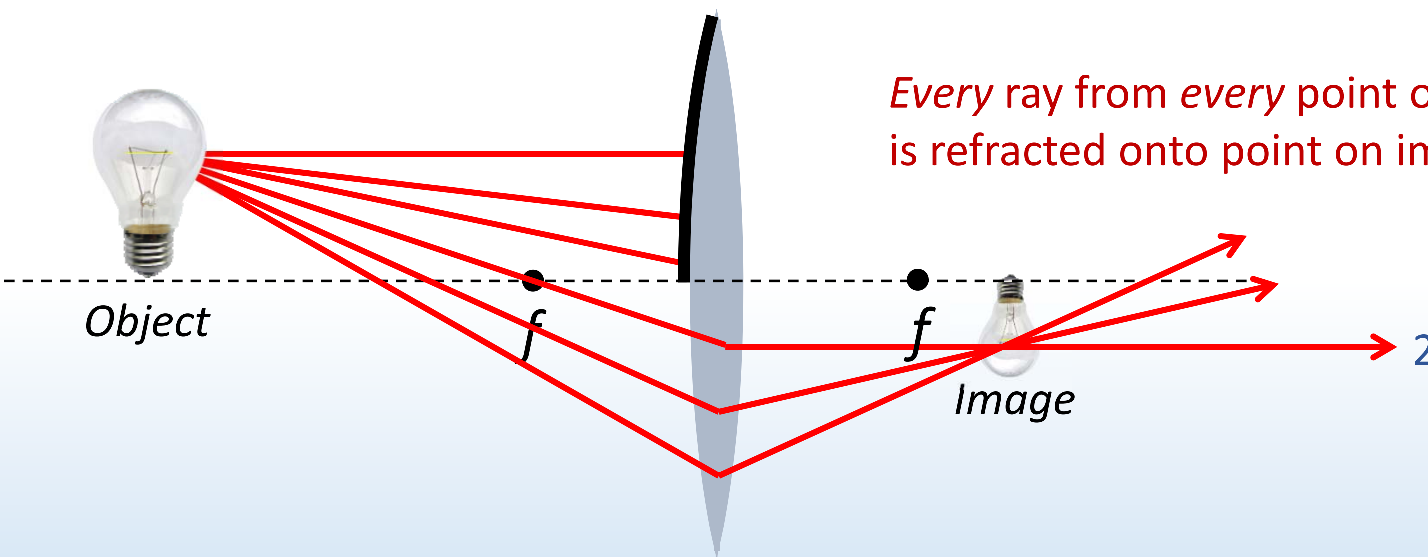
Virtual (light rays don't really cross)

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

Which of the following is true:

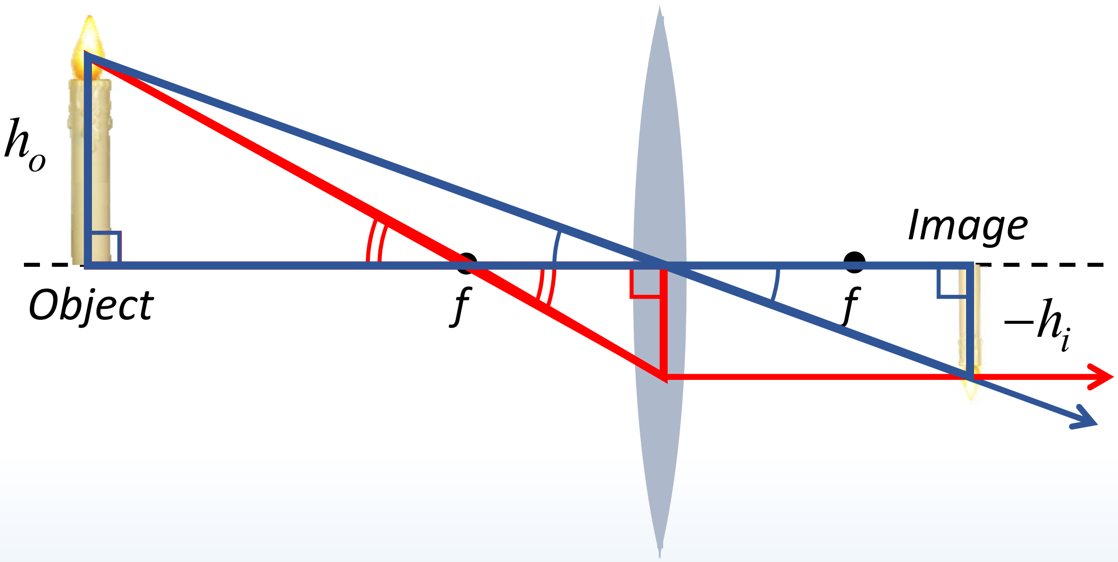
½ the rays get through, so image is ½ as bright

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

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

$h_o$ $\quad f \quad$ $h_o$ $\quad d_i$

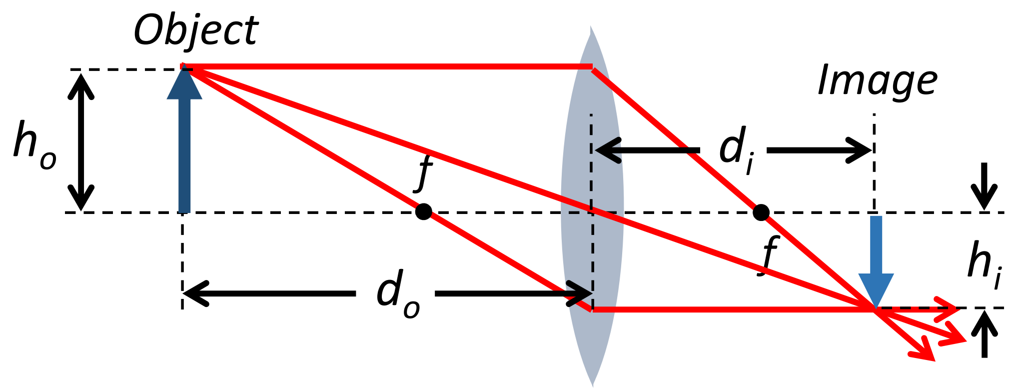
$d_o - f$ $\quad -h_i$ $\quad d_o$ $\quad -h_i$

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

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

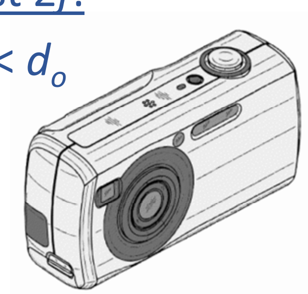
Note similarities to mirror conventions

# *3 cases for converging lens*

**Object is:** | **Image is:**

Past $2f$:

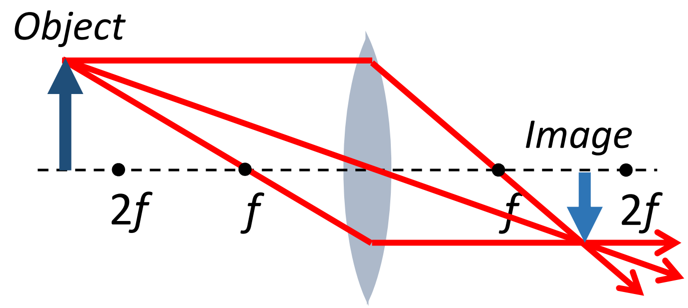
$2f < d_o$



Inverted: $h_i < 0$

Reduced: $m < 1$

Real: $d_i > 0$



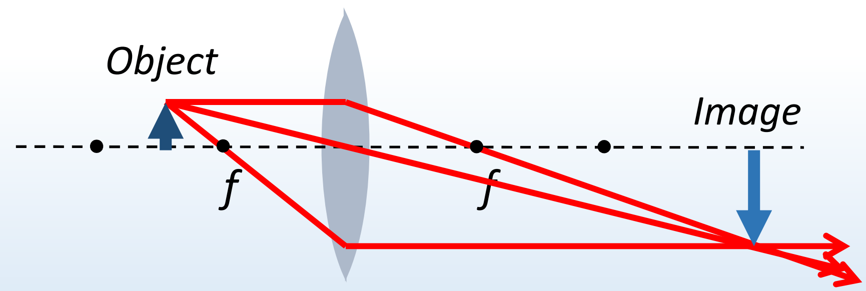

Between $2f$ & $f$:

$f < d_o < 2f$

Inverted: $h_i < 0$

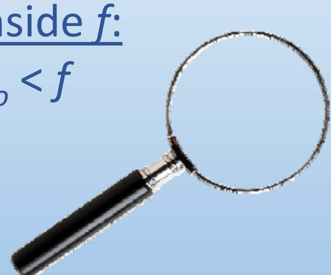
Enlarged: $m > 1$

Real: $d_i > 0$




Inside $f$:

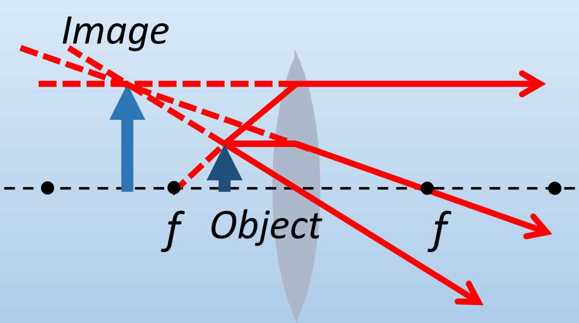
$d_o < f$



Upright: $h_i > 0$

Enlarged: $m > 1$

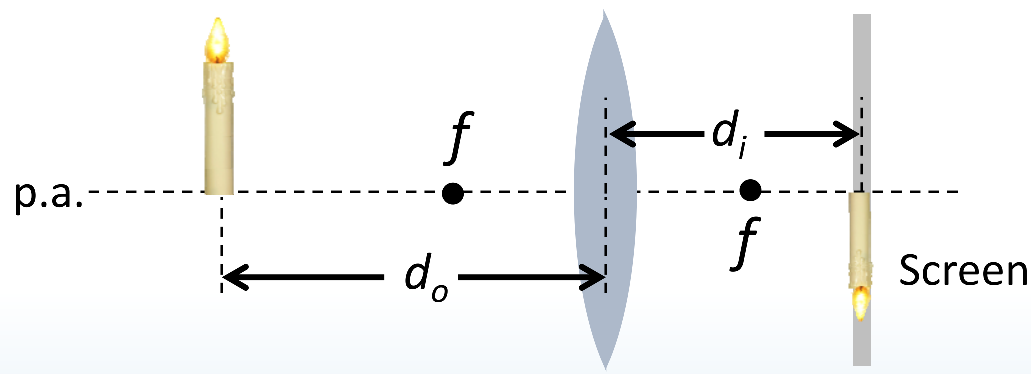
Virtual: $d_i < 0$




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

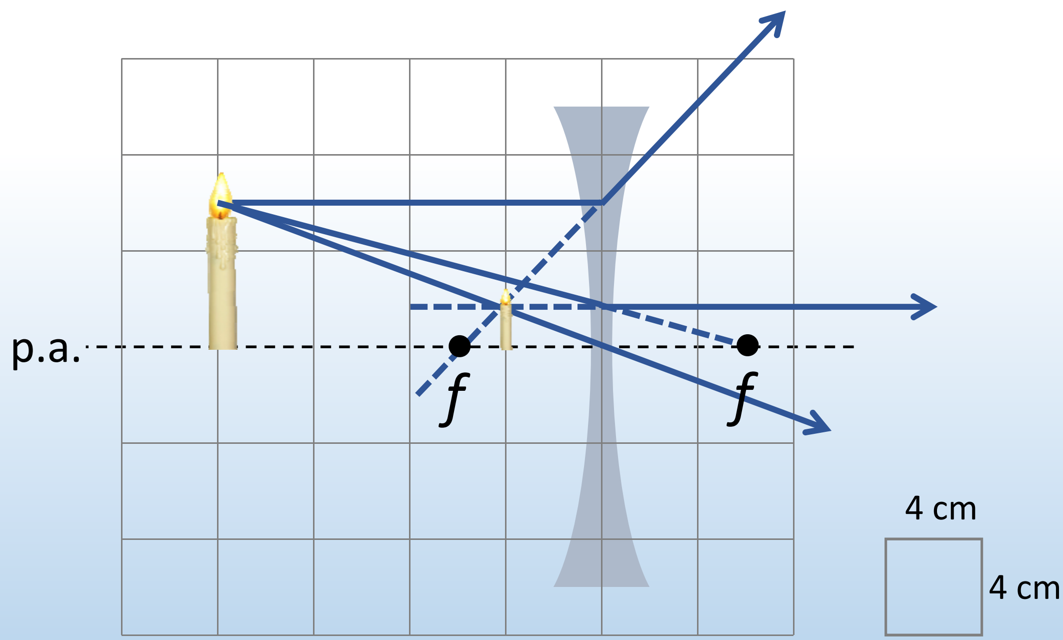
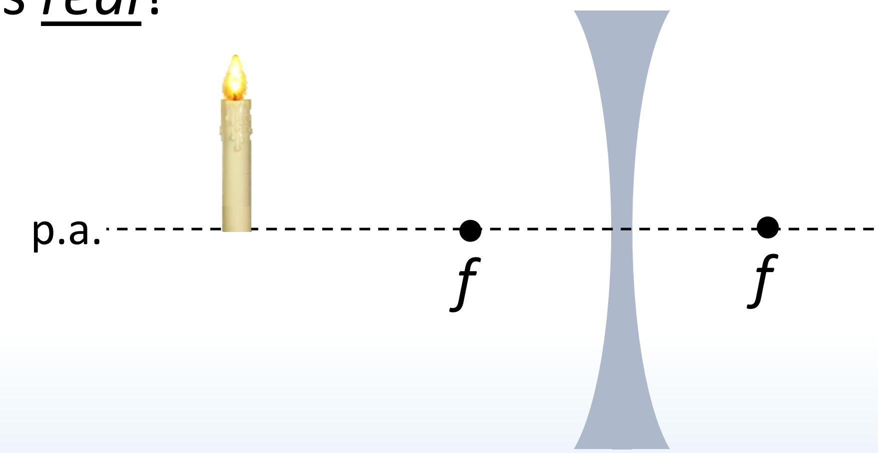



Diagram should agree!

# *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

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