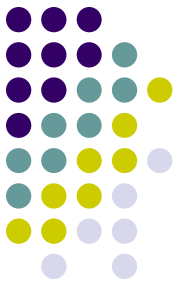# Chapter 36

Image Formation

# Notation for Mirrors and Lenses

- 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

# Types of Images

- 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



©2004 Thomson - Brooks/Cole
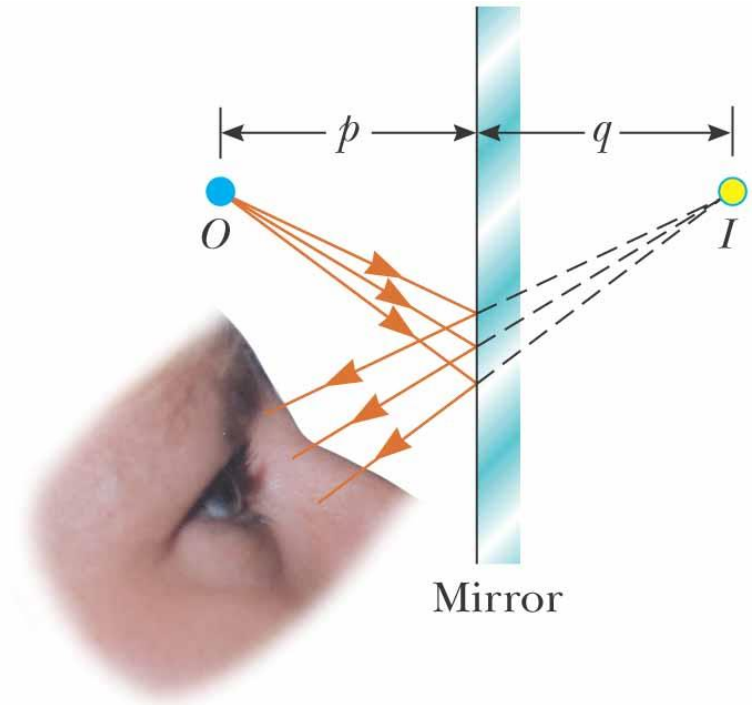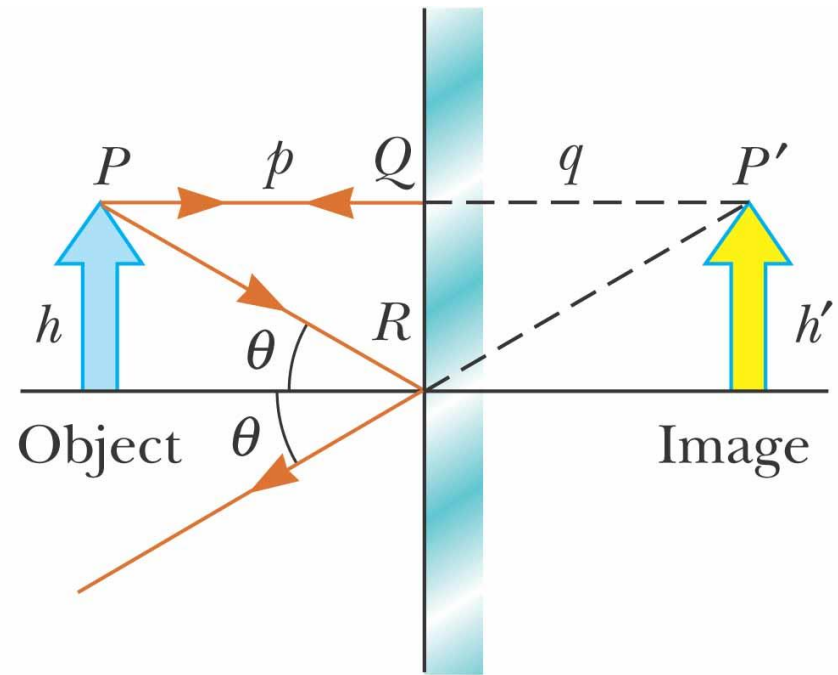
# Images Formed by Flat Mirrors, 2

- 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
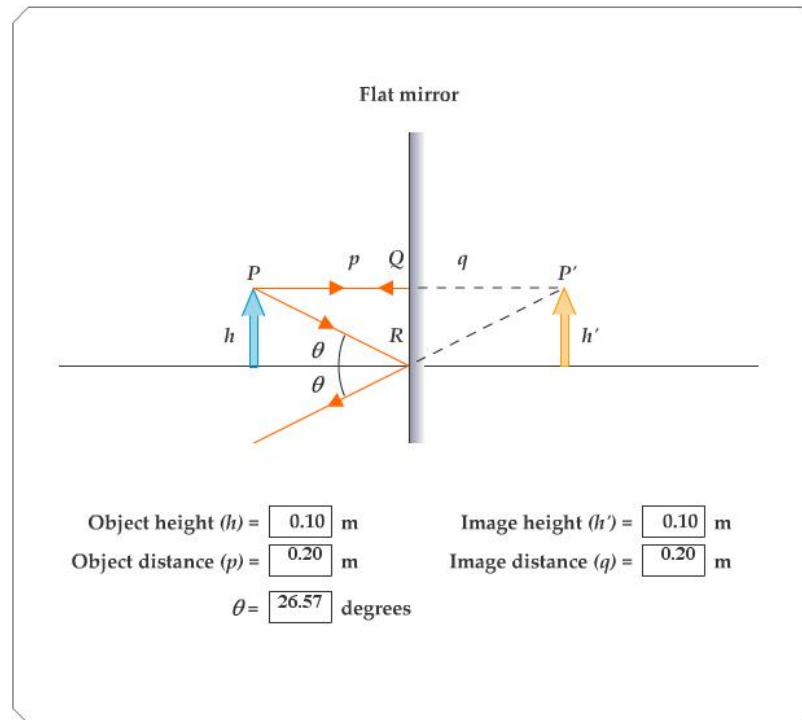
# Images Formed by Flat Mirrors, 3

- 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
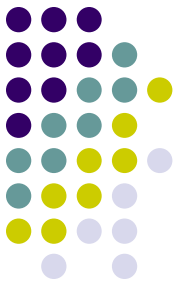- The triangles *PQR* and *P'QR* are congruent



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# Active Figure 36.2

- Use the active figure to move the object
- Observe the effect on the image



Flat mirror

Object height (h) = 0.10 m
Object distance (p) = 0.20 m

Image height (h') = 0.10 m
Image distance (q) = 0.20 m

$\theta$ = 26.57 degrees

**PLAY ACTIVE FIGURE**

# Images Formed by Flat Mirrors, 4

- 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 general 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

- 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

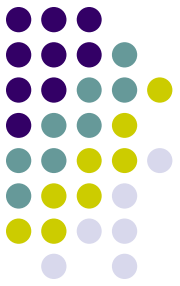  - For example, if you raise your right hand the image you see raises its left hand



© 2004 Thomson - Brooks/Cole
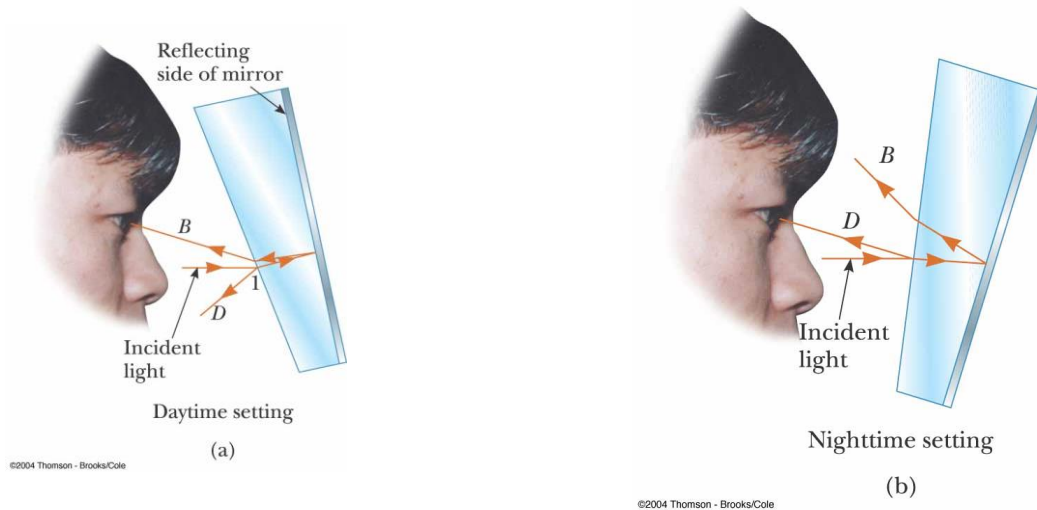
# **Reversals, cont.**

- 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

# 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



Reflecting side of mirror

B

I

D

Incident light

Daytime setting

(a)

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B

D

Incident light

Nighttime setting

(b)

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- 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



Mirror

Center of curvature

*R*

*C*

*V*

Principal axis

(a)
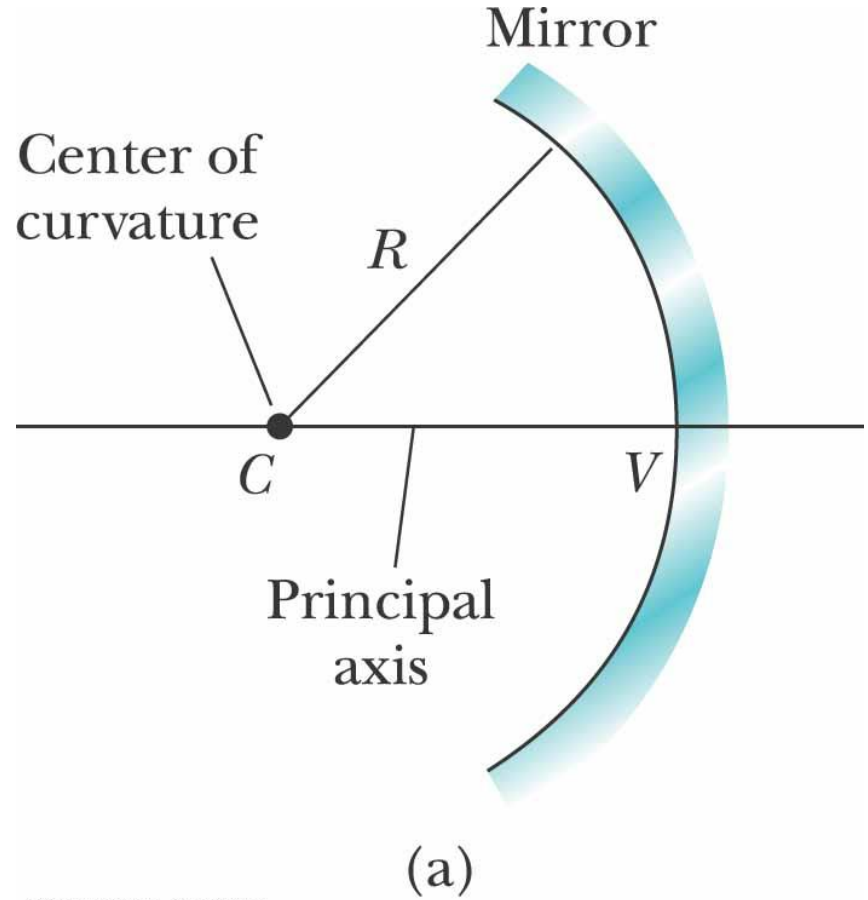
# **Paraxial Rays**

- 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

# Spherical Aberration

- Rays that are far from the principal axis converge to other points on the principal axis

- This produces a blurred image
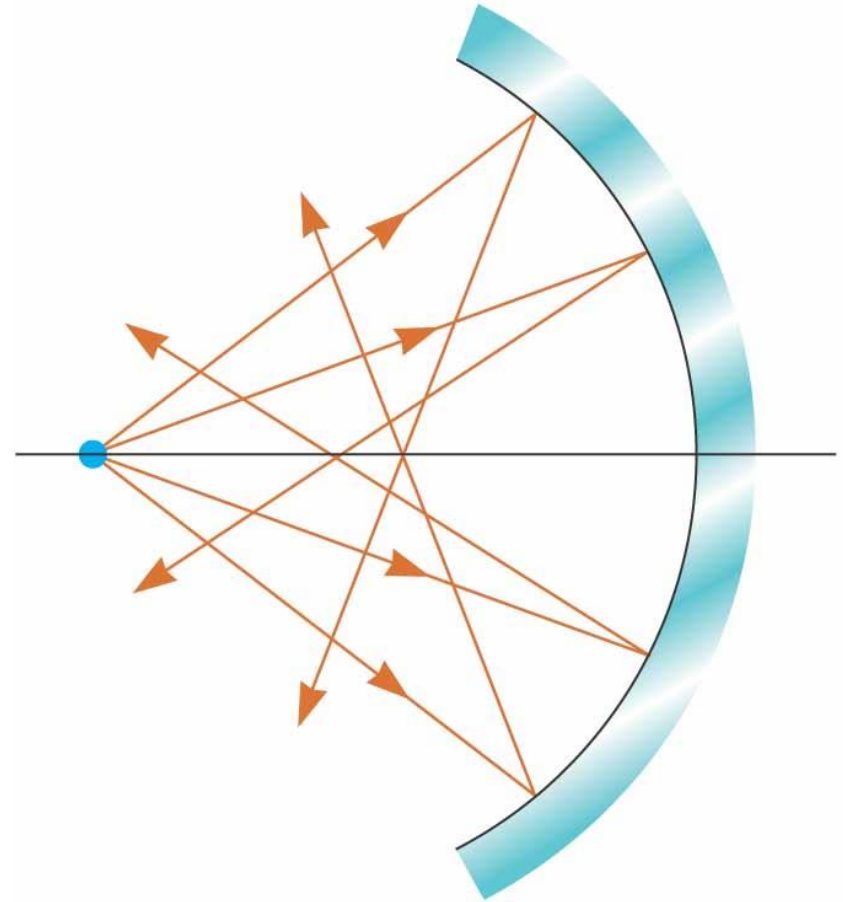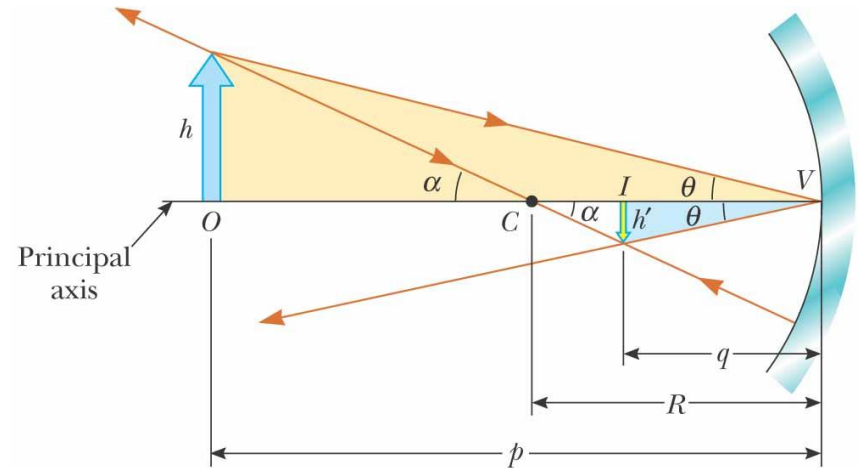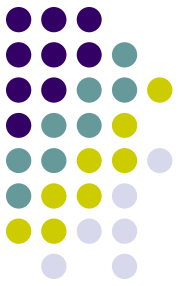
- The effect is called **spherical aberration**

# Image Formed by a Concave Mirror

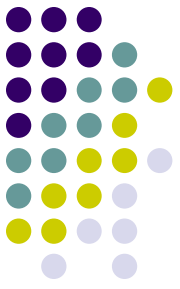- Geometry can be used to determine the magnification of the image

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

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



©2004 Thomson - Brooks/Cole

# 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 ½ the radius of curvature
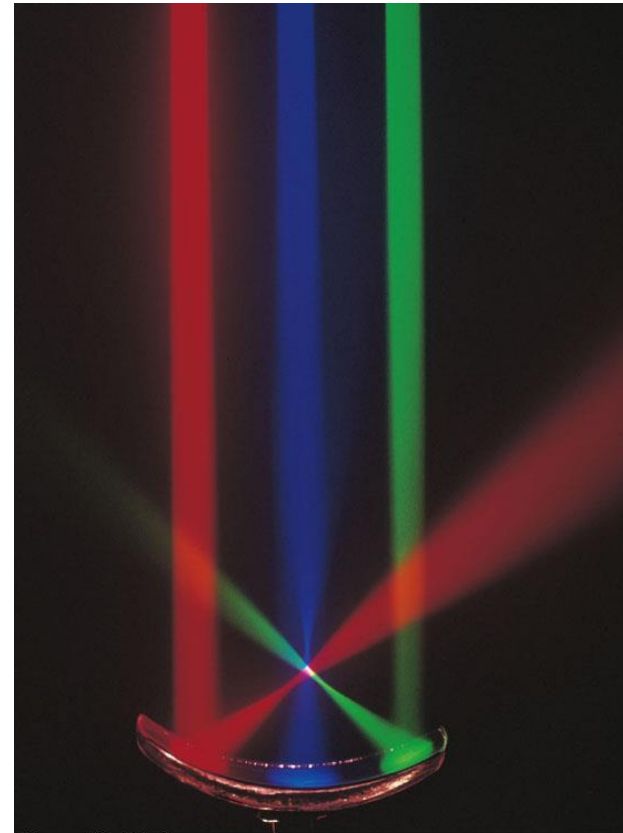


(a)

©2004 Thomson - Brooks/Cole
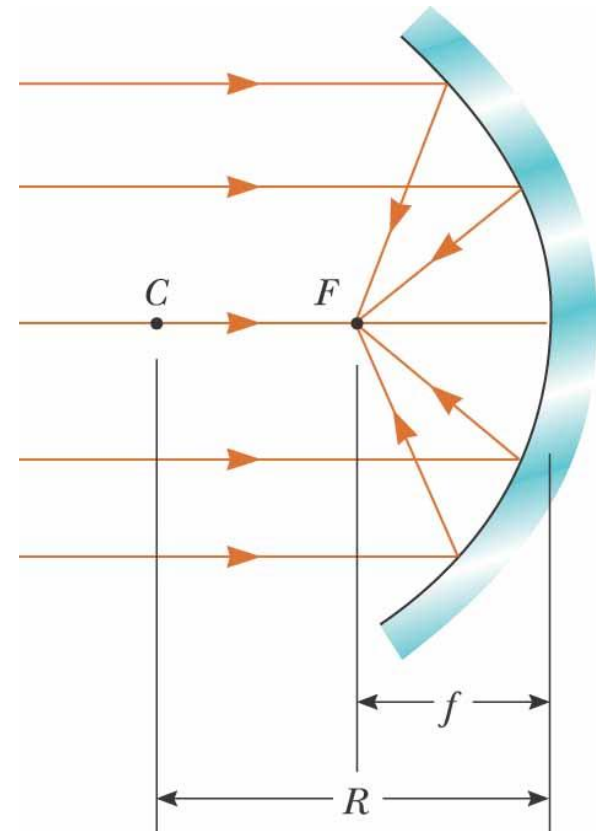
# Focal Point, cont.

- 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
  - It is the white point
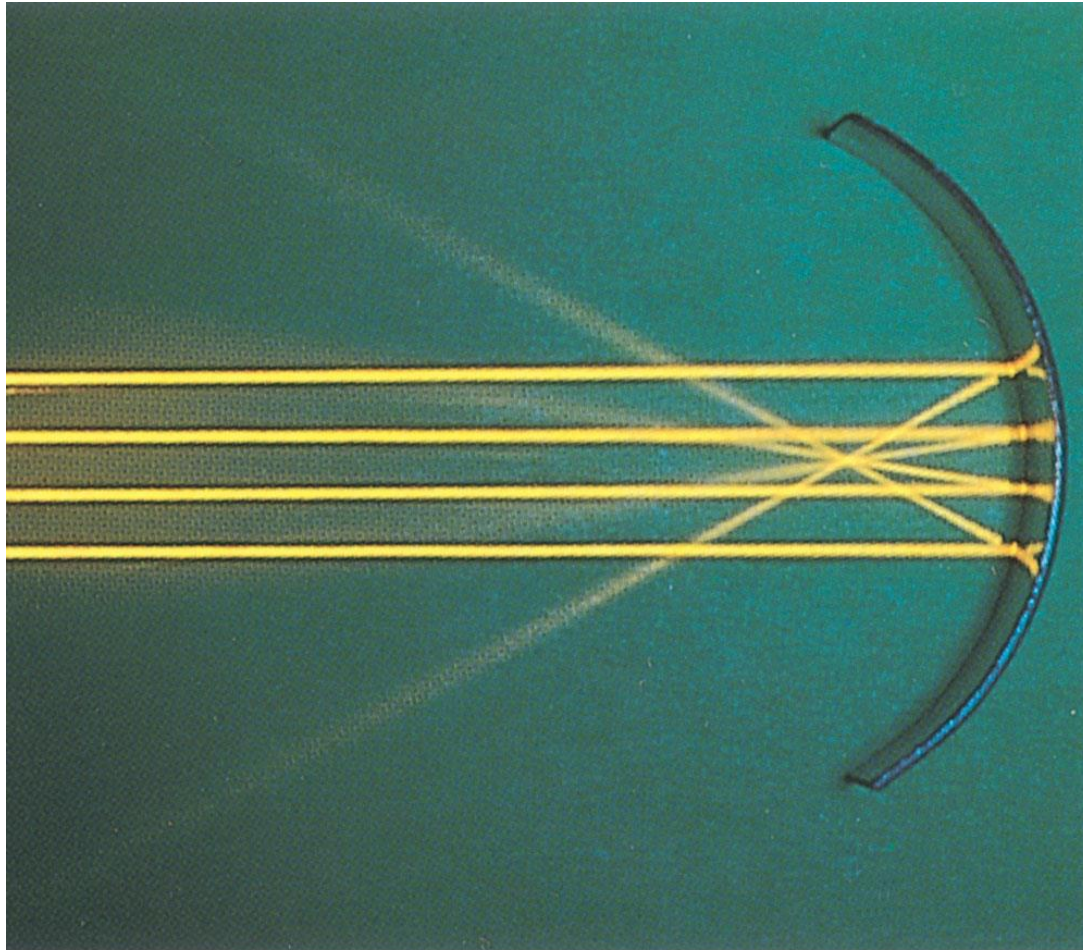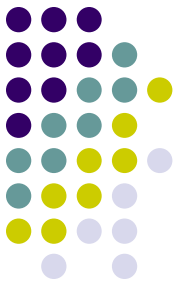


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# Focal Point and Focal Length, cont.

- The focal point is dependent solely on the curvature of the mirror, not on the location of the object
  - It also does not depend on the material from which the mirror is made
- $f$ = R / 2
- The mirror equation can be expressed as

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

# Focal Length Shown by Parallel Rays

# 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



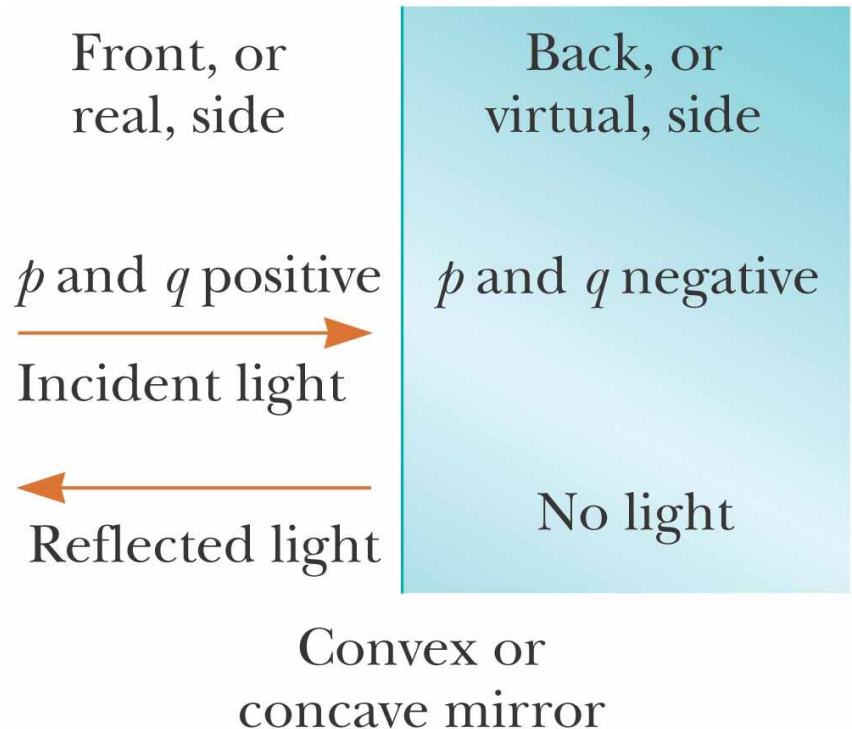©2004 Thomson - Brooks/Cole
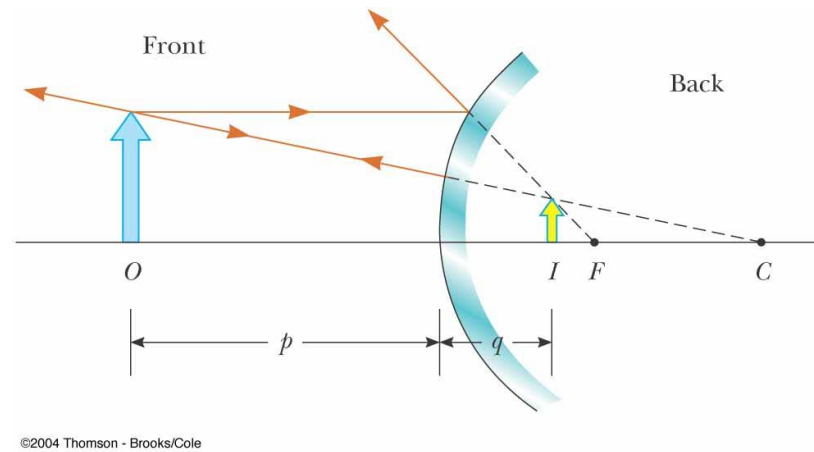
- In general, the image formed by a convex mirror is upright, virtual, and smaller than the object

# 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

Front, or real, side

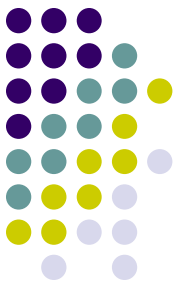Back, or virtual, side

$p$ and $q$ positive

$p$ and $q$ negative

Incident light →

← Reflected light

No light

Convex or concave mirror

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# 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
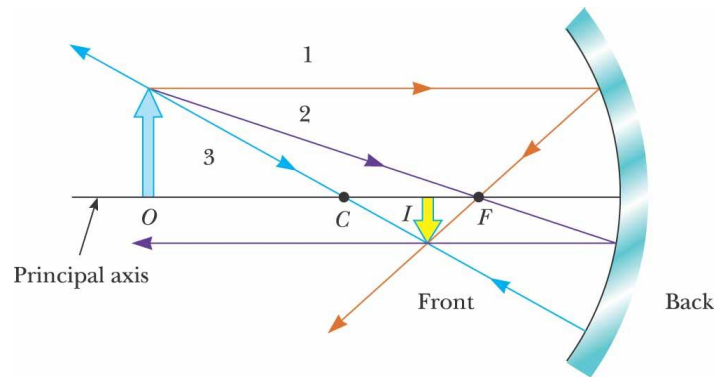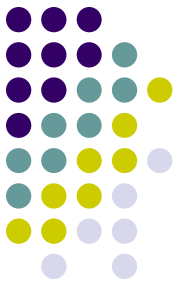
# The Rays in a Ray Diagram – Concave Mirrors

- 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

# **Notes About the Rays**

- The 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

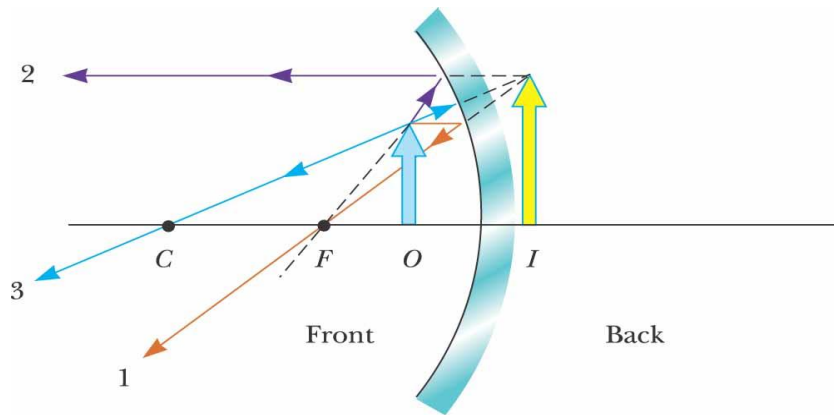# Ray Diagram for a Concave Mirror, p > R



©2004 Thomson - Brooks/Cole
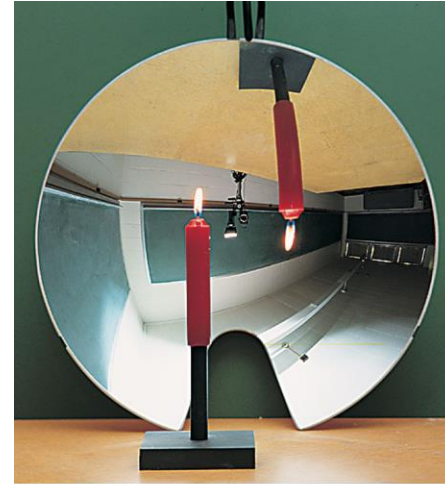


© 2004 Thomson - Brooks/Cole

- 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*



(b)
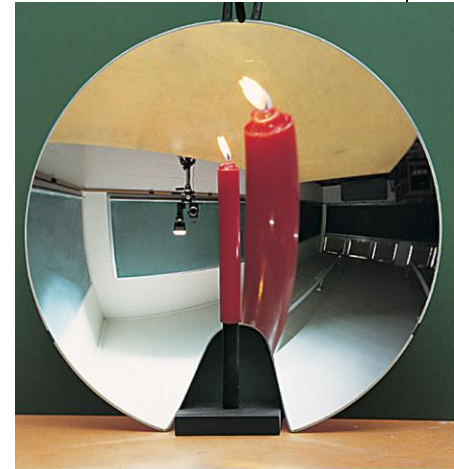
©2004 Thomson - Brooks/Cole

- 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



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- 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)

# Active Figure 36.13

- Use the active figure to
  - Move the object
  - Change the focal length
- Observe the effect on the images



concave   parabolic      convex

concave mirror

C   F

| Object height | 0.10 | m | Image height | -0.05 | m |
| Object distance | 0.45 | m | Image distance | 0.21 | m |
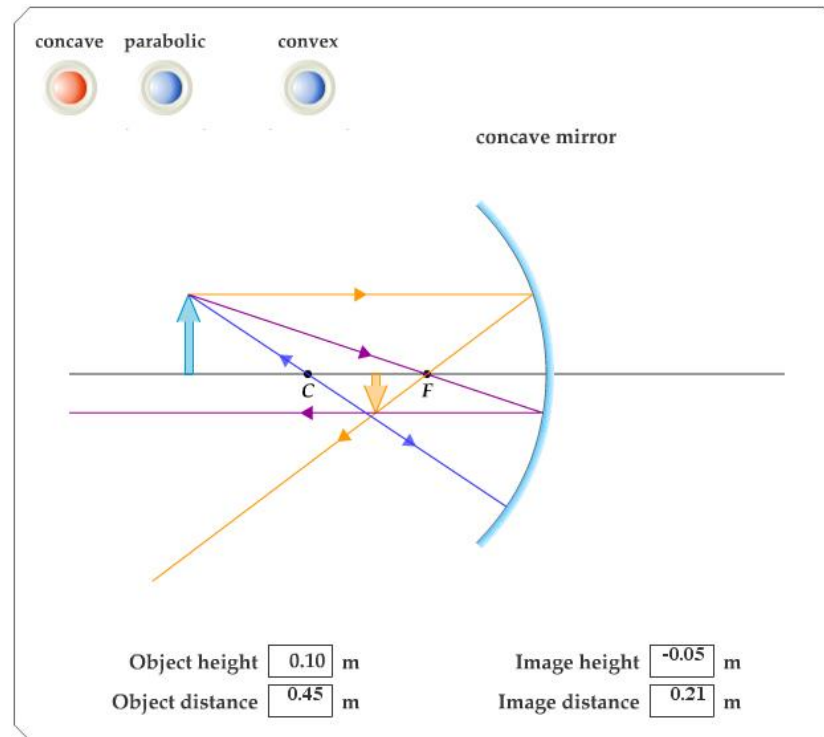
**PLAY ACTIVE FIGURE**

# 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 $n = n_1$



$n_1 < n_2$

$n_1$

$n_2$

$R$

$O$

$I$

$p$

$q$
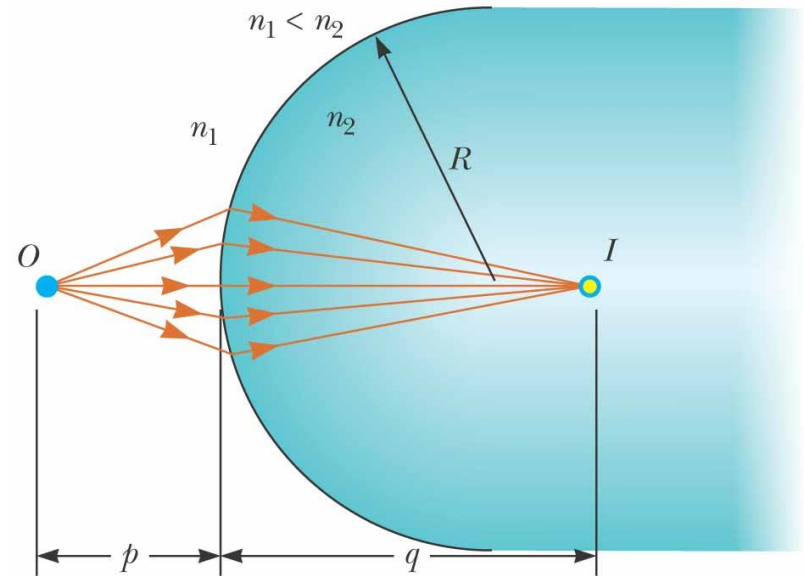
©2004 Thomson - Brooks/Cole

# 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

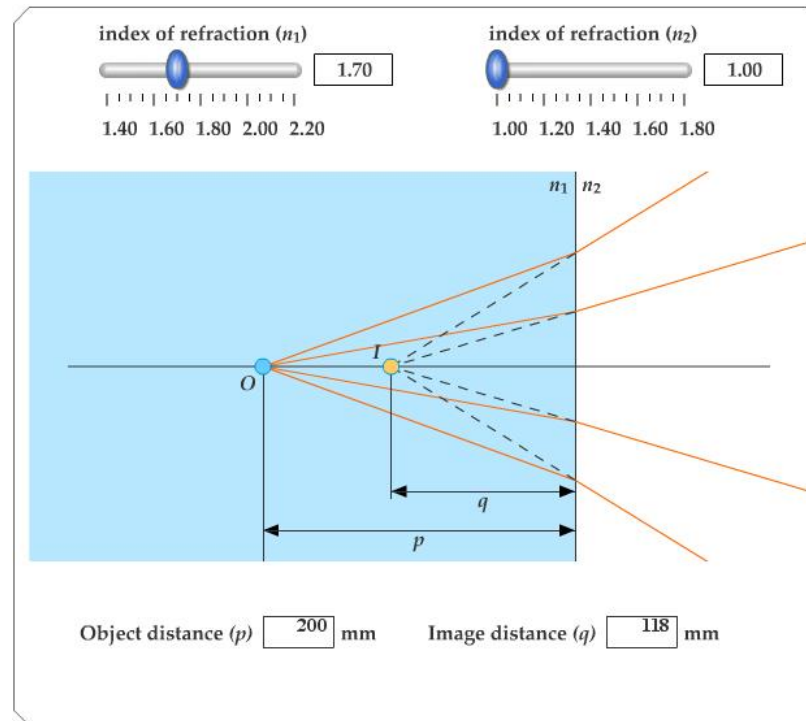| Quantity | Positive When . . . | Negative When . . . |
|---|---|---|
| Object location ($p$) | object is in front of surface (real object). | object is in back of surface (virtual object). |
| Image location ($q$) | image is in back of surface (real image). | image is in front of surface (virtual image). |
| 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



$n_1 > n_2$

$n_1$  $n_2$

$I$

$O$

$q$

$p$

©2004 Thomson - Brooks/Cole
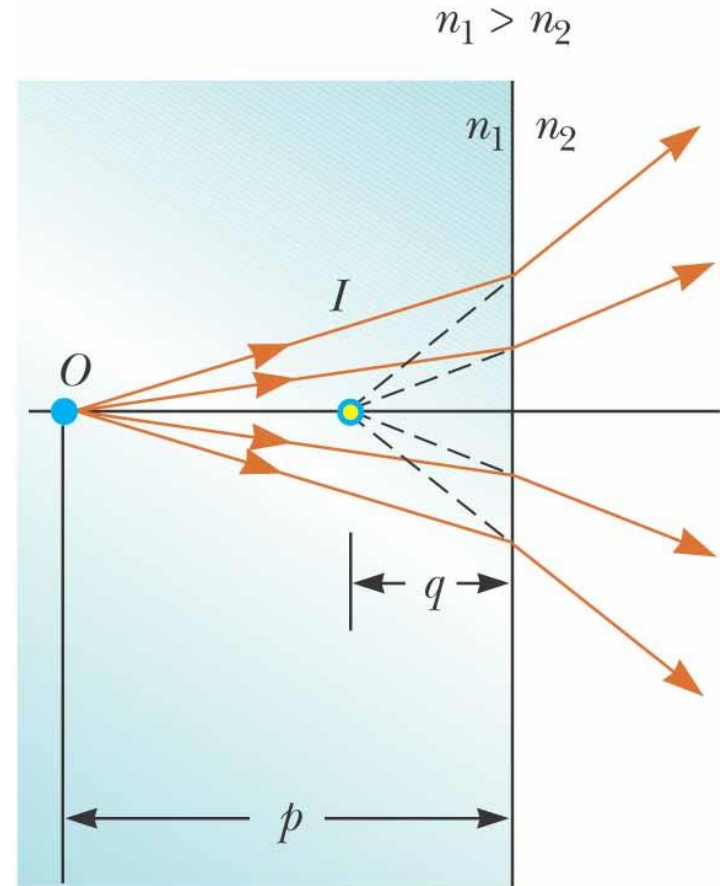
# Active Figure 36.18

- Use the active figure to move the object

- Observe the effect on the location of the image



**index of refraction ($n_1$)** 1.70
1.40 1.60 1.80 2.00 2.20

**index of refraction ($n_2$)** 1.00
1.00 1.20 1.40 1.60 1.80

$n_1$ $n_2$

O

I

q

p

Object distance ($p$) 200 mm     Image distance ($q$) 118 mm

**PLAY ACTIVE FIGURE**

# Lenses

- Lenses are commonly used to form images by refraction

- Lenses are used in optical instruments
  - Cameras
  - Telescopes
  - Microscopes

# Images from Lenses

- 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
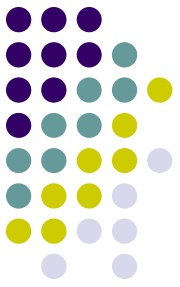
# Locating the Image Formed by a Lens

- 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



©2004 Thomson - Brooks/Cole
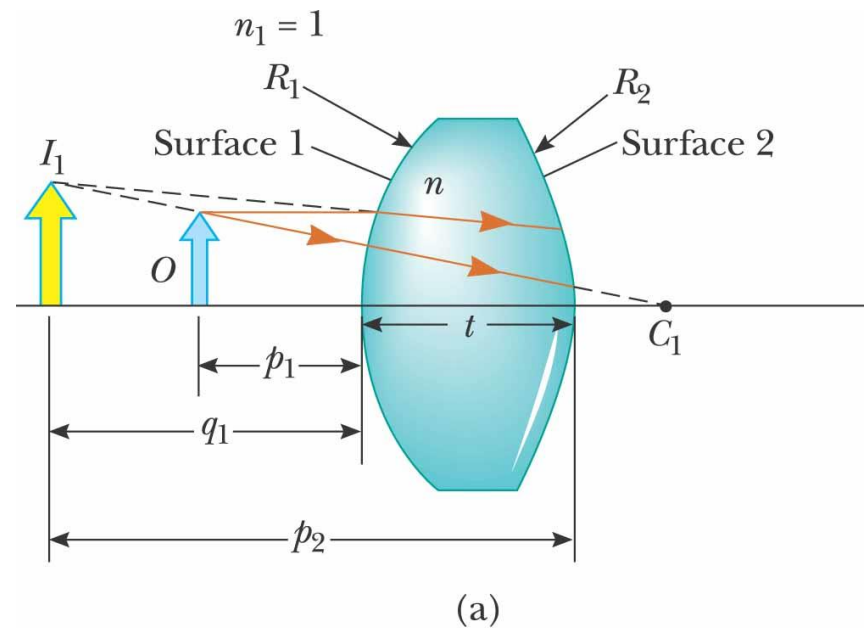
# Locating the Image Formed by a Lens, Image From Surface 1

- 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

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

# Image Formed by a Thick Lens

- 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

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

# 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

# Lens Makers' Equation

- The focal length of a thin lens is the image distance that corresponds to an infinite object distance

  - This is the same as for a mirror

- The **lens makers' equation** is

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

# **Thin Lens Equation**

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

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

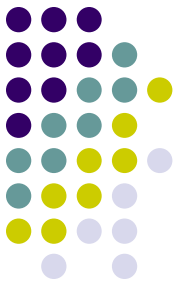# Notes on Focal Length and Focal Point of a Thin Lens

- 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



(a)

©2004 Thomson - Brooks/Cole
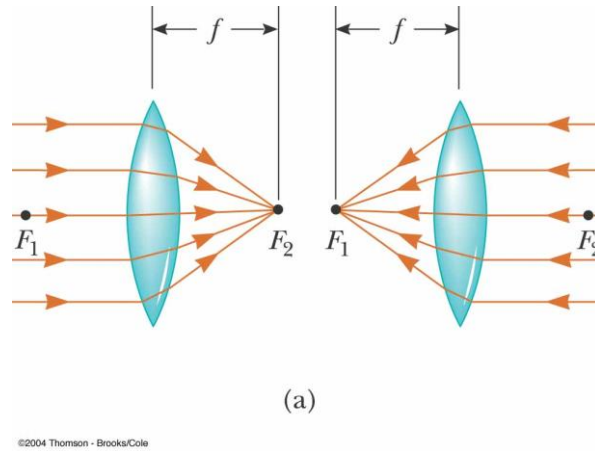
- The parallel rays pass through the lens and converge at the focal point
- The parallel rays can come from the left or right of the lens
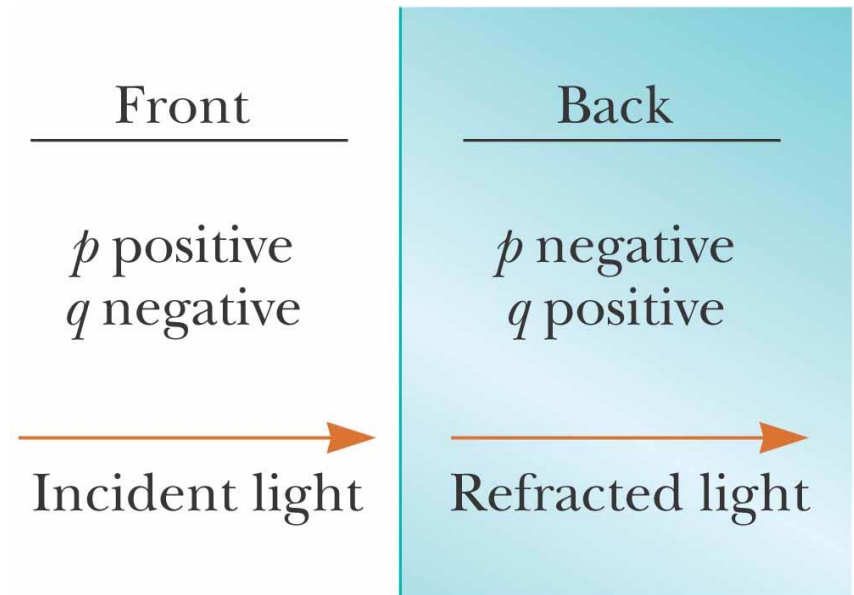
# Focal Length of a Diverging Lens



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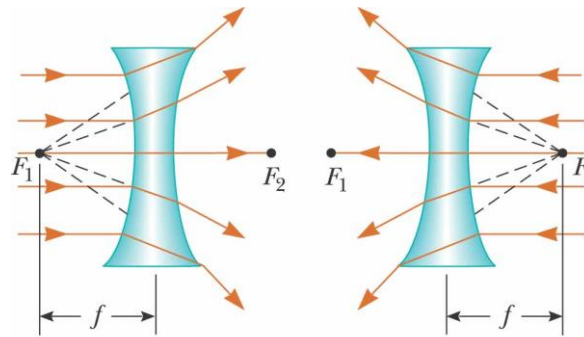
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- The parallel rays diverge after passing through the diverging lens
- The focal point is the point where the rays appear to have originated

# 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
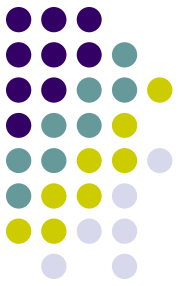- This is also valid for a refracting surface

| Front | Back |
|---|---|
| $p$ positive $q$ negative | $p$ negative $q$ positive |
| Incident light | Refracted light |

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# 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. |

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# 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
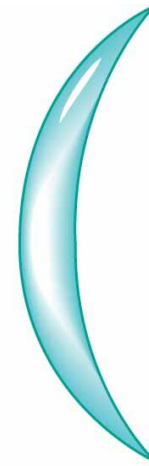- When *M* is negative, the image is inverted and on the side of the lens opposite the object

# Thin Lens Shapes

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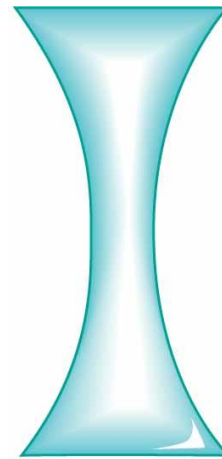- They are thickest in the middle

Biconvex

Convex–concave
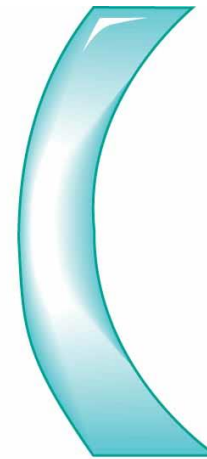
Plano–convex

(a)

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# More Thin Lens Shapes
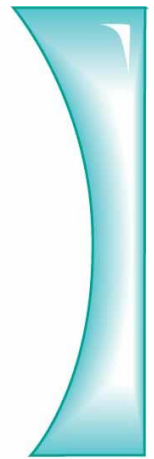
- These are examples of *diverging* lenses
- They have negative focal lengths
- They are thickest at the edges

Biconcave

Convex–concave

Plano–concave

(b)

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# 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*
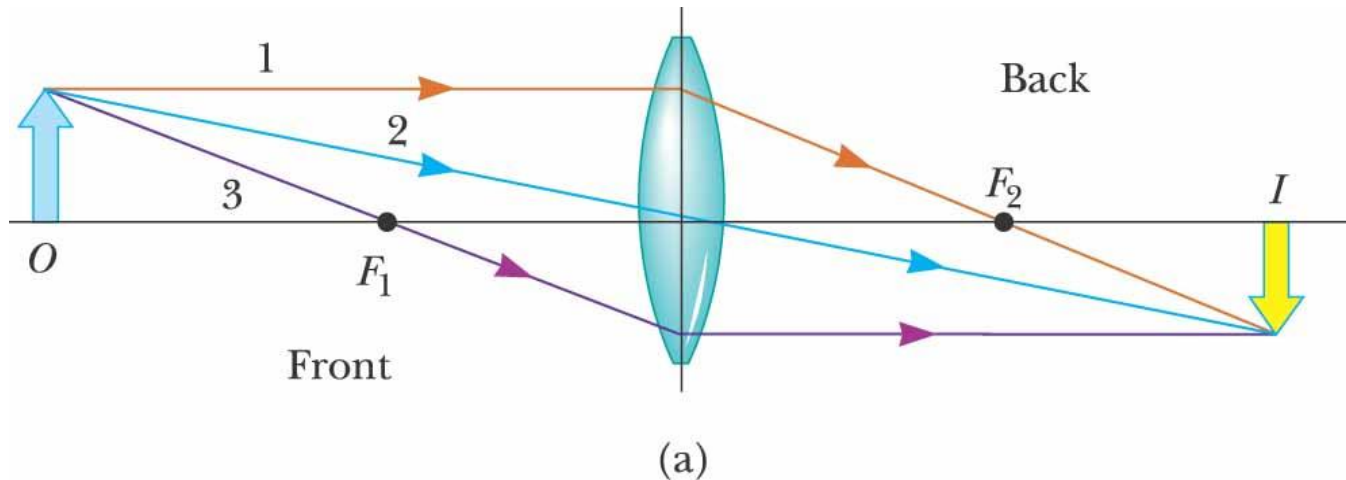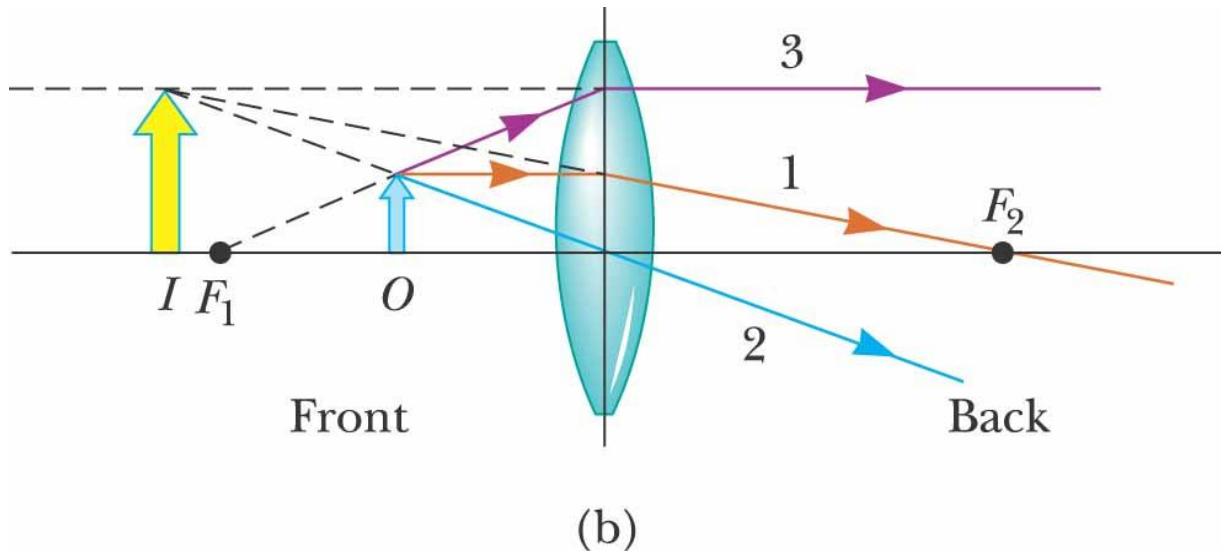


©2004 Thomson - Brooks/Cole

- 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*



3

1

$F_2$

2

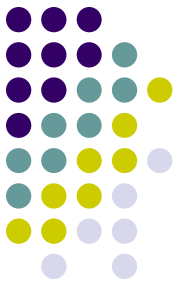*I* $F_1$

*O*

Front

Back

(b)

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- 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

# 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



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

# Active Figure 36.26
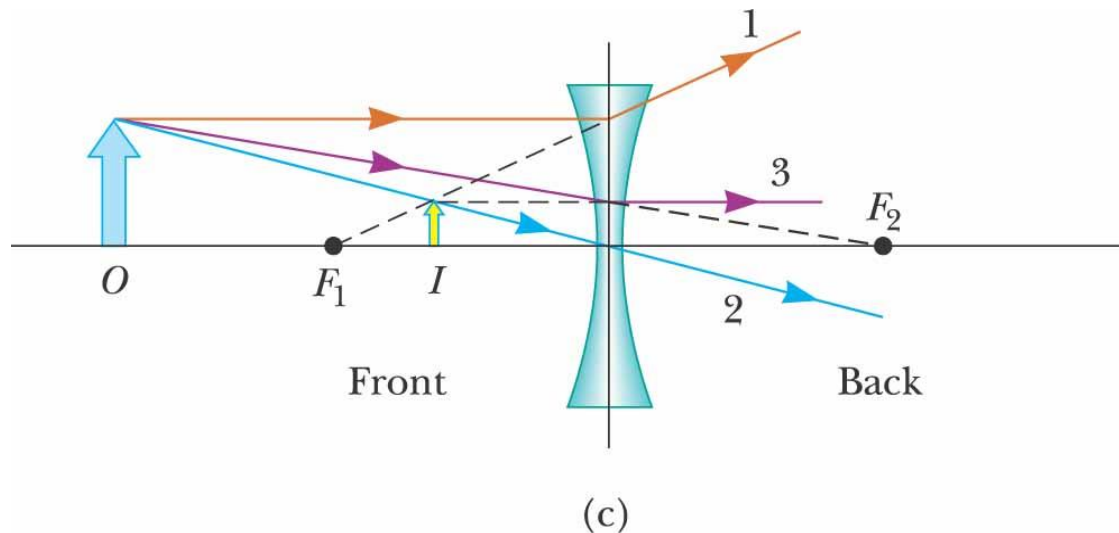
- Use the active figure to
  - Move the object
  - Change the focal length of the lens
- Observe the effect on the image

Convex lens

| | | |
|---|---|---|
| Object height | 0.05 | m |
| Object distance | 0.40 | m |

| | | |
|---|---|---|
| Image height | -0.05 | m |
| Image distance | 0.40 | m |

concave
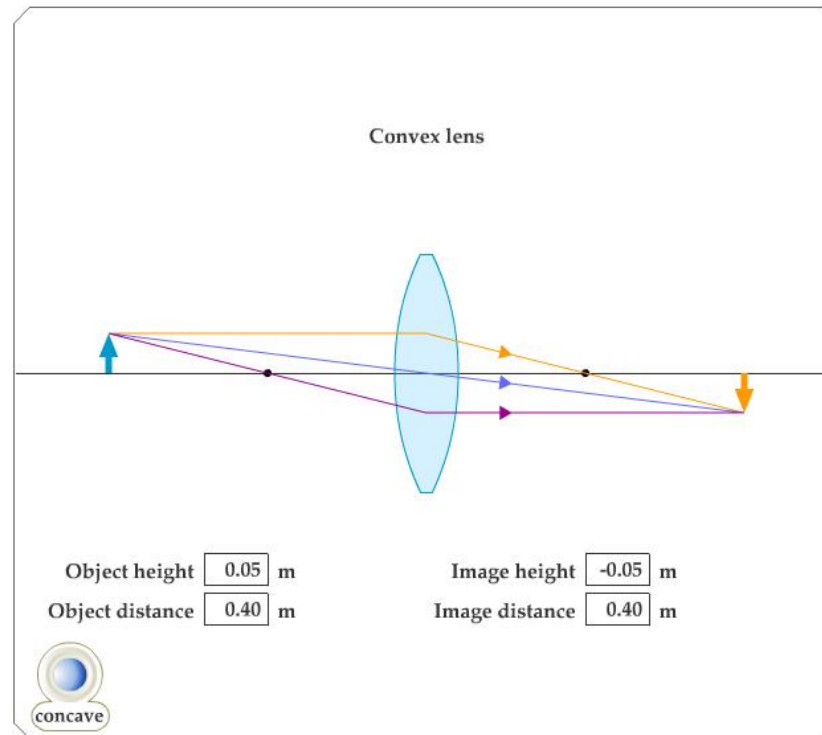
**PLAY
ACTIVE FIGURE**

# 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
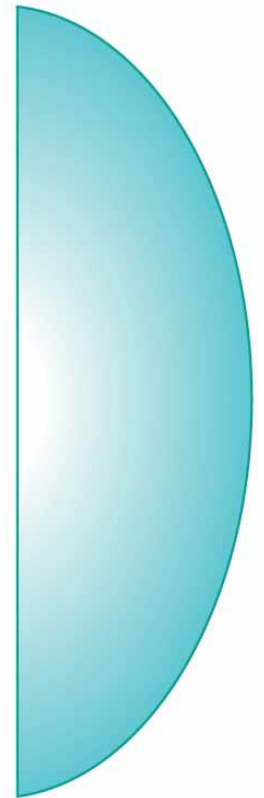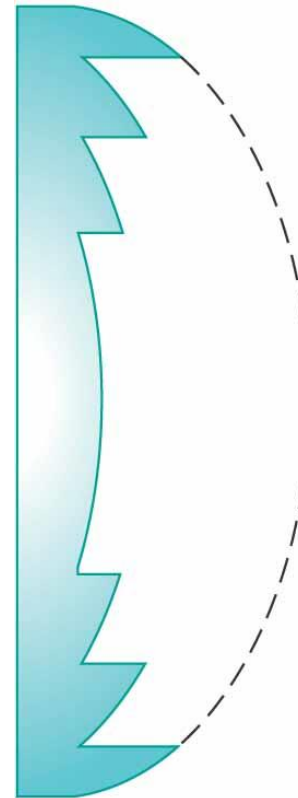
©2004 Thomson - Brooks/Cole

# Fresnal Lens, cont.

- 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

# Combination of Thin Lenses, 2

- 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



$I_2$  $I_1$

10.0 cm ⟶⟵ 15.0 cm

6.67 cm

$O_1$

30.0 cm

20.0 cm

Lens 1

Lens 2

(b)

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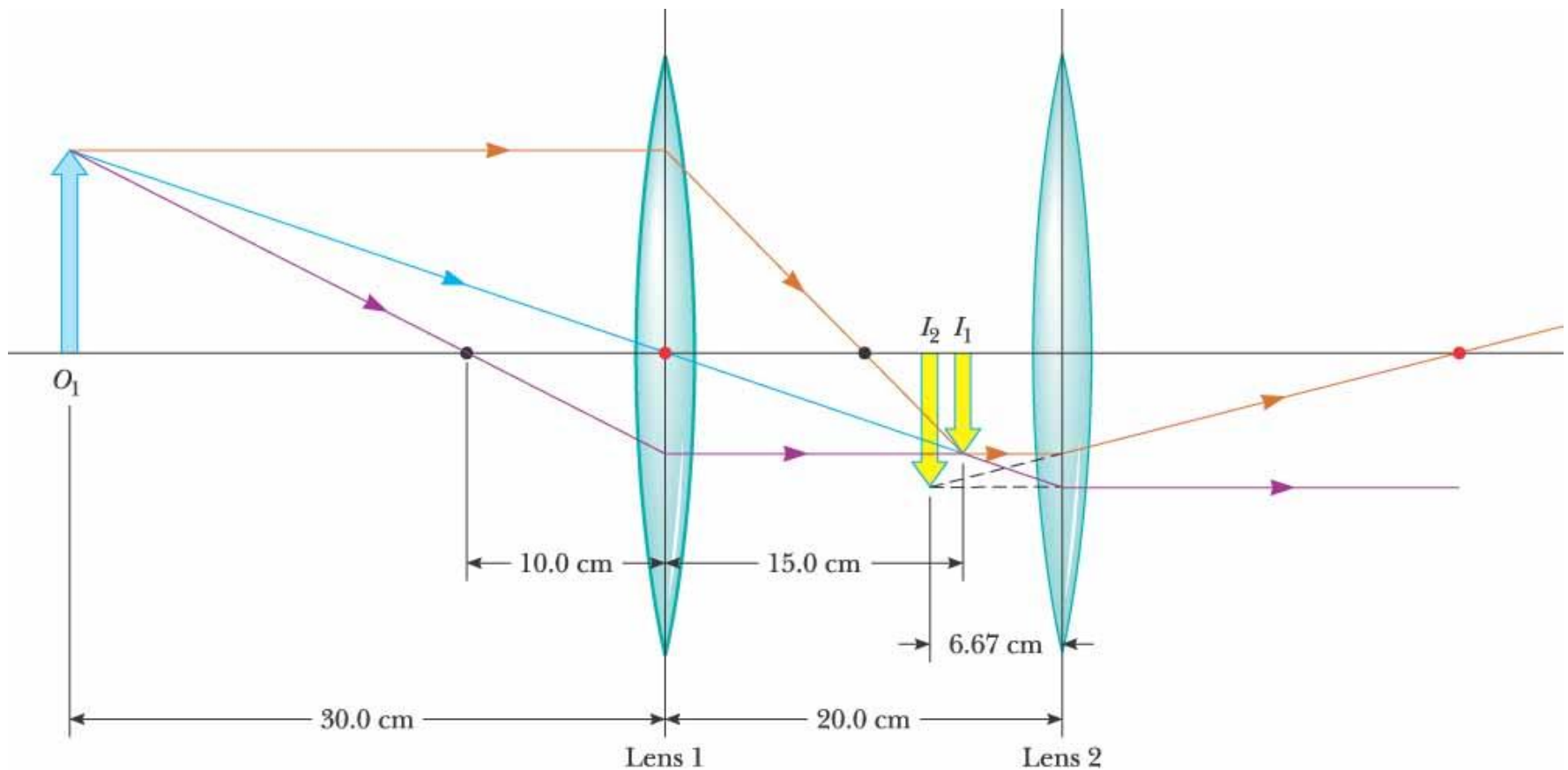
# Combination of Thin Lenses, example

- 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
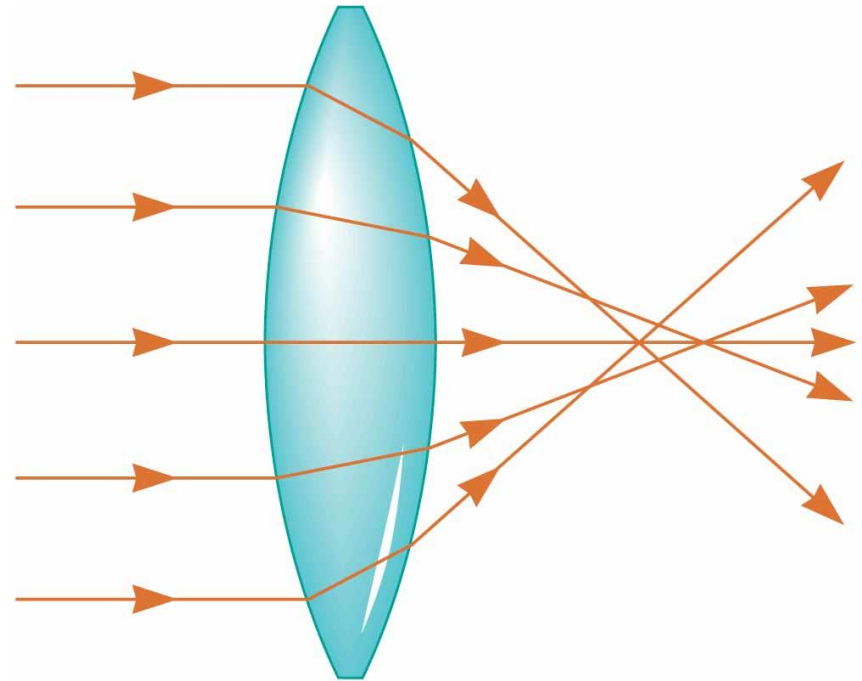
# Lens Aberrations

- 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



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# 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



Violet

Red

$F_R$

$F_V$

Red

Violet

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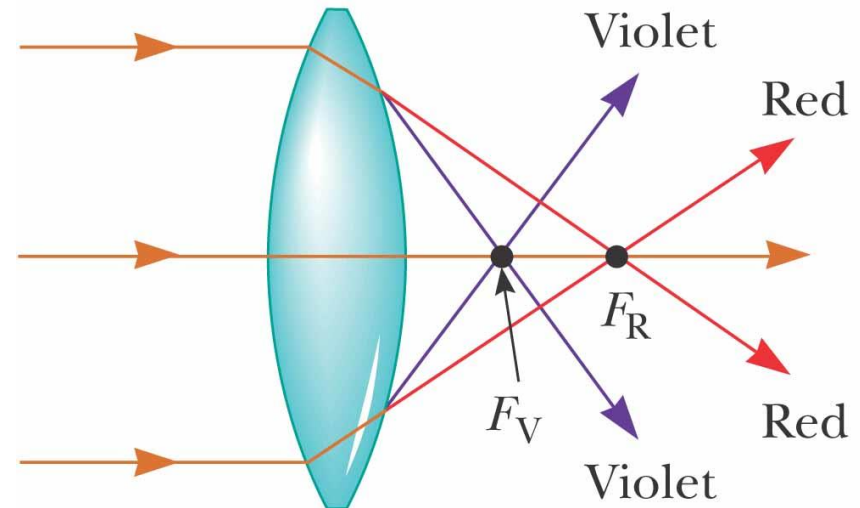
# The Camera

- The photographic camera is a simple optical instrument
- Components
  - Light-tight chamber
  - Converging lens
    - Produces a real image
  - Film behind the lens
    - Receives the image



©2004 Thomson - Brooks/Cole
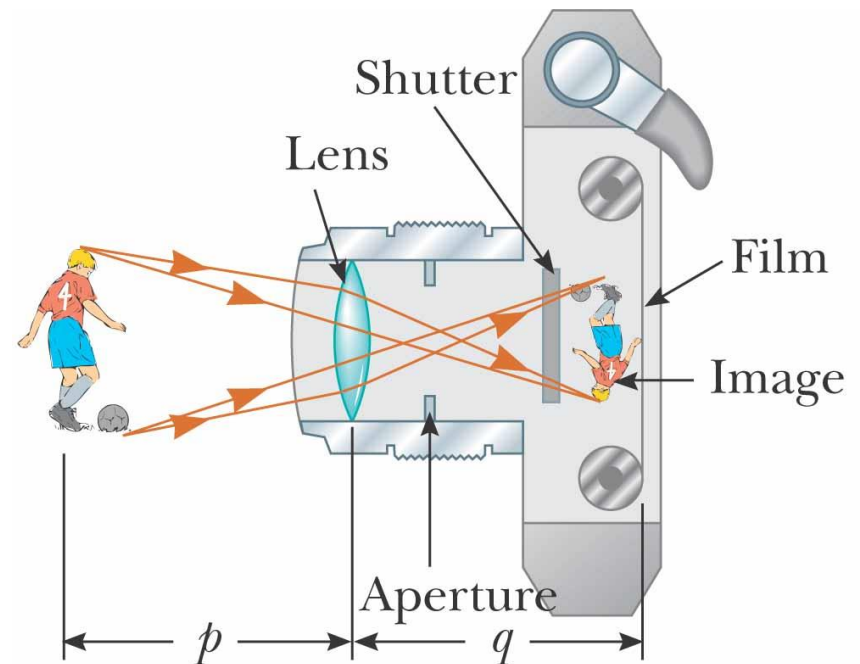
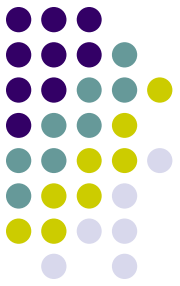# Camera Operation

- Proper focusing will result in sharp images
- The camera is focused by varying the distance between the lens and the film
  - The lens-to-film 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

- Light intensity is a measure of the rate at which energy is received by the film per unit area of the image
  - The intensity of the light reaching the film is proportional to the area of the lens
- The brightness of the image formed on the film 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*-number ≡ *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

- 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
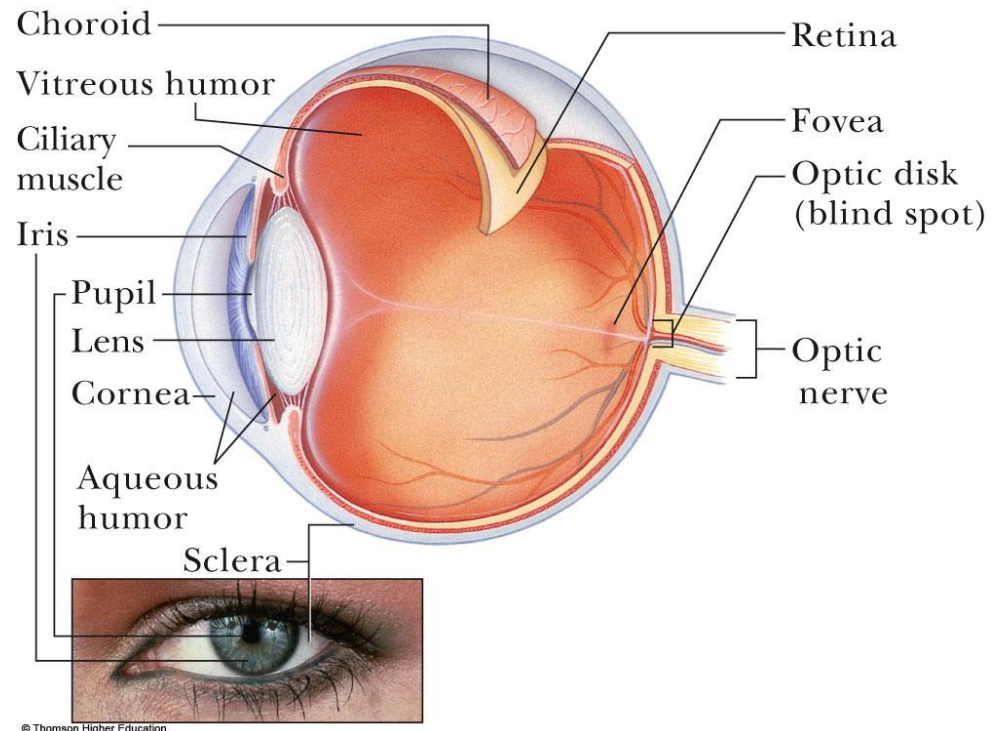    - The camera would not have to be focused for various objects

# Digital Camera

- Digital cameras are similar in operation

- The image does not form on photographic film

- The image does form on a charge-coupled device (CCD)
  - This digitizes the image and turns it into a binary code
  - The digital information can then be stored on a memory chip for later retrieval

# 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



Choroid

Vitreous humor

Ciliary muscle

Iris

Pupil

Lens

Cornea

Aqueous humor

Sclera

Retina

Fovea

Optic disk (blind spot)

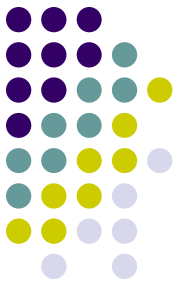Optic nerve

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# **The Eye – Parts, cont.**

- The pupil
  - A variable aperture
  - An opening in the iris
- The crystalline lens
- Most of the refraction takes place at the outer surface of the eye
  - Where the cornea is covered with a film of tears

# The Eye – Close-up of the Cornea
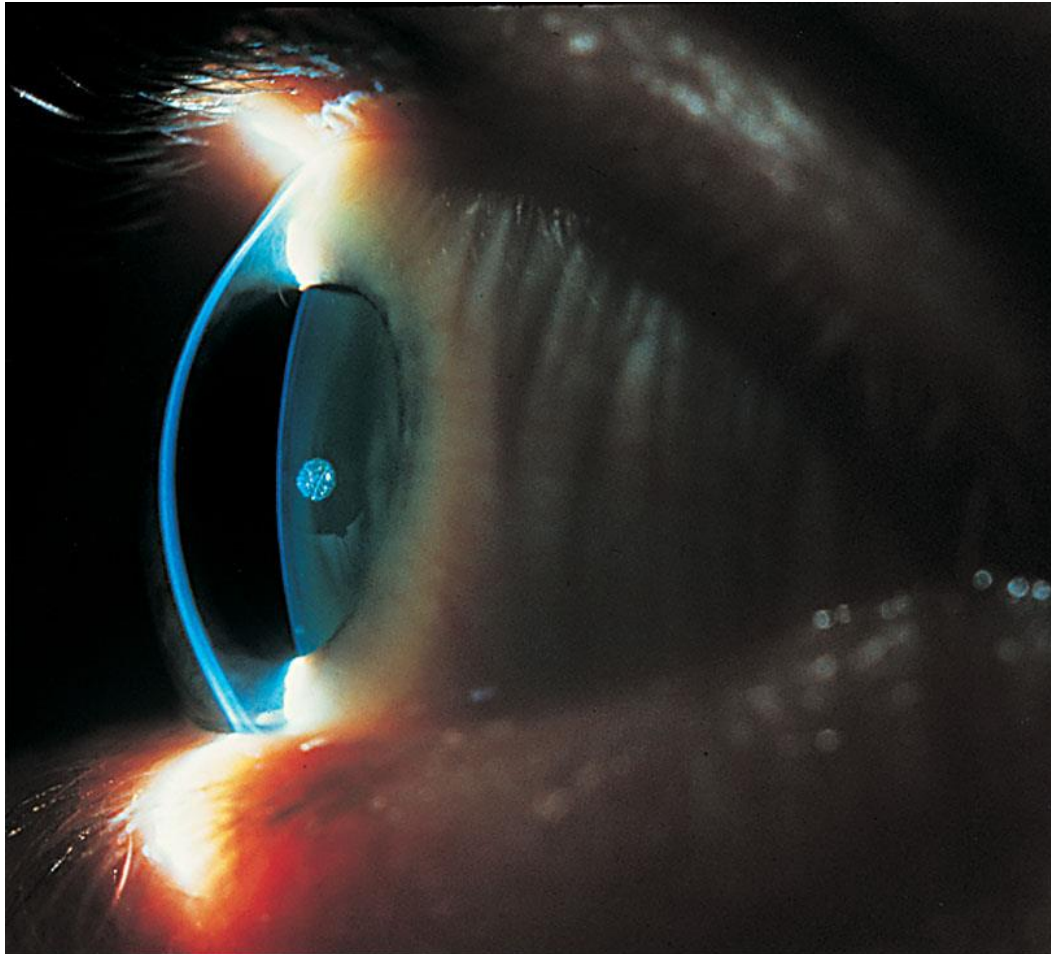


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# The Eye – Parts, final

- 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
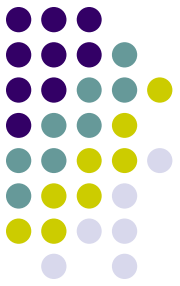
# The Eye – Operation

- 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

# The Eye – Operation, cont.

- 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

- 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

Relative sensitivity

420 nm   534 nm   564 nm

Wavelength
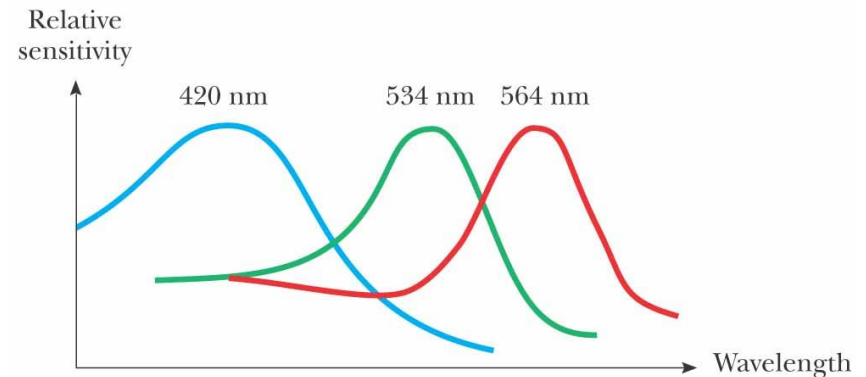
©2004 Thomson - Brooks/Cole

# 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
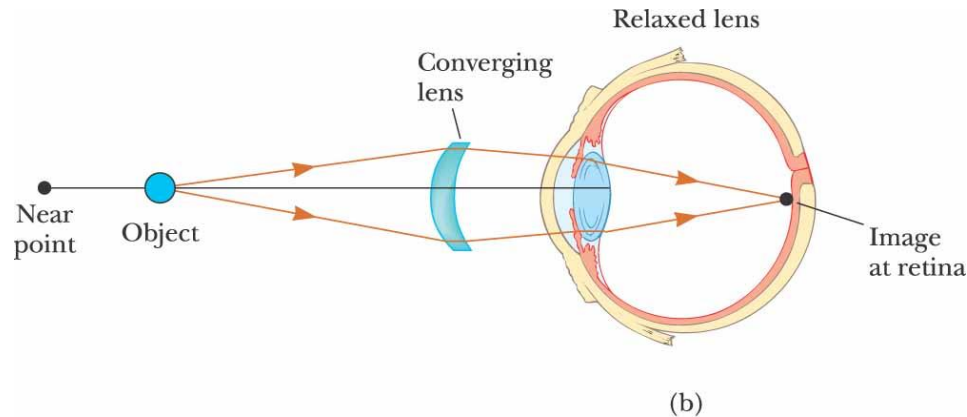    - Person can focus on nearby objects but not those far away

# Farsightedness



Contracted muscle

Near point

Object

Image behind retina

(a)
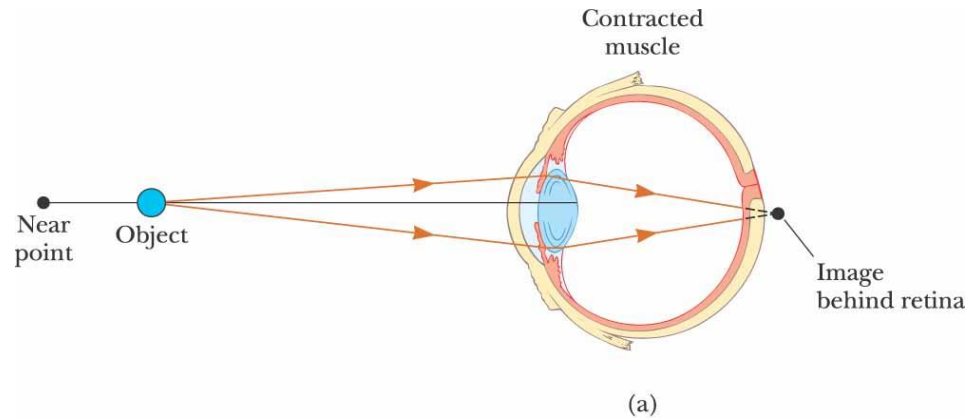
©2004 Thomson - Brooks/Cole

- 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

# Correcting Farsightedness



Relaxed lens
Converging lens
Near point
Object
Image at retina
(b)
©2004 Thomson - Brooks/Cole

- 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**



Relaxed lens

Object    Far point

Image in front of retina

(a)
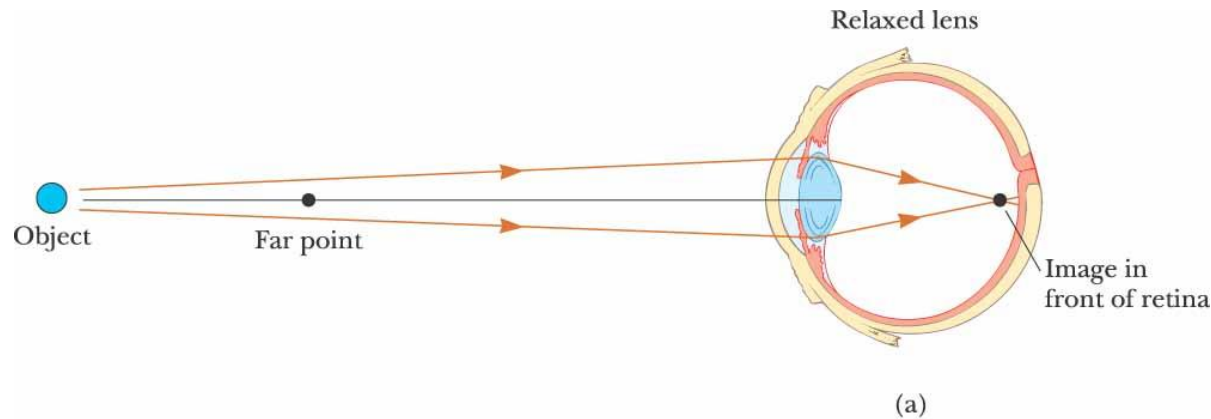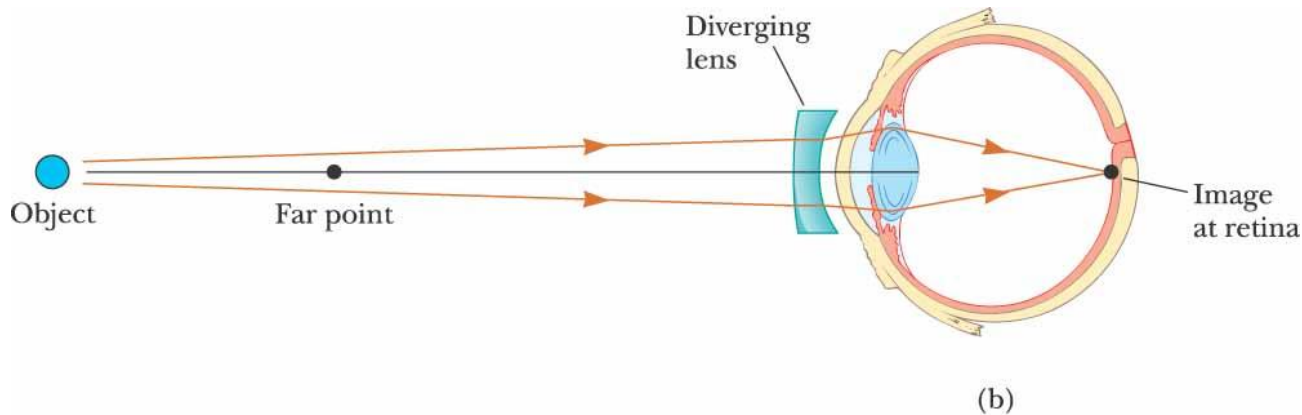
©2004 Thomson - Brooks/Cole

- 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

# Correcting Nearsightedness



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- 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

# 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



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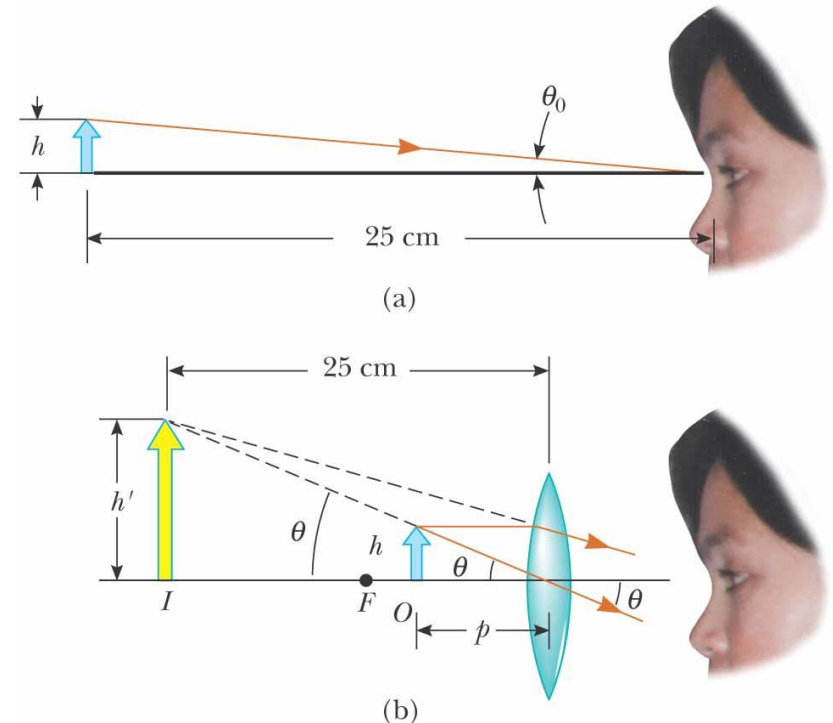
# Angular Magnification

- **Angular magnification** is defined as

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

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

  - q = - 25 cm
  - Calculated by $m_{max} = 1 + \dfrac{25 \text{ cm}}{f}$
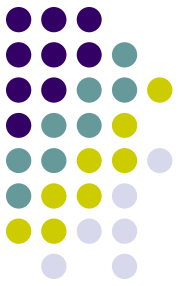
# Angular Magnification, cont.

- 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 $m_{min} = \dfrac{\theta}{\theta_o} = \dfrac{25\ cm}{f}$

# Magnification by a Lens

- 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, $f_o < 1$ cm
  - The eyepiece has a focal length, $f_e$ of a few cm
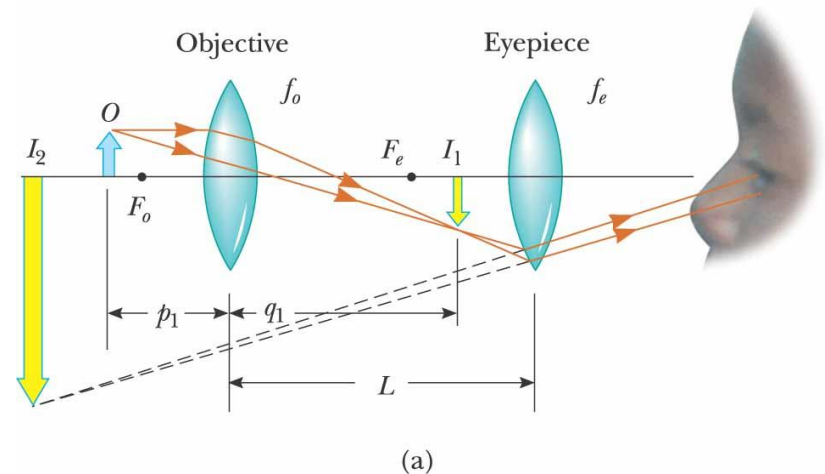


©2004 Thomson - Brooks/Cole
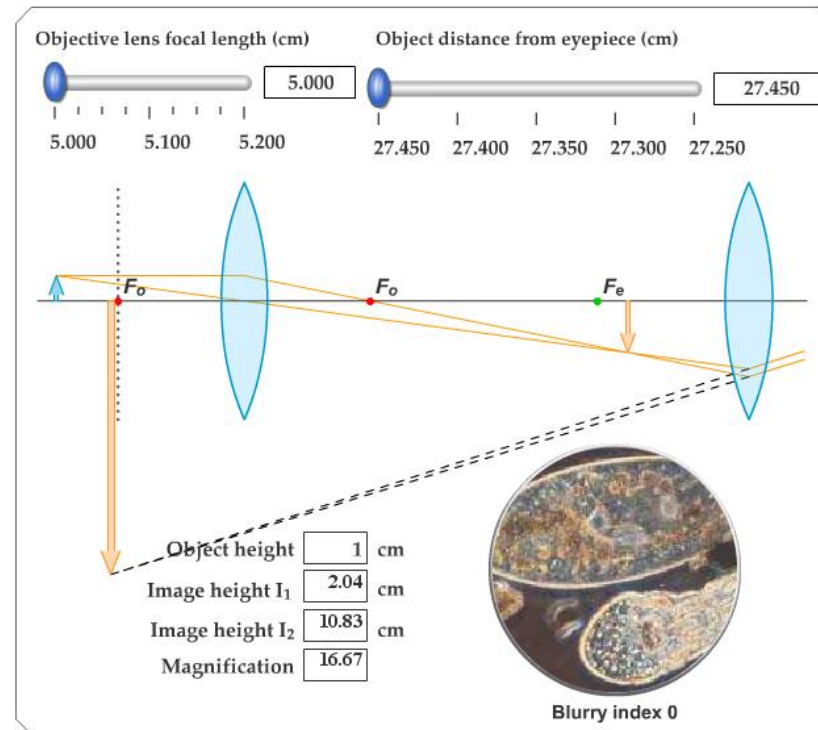
# Compound Microscope, cont.

- 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

# Active Figure 36.41

- Use the active figure to adjust the focal lengths of the objective and eyepiece lenses

- Observe the effect on the final image



**PLAY
ACTIVE FIGURE**

# 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
  - $m_e = 25\ cm / f_e$
- The overall magnification of the microscope is the product of the individual magnifications

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

# 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 nm) with visible light ($\lambda \approx$ 500 nm)
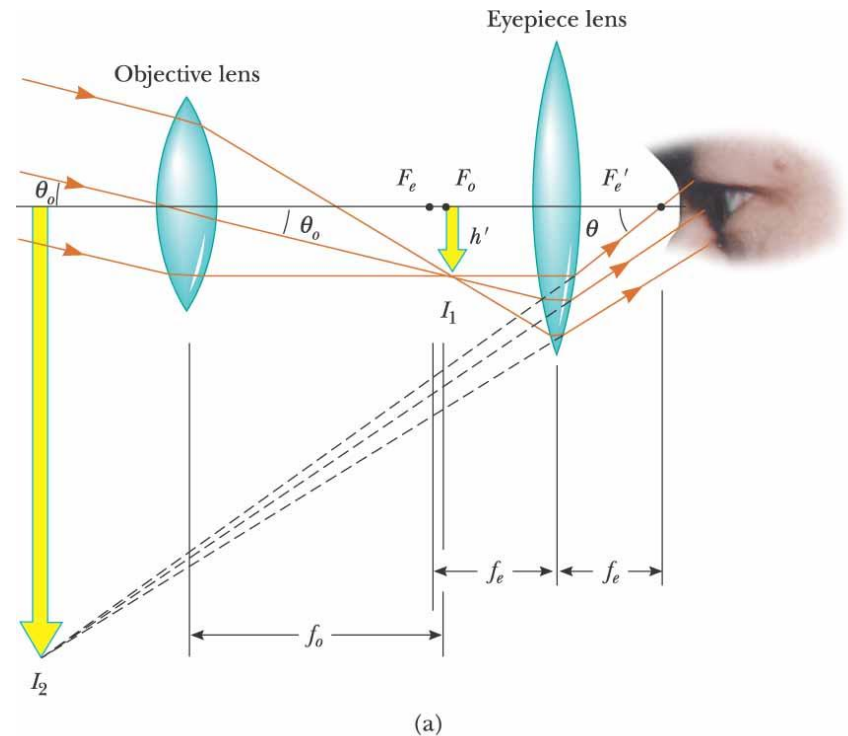
# Telescopes

- 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
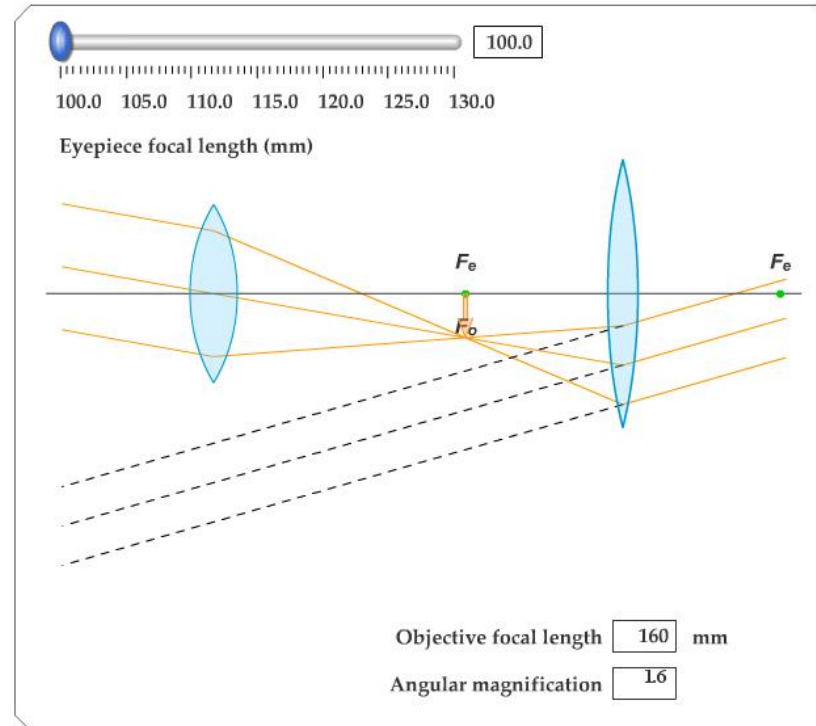- The eyepiece forms an enlarged, inverted image of the first image



Eyepiece lens

Objective lens

©2004 Thomson - Brooks/Cole
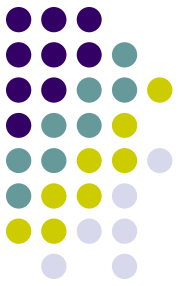
# Active Figure 36.42

- Use the active figure to adjust the focal lengths of the objective and eyepiece lenses
- Observe the effects on the image



**PLAY ACTIVE FIGURE**

# 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*



A •

M

Eyepiece

Parabolic mirror

(a)

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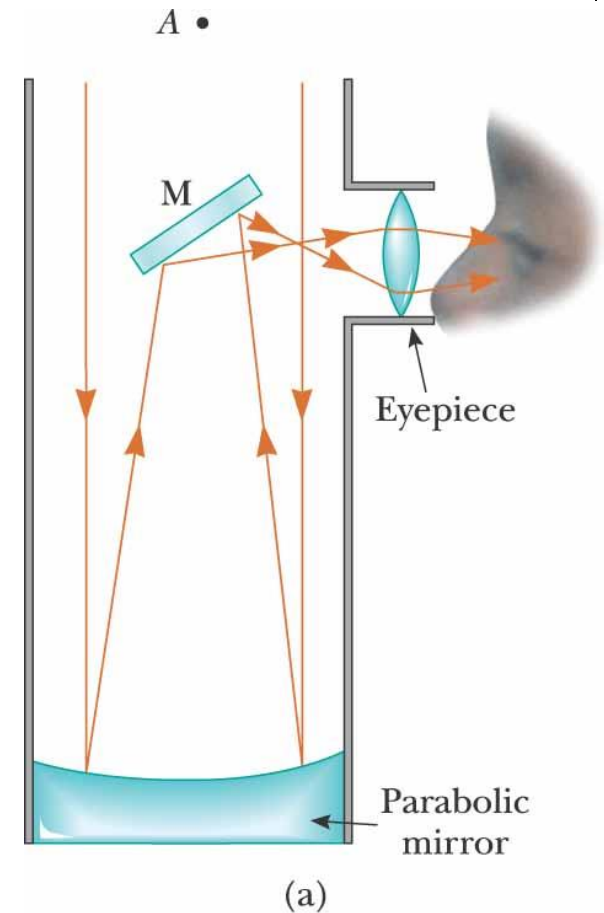
# **Examples of Telescopes**

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