

# Part II: Light and Optics

## Chapter 36

### Image Formation

**Dr. Saif M. H. Qaid**

# LECTURE OUTLINE

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- **36.1** Images Formed by Flat Mirrors
- **36.2** Images Formed by Spherical Mirrors
- **36.3** Images Formed by Refraction
- **36.4** Images Formed by Thin Lenses
- **36.5** Lens Aberrations
- **36.6** The Camera
- **36.7** The Eye
- **36.8** The Simple Magnifier
- **36.9** The Compound Microscope
- **36.10** The Telescope

# Image of Formation

- Images can result when light rays encounter flat • or curved surfaces between two media.
- Images can be formed either by reflection or • refraction due to these surfaces.
- Mirrors and lenses can be designed to form • images with desired characteristics.

# Notation for Mirrors and Lenses

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- The **object distance** is the distance from the object to the mirror or lens.
  - Denoted by  $p$
- The **image distance** is the distance from the image to the mirror or lens.
  - Denoted by  $q$
- The **lateral magnification** of the mirror or lens is the ratio of the image height to the object height.
  - Denoted by  $M$

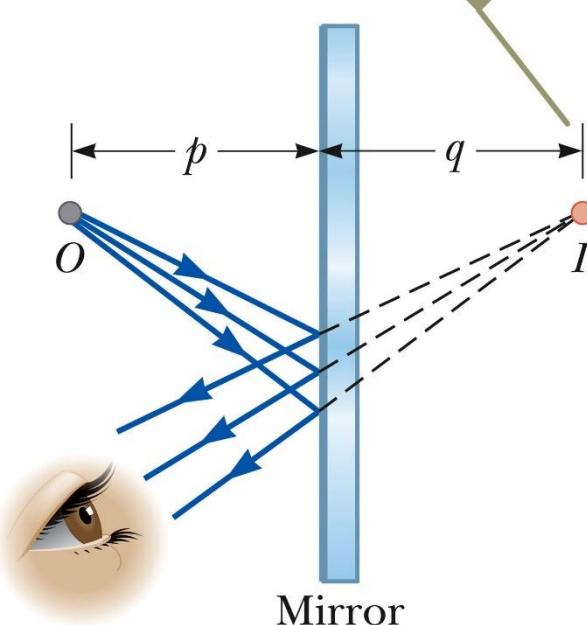
# Images

- Images are always located by extending diverging rays back to a point at which they intersect.
- Images are located either at a point from which the rays of light *actually* diverge or at a point from which they *appear* to diverge.
- A *real image* is formed when light rays pass through and diverge from the image point.
  - Real images can be displayed on screens.
- A *virtual image* is formed when light rays do not pass through the image point but only appear to diverge from that point.
  - Virtual images cannot be displayed on screens.

# Images Formed by Flat Mirrors

- Simplest possible mirror
- Light rays leave the source and are reflected from the mirror.
- Point  $I$  is called the **image** of the object at point  $O$ .
- The image is virtual .
- No light ray from the object can exist behind the mirror, so the light rays in front of the mirror only seem to be diverging from  $I$ .

The image point  $I$  is located behind the mirror a distance  $q$  from the mirror. The image is virtual.



# Images Formed by Flat Mirrors, cont.

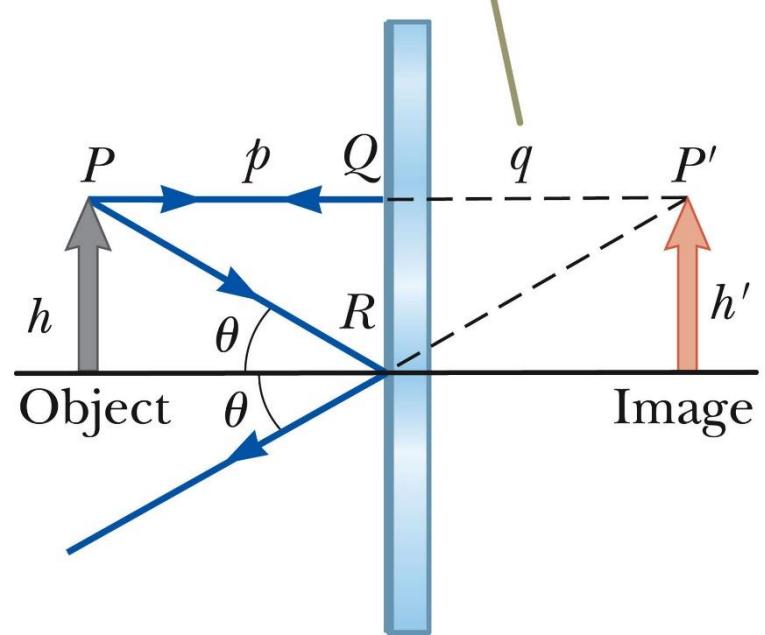
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- A flat mirror *always* produces a virtual image.
- Geometry can be used to determine the properties of the image.
- There are an infinite number of choices of direction in which light rays could leave each point on the object.
- Two rays are needed to determine where an image is formed.

# Images Formed by Flat Mirrors, Geometry

- One ray starts at point  $P$ , travels to  $Q$  and reflects back on itself.
- Another ray follows the path  $PR$  and reflects according to the law of reflection.
- The triangles  $PQR$  and  $P'QR$  are congruent.

Because the triangles  $PQR$  and  $P'QR$  are congruent,  
 $|p| = |q|$  and  $h = h'$ .



# Images Formed by Flat Mirrors, final

- To observe the image, the observer would trace back the two reflected rays to  $P'$ .
- Point  $P'$  is the point where the rays appear to have originated.
- The image formed by an object placed in front of a flat mirror is as far behind the mirror as the object is in front of the mirror.
  - $|p| = |q|$

# Lateral Magnification

- Lateral magnification,  $M$ , is defined as

$$M \equiv \frac{\text{Image height}}{\text{Object height}} = \frac{h'}{h}$$

- This is the lateral magnification for any type of mirror.
- It is also valid for images formed by lenses.
- Magnification does not always mean bigger, the size can either increase or decrease.
  - $M$  can be less than or greater than 1.

# Lateral Magnification of a Flat Mirror

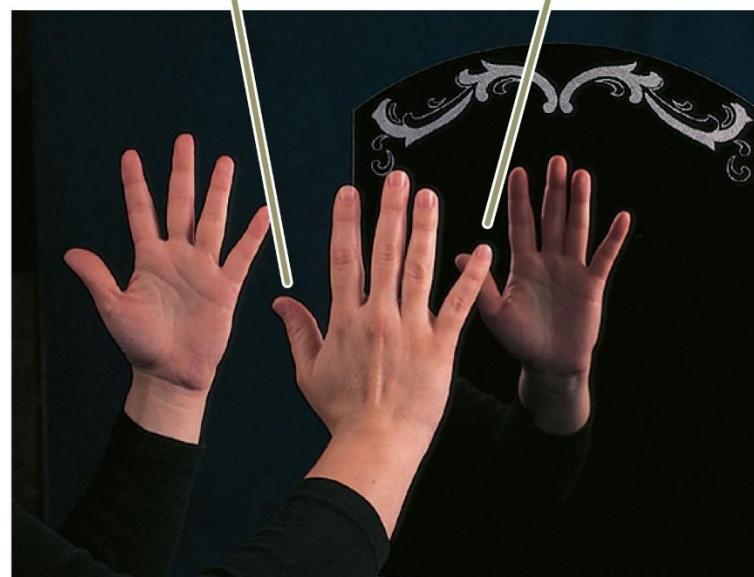
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- The lateral magnification of a flat mirror is +1.
- This means that  $h' = h$  for all images.
- The positive sign indicates the object is upright.
  - Same orientation as the object

# Reversals in a Flat Mirror

- A flat mirror produces an image that has an *apparent* left-right reversal.
  - For example, if you raise your right hand the image you see raises its left hand.
- The reversal is not *actually* a left-right reversal.
- The reversal is actually a *front-back* reversal.
  - It is caused by the light rays going forward toward the mirror and then reflecting back from it.

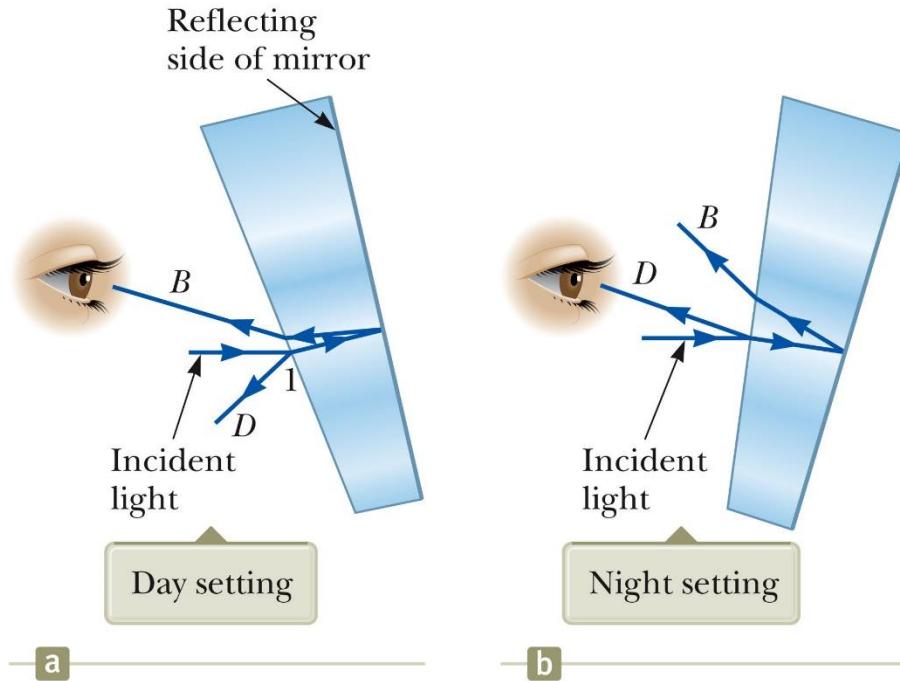
The thumb is on the left side of both real hands and on the left side of the image. That the thumb is not on the right side of the image indicates that there is no left-to-right reversal.



# Properties of the Image Formed by a Flat Mirror – Summary

- The image is as far behind the mirror as the object is in front.
  - $|p| = |q|$
- The image is unmagnified.
  - The image height is the same as the object height.
    - $h' = h$  and  $M = +1$
- The image is virtual.
- The image is upright.
  - It has the same orientation as the object.
- There is a front-back reversal in the image.

# Application – Day and Night Settings on Auto Mirrors



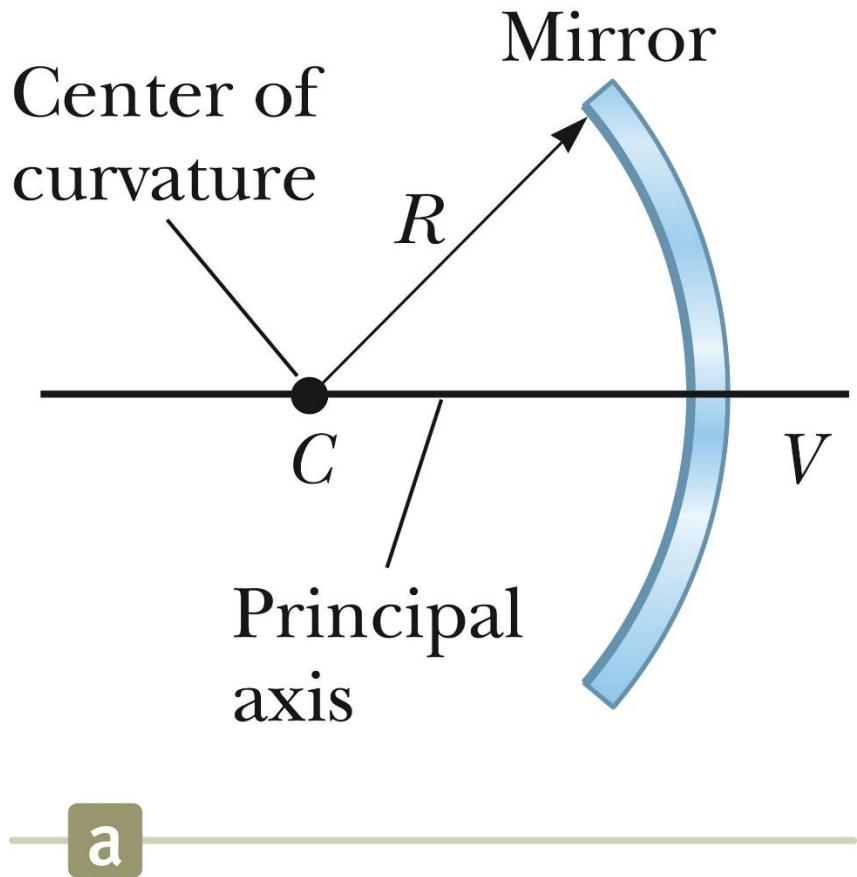
- With the daytime setting, the bright beam (B) of reflected light is directed into the driver's eyes.
- With the nighttime setting, the dim beam (D) of reflected light is directed into the driver's eyes, while the bright beam goes elsewhere.

# Spherical Mirrors

- A **spherical mirror** has the shape of a section of a sphere.
- The mirror focuses incoming parallel rays to a point.
- A *concave* spherical mirror has the silvered surface of the mirror on the inner, or concave, side of the curve.
- A *convex* spherical mirror has the silvered surface of the mirror on the outer, or convex, side of the curve.

# Concave Mirror, Notation

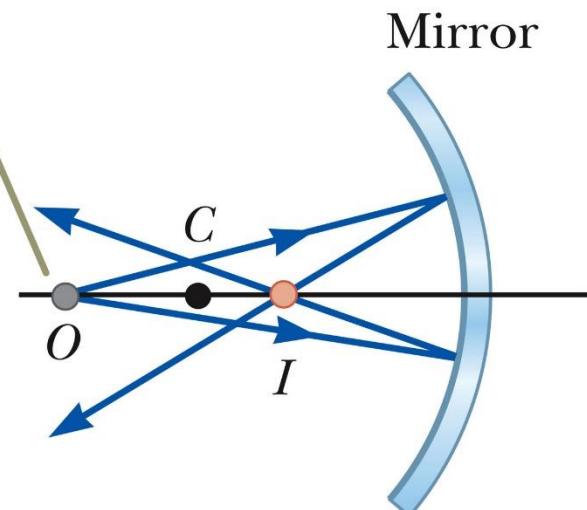
- The mirror has a *radius of curvature* of  $R$ .
- Its *center of curvature* is the point  $C$
- Point  $V$  is the center of the spherical segment.
- A line drawn from  $C$  to  $V$  is called the *principal axis* of the mirror.
- The blue band represents the structural support for the silvered surface.



# Paraxial Rays

- We use only rays that diverge from the object and make a small angle with the principal axis.
- Such rays are called **paraxial rays**.
- All paraxial rays reflect through the image point.

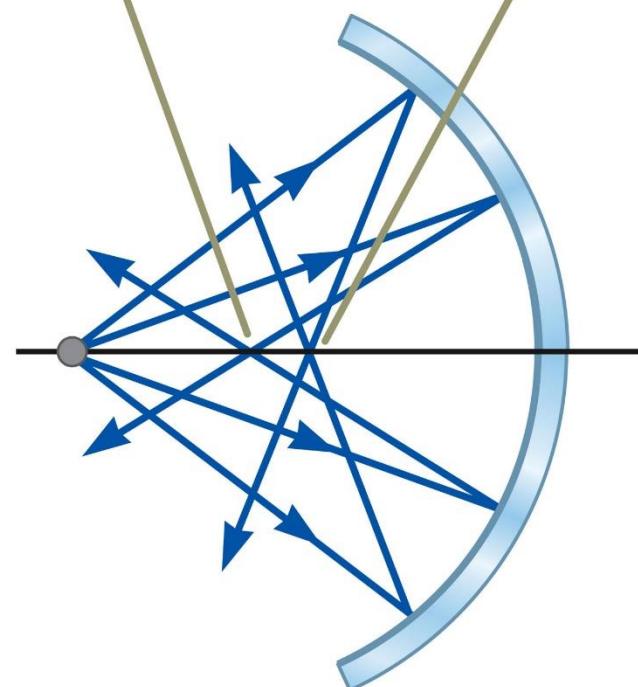
If the rays diverge from  $O$  at small angles, they all reflect through the same image point  $I$ .



# Spherical Aberration

- Rays that are far from the principal axis converge to other points on the principal axis .
  - The light rays make large angles with the principal axis.
- This produces a blurred image.
- The effect is called **spherical aberration**.

The reflected rays intersect at different points on the principal axis.

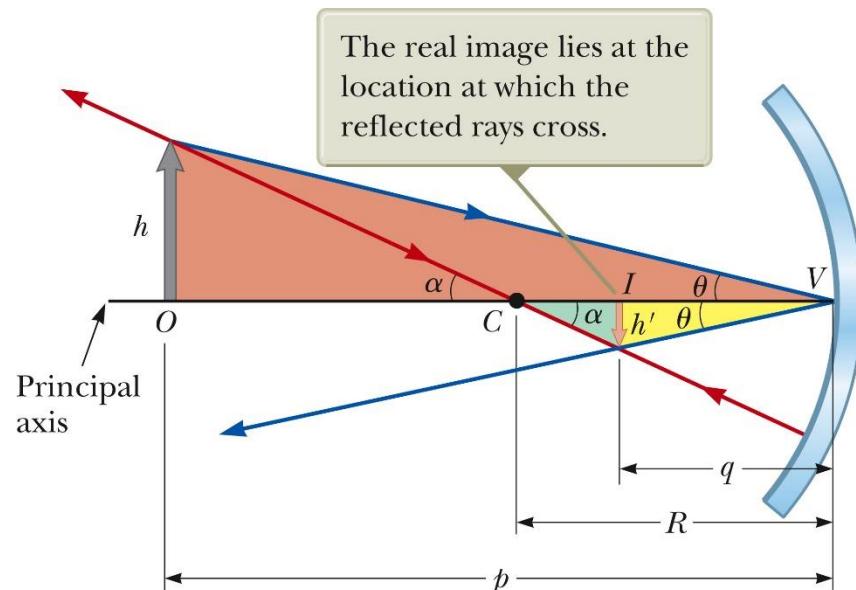


# Image Formed by a Concave Mirror

- Distances are measured from V
- Geometry can be used to determine the magnification of the image.

$$M = \frac{h'}{h} = -\frac{q}{p}$$

- $h'$  is negative when the image is inverted with respect to the object.



# Image Formed by a Concave Mirror

- Geometry also shows the relationship between the image and object distances.

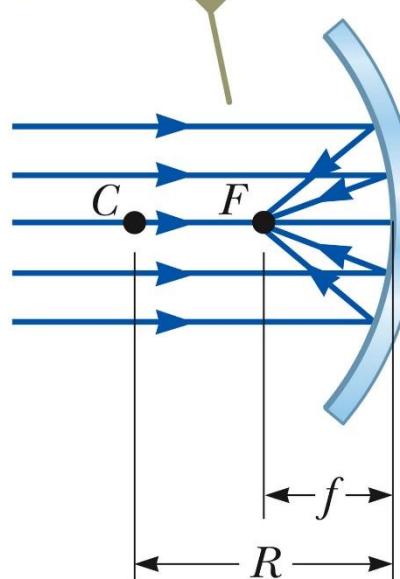
$$\frac{1}{p} + \frac{1}{q} = \frac{2}{R}$$

- This is called the **mirror equation**.
- If  $p$  is much greater than  $R$ , then the image point is half-way between the center of curvature and the center point of the mirror.
  - $p \rightarrow \infty$ , then  $1/p \approx 0$  and  $q \approx R/2$

# Focal Length

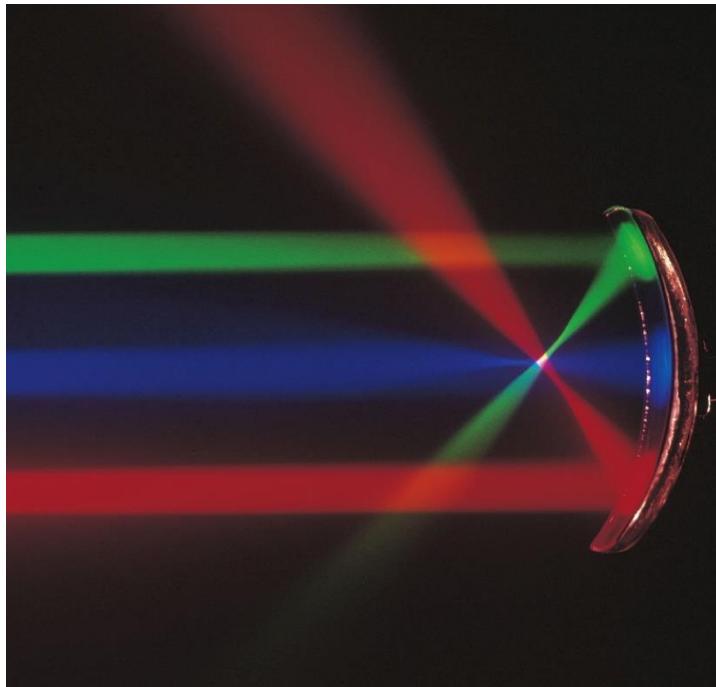
- When the object is very far away, then  $p \rightarrow \infty$  and the incoming rays are essentially parallel.
- In this special case, the image point is called the **focal point**.
- The distance from the mirror to the focal point is called the **focal length**.
  - The focal length is  $\frac{1}{2}$  the radius of curvature.

When the object is very far away, the image distance  $q \approx R/2 = f$ , where  $f$  is the focal length of the mirror.



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# Focal Point, cont.

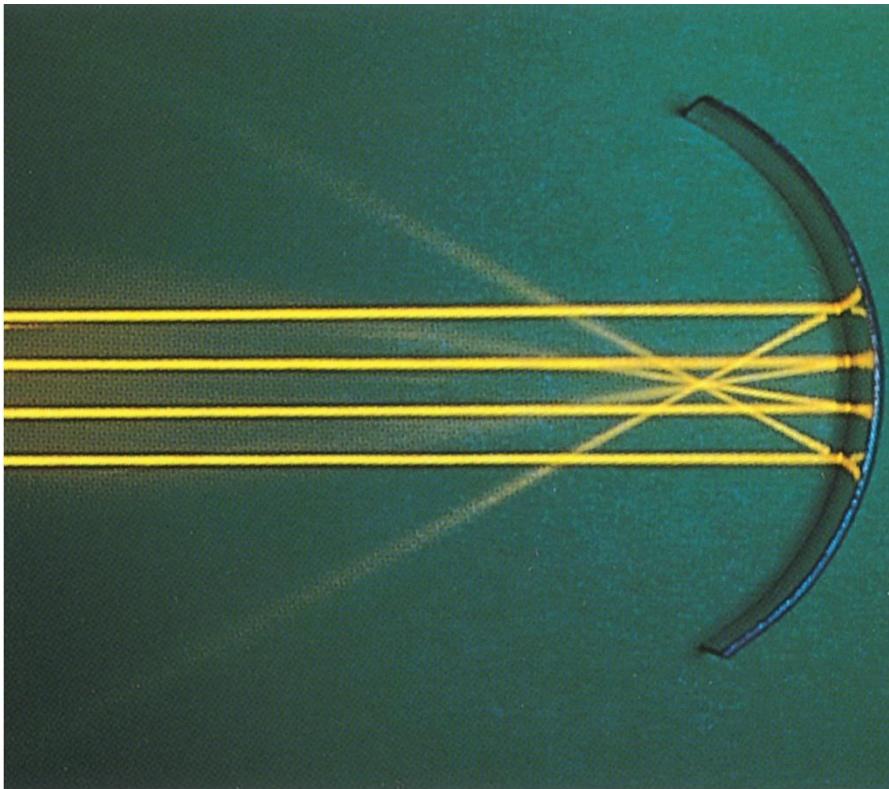


- The colored beams are traveling parallel to the principal axis.
- The mirror reflects all three beams to the focal point.
- The focal point is where all the beams intersect.
  - The colors add to white.

# Focal Point and Focal Length, cont.

- The focal point is dependent solely on the curvature of the mirror, not on the location of the object.  $\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$ 
  - It also does not depend on the material from which the mirror is made.
- Since the focal length is related to the radius of curvature by  $f = R / 2$ , the mirror equation can be expressed as

# Focal Length Shown by Parallel Rays



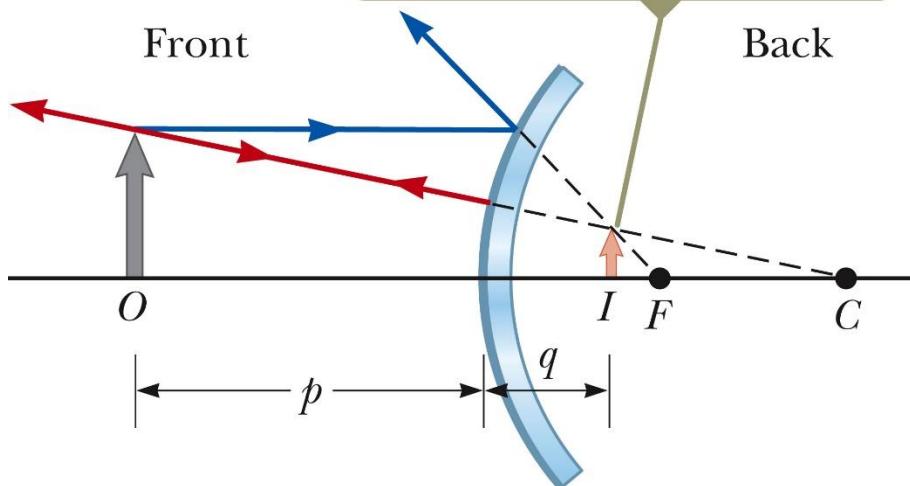
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# Convex Mirrors

- A **convex mirror** is sometimes called a *diverging mirror*.
  - The light reflects from the outer, convex side.
- The rays from any point on the object diverge after reflection as though they were coming from some point behind the mirror.
- The image is virtual because the reflected rays only appear to originate at the image point.

# Image Formed by a Convex Mirror

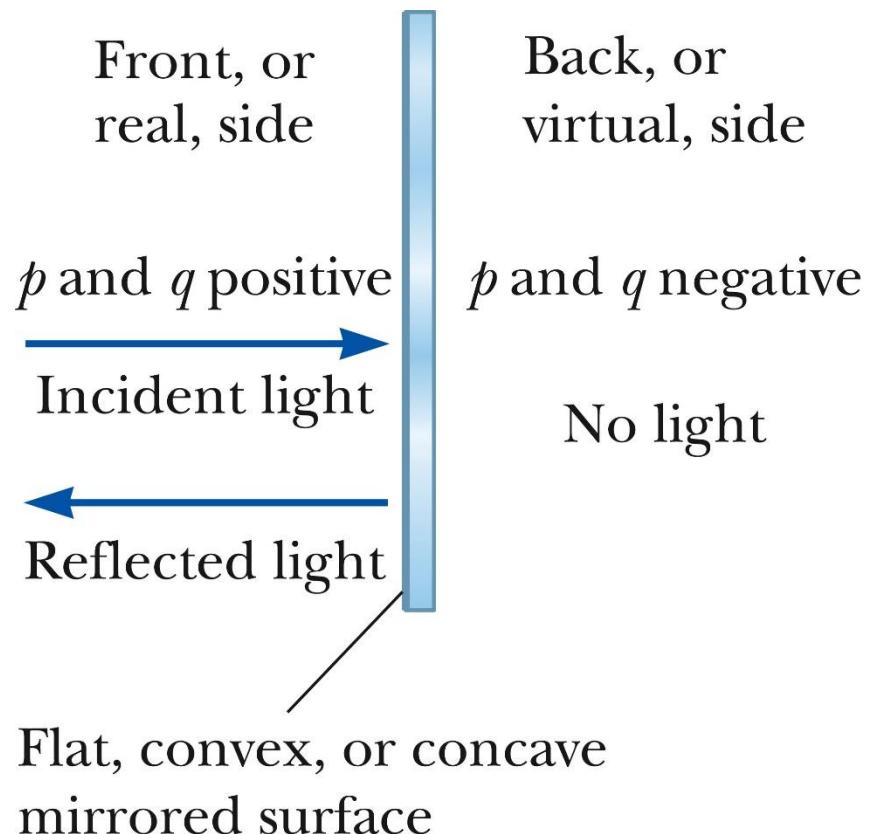
The image formed by the object is virtual, upright, and behind the mirror.



- In general, the image formed by a convex mirror is upright, virtual, and smaller than the object.

# Sign Conventions

- These sign conventions apply to both concave and convex mirrors.
- The equations used for the concave mirror also apply to the convex mirror.
- Be sure to use proper sign choices when substituting values into the equations.



# Sign Conventions, Summary Table

**TABLE 36.1** *Sign Conventions for Mirrors*

Quantity	Positive When ...	Negative When ...
Object location ( $p$ )	object is in front of mirror (real object).	object is in back of mirror (virtual object).
Image location ( $q$ )	image is in front of mirror (real image).	image is in back of mirror (virtual image).
Image height ( $h'$ )	image is upright.	image is inverted.
Focal length ( $f$ ) and radius ( $R$ )	mirror is concave.	mirror is convex.
Magnification ( $M$ )	image is upright.	image is inverted.

# Ray Diagrams

- A *ray diagram* can be used to determine the position and size of an image.
- They are graphical constructions which reveal the nature of the image.
- They can also be used to check the parameters calculated from the mirror and magnification equations.

# Drawing a Ray Diagram

- To draw a ray diagram, you need to know:
  - The position of the object
  - The locations of the focal point and the center of curvature.
- Three rays are drawn.
  - They all start from the same position on the object.
- The intersection of any two of the rays at a point locates the image.
  - The third ray serves as a check of the construction.

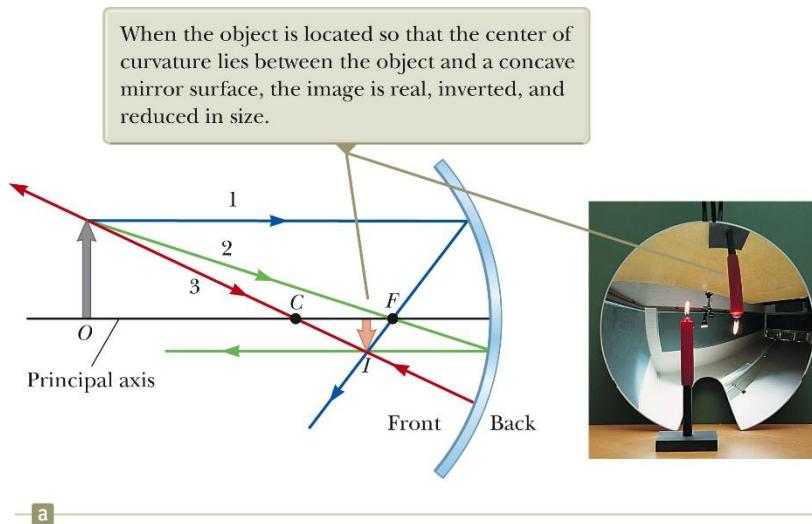
# The Rays in a Ray Diagram – Concave Mirrors

- Ray 1 is drawn from the top of the object parallel to the principal axis and is reflected through the focal point,  $F$ .
- Ray 2 is drawn from the top of the object through the focal point and is reflected parallel to the principal axis.
- Ray 3 is drawn through the center of curvature,  $C$ , and is reflected back on itself.
  - Draw as if coming from the center  $C$  is  $p < f$

# Notes About the Rays

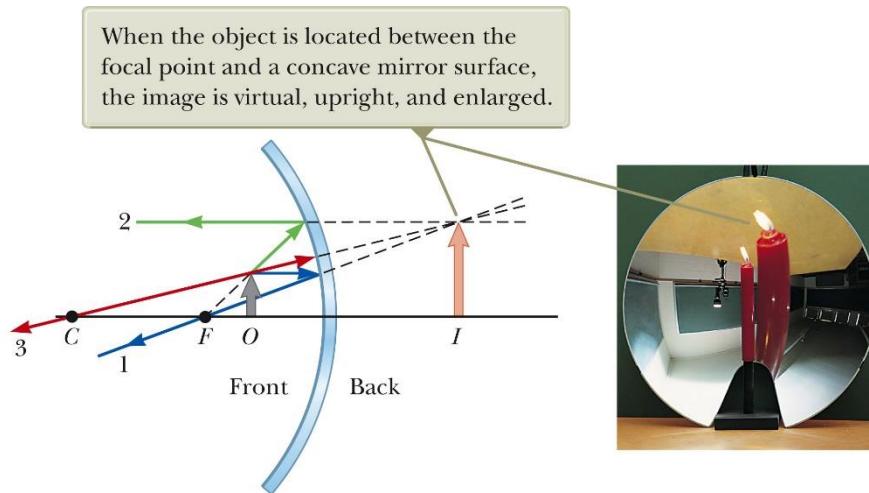
- A huge number of rays actually go in all directions from the object.
- The three rays were chosen for their ease of construction.
- The image point obtained by the ray diagram must agree with the value of  $q$  calculated from the mirror equation.

# Ray Diagram for a Concave Mirror, $p > R$



- The center of curvature is between the object and the concave mirror surface.
- The image is real.
- The image is inverted.
- The image is smaller than the object (reduced).

# Ray Diagram for a Concave Mirror, $p < f$

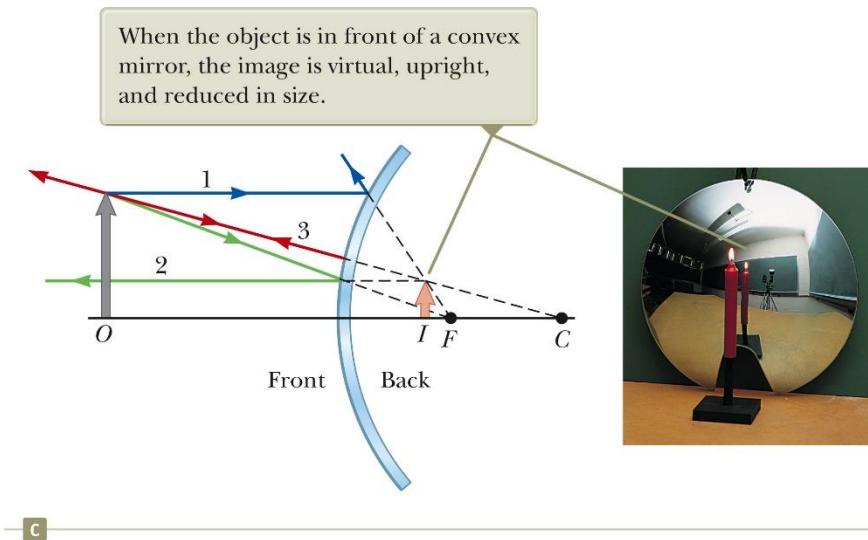


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- The object is between the mirror surface and the focal point.
  - The image is virtual.
  - The image is upright.
  - The image is larger than the object (enlarged).

# The Rays in a Ray Diagram – Convex Mirrors

- Ray 1 is drawn from the top of the object parallel to the principal axis and is reflected away from the focal point,  $F$ .
- Ray 2 is drawn from the top of the object toward the focal point and is reflected parallel to the principal axis.
- Ray 3 is drawn through the center of curvature, C, on the back side of the mirror and is reflected back on itself.

# Ray Diagram for a Convex Mirror



- The object is in front of a convex mirror.
- The image is virtual.
- The image is upright.
- The image is smaller than the object (reduced).

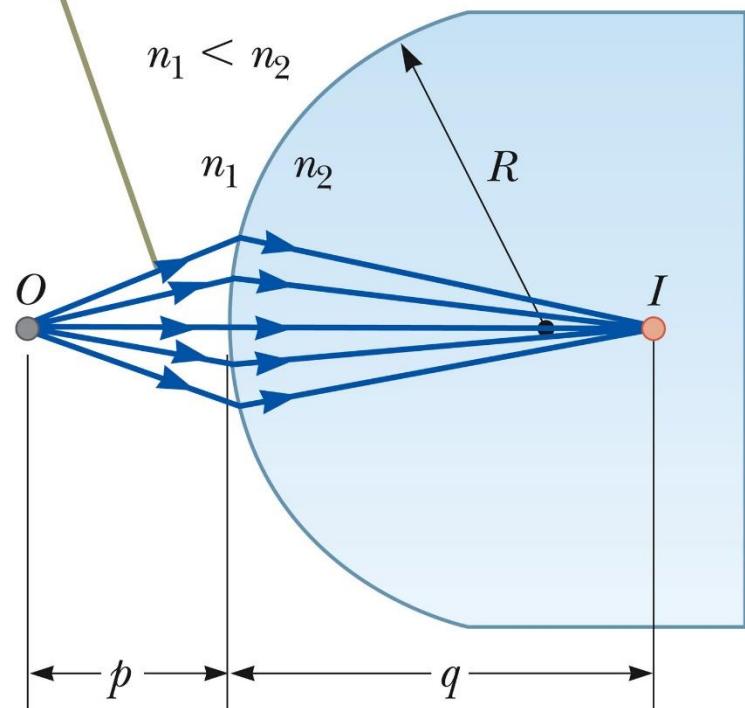
# Notes on Images

- With a concave mirror, the image may be either real or virtual.
  - When the object is outside the focal point, the image is real.
  - When the object is at the focal point, the image is infinitely far away.
  - When the object is between the mirror and the focal point, the image is virtual.
- With a convex mirror, the image is always virtual and upright.
  - As the object distance decreases, the virtual image increases in size.

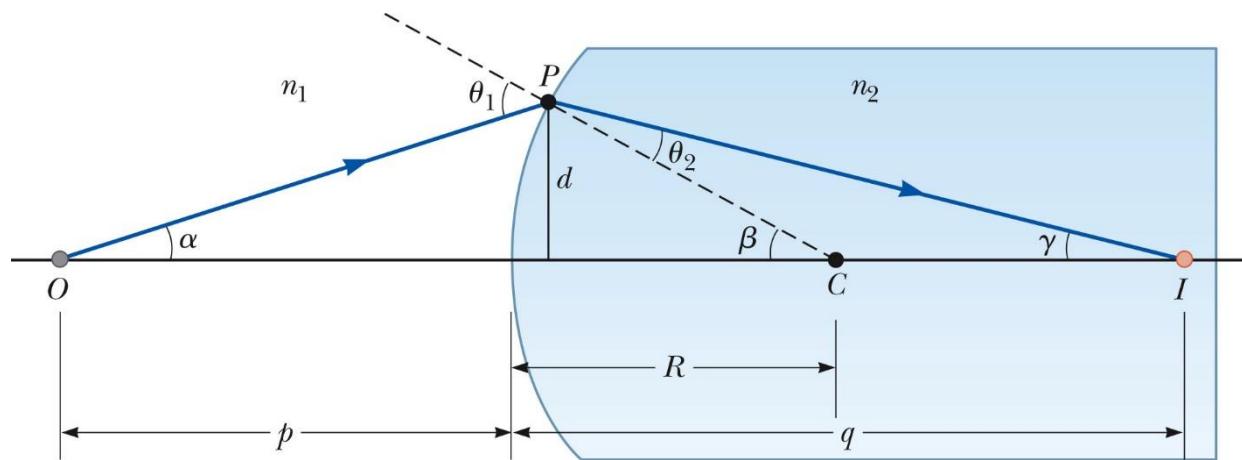
# Images Formed by Refraction

- Consider two transparent media having indices of refraction  $n_1$  and  $n_2$ .
- The boundary between the two media is a spherical surface of radius  $R$ .
- Rays originate from the object at point  $O$  in the medium with  $n = n_1$ .

Rays making small angles with the principal axis diverge from a point object at  $O$  and are refracted through the image point  $I$ .



# Images Formed by Refraction, 2



- We will consider the paraxial rays leaving  $O$ .
- All such rays are refracted at the spherical surface and focus at the image point,  $I$ .
- The relationship between object and image distances can be given by

$$\frac{n_1}{p} + \frac{n_2}{q} = \frac{n_2 - n_1}{R}$$

# Images Formed by Refraction, 3

- The side of the surface in which the light rays originate is defined as the front side.
- The other side is called the back side.
- Real images are formed by refraction in the back of the surface.
  - Because of this, the sign conventions for  $q$  and  $R$  for refracting surfaces are opposite those for reflecting surfaces.

# Sign Conventions for Refracting Surfaces

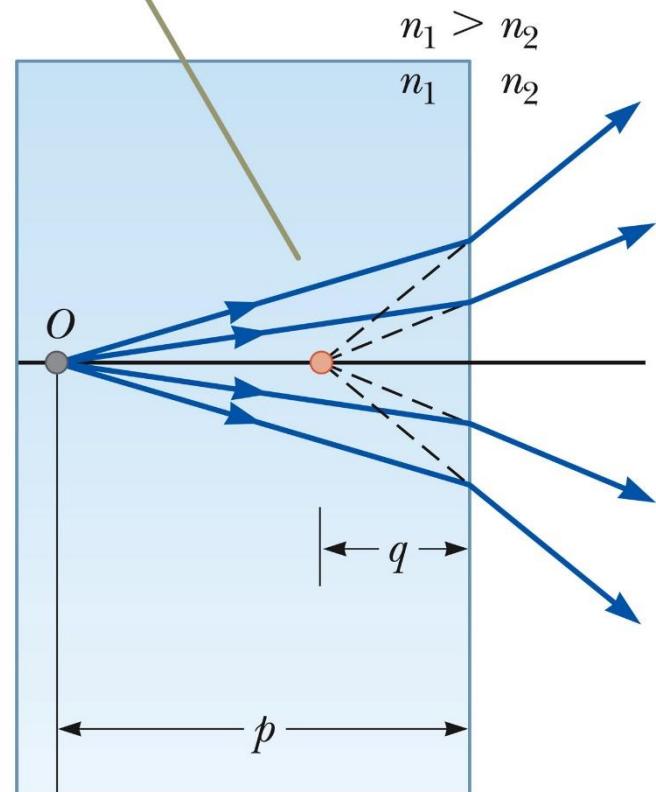
**TABLE 36.2** *Sign Conventions for Refracting Surfaces*

Quantity	Positive When ...	Negative When ...
Object location ( $p$ )	object is in front of surface (real object).	object is in back of surface (virtual object).
Image location ( $q$ )	image is in back of surface (real image).	image is in front of surface (virtual image).
Image height ( $h'$ )	image is upright.	image is inverted.
Radius ( $R$ )	center of curvature is in back of surface.	center of curvature is in front of surface.

# Flat Refracting Surfaces

- If a refracting surface is flat, then  $R$  is infinite.
- Then  $q = -(n_2 / n_1)p$ 
  - The image formed by a flat refracting surface is on the same side of the surface as the object.
- A virtual image is formed.

The image is virtual and on the same side of the surface as the object.



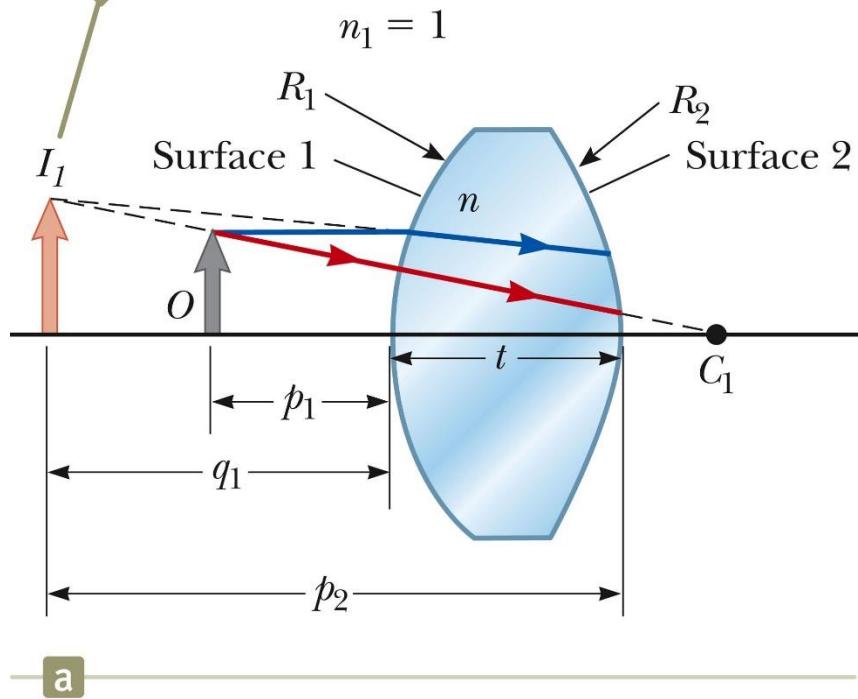
# Images Formed by Thin Lenses

- Lenses are commonly used to form images by refraction.
- Lenses are used in optical instruments.
  - Cameras
  - Telescopes
  - Microscopes
- Light passing through a lens experiences refraction at two surfaces.
- The image formed by one refracting surface serves as the object for the second surface.

# Locating the Image Formed by a Lens

- The lens has an index of refraction  $n$  and two spherical surfaces with radii of  $R_1$  and  $R_2$ .
  - $R_1$  is the radius of curvature of the lens surface that the light of the object reaches first.
  - $R_2$  is the radius of curvature of the other surface.
- The object is placed at point  $O$  at a distance of  $p_1$  in front of the first surface.

The image due to surface 1 is virtual, so  $I_1$  is to the left of the surface.



# Locating the Image Formed by a Lens, Image From Surface 1

- There is an image formed by surface 1.
- Since the lens is surrounded by the air,  $n_1 = 1$  and

$$\frac{n_1}{p} + \frac{n_2}{q} = \frac{n_2 - n_1}{R} \rightarrow \frac{1}{p_1} + \frac{n}{q_1} = \frac{n-1}{R_1}$$

- If the image due to surface 1 is virtual,  $q_1$  is negative; and it is positive if the image is real.

# Locating the Image Formed by a Lens, Image From Surface 2

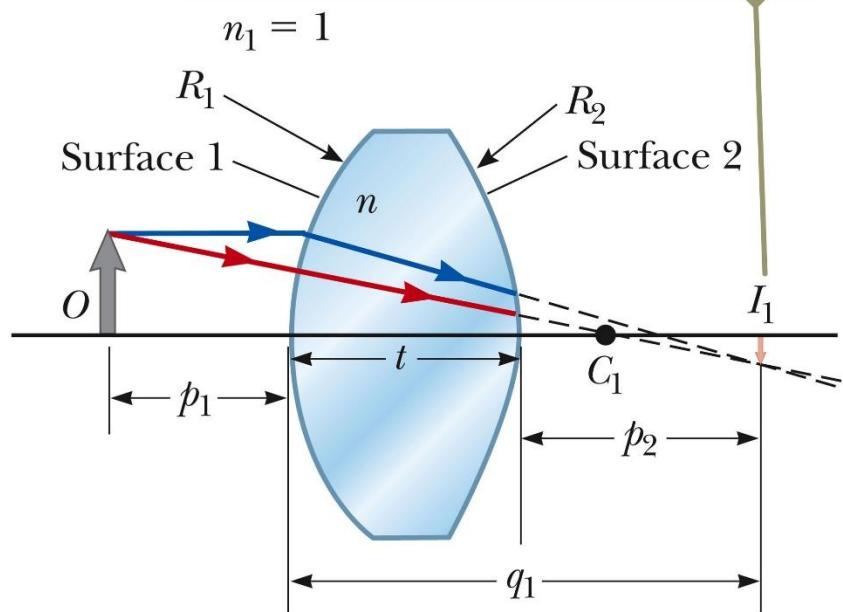
- For surface 2,  $n_1 = n$  and  $n_2 = 1$ 
  - The light rays approaching surface 2 are in the lens and are refracted into air.
- Use  $p_2$  for the object distance for surface 2 and  $q_2$  for the image distance.

$$\frac{n_1}{p} + \frac{n_2}{q} = \frac{n_2 - n_1}{R} \rightarrow \frac{n}{p_2} + \frac{1}{q_2} = \frac{1-n}{R_2}$$

# Locating the Image, Surface 2

- The image due to surface 1 acts as the object for surface 2.

The image due to surface 1 is real, so  $I_1$  is to the right of the surface.



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# Lens-makers' Equation

- If a virtual image is formed from surface 1, then  $p_2 = -q_1 + t$ 
  - $q_1$  is negative
  - $t$  is the thickness of the lens
- If a real image is formed from surface 1, then  $p_2 = -q_1 + t$ 
  - $q_1$  is positive
- Then

$$\frac{1}{p_1} + \frac{1}{q_2} = (n-1) \left( \frac{1}{R_1} - \frac{1}{R_2} \right) = \frac{1}{f}$$

- This is called the lens-makers' equation.
  - It can be used to determine the values of  $R_1$  and  $R_2$  needed for a given index of refraction and a desired focal length  $f$ .

# Image Formed by a Thin Lens

- A thin lens is one whose thickness is small compared to the radii of curvature.
- For a thin lens, the thickness,  $t$ , of the lens can be neglected.
- In this case,  $p_2 = -q_1$  for either type of image
- Then the subscripts on  $p_1$  and  $q_2$  can be omitted.

# Thin Lens Equation

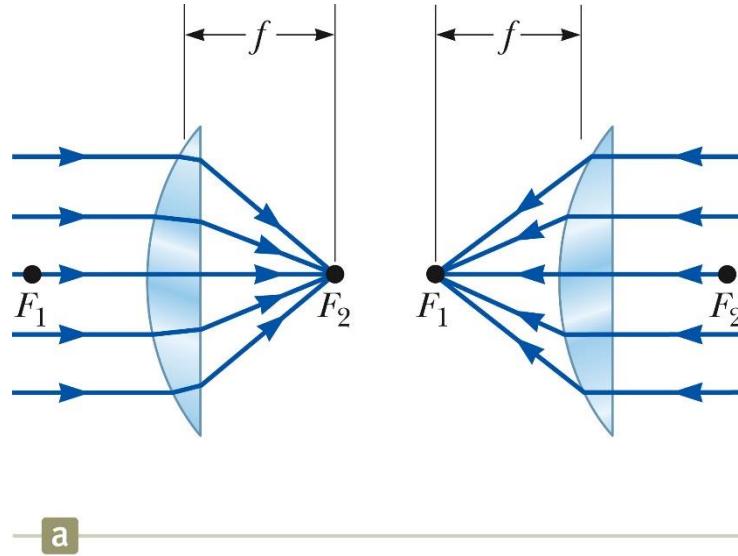
- The relationship among the focal length, the object distance and the image distance is the same as for a mirror.

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

# Notes on Focal Length and Focal Point of a Thin Lens

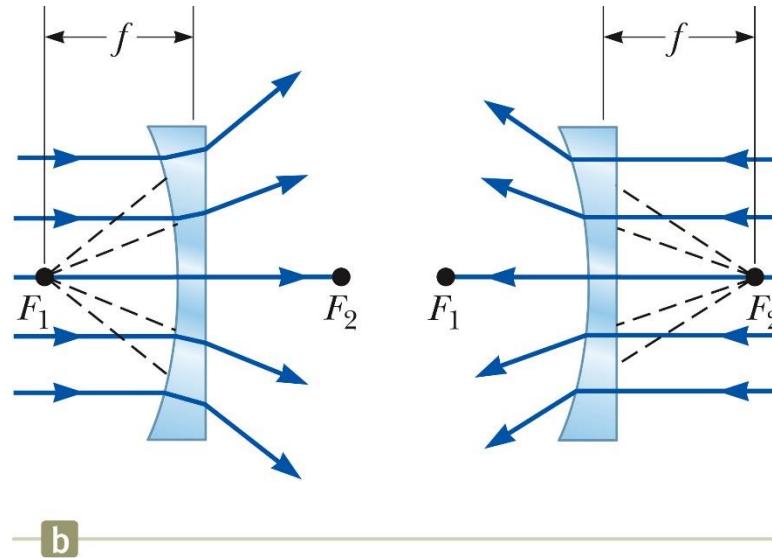
- Because light can travel in either direction through a lens, each lens has two focal points.
  - One focal point is for light passing in one direction through the lens and one is for light traveling in the opposite direction.
- However, there is only one focal length.
- Each focal point is located the same distance from the lens.

# Focal Length of a Converging Lens



- The parallel rays pass through the lens and converge at the focal point.
- The parallel rays can come from the left or right of the lens.

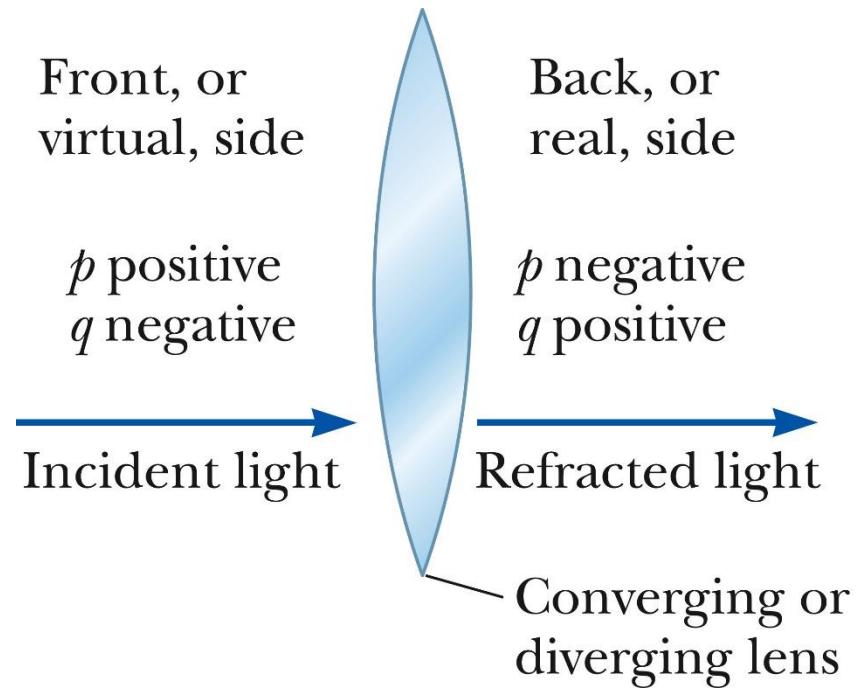
# Focal Length of a Diverging Lens



- The parallel rays diverge after passing through the diverging lens.
- The focal point is the point where the rays appear to have originated.

# Determining Signs for Thin Lenses

- The front side of the thin lens is the side of the incident light.
- The light is refracted into the back side of the lens.
- This is also valid for a refracting surface.



# Sign Conventions for Thin Lenses

**TABLE 36.3** *Sign Conventions for Thin Lenses*

Quantity	Positive When . . .	Negative When . . .
Object location ( $p$ )	object is in front of lens (real object).	object is in back of lens (virtual object).
Image location ( $q$ )	image is in back of lens (real image).	image is in front of lens (virtual image).
Image height ( $h'$ )	image is upright.	image is inverted.
$R_1$ and $R_2$	center of curvature is in back of lens.	center of curvature is in front of lens.
Focal length ( $f$ )	a converging lens.	a diverging lens.

# Magnification of Images Through a Thin Lens

- The lateral magnification of the image is

$$M = \frac{h'}{h} = -\frac{q}{p}$$

- When  $M$  is positive, the image is upright and on the same side of the lens as the object.
- When  $M$  is negative, the image is inverted and on the side of the lens opposite the object.

# Thin Lens Shapes

- These are examples of *converging lenses*.
- They have positive focal lengths.
- They are thickest in the middle.

Biconvex



Convex-concave



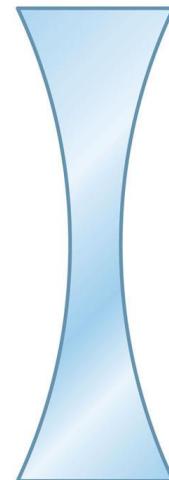
Plano-convex



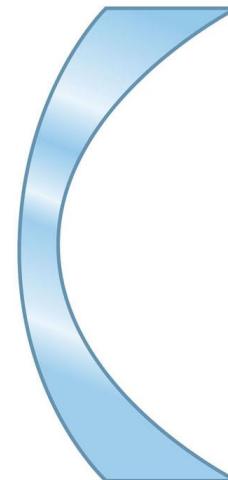
# More Thin Lens Shapes

- These are examples of *diverging* lenses.
- They have negative focal lengths.
- They are thickest at the edges.

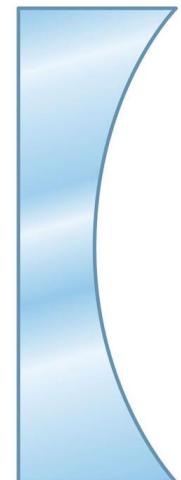
Biconcave



Convex-concave



Plano-concave

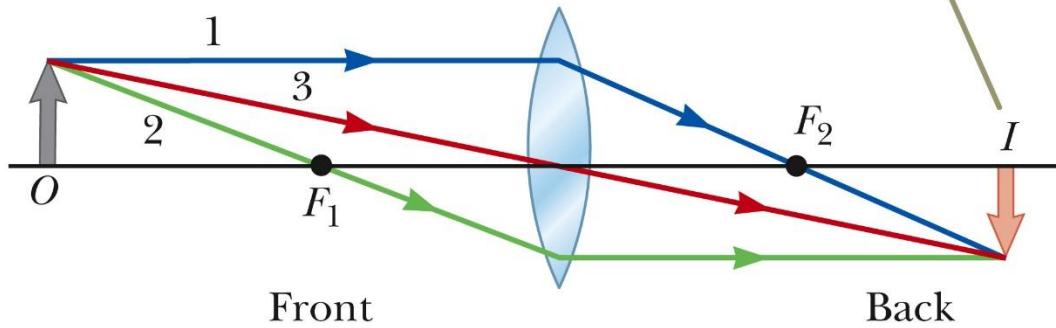


# Ray Diagrams for Thin Lenses – Converging

- Ray diagrams are convenient for locating the images formed by thin lenses or systems of lenses.
- For a converging lens, the following three rays are drawn:
  - Ray 1 is drawn parallel to the principal axis and then passes through the focal point on the back side of the lens.
  - Ray 2 is drawn through the center of the lens and continues in a straight line.
  - Ray 3 is drawn through the focal point on the front of the lens (or as if coming from the focal point if  $p < f$ ) and emerges from the lens parallel to the principal axis.

# Ray Diagram for Converging Lens, $p > f$

When the object is in front of and outside the focal point of a converging lens, the image is real, inverted, and on the back side of the lens.

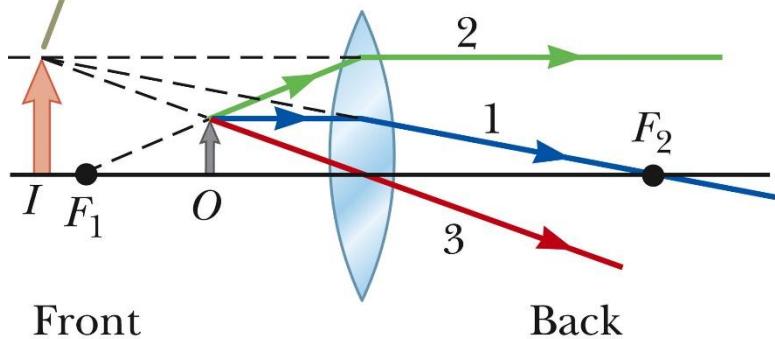


- The image is **real**.
- The image is inverted.
- The image is on the back side of the lens.

# Ray Diagram for Converging Lens, $p < f$

- The image is virtual.
- The image is upright.
- The image is larger than the object.
- The image is on the front side of the lens.

When the object is between the focal point and a converging lens, the image is virtual, upright, larger than the object, and on the front side of the lens.



b

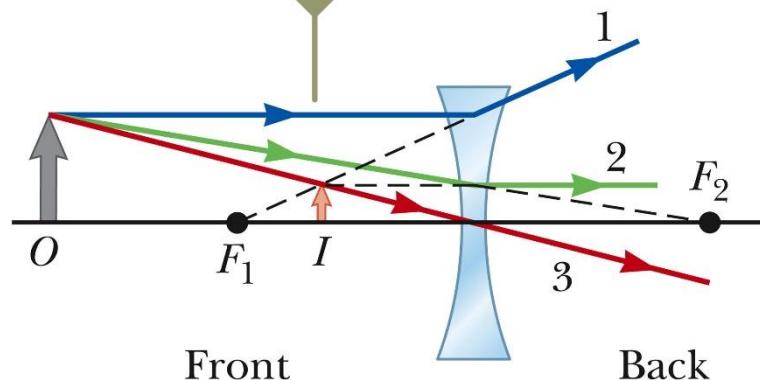
# Ray Diagrams for Thin Lenses – Diverging

- For a diverging lens, the following three rays are drawn:
  - Ray 1 is drawn parallel to the principal axis and emerges directed away from the focal point on the front side of the lens.
  - Ray 2 is drawn through the center of the lens and continues in a straight line.
  - Ray 3 is drawn in the direction toward the focal point on the back side of the lens and emerges from the lens parallel to the principal axis.

# Ray Diagram for Diverging Lens

- The image is virtual.
- The image is upright.
- The image is smaller.
- The image is on the front side of the lens.

When an object is anywhere in front of a diverging lens, the image is virtual, upright, smaller than the object, and on the front side of the lens.

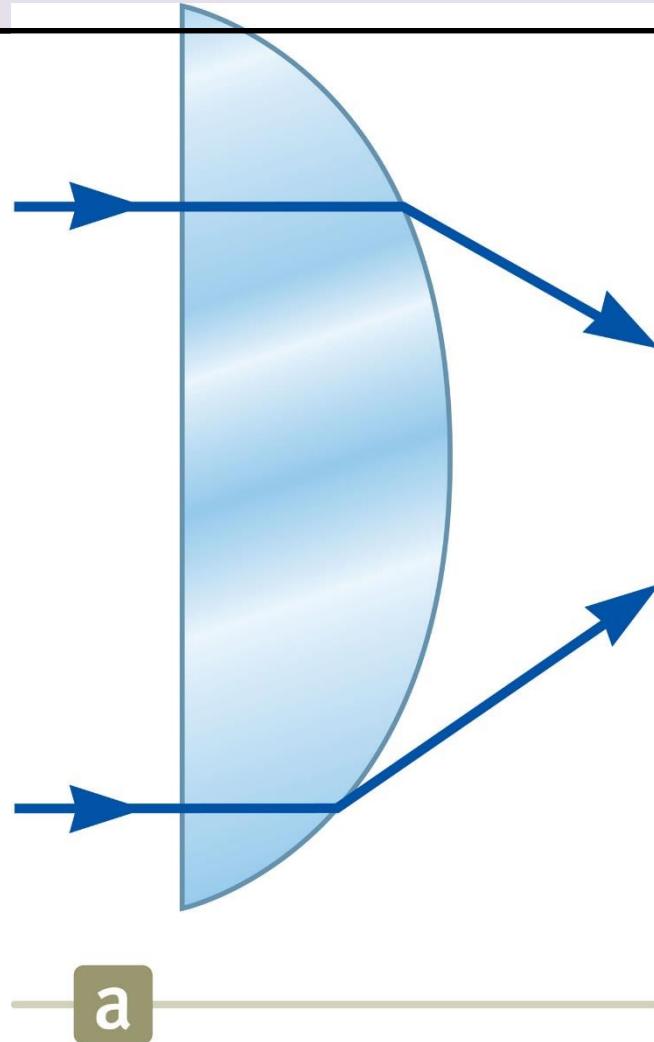


# Image Summary

- For a converging lens, when the object distance is greater than the focal length, ( $p > f$ )
  - The image is real and inverted.
- For a converging lens, when the object is between the focal point and the lens, ( $p < f$ )
  - The image is virtual and upright.
- For a diverging lens, the image is always virtual and upright.
  - This is regardless of where the object is placed.

# Fresnal Lens

- Refraction occurs only at the surfaces of the lens.
- A *Fresnal lens* is designed to take advantage of this fact.
- It produces a powerful lens without great thickness.



# Fresnal Lens, cont.

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- Only the surface curvature is important in the refracting qualities of the lens.
- The material in the middle of the Fresnal lens is removed.
- Because the edges of the curved segments cause some distortion, Fresnal lenses are usually used only in situations where image quality is less important than reduction of weight.

# Combinations of Thin Lenses

- The image formed by the first lens is located as though the second lens were not present.
- Then a ray diagram is drawn for the second lens.
- *The image of the first lens is treated as the object of the second lens.*
- The image formed by the second lens is the final image of the system.
- If the image formed by the first lens lies on the back side of the second lens, then the image is treated as a *virtual object* for the second lens.
  - $p$  will be negative
- The same procedure can be extended to a system of three or more lenses.
- The overall magnification is the product of the magnification of the separate lenses.

# Two Lenses in Contact

- Consider a case of two lenses in contact with each other:
  - The lenses have focal lengths of  $f_1$  and  $f_2$ .
- For the first lens,

$$\frac{1}{p} + \frac{1}{q_1} = \frac{1}{f_1}$$

- Since the lenses are in contact,  $p_2 = -q_1$

# Two Lenses in Contact, cont.

- For the second lens,

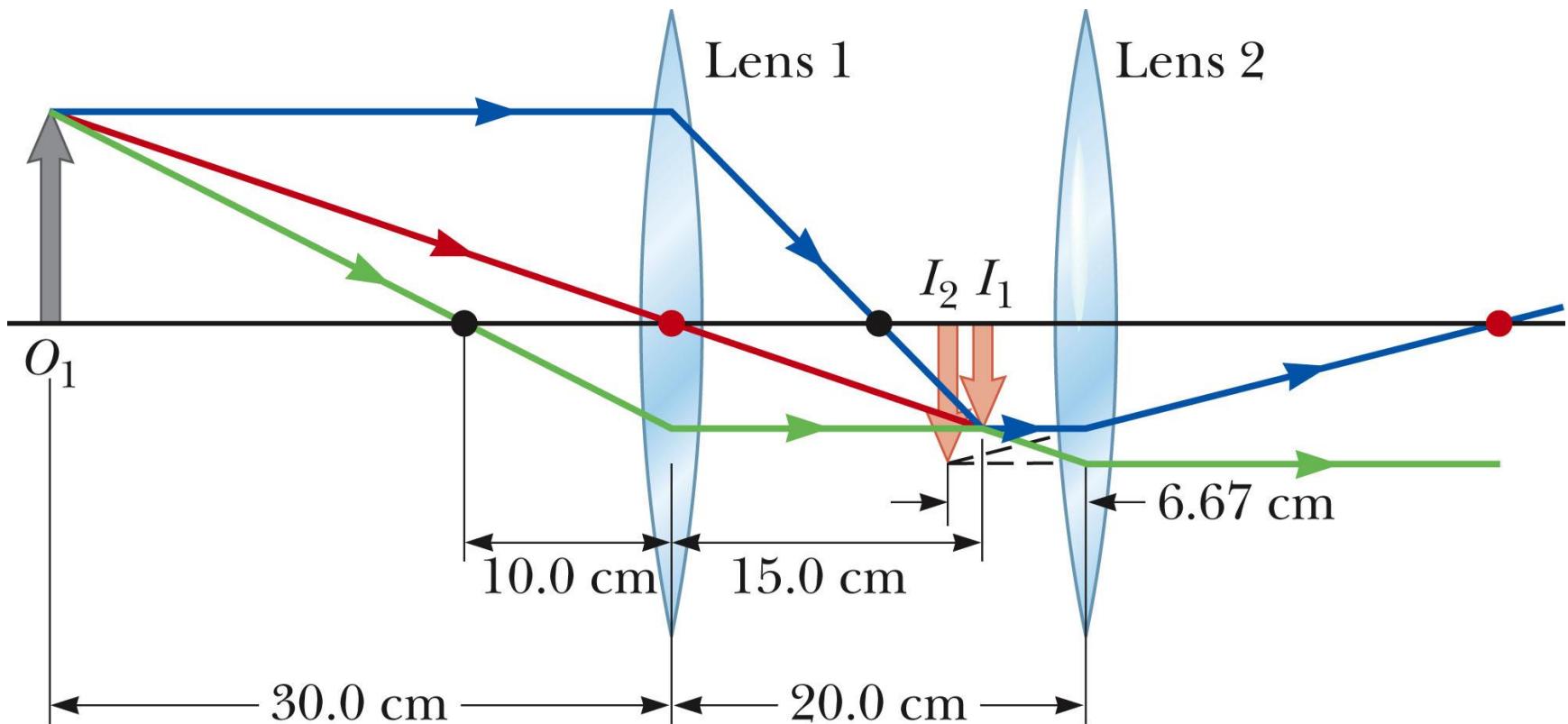
$$\frac{1}{p_2} + \frac{1}{q_2} = \frac{1}{f_2} = -\frac{1}{q_1} + \frac{1}{q}$$

- For the combination of the two lenses

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2}$$

- Two thin lenses in contact with each other are equivalent to a single thin lens having a focal length given by the above equation.

# Combination of Thin Lenses, example



# Combination of Thin Lenses, example

- Find the location of the image formed by lens 1.
- Find the magnification of the image due to lens 1.
- Find the object distance for the second lens.
- Find the location of the image formed by lens 2.
- Find the magnification of the image due to lens 2.
- Find the overall magnification of the system.

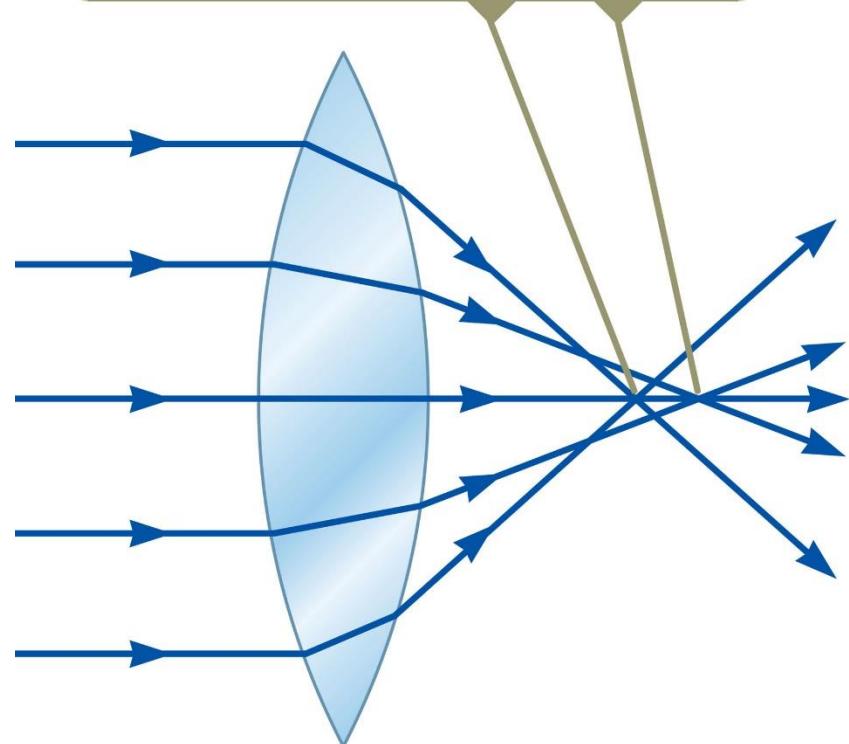
# Lens Aberrations

- Assumptions have been:
  - Rays make small angles with the principal axis.
  - The lenses are thin.
- The rays from a point object do not focus at a single point.
  - The result is a blurred image.
  - This is a situation where the approximations used in the analysis do not hold.
- The departures of actual images from the ideal predicted by our model are called **aberrations**.

# Spherical Aberration

- This results from the focal points of light rays far from the principal axis being different from the focal points of rays passing near the axis.
- For a camera, a small aperture allows a greater percentage of the rays to be paraxial.
- For a mirror, parabolic shapes can be used to correct for spherical aberration.

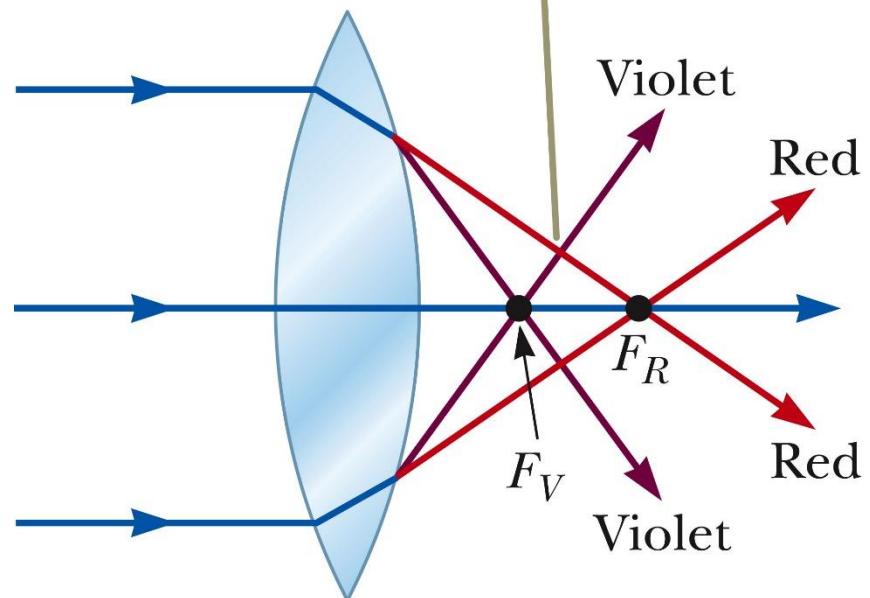
The refracted rays intersect at different points on the principal axis.



# Chromatic Aberration

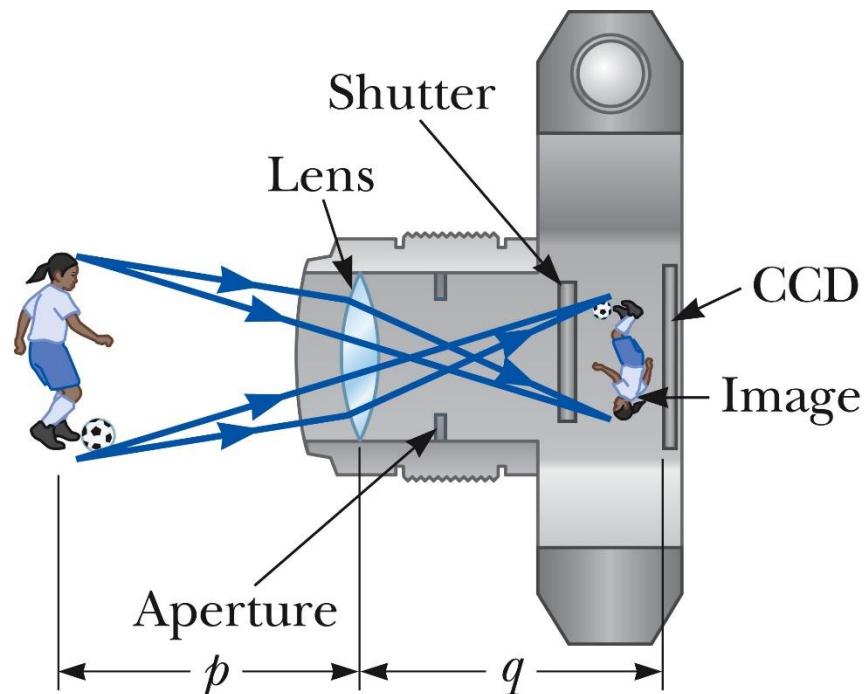
- Different wavelengths of light refracted by a lens focus at different points.
  - Violet rays are refracted more than red rays.
  - The focal length for red light is greater than the focal length for violet light.
- Chromatic aberration can be minimized by the use of a combination of converging and diverging lenses made of different materials.

Rays of different wavelengths focus at different points.



# The Camera

- The photographic camera is a simple optical instrument.
- Components
  - Light-tight chamber
  - Converging lens
    - Produces a real image
  - Light sensitive component behind the lens
    - Where the image is formed
    - Could be a CCD or film



# Camera Operation

- Proper focusing will result in sharp images.
- The camera is focused by varying the distance between the lens and the CCD.
  - The lens-to-CCD distance will depend on the object distance and on the focal length of the lens.
- The shutter is a mechanical device that is opened for selected time intervals.
  - The time interval that the shutter is opened is called the *exposure time*.

# Camera Operation, Intensity

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- Light intensity is a measure of the rate at which energy is received by the CCD per unit area of the image.
  - The intensity of the light reaching the CCD is proportional to the area of the lens.
- The brightness of the image formed on the CCD depends on the light intensity.
  - Depends on both the focal length and the diameter of the lens

# Camera, f-numbers

- The **f-number** of a camera lens is the ratio of the focal length of the lens to its diameter.
  - $f\text{-number} \equiv f / D$
  - The f-number is often given as a description of the lens “speed”.
    - A lens with a low f-number is a “fast” lens.
- The intensity of light incident on the film is related to the f-number:  $I \propto 1/(f\text{-number})^2$ .

# Camera, f-numbers, cont.

- Increasing the setting from one f-number to the next higher value decreases the area of the aperture by a factor of 2.
- The lowest f-number setting on a camera corresponds to the aperture wide open and the use of the maximum possible lens area.
- Simple cameras usually have a fixed focal length and a fixed aperture size, with an f-number of about 11.
  - Most cameras with variable f-numbers adjust them automatically.

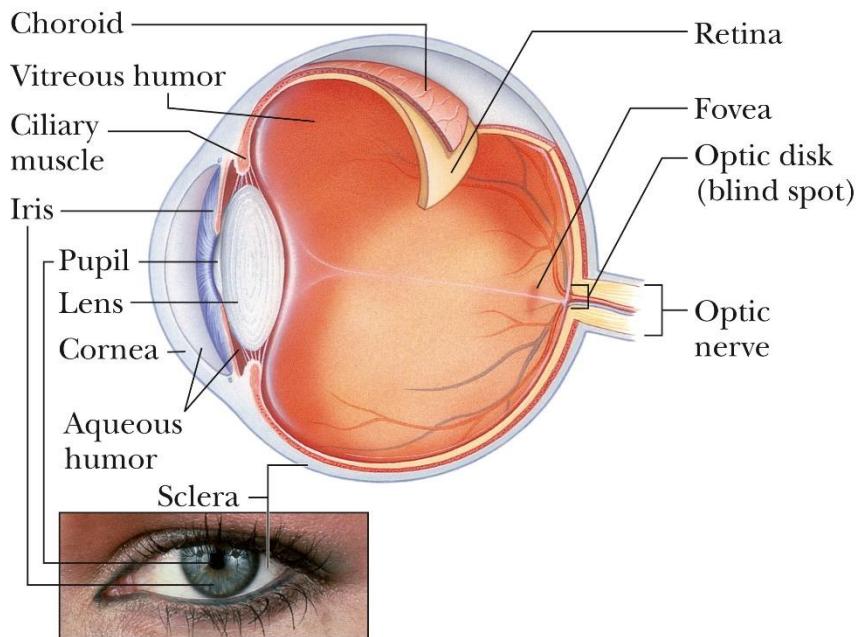
# Camera, Depth of Field

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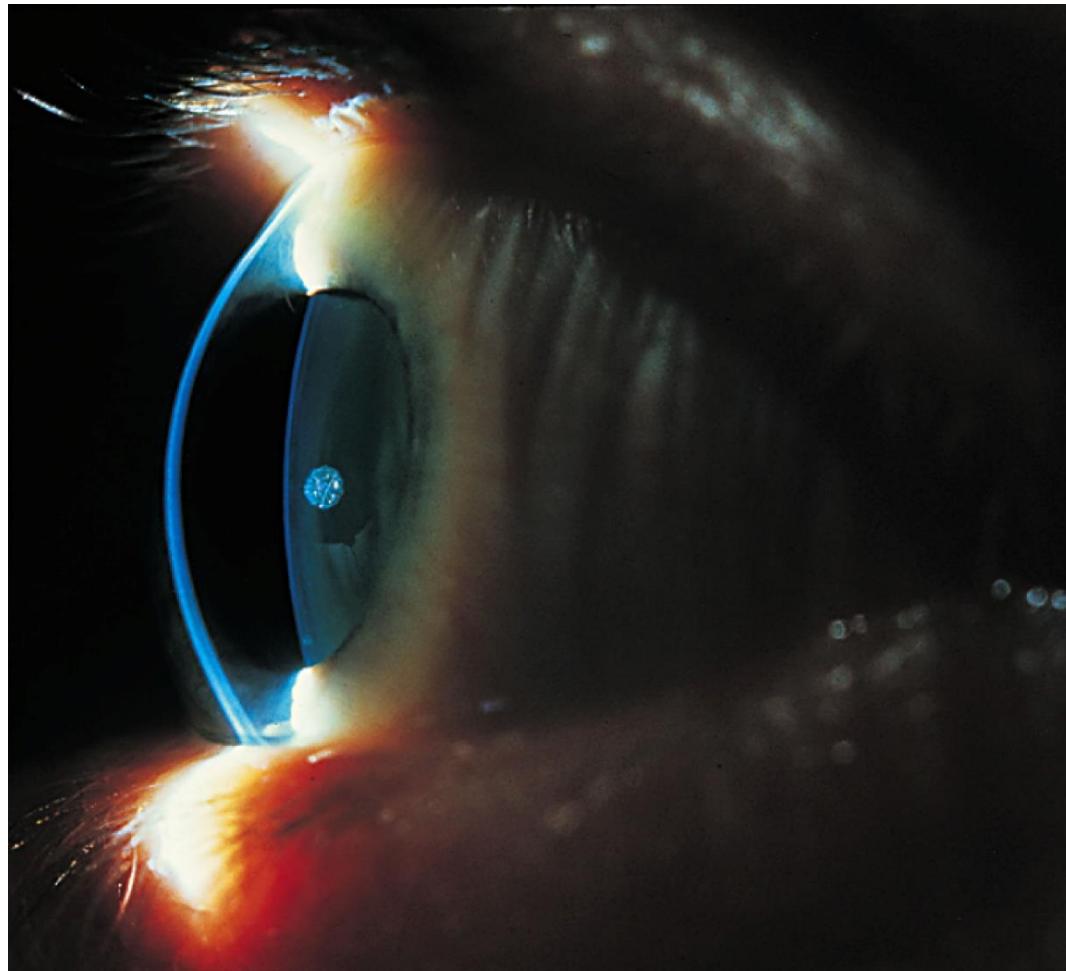
- A high value for the f-number allows for a large depth of field.
  - This means that objects at a wide range of distances from the lens form reasonably sharp images on the film.
  - The camera would not have to be focused for various objects.

# The Eye

- The normal eye focuses light and produces a sharp image.
- Essential parts of the eye:
  - Cornea – light passes through this transparent structure
  - Aqueous Humor – clear liquid behind the cornea
  - The pupil
    - A variable aperture
    - An opening in the iris
  - The crystalline lens



# The Eye – Close-up of the Cornea



# The Eye – Parts, cont.

- Most of the refraction takes place at the outer surface of the eye.
  - Where the cornea is covered with a film of tears.
- The iris is the colored portion of the eye.
  - It is a muscular diaphragm that controls pupil size.
  - The iris regulates the amount of light entering the eye.
    - It dilates the pupil in low light conditions.
    - It contracts the pupil in high-light conditions.
  - The f-number of the eye is from about 2.8 to 16.

# The Eye – Operation

- The cornea-lens system focuses light onto the back surface of the eye.
  - This back surface is called the *retina*.
  - The retina contains sensitive receptors called *rods* and *cones*.
  - These structures send impulses via the optic nerve to the brain.
    - This is where the image is perceived.
- Accommodation
  - The eye focuses on an object by varying the shape of the pliable crystalline lens through this process.
  - Takes place very quickly
  - Limited in that objects very close to the eye produce blurred images

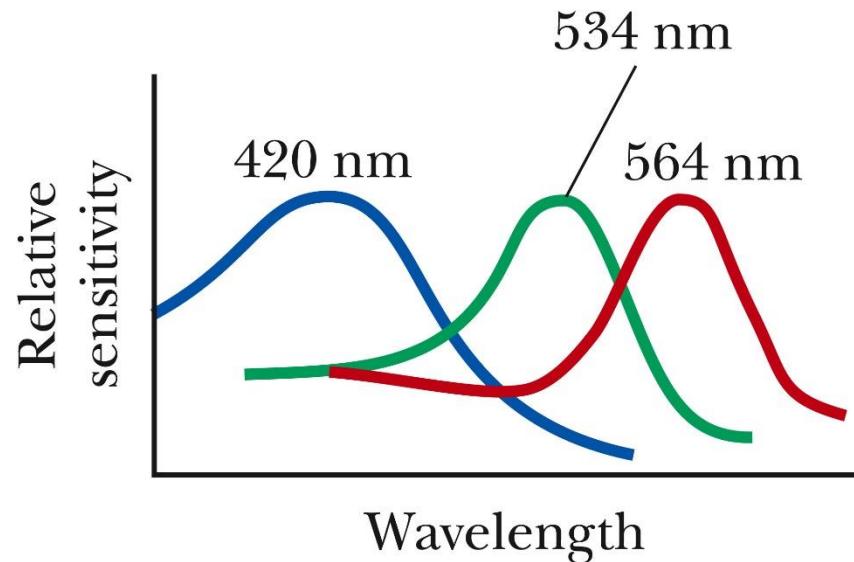
# The Eye – Near and Far Points

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- The *near point* is the closest distance for which the lens can accommodate to focus light on the retina.
  - Typically at age 10, this is about 18 cm
  - The average value is about 25 cm.
  - It increases with age.
    - Up to 500 cm or greater at age 60
- The *far point* of the eye represents the largest distance for which the lens of the relaxed eye can focus light on the retina.
  - Normal vision has a far point of infinity.

# The Eye – Seeing Colors

- Only three types of color-sensitive cells are present in the retina.
  - They are called red, green and blue cones.
- What color is seen depends on which cones are stimulated.



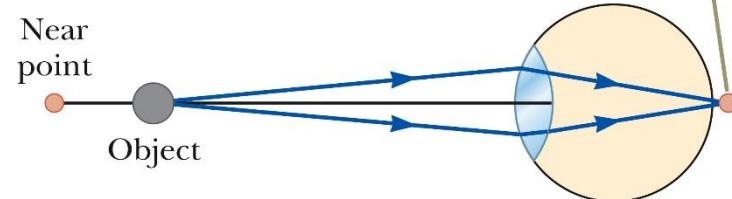
# Conditions of the Eye

- Eyes may suffer a mismatch between the focusing power of the lens-cornea system and the length of the eye.
- Eyes may be:
  - Farsighted
    - Light rays reach the retina before they converge to form an image.
  - Nearsighted
    - Person can focus on nearby objects but not those far away

# Farsightedness

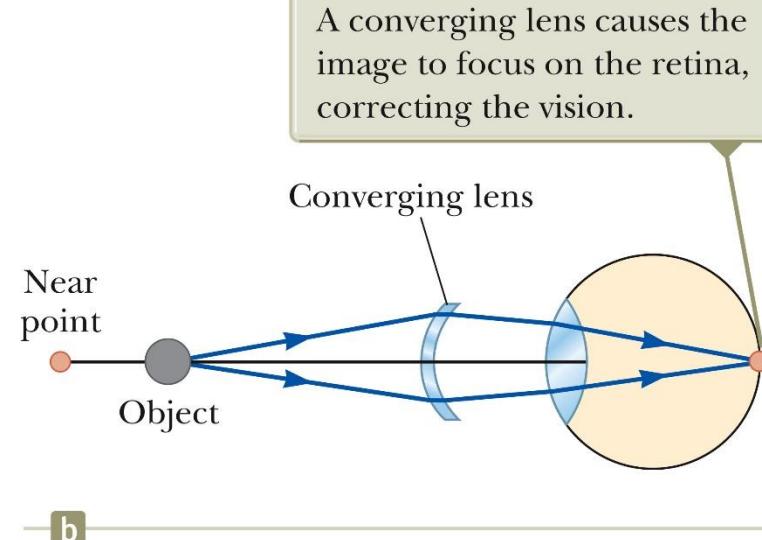
- Also called *hyperopia*
- The near point of the farsighted person is much farther away than that of the normal eye.
- The image focuses behind the retina.
- Can usually see far away objects clearly, but not nearby objects

When a farsighted eye looks at an object located between the near point and the eye, the image point is behind the retina, resulting in blurred vision.



# Correcting Farsightedness

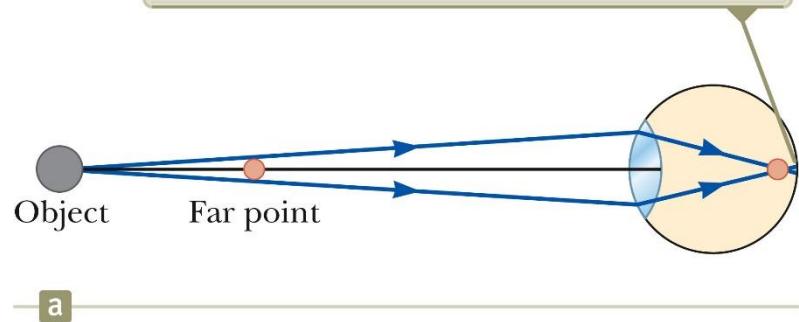
- A converging lens placed in front of the eye can correct the condition.
- The lens refracts the incoming rays more toward the principal axis before entering the eye.
  - This allows the rays to converge and focus on the retina.



# Nearsightedness

- Also called *myopia*
- The far point of the nearsighted person is not infinity and may be less than one meter.
- The nearsighted person can focus on nearby objects but not those far away.

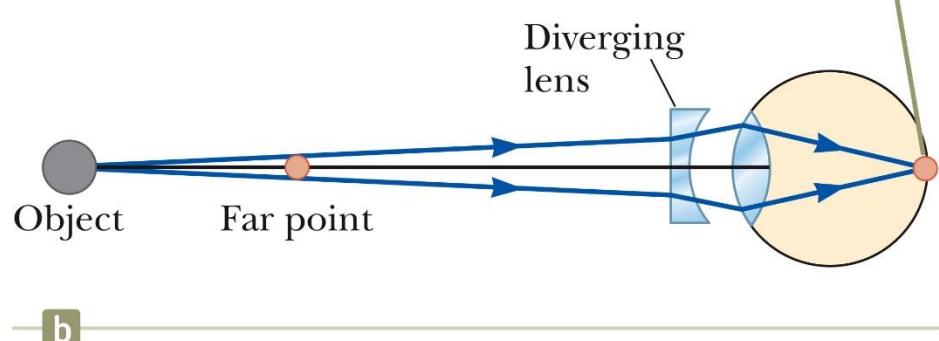
When a nearsighted eye looks at an object located beyond the eye's far point, the image point is in front of the retina, resulting in blurred vision.



# Correcting Nearsightedness

- A diverging lens can be used to correct the condition.
- The lens refracts the rays away from the principal axis before they enter the eye.
  - This allows the rays to focus on the retina.

A diverging lens causes the image to focus on the retina, correcting the vision.



# Presbyopia and Astigmatism

- **Presbyopia** (literally, “old-age vision”) is due to a reduction in accommodation ability.
  - The cornea and lens do not have sufficient focusing power to bring nearby objects into focus on the retina.
  - Condition can be corrected with converging lenses
- In **astigmatism**, light from a point source produces a line image on the retina.
  - Produced when either the cornea or the lens or both are not perfectly symmetric
  - Can be corrected with lenses with different curvatures in two mutually perpendicular directions

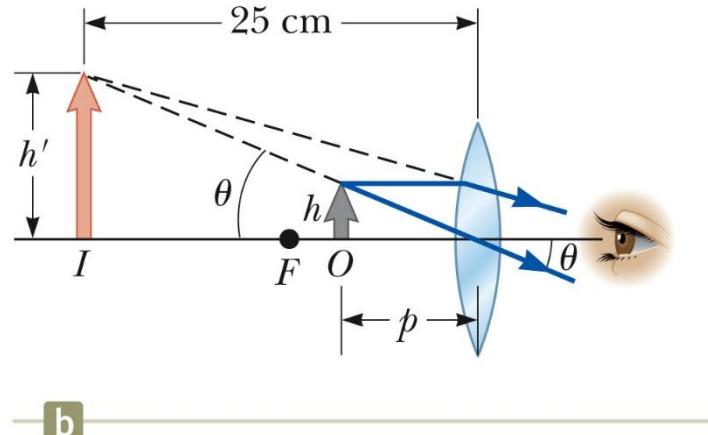
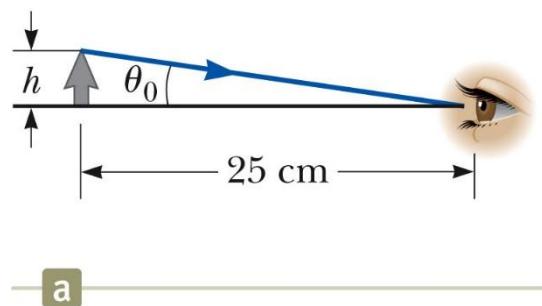
# Diopters

- Optometrists and ophthalmologists usually prescribe lenses measured in *diopters*.
  - The power  $P$  of a lens in diopters equals the inverse of the focal length in meters.
    - $P = 1/f$

# Simple Magnifier

- A simple magnifier consists of a single converging lens.
- This device is used to increase the apparent size of an object.
- The size of an image formed on the retina depends on the angle subtended by the eye.

# The Size of a Magnified Image



- When an object is placed at the near point, the angle subtended is a maximum.
  - The near point is about 25 cm.
- When the object is placed near the focal point of a converging lens, the lens forms a virtual, upright, and enlarged image.

# Angular Magnification

- **Angular magnification** is defined as

$$m = \frac{\theta}{\theta_0} = \frac{\text{angle with lens}}{\text{angle without lens}}$$

- The angular magnification is at a maximum when the image formed by the lens is at the near point of the eye.

- $q = -25 \text{ cm}$

- Calculated by

$$m_{\max} = 1 + \frac{25 \text{ cm}}{f}$$

# Angular Magnification, cont.

- The eye is most relaxed when the image is at infinity.
  - Although the eye can focus on an object anywhere between the near point and infinity.
- For the image formed by a magnifying glass to appear at infinity, the object has to be at the focal point of the lens.
- The angular magnification is

$$m_{\min} = \frac{\theta}{\theta_o} = \frac{25 \text{ cm}}{f}$$

# Magnification by a Lens

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- With a single lens, it is possible to achieve angular magnification up to about 4 without serious aberrations.
- With multiple lenses, magnifications of up to about 20 can be achieved.
  - The multiple lenses can correct for aberrations.

# Compound Microscope

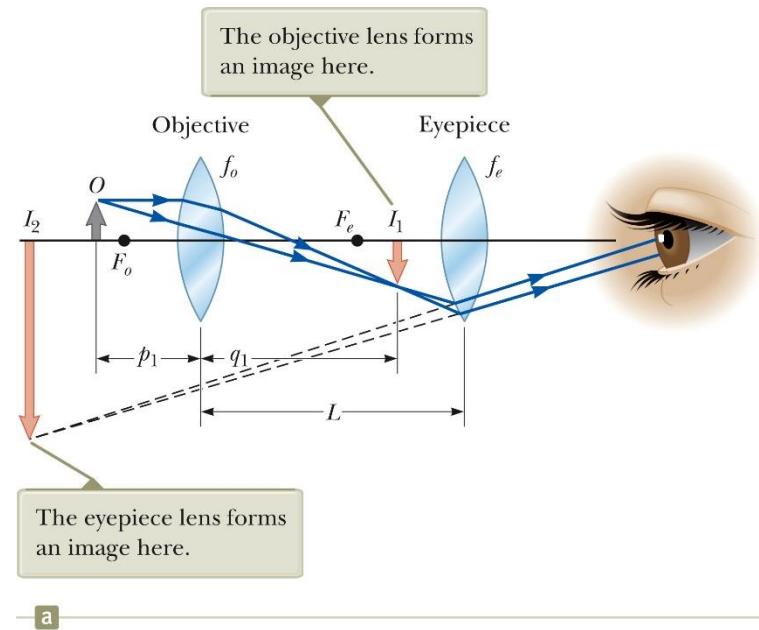
- A compound microscope consists of two lenses.

- Gives greater magnification than a single lens

- The objective lens has a short focal length,

$$f_o < 1 \text{ cm}$$

- The eyepiece has a focal length,  $f_e$  of a few cm.



# Compound Microscope, cont.

- The lenses are separated by a distance  $L$ .
  - $L$  is much greater than either focal length.
- The object is placed just outside the focal point of the objective.
  - This forms a real, inverted image
  - This image is located at or close to the focal point of the eyepiece.
- This image acts as the object for the eyepiece.
  - The image seen by the eye,  $I_2$ , is virtual, inverted and very much enlarged.

# Magnifications of the Compound Microscope

- The lateral magnification by the objective is
  - $M_o = -L/f_o$
- The angular magnification by the eyepiece of the microscope is
  - $m_e = 25 \text{ cm}/f_e$
$$M = M_o m_e = -\frac{L}{f_o} \left( \frac{25 \text{ cm}}{f_e} \right)$$
- The overall magnification of the microscope is the product of the individual magnifications.

# Other Considerations with a Microscope

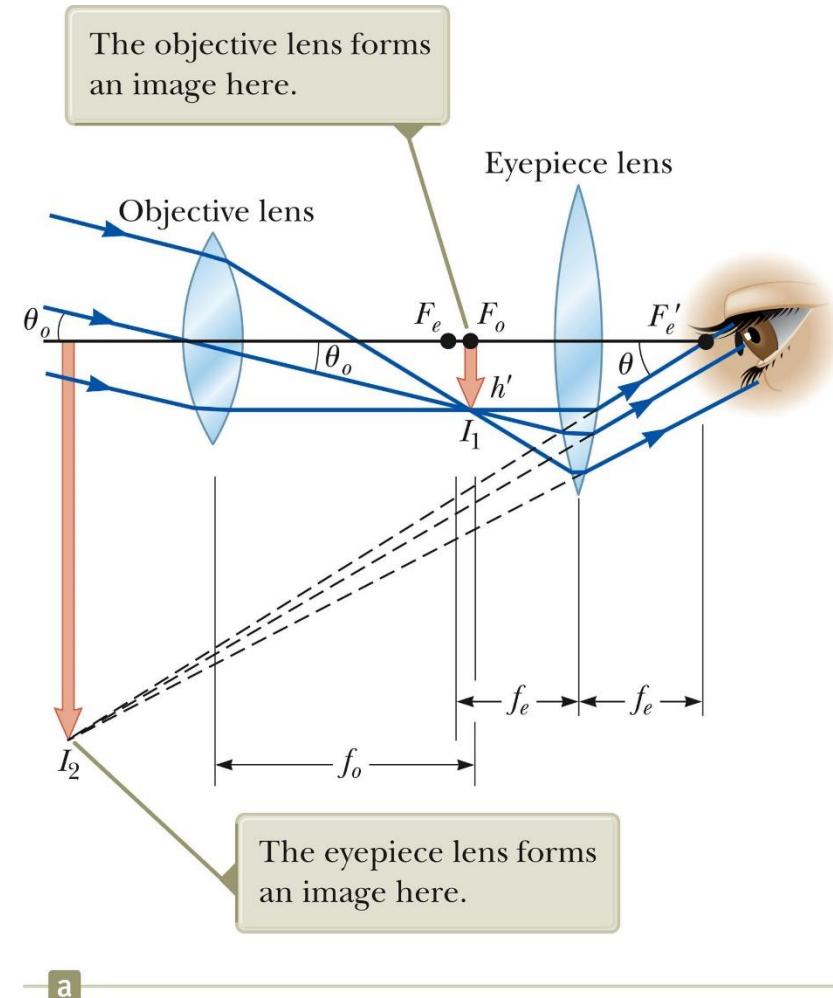
- The ability of an optical microscope to view an object depends on the size of the object relative to the wavelength of the light used to observe it.
  - For example, you could not observe an atom ( $d \approx 0.1 \text{ nm}$ ) with visible light ( $\lambda \approx 500 \text{ nm}$ ).

# Telescopes

- Telescopes are designed to aid in viewing distant objects.
- Two fundamental types of telescopes
  - Refracting telescopes use a combination of lenses to form an image.
  - Reflecting telescopes use a curved mirror and a lens to form an image.
- Telescopes can be analyzed by considering them to be two optical elements in a row.
  - The image of the first element becomes the object of the second element.

# Refracting Telescope

- The two lenses are arranged so that the objective forms a real, inverted image of a distant object.
- The image is formed at the focal point of the eyepiece.
  - $p$  is essentially infinity
- The two lenses are separated by the distance  $f_o + f_e$  which corresponds to the length of the tube.
- The eyepiece forms an enlarged, inverted image of the first image.



# Angular Magnification of a Telescope

- The angular magnification depends on the focal lengths of the objective and eyepiece.

$$m = \frac{\theta}{\theta_o} = -\frac{f_o}{f_e}$$

- The negative sign indicates the image is inverted.
- Angular magnification is particularly important for observing nearby objects.
  - Nearby objects would include the sun or the moon.
  - Very distant objects still appear as a small point of light.

# Disadvantages of Refracting Telescopes

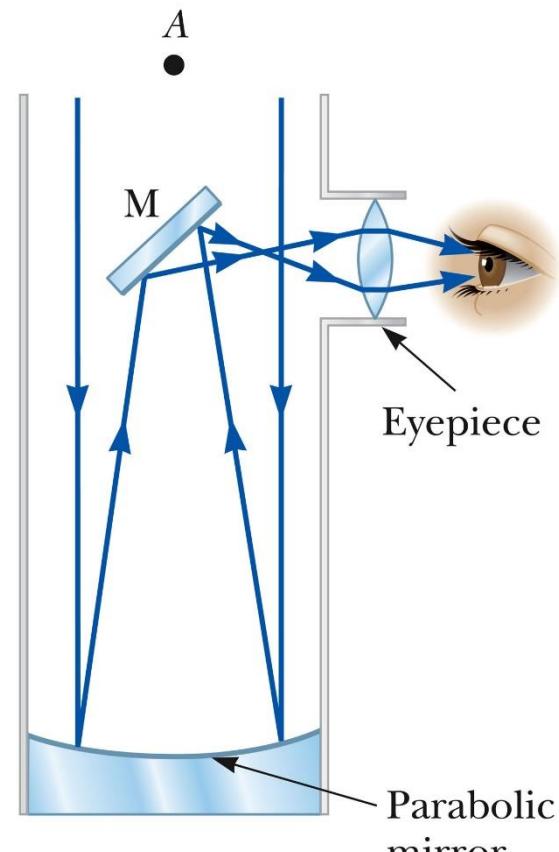
- Large diameters are needed to study distant objects.
- Large lenses are difficult and expensive to manufacture.
- The weight of large lenses leads to sagging which produces aberrations.

# Reflecting Telescope

- Helps overcome some of the disadvantages of refracting telescopes
  - Replaces the objective lens with a mirror
  - The mirror is often parabolic to overcome spherical aberrations.
- In addition, the light never passes through glass.
  - Except the eyepiece
  - Reduced chromatic aberrations
  - Allows for support and eliminates sagging

# Reflecting Telescope, Newtonian Focus

- The incoming rays are reflected from the mirror and converge toward point A.
  - At A, an image would be formed.
- A small flat mirror, M, reflects the light toward an opening in the side and it passes into an eyepiece.
  - This occurs before the image is formed at A.



# Examples of Telescopes

- Reflecting Telescopes

- Largest in the world are the 10-m diameter Keck telescopes on Mauna Kea in Hawaii
  - Each contains 36 hexagonally shaped, computer-controlled mirrors that work together to form a large reflecting surface.
  - Telescopes with different mirrors working together can result in an effective diameter up to 30 m.

- Refracting Telescopes

- Largest in the world is Yerkes Observatory in Williams Bay, Wisconsin
  - Has a diameter of 1 m

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# Thank You

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# ACKNOWLEDGEMENTS