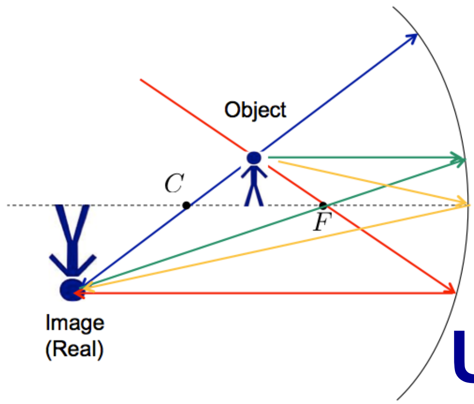

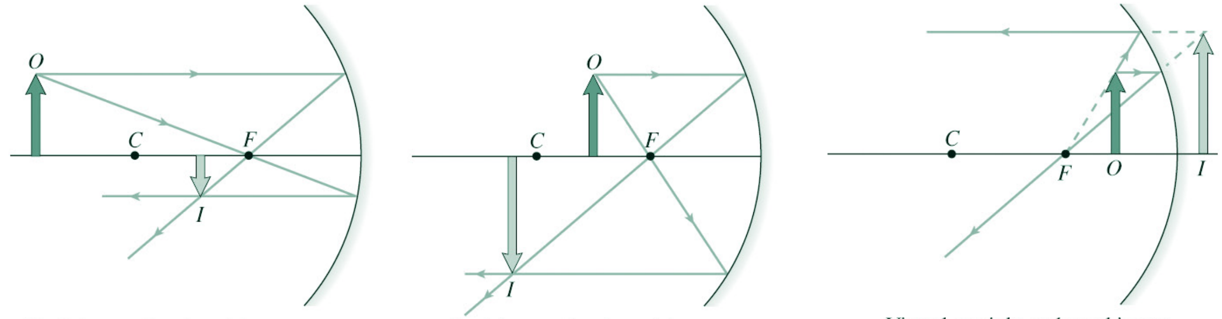

Real, inverted, reduced image   Real, inverted, enlarged image   Virtual, upright, enlarged image

University Physics 227N/232N

Mirrors and Lenses

Homework "Optics 2" due Friday AM
Quiz Friday
Optional review session next Monday (Apr 28)
Bring Homework Notebooks to Final for Grading

Dr. Todd Satogata (ODU/Jefferson Lab)

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http://www.toddsatogata.net/2014-ODU

Monday, April 21 2014

Happy Birthday to Machine Gun Kelly, Marshawn Lynch, Amber Heard, Ryan Stiles, Peter Frampton, Jack Nicholson, Aaron Spelling, and J. Robert Oppenheimer!
(and Immanuel Kant and Vladimir Lenin too)

Your Opinion Matters

According to University records, your course(s) will end soon, and therefore is (are) available for students to provide feedback.

Your students are notified via email that they can provide feedback on your course and are reminded of this during the feedback period. You may also wish to remind them to participate and allow time at the end of class to complete the survey on their laptop or mobile device. Please remind them that their feedback is anonymous – the authentication is NOT linked to the response. The email to students contains a web link to the survey. They can also access the Student Opinion Survey from the University's Current Students page:

Go to http://www.odu.edu
Click Current Students
Click Student Opinion Survey (under Academics)

Review: An Example

- The image formed in a curved mirror can be found using any two of four special light rays: where rays meet again is where image is

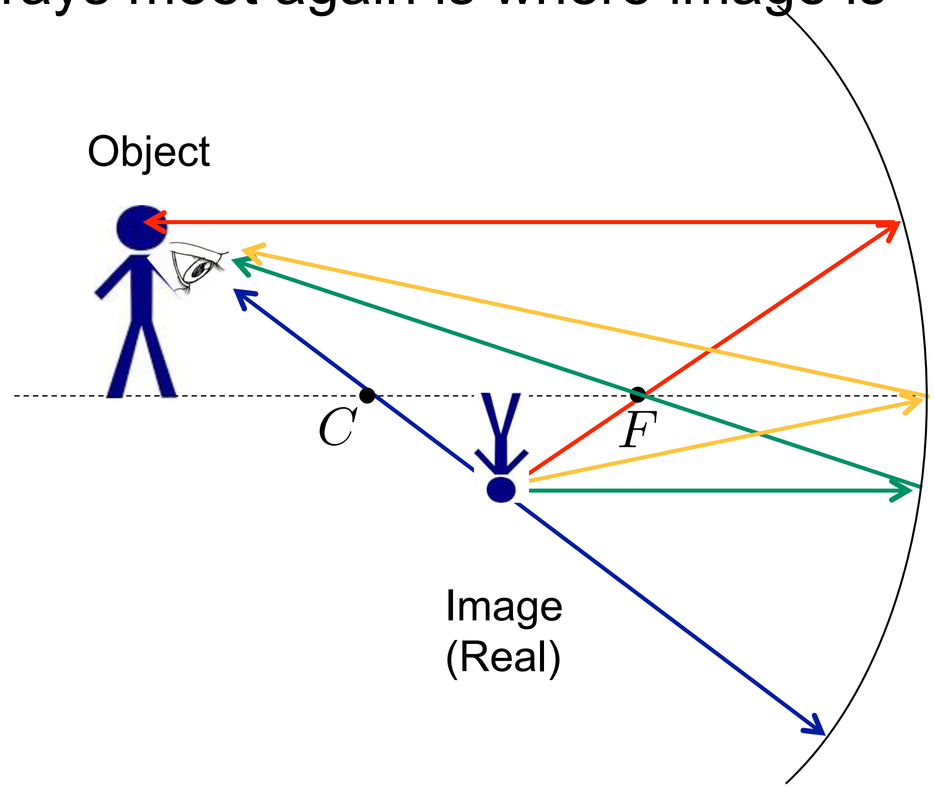
(1) A ray parallel to the mirror axis reflects through the focal point.

(2) A ray passing through the focal point reflects parallel to the axis.

(3) A ray striking the center of the mirror reflects symmetrically about the mirror axis.

(4) A ray through the center of curvature of the mirror returns on itself.

You need only two rays to determine where an image is



C: Center of curvature (center of the semicircular mirror)
F: Focal point of mirror, F=C/2

A real image is in a real point in space and can be projected on a screen.

A Very Similar (But More Seasonal) Example

- The image formed in a curved mirror can be found using any two of four special light rays:

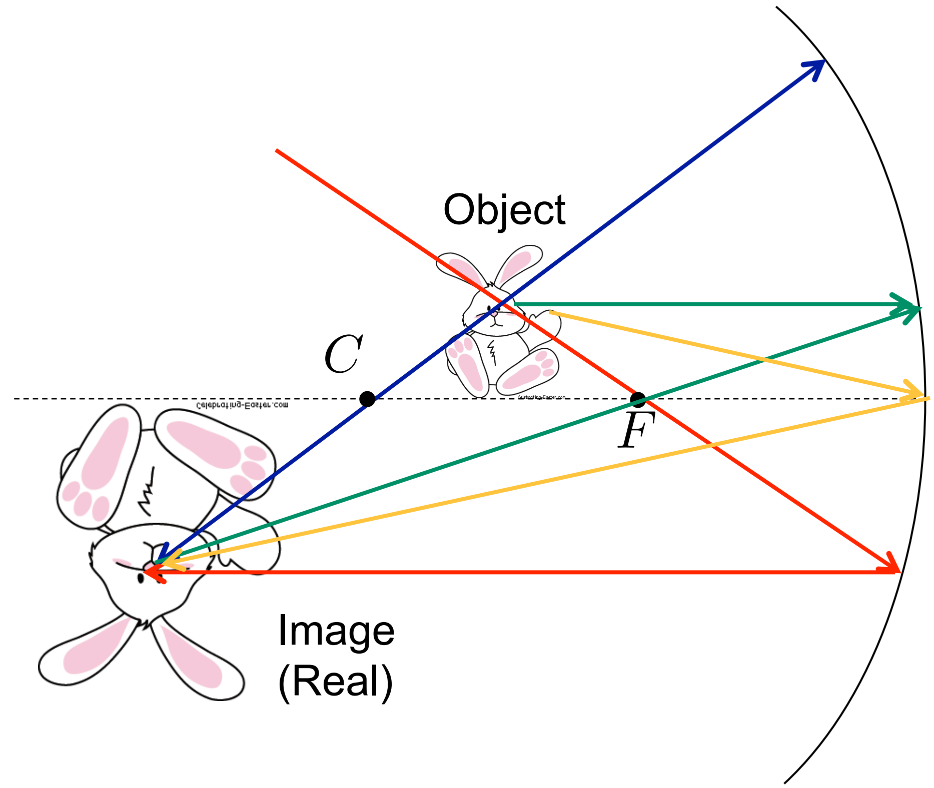
  (1) A ray parallel to the mirror axis reflects through the focal point.

  (2) A ray passing through the focal point reflects parallel to the axis.

  (3) A ray striking the center of the mirror reflects symmetrically about the mirror axis.

  (4) A ray through the center of curvature of the mirror returns on itself.

  You need only two rays to determine where an image is

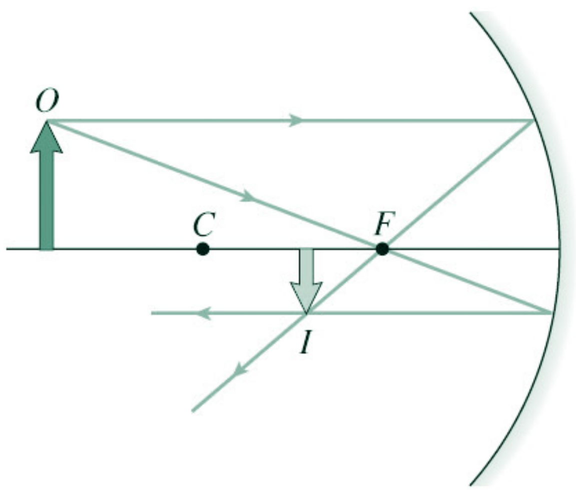


C: Center of curvature (center of the semicircular mirror)
F: Focal point of mirror, F=C/2

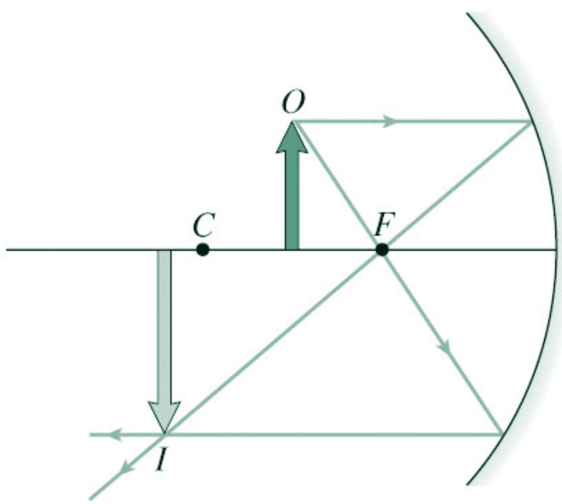
A real image is in a real point in space and can be projected on a screen.

Review: Image Formation with Curved Mirrors

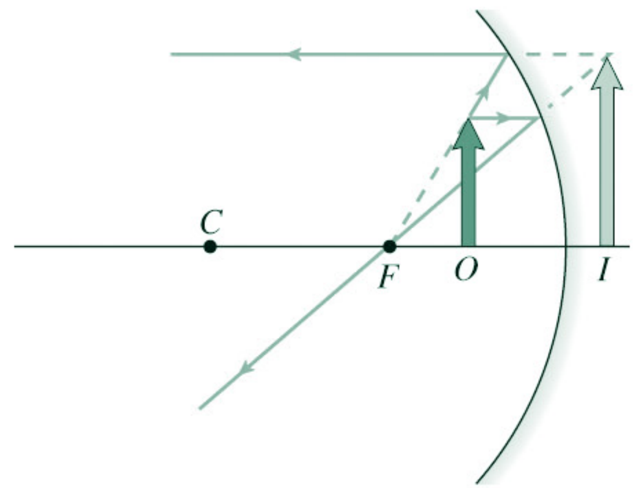
- **Concave mirrors** can form either real or virtual images.
  - If the object is beyond the center of curvature, the image is real, inverted, and reduced in size.
  - If the object is between the center of curvature and the focal point, the image is real, inverted, and enlarged.
  - If the object is closer to the mirror than the focal point, the image is virtual, upright, and enlarged.



Real, inverted, reduced image



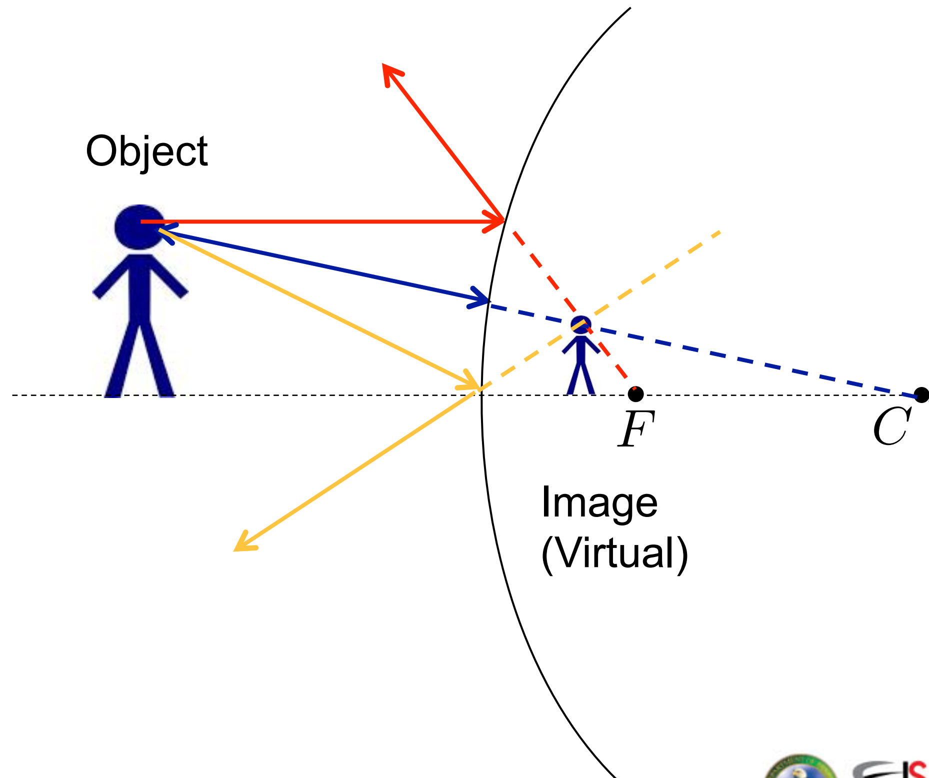
Real, inverted, enlarged image



Virtual, upright, enlarged image

Convex Mirrors

- **Convex mirrors** only form virtual images.
  - The mirror can't focus incoming rays to a real point to form a real image.
  - The image is always upright and reduced in size.
  - To see the reflection of your eyes, you have to look "down" towards the axis of the mirror.



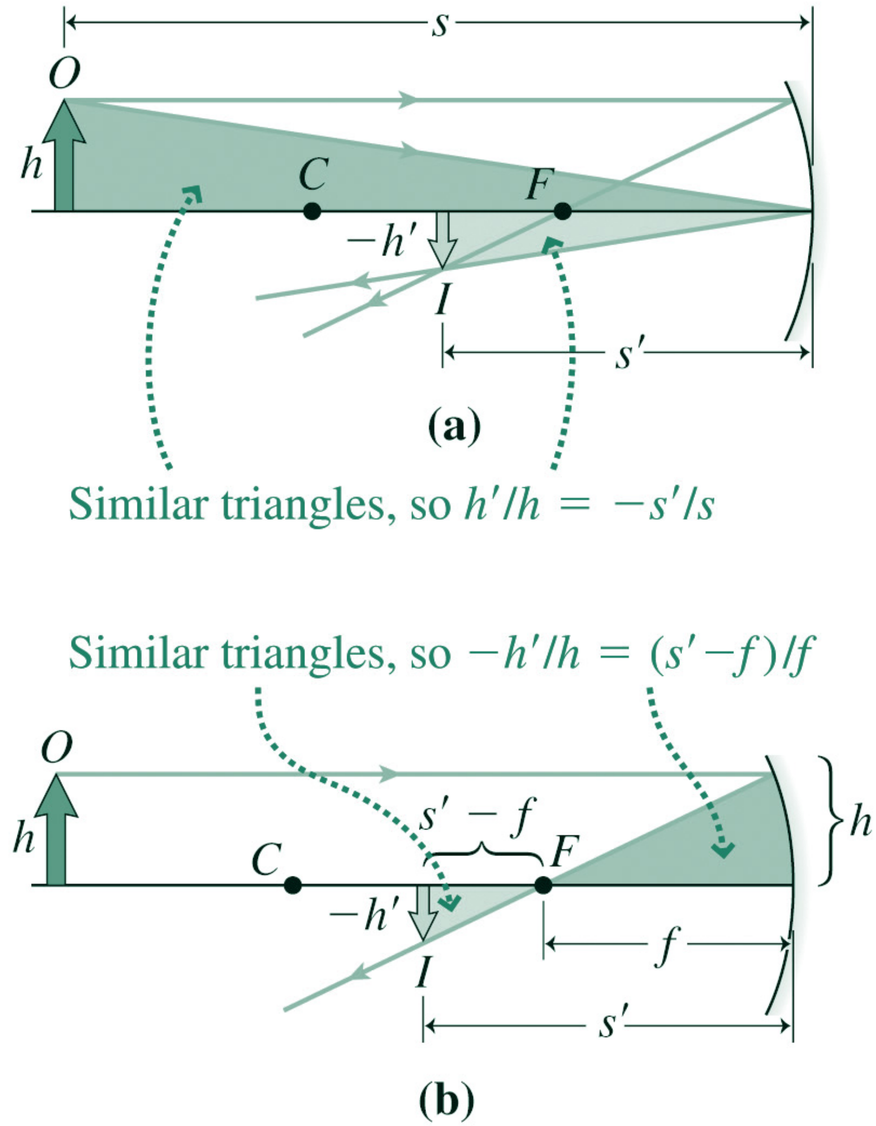
Review: The Mirror Equation

- Analysis using similar triangles yields the **mirror equation**, relating object distance *s*, image distance *s*′, and the focal length *f*:

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

- The image **magnification** *M* is the negative ratio of image distance *s*′ to object distance *s*:

$$M = \frac{h'}{h} = -\frac{s'}{s}$$



Ponderable

- You have a concave spherical mirror with focal length *f*.
  - Where should you place an object (in terms of *f*) for its image to be two times the object's actual size?

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

$$M = \frac{h'}{h} = -\frac{s'}{s}$$

Ponderable: Solution

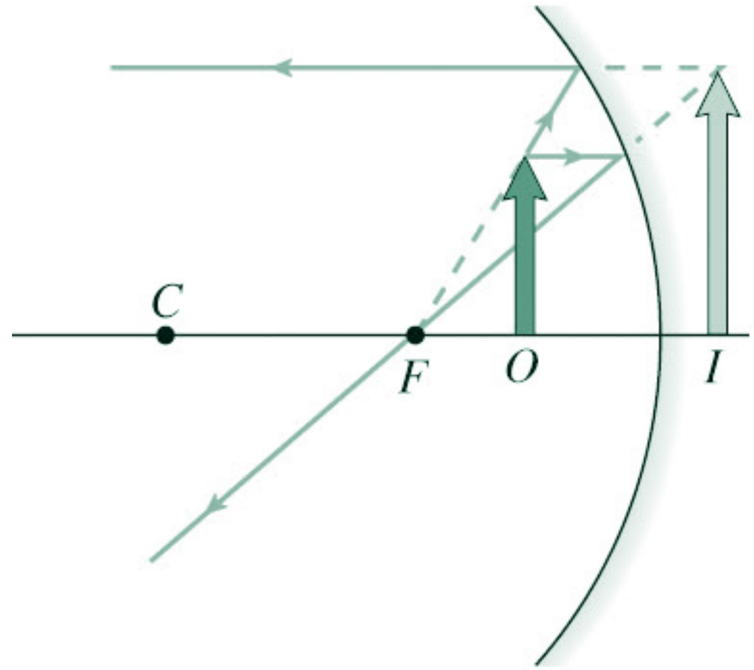
- You have a convex spherical mirror with focal length *f*.
  - Where should you place an object (in terms of *f*) for its image to be two times the object's actual size?

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

$$M = \frac{h'}{h} = -\frac{s'}{s}$$

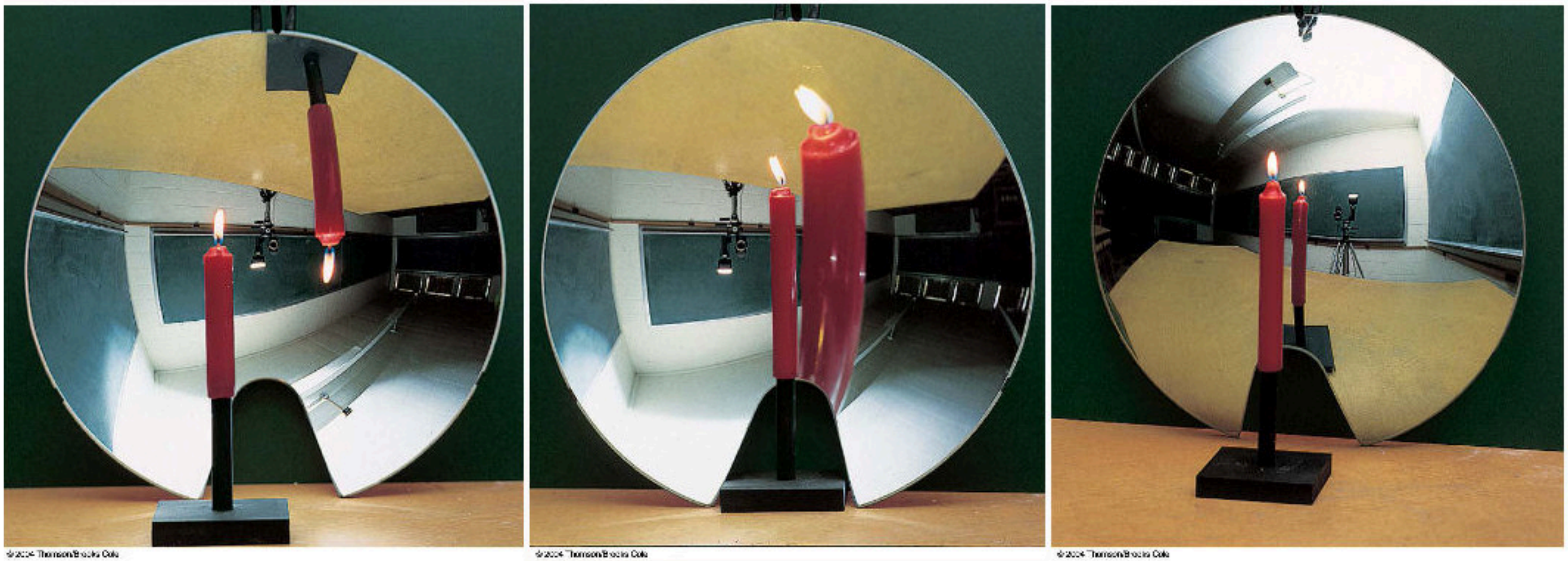
$$M = 2 = -\frac{s'}{s} \quad \Rightarrow \quad s' = -2s$$

$$\frac{1}{s} - \frac{1}{2s} = \frac{1}{f} \quad \Rightarrow \quad \frac{1}{2s} = \frac{1}{f} \quad \Rightarrow \quad s = \frac{f}{2}$$



Virtual, upright, enlarged image

Three Spherical Mirror Images



- Left: Image is inverted and slightly reduced (M~-0.9)
  - Background inverted, so mirror must be **concave**
  - Candle is located a little more than *F* away from mirror
- Middle: Image is upright and magnified (M~+1.4)
  - Candle is located a little less than *F* away from mirror (ponderable)
- Right: Image is upright and reduced
  - Mirror is **convex**, candle is located about *F* away from mirror

Quick Question

- The rear-view mirrors on the passenger side of many cars have a warning statement: "OBJECTS IN MIRROR ARE CLOSER THAN THEY APPEAR." The image of objects in the mirror is also not inverted. This means that the mirror must be

A. Concave

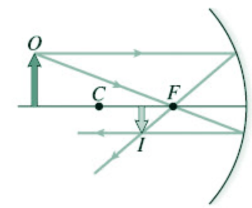
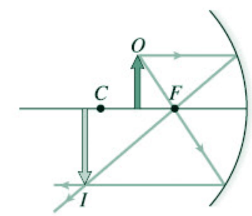
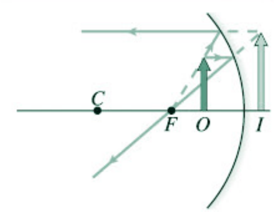
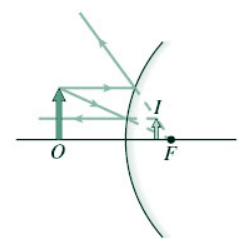
B. Convex

Escher (and Dino Illusion)

Sign Conventions for Mirrors

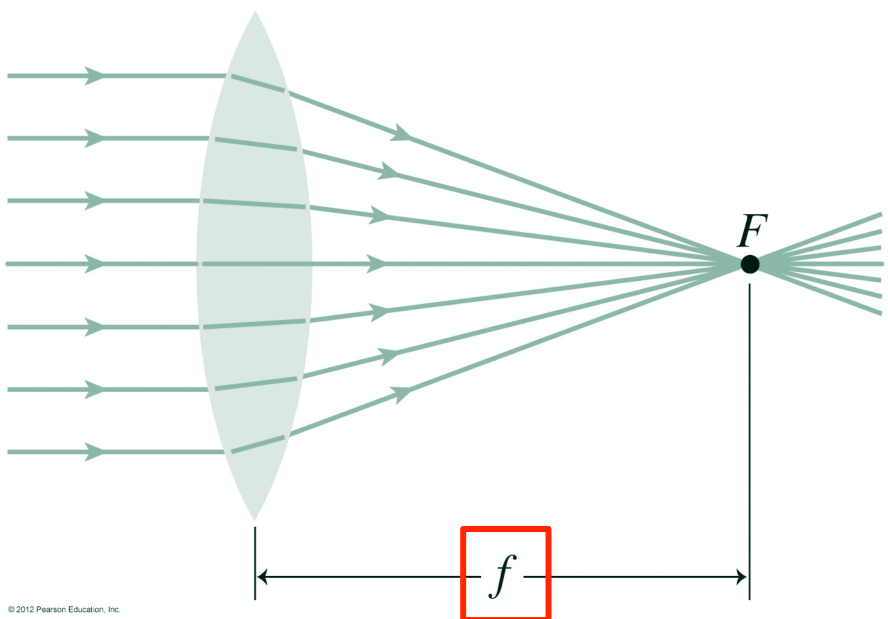
- The mirror equation describes all possible cases of image formation, according to the following sign conventions:

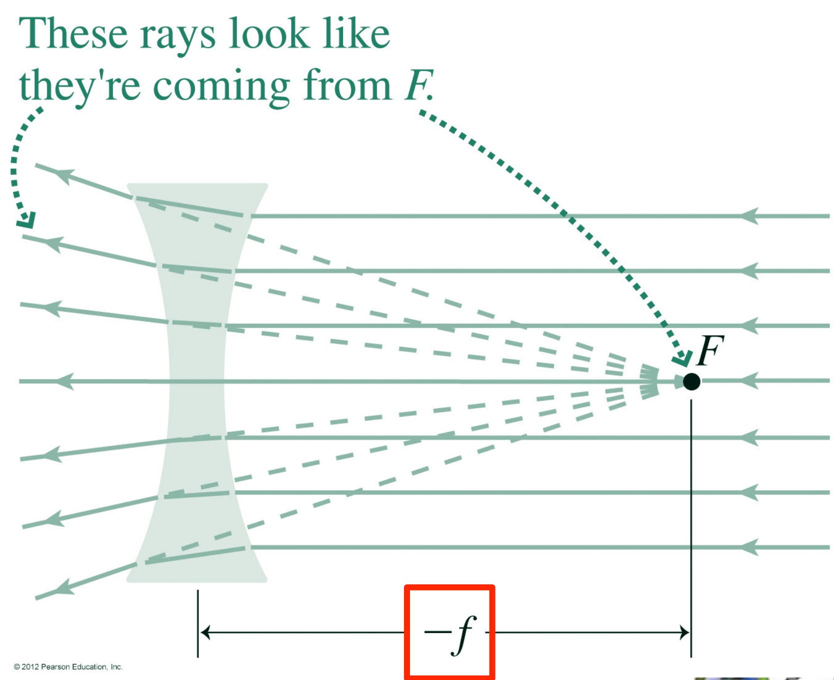
Table 31.1 Image Formation with Mirrors: Sign Conventions

Focal Length, f	Object Distance, s	Image Distance, s'	Type of Image	Ray Diagram
+ (concave)	+ (in front of mirror) $s > 2f$	+ (in front of mirror) $s' < 2f$	Real, inverted, reduced	
+ (concave)	+ (in front of mirror) $2f > s > f$	+ (in front of mirror) $s' > 2f$	Real, inverted, enlarged	
+ (concave)	+ (in front of mirror) $s < f$	− (behind mirror)	Virtual, upright, enlarged	
− (convex)	+ (in front of mirror)	− (behind mirror)	Virtual, upright, reduced	

Converging and Diverging Lenses

- A **converging lens** brings parallel light to a focus.
  - If the lens's refractive index is larger than that of its surroundings, a converging lens is **convex** and has **positive focal length.**
- A **diverging lens** bends parallel light so it appears to diverge from a focus.
  - A diverging lens is **concave** and has **negative focal length.**





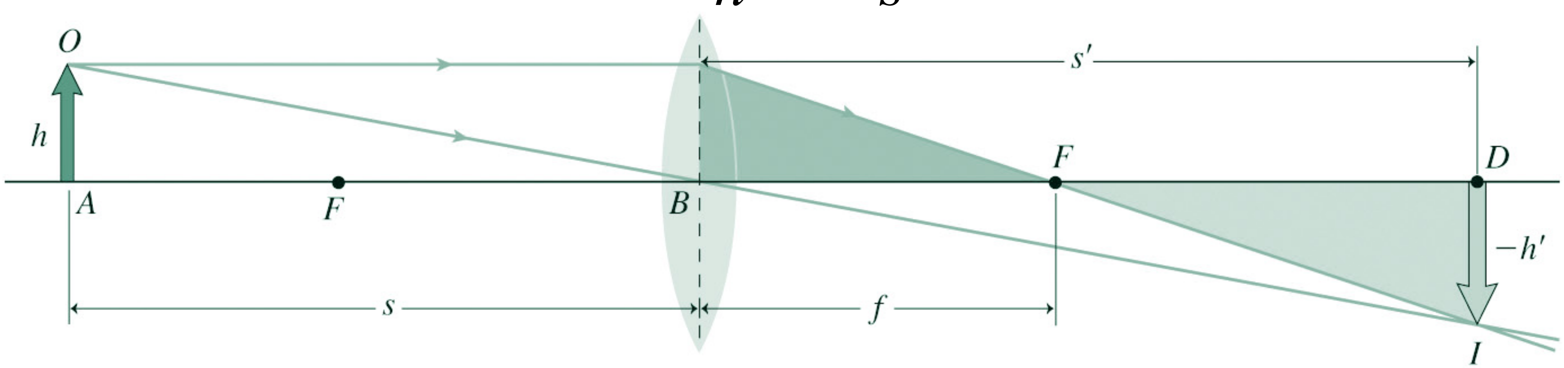
The Lens Equation

- Analysis using similar triangles yields the **lens equation**, relating object and image distances and the focal length:

$$\frac{1}{s}+\frac{1}{s'}=\frac{1}{f}$$

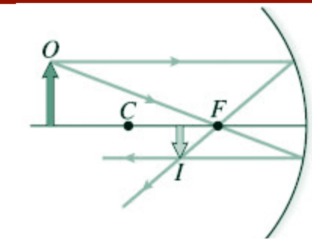
- The image **magnification** is the negative ratio of image to object distance:

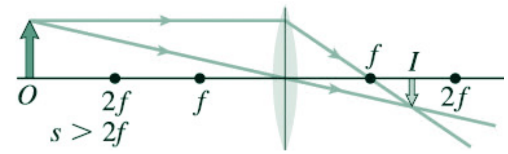
$$M=\frac{h'}{h}=-\frac{s'}{s}$$



Mirrors and Lenses

- Mirrors are not the only optical devices!
  - Mirrors manipulate light through **reflection**
  - Lenses manipulate light through **refraction**

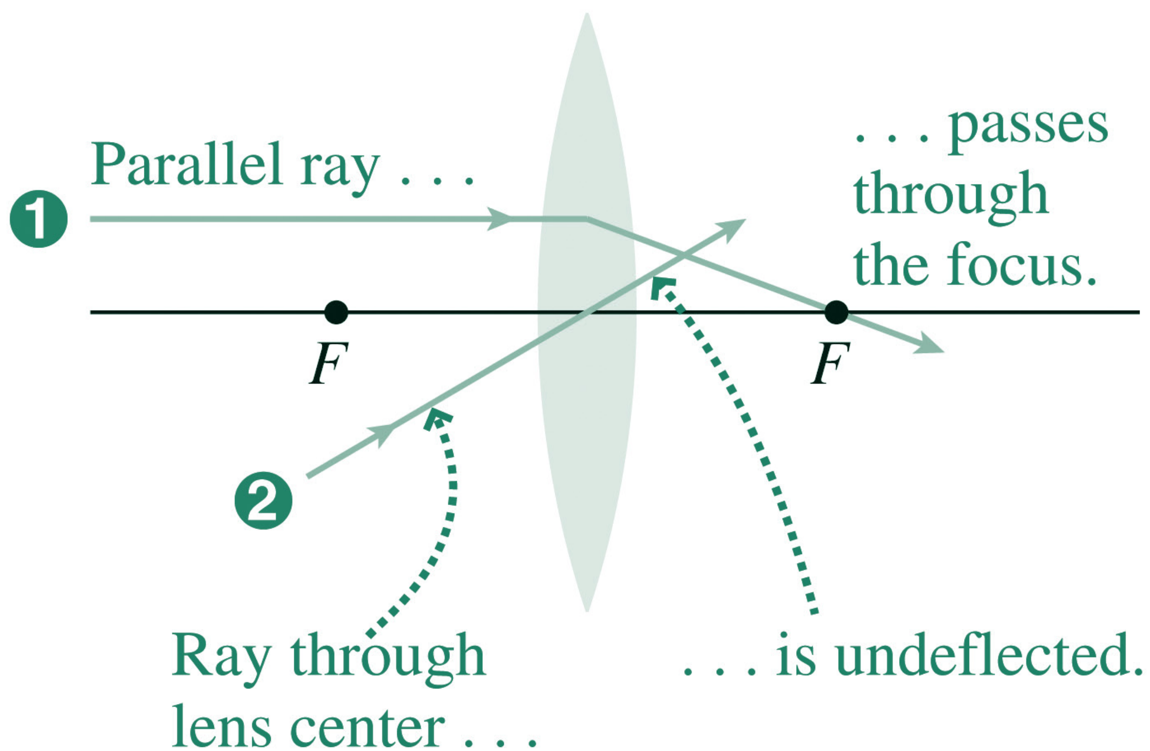




- Lenses are treated with the same geometric approach to light rays
  - But light always passes through the lens
  - For now we don't worry about internal reflection in lenses
  - We also assume for now that our lenses are **thin** compared to their focal length |*f* |
    - This lets us approximate the effect as just a single bend of the light
    - We'll get to thicker lenses a bit later in this lecture with the **lensmaker's equation**
  - We generally concentrate on only two rays necessary to figure out an image

Ray Tracing with Lenses

- The image formed by a lens can be found using two special light rays:
  - (1) A ray parallel to the lens axis reflects through the focal point.
  - (2) A ray passing through the center of the lens is undeflected.
    - This is an approximation valid for **thin lenses**—those whose thickness is small compared to the focal length f of the lens.



The Lens Equation: Same as the Mirror Equation

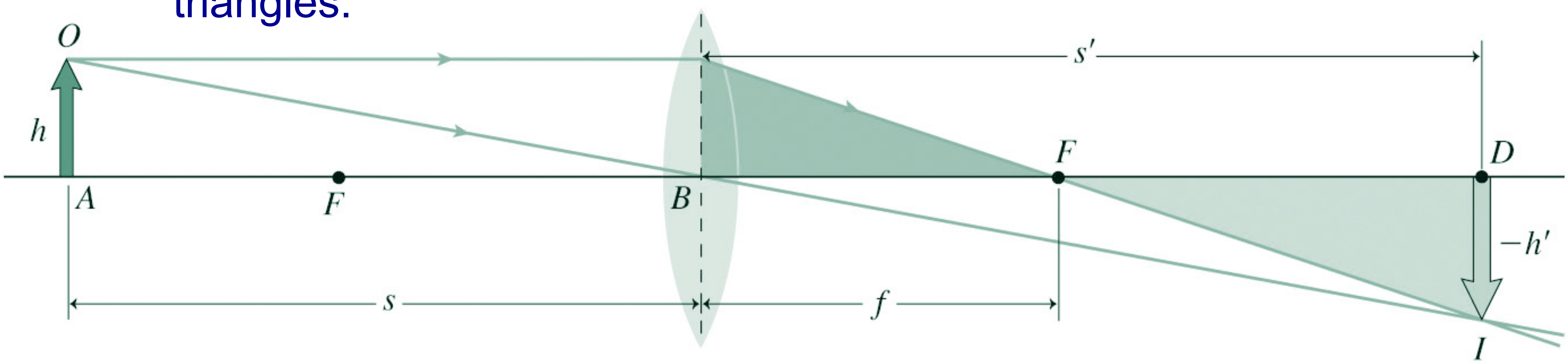
- Rather remarkably, the mirror equation also works for lenses if we use the sign convention that *f* is positive for convex lenses.
- Since the mirror equation works, the equation for magnification also works!

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

$$M = \frac{h'}{h} = -\frac{s'}{s}$$

center $C = 2f$
For spherical lenses

- We can again demonstrate them using a bit of geometry and similar triangles.



$$\text{shaded similar triangles}: \frac{s'-f}{f} = \frac{s'}{f} - 1 = \frac{-h'}{h} = \frac{s'}{s} \qquad \text{divide by s}' \quad \Rightarrow \quad \frac{1}{f} = \frac{1}{s} + \frac{1}{s'}$$

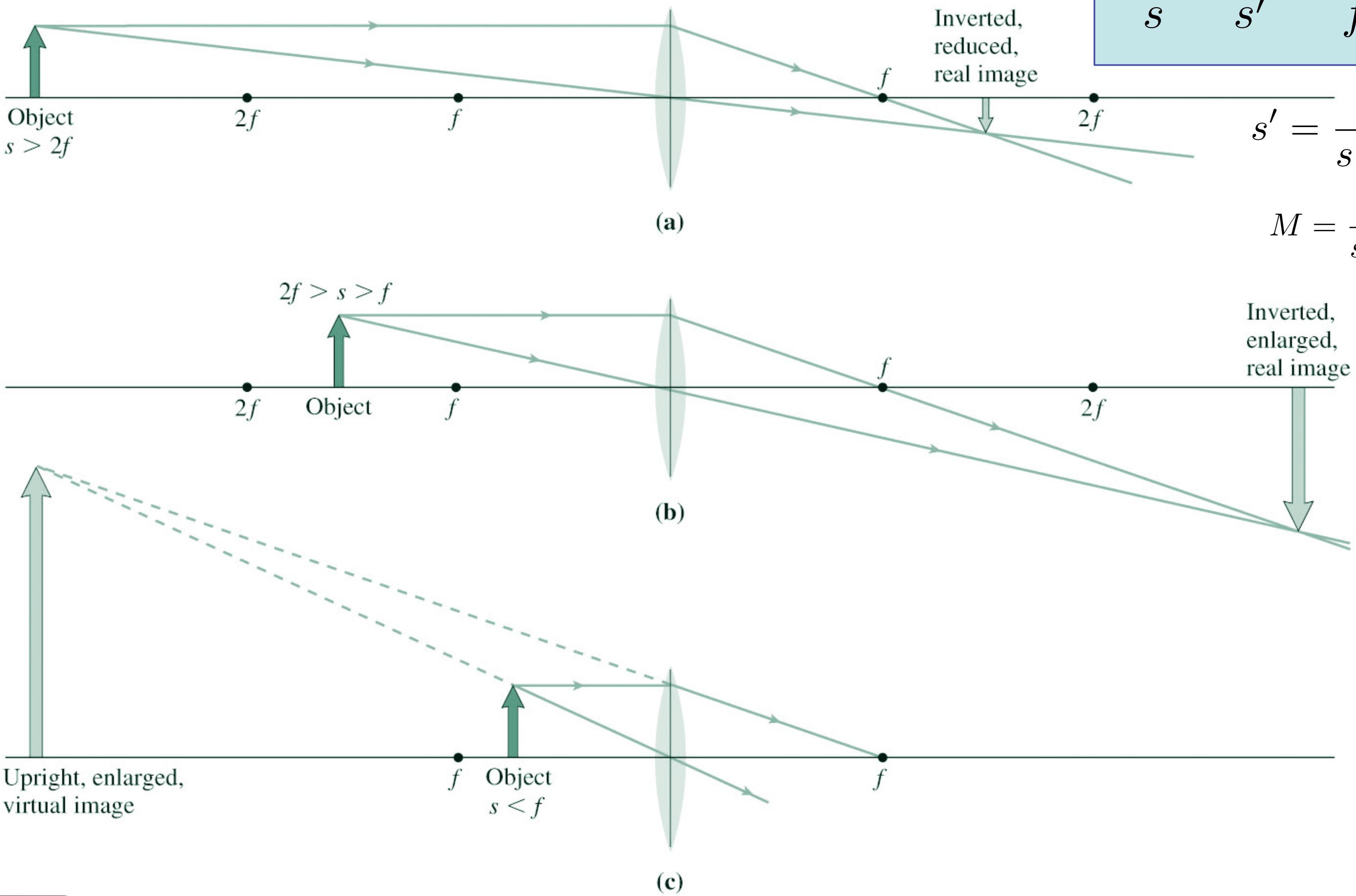
Convex Lenses and Images

- Convex lenses can create real or virtual images

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

$$s' = \frac{sf}{s-f}$$

$$M = \frac{-f}{s-f}$$



Concave Lenses and Images

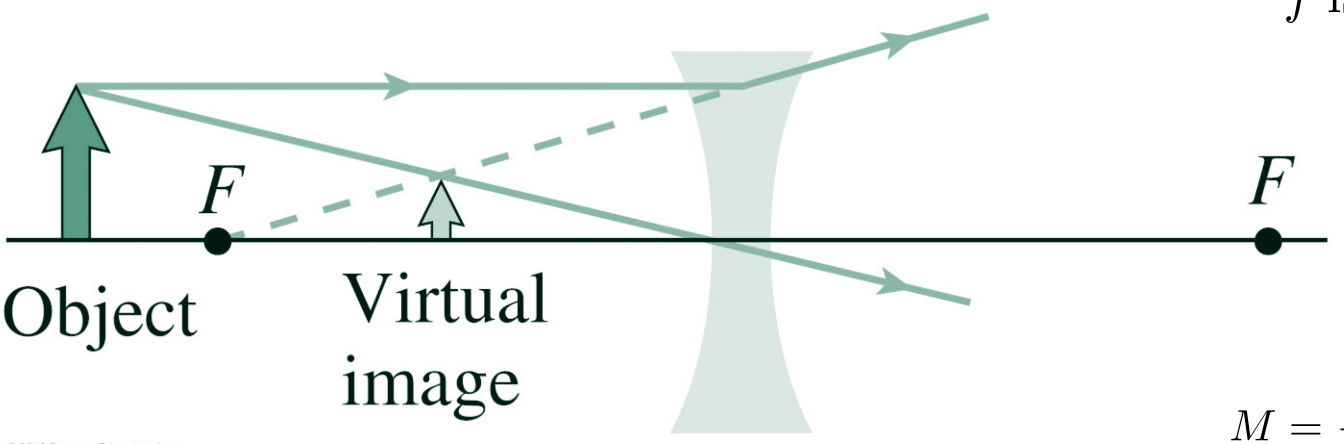
- Concave lenses diverge the incoming light
  - Those light beams are always spreading apart past the lens
  - So the image is always virtual (behind the lens), reduced, and upright

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

$$s' = \frac{sf}{s-f}$$

$$M = \frac{-f}{s-f}$$

f is negative

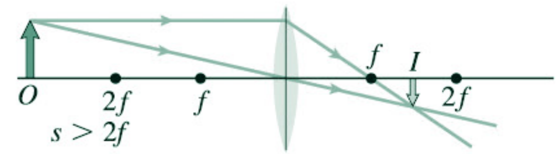
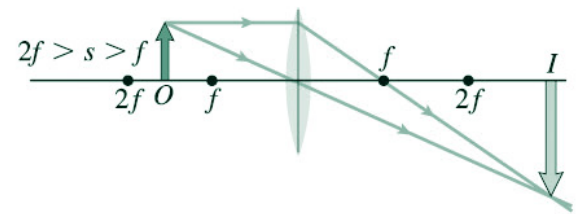
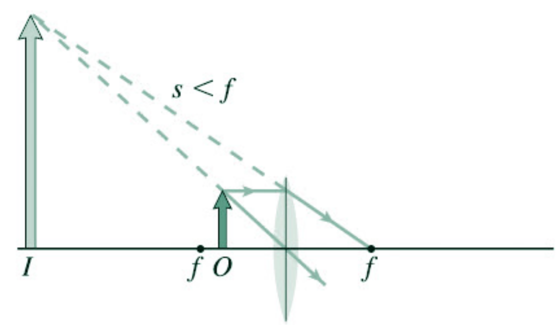


$$s' = \frac{-s|f|}{s+|f|} < 0$$

$$M = \frac{|f|}{s+|f|} \quad \Rightarrow \quad 0 < M < 1$$

Sign Conventions for Lenses

Table 31.2 Image Formation with Lenses: Sign Conventions

Focal Length, f	**Object Distance, s**	**Image Distance, s'**	**Type of Image**	**Ray Diagram**
$+$ (convex)	$+$ $s > 2f$	$+$ (opposite side of lens) $2f > s' > f$	Real, inverted, reduced	
$+$ (convex)	$+$ $2f > s > f$	$+$ (opposite side of lens) $s' > 2f$	Real, inverted, enlarged	
$+$ (convex)	$+$ $s < f$	$-$ (same side of lens)	Virtual, upright, enlarged	
$-$ (concave)	$+$	$-$ (same side of lens)	Virtual, upright, reduced	

Example: Convex Lens Imaging

- You hold a magnifying glass (a convex lens) 14.0 cm away from ant, and it looks ten times bigger than without magnification. What is the focal length of the lens?

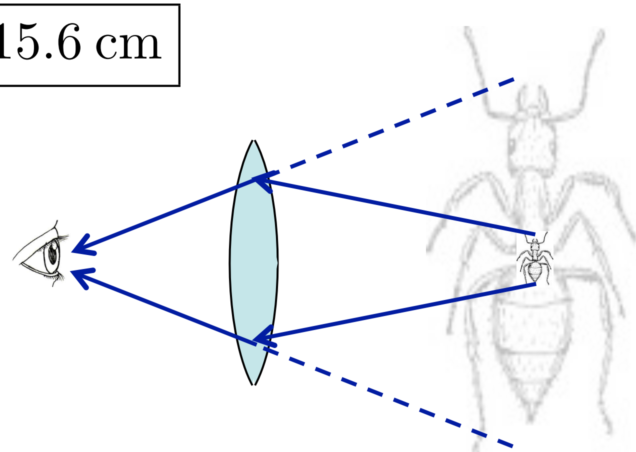
$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

$$M = \frac{h'}{h} = -\frac{s'}{s}$$

$$M = 10.0 = -\frac{s'}{s} = -\frac{s'}{14.0\ \mathrm{cm}} \quad \Rightarrow \quad s' = -140.0\ \mathrm{cm}$$

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s'} = \frac{1}{(14.0\ \mathrm{cm})} + \frac{1}{(-140.0\ \mathrm{cm})} = 0.06428\ \mathrm{cm}^{-1}$$

$$\boxed{f = 15.6\ \mathrm{cm}}$$



Quick Question

- You look through a lens at a page and see the words enlarged and right side up. Describe the image and the lens, respectively.

A. Real; Concave

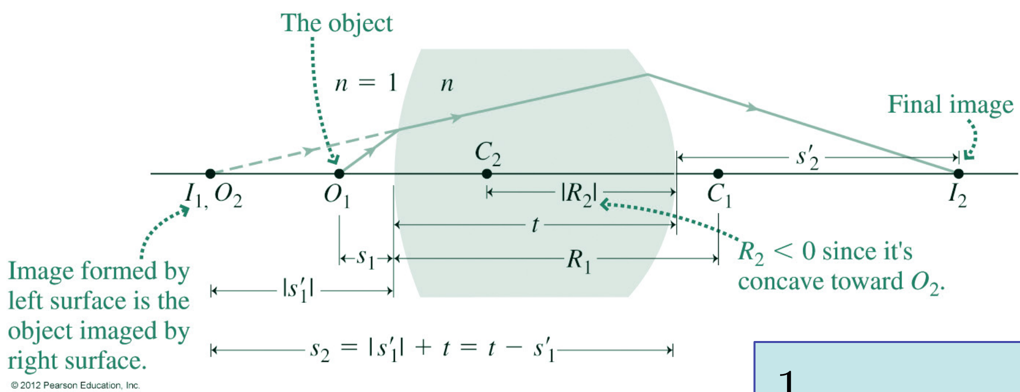
B. Real; Convex

C. Virtual; Concave

D. Virtual; Convex

The Lensmaker's Formula

- Lens makers can't always make the curvature of both sides of a lens the same.
  - The two interfaces (air to lens and lens back to air) then have to be treated separately; they can have different radii of curvature.
  - The total focal length *f* is calculated by figuring out the image from the first surface, and using that as the object for the second surface to create a final image



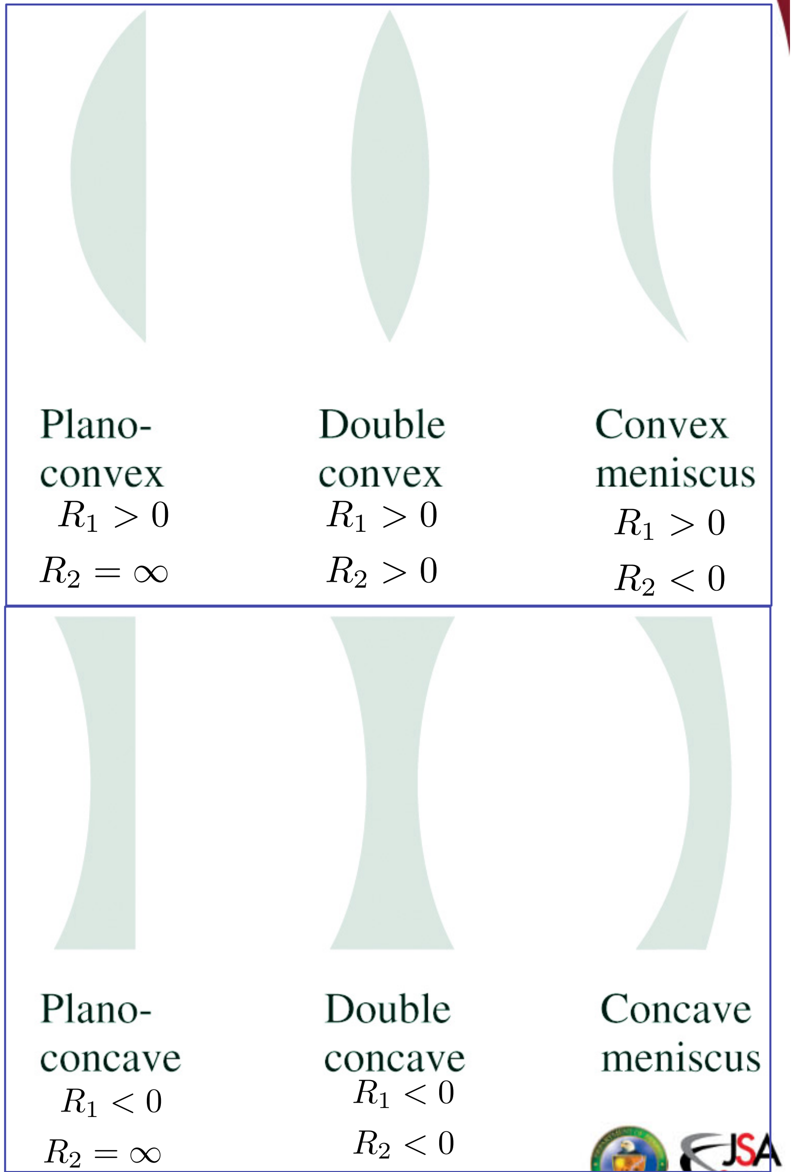
- We'll simply state the result here: in air, and for a thin lens

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

  - Positive R is the normal positive direction for a lens (to the right), so for the above picture, R_1 is positive and R_2 is negative.

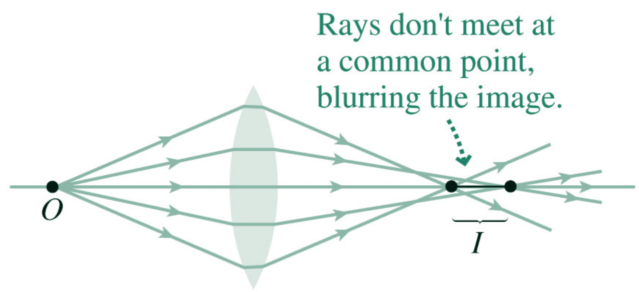
Types of Lenses

- There are many types of lenses depending on the relative curvatures of the two surfaces
  - The most common are double convex (focusing) and double concave (defocusing)
  - Remember that radius of curvature is positive if the surface is convex away from the body of a lens
  - The easiest way to remember this is to remember that the most common lens (double convex) has both radii as positive.
  - A flat surface has an infinite radius of curvature

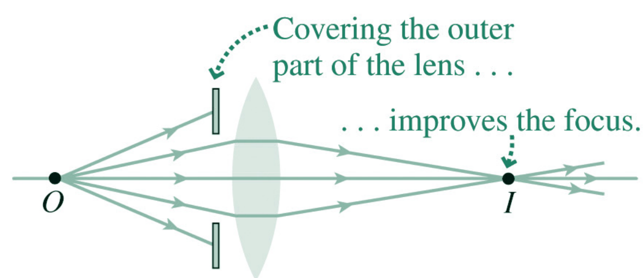


Lens Aberrations

- Lenses are subject to defects called **aberrations**.
  - **Spherical aberration** occurs because spherical lens surfaces don't focus exactly to a point.
    - The diagram shows how spherical aberration can be reduced by using less of the sphere; equivalently, by "stopping down" the lens at the expense of less light passing through the lens.
  - **Chromatic aberration** occurs because the wavelength dependence of the refractive index causes different colors to focus at different points.
  - **Astigmatism** occurs when the lens has different curvature radii in different directions.
    - Astigmatism is common in the human eye.



(a)

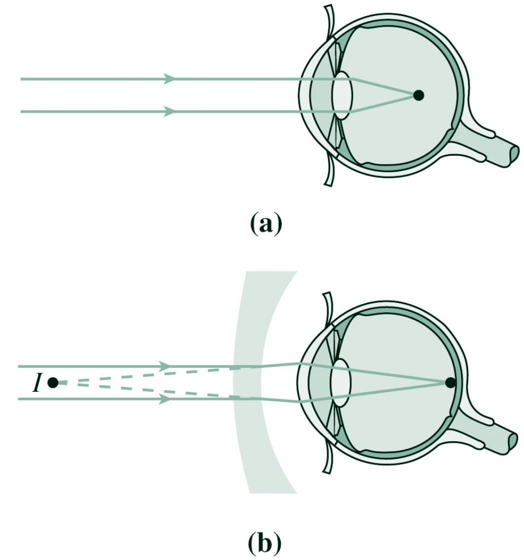


(b)

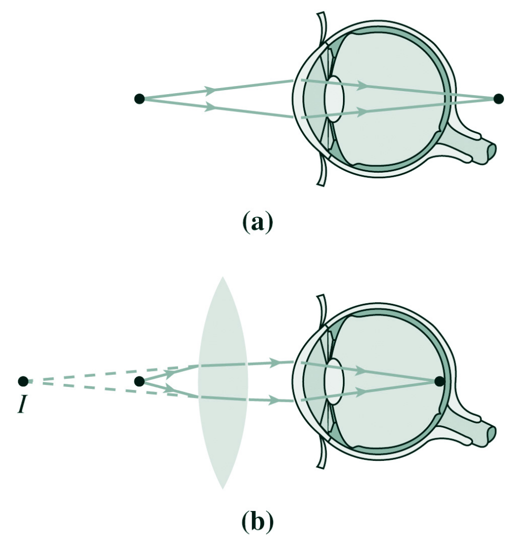
Vision Correction

- A nearsighted eye focuses light from distant objects in front of the retina.
  - A diverging lens corrects the problem.

- A farsighted eye focuses light from nearby objects behind the retina.
  - A converging lens corrects the problem.



- The power of corrective lenses is measured in **diopters**:
  - $P = 1/f$, with f measured in meters.
    - A 1-diopter lens has $f = 1$ m, a 2-diopter lens has $f = 0.5$ m.



- Laser vision correction achieves the same effects by reshaping the cornea.

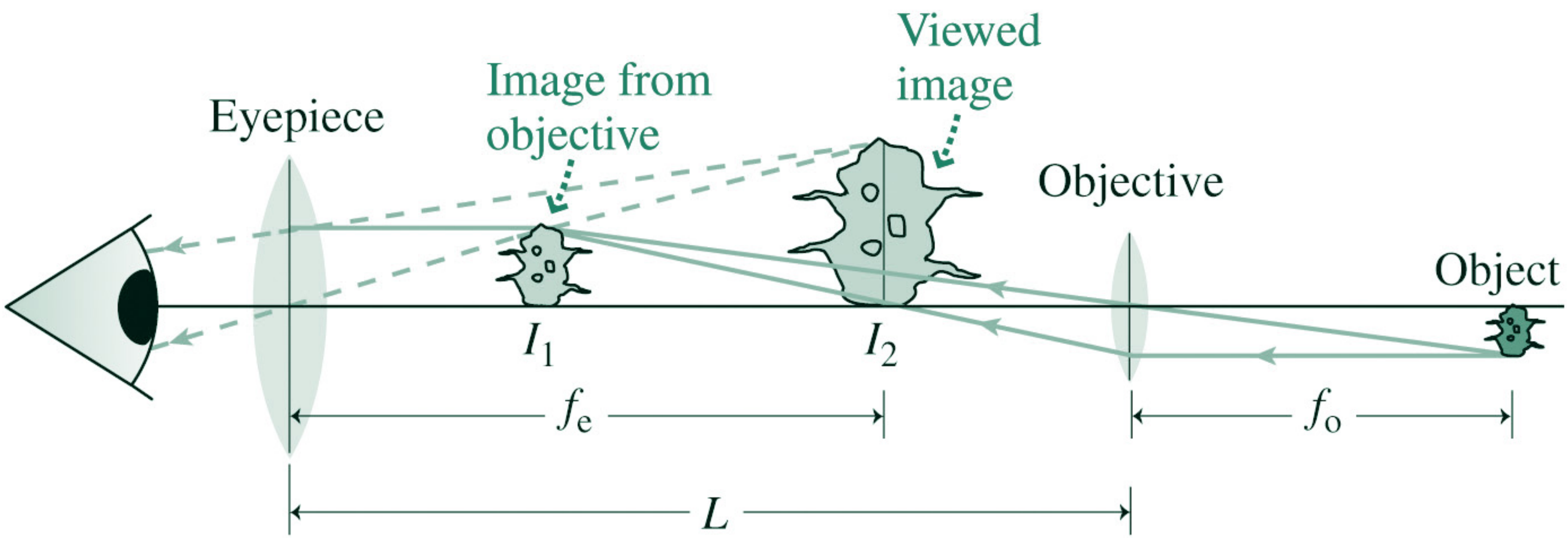
Microscopes

- **Compound microscopes** use two convex lenses—the **objective** and the **eyepiece**—to produce magnified images of small objects.
  - The magnification is

$$M = -\frac{L}{f_o}\left(\frac{25\text{ cm}}{f_e}\right)$$

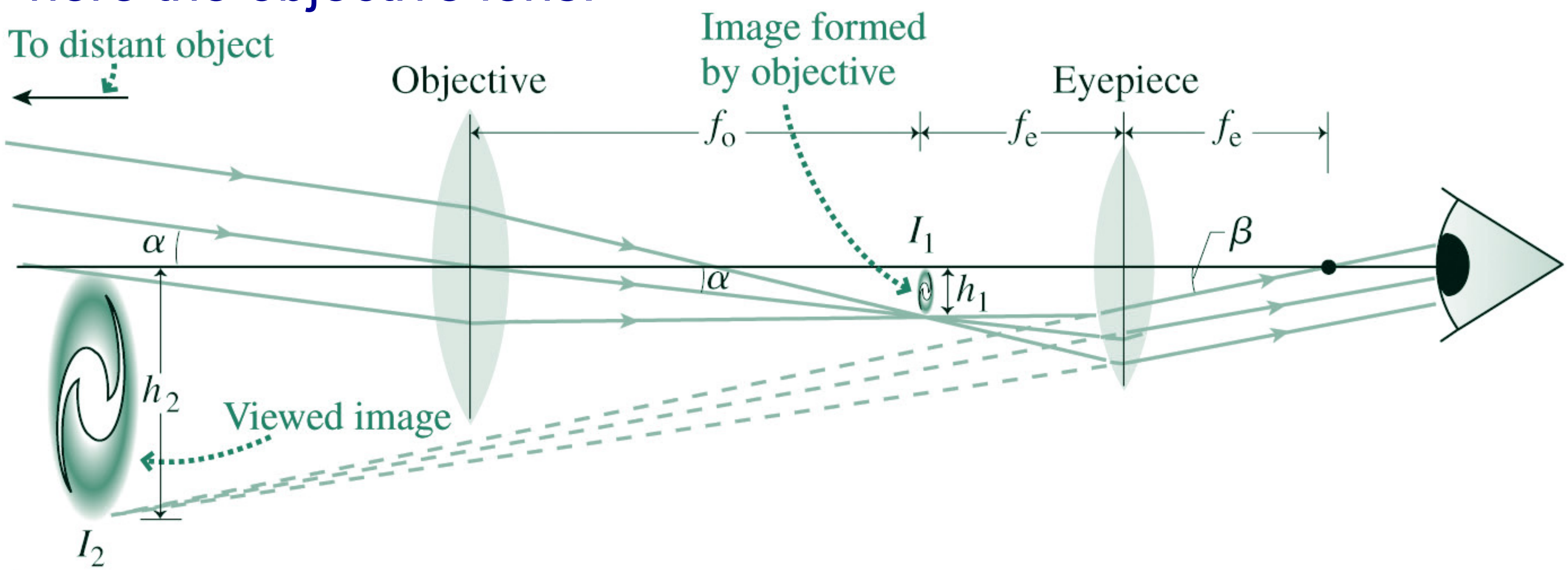
25 cm is a typical "close focus" distance for good eyesight.

$$f_o < f_e$$



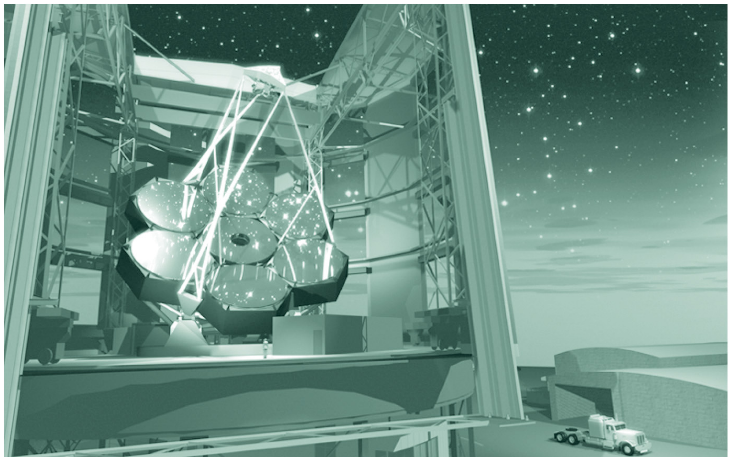
Refracting Telescopes

- **Refracting telescopes** use two lenses—the **objective** and the **eyepiece**—to produce images of distant objects.
  - The relevant measure of magnification is the **angular magnification**, the enlargement of the angle subtended by the object at the eye: $m = f_0/f_e$ with $f_0 > f_e$.
  - More important is the telescope's light-gathering ability, determined by the area of its primary light-gathering element, here the objective lens.



Reflecting Telescopes

- All large telescopes are **reflecting telescopes**, using mirrors as the primary light-gathering elements.
  - Easier to build, better optical properties
  - Reflectors come in many configurations.
  - The newest have large, multipart mirrors that can adapt to compensate for atmospheric turbulence.



The Giant Magellan Telescope, scheduled for completion in 2016, has a 7-piece mirror equivalent to a single mirror 21 m in diameter. Grinding/polishing of first mirror took over 6 years!