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

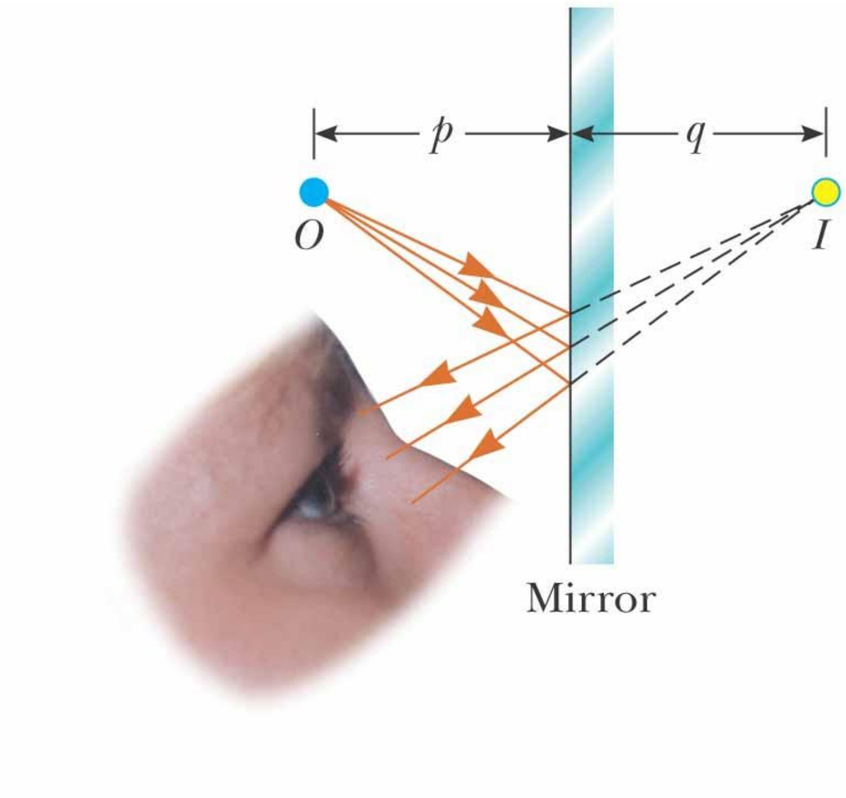
- Images are always located by extending diverging rays back to a point at which they intersect
- Images are located either at a point from which the rays of light *actually* diverge or at a point from which they *appear* to diverge

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

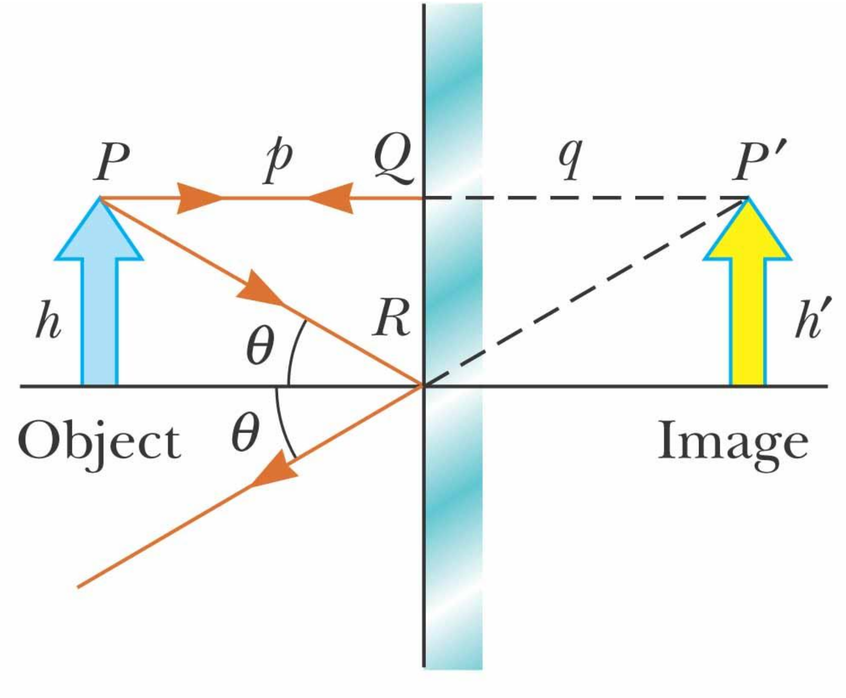


Images Formed by Flat Mirrors, 2

- 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

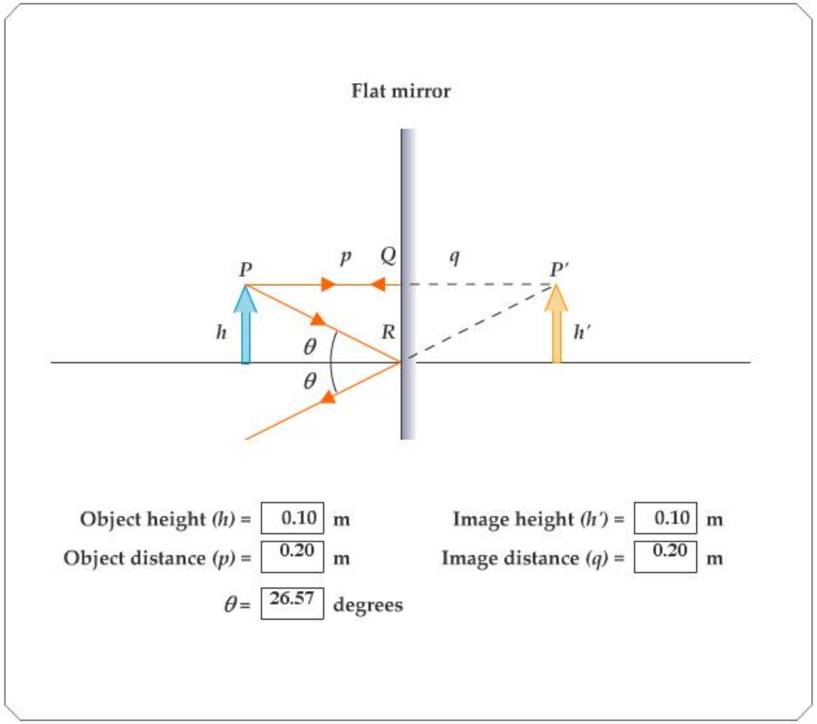
Images Formed by Flat Mirrors, 3

- 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



Active Figure 36.2

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



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

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

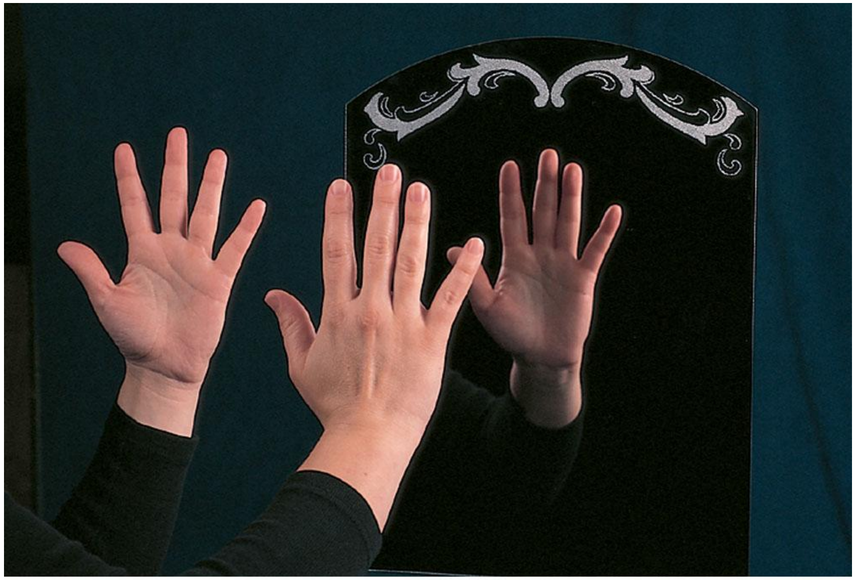
  - This is the general magnification for any type of mirror
  - It is also valid for images formed by lenses
  - Magnification does not always mean bigger, the size can either increase or decrease
    - M can be less than or greater than 1

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



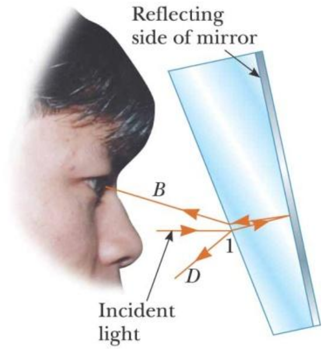
Reversals, cont.

- 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

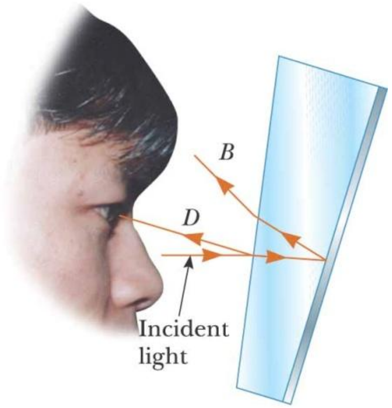
- The image is as far behind the mirror as the object is in front
  - $|p| = |q|$
- The image is unmagnified
  - The image height is the same as the object height
    - $h' = h$ and $M = +1$
- The image is virtual
- The image is upright
  - It has the same orientation as the object
- There is a front-back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

Application – Day and Night Settings on Auto Mirrors



Daytime setting

(a)



Nighttime setting

(b)

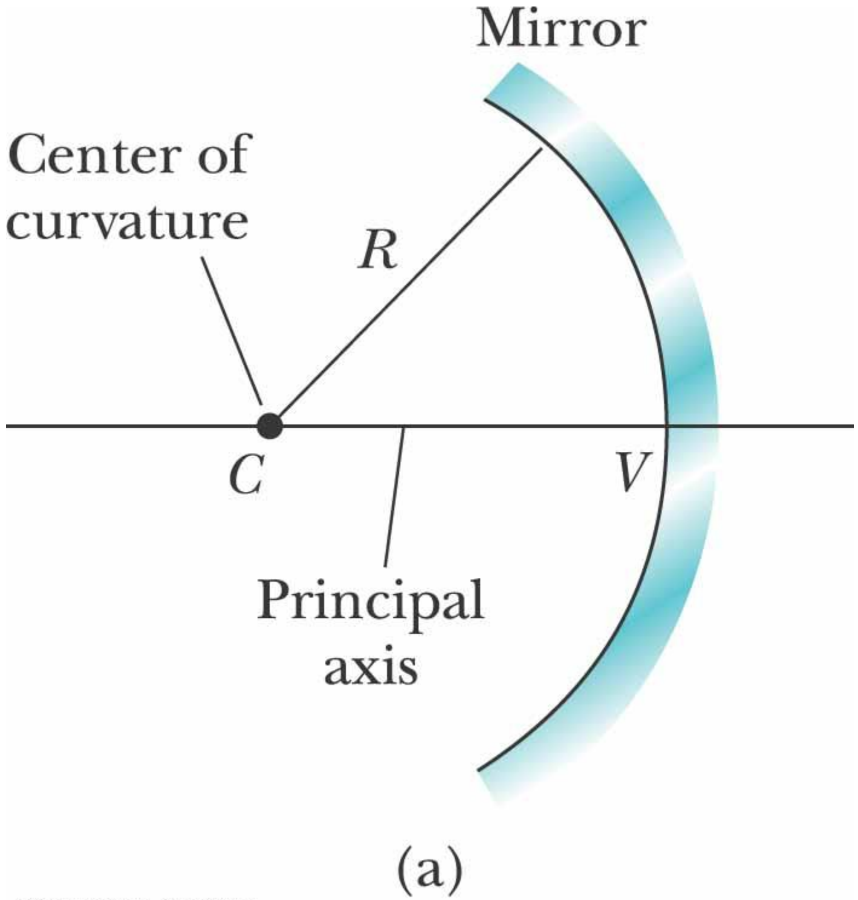
- With the daytime setting, the bright beam (B) of reflected light is directed into the driver's eyes
- With the nighttime setting, the dim beam (D) of reflected light is directed into the driver's eyes, while the bright beam goes elsewhere

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



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**

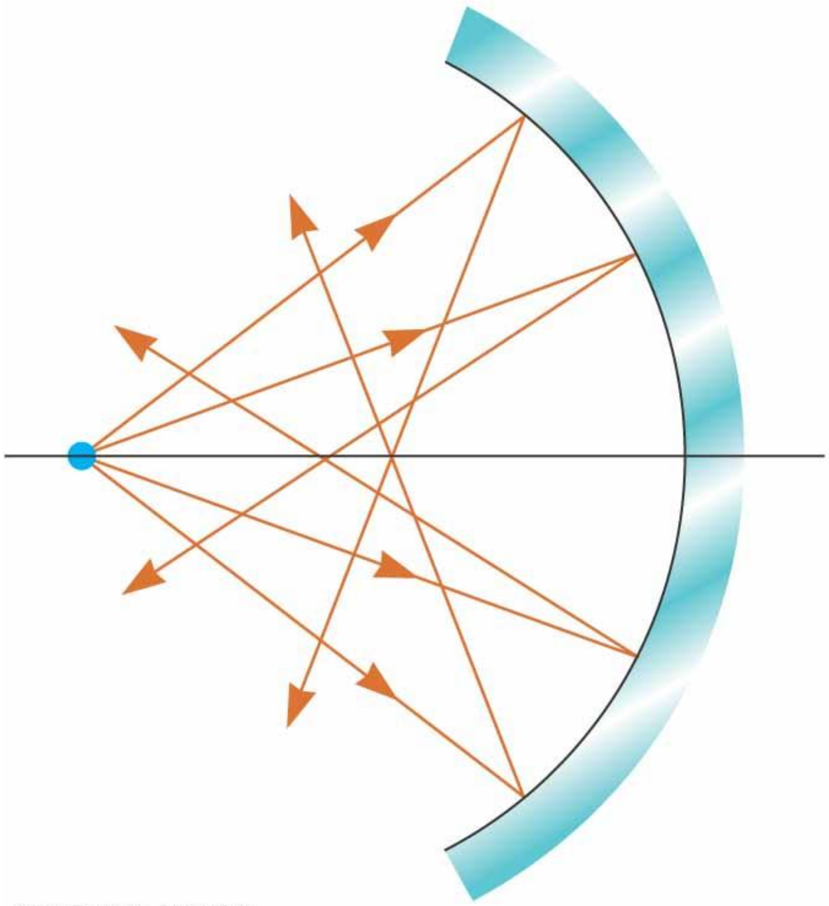


Image Formed by a Concave Mirror

- 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

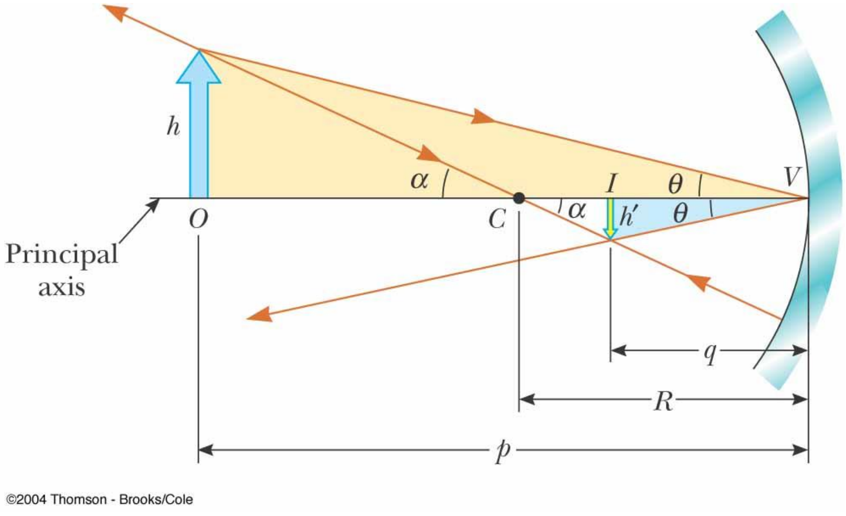


Image Formed by a Concave Mirror

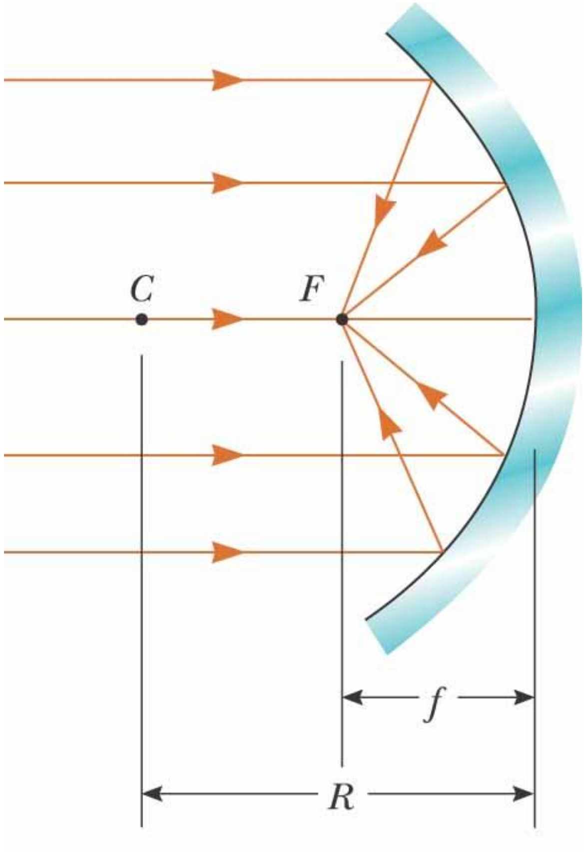
- Geometry also shows the relationship between the image and object distances

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

  - 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

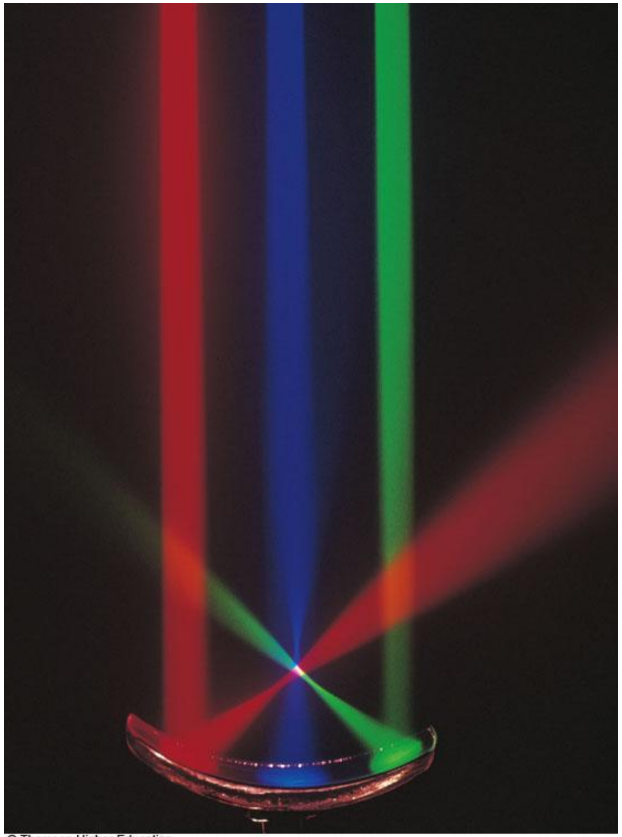
- When the object is very far away, then p → ∞ and the incoming rays are essentially parallel
- In this special case, the image point is called the **focal point**
- The distance from the mirror to the focal point is called the **focal length**
  - The focal length is ½ the radius of curvature



(a)

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

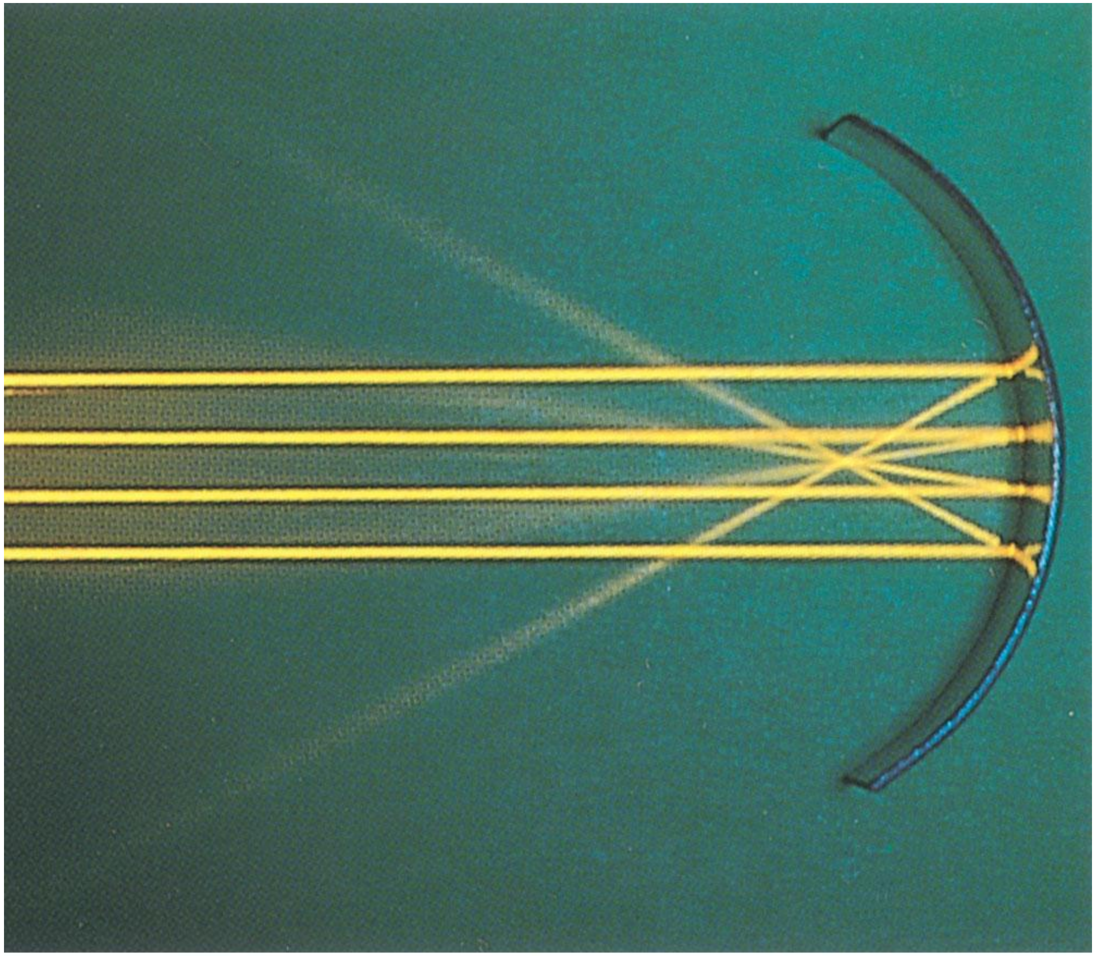


Focal Point and Focal Length, cont.

- 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

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

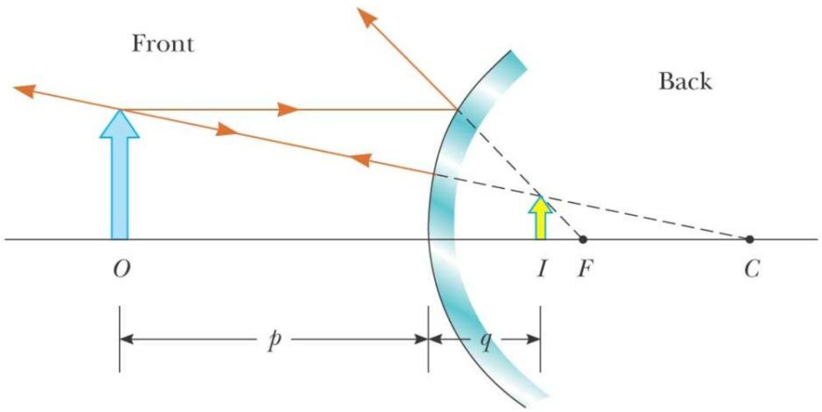
Focal Length Shown by Parallel Rays



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

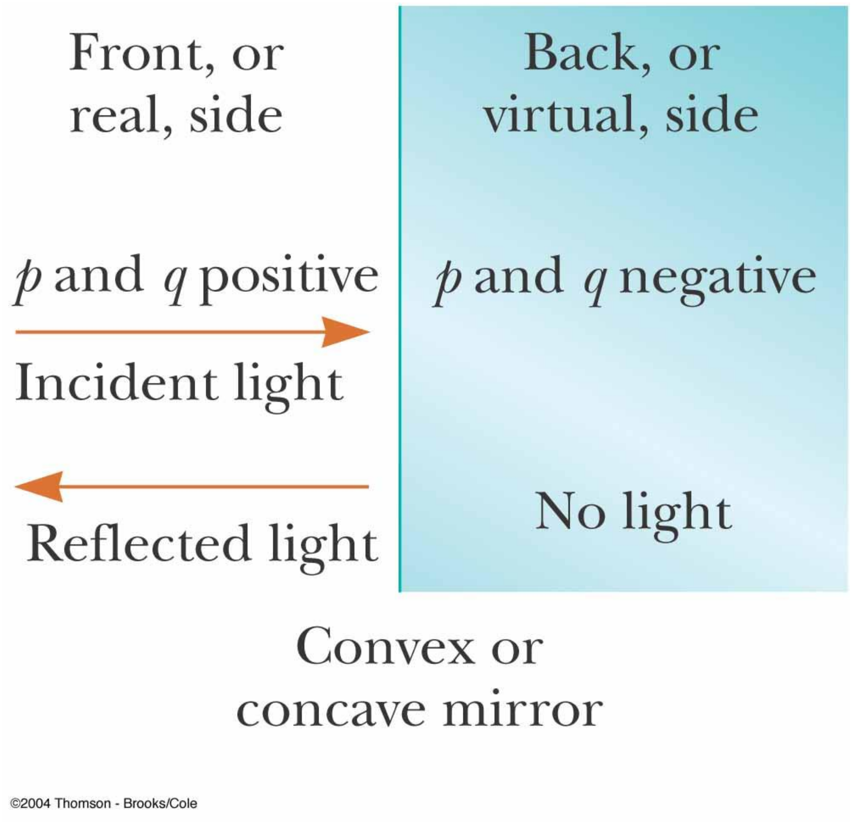
Image Formed by a Convex Mirror



- 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



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

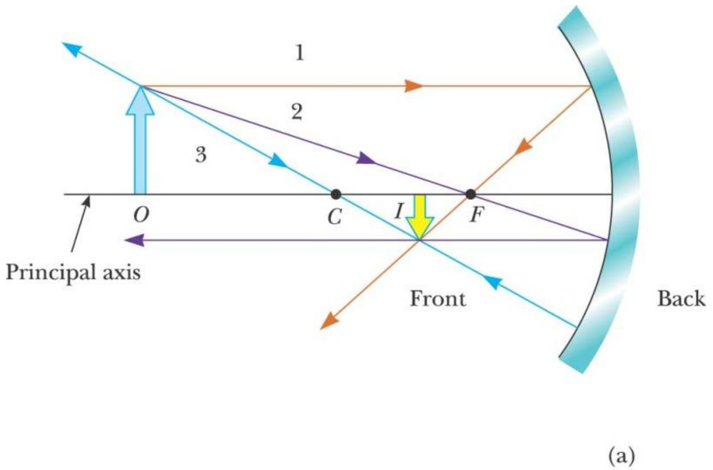
The Rays in a Ray Diagram – Concave Mirrors

- 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

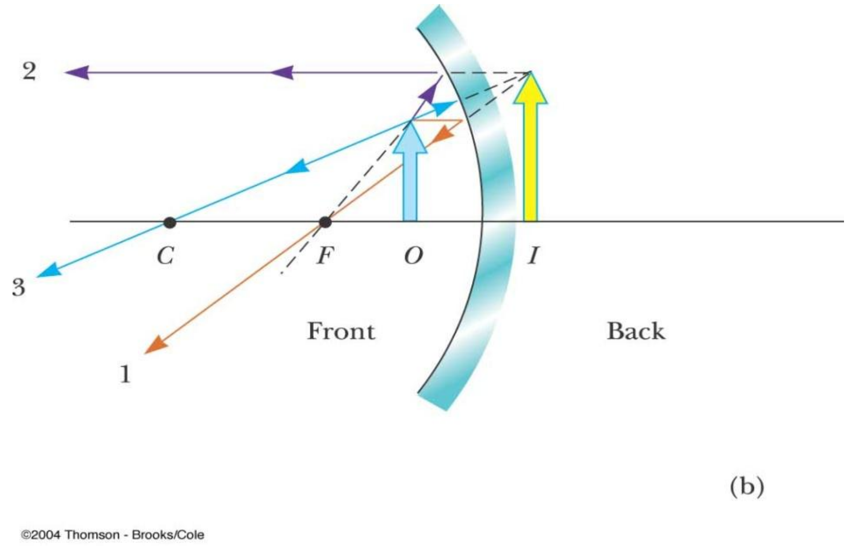
- The rays actually go in all directions from the object
- The three rays were chosen for their ease of construction
- The image point obtained by the ray diagram must agree with the value of q calculated from the mirror equation

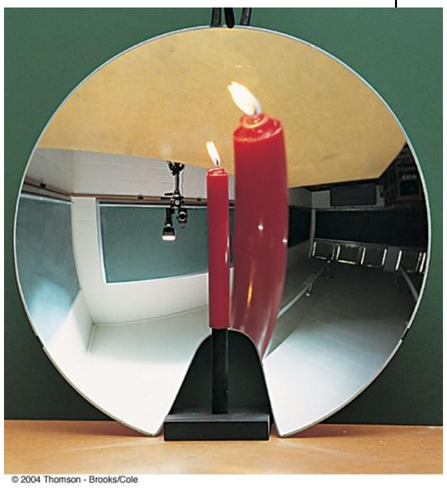
Ray Diagram for a Concave Mirror, p > R



- 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, $p < f$



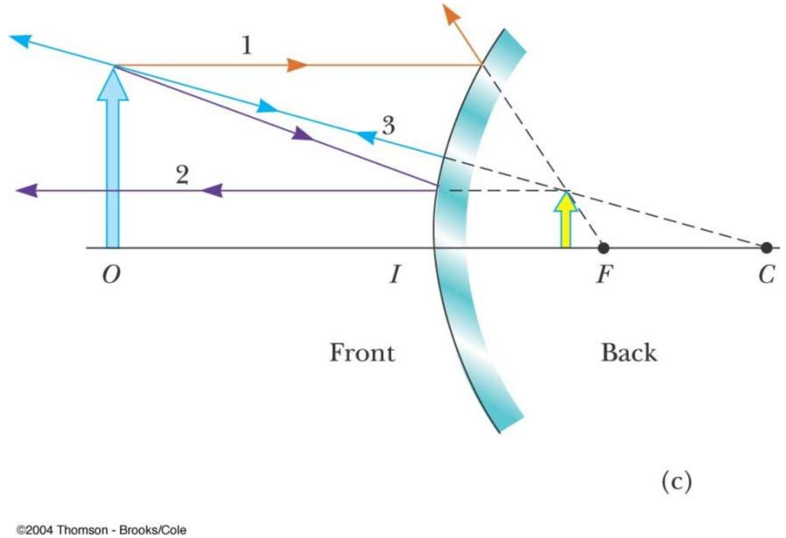


- The object is between the mirror surface and the focal point
- The image is virtual
- The image is upright
- The image is larger than the object (enlarged)

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

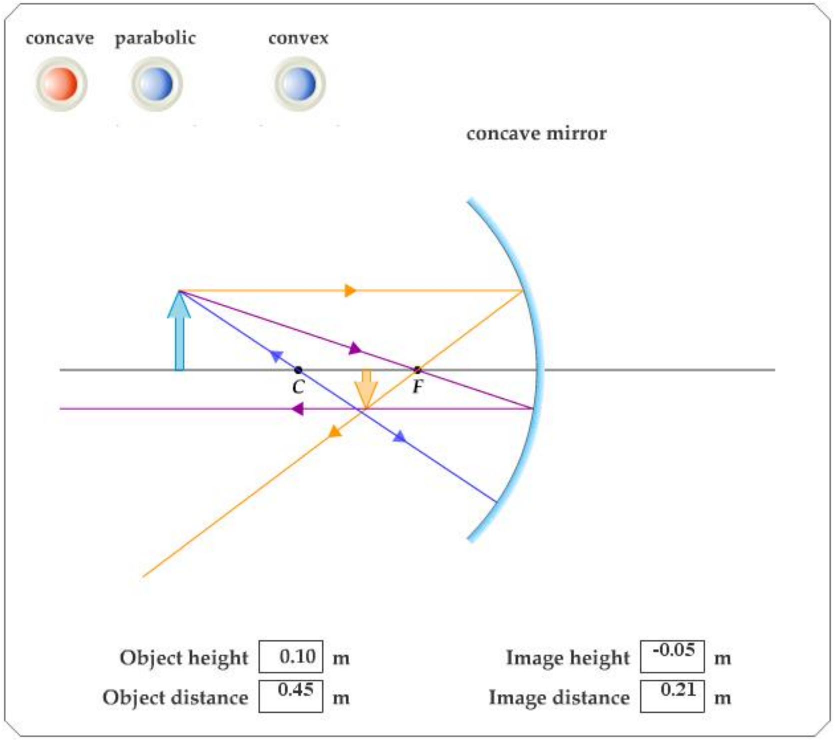
Ray Diagram for a Convex Mirror



- 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)

Active Figure 36.13

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



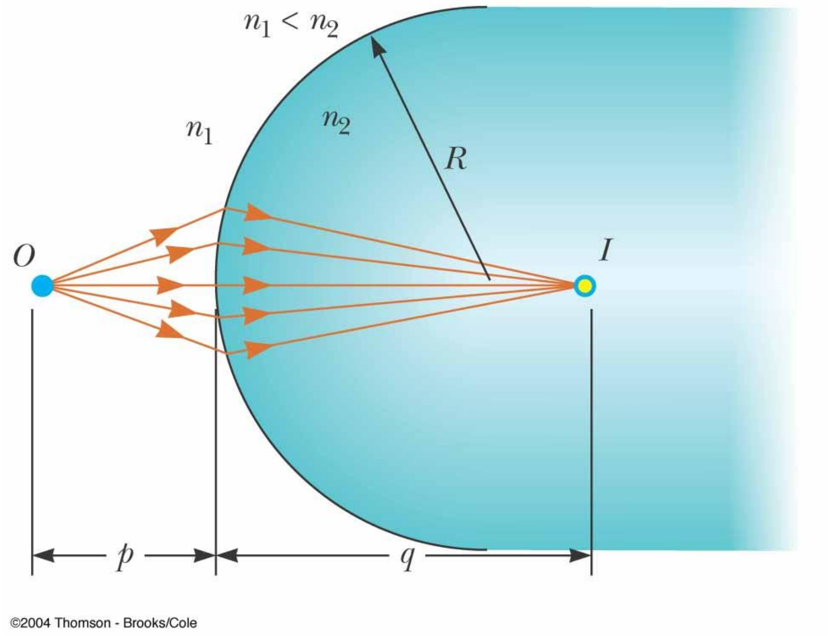
PLAY ACTIVE FIGURE

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 $n = n_1$



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

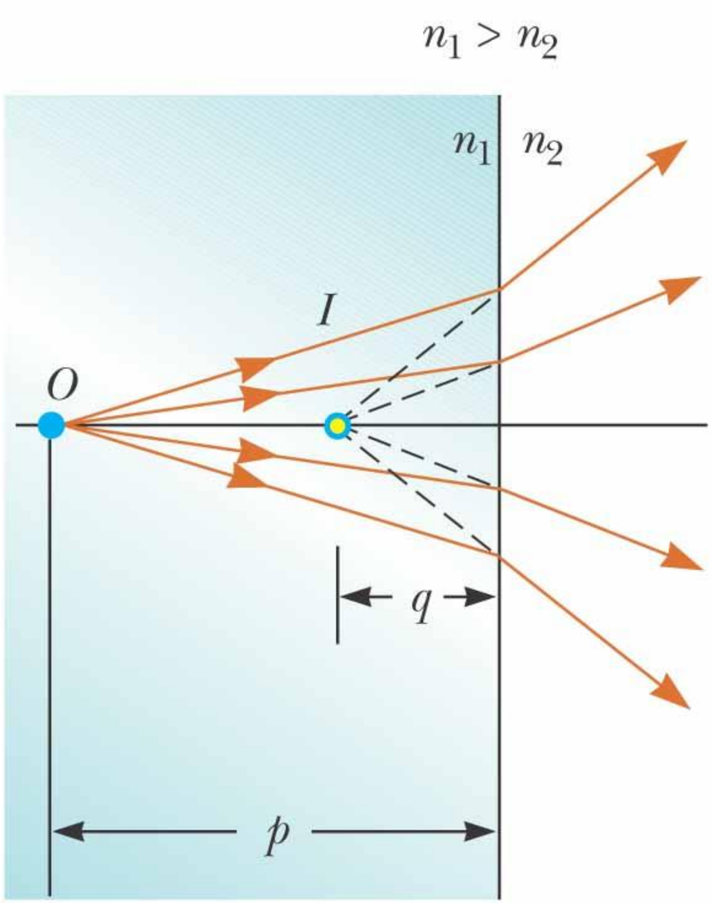
TABLE 36.2

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.

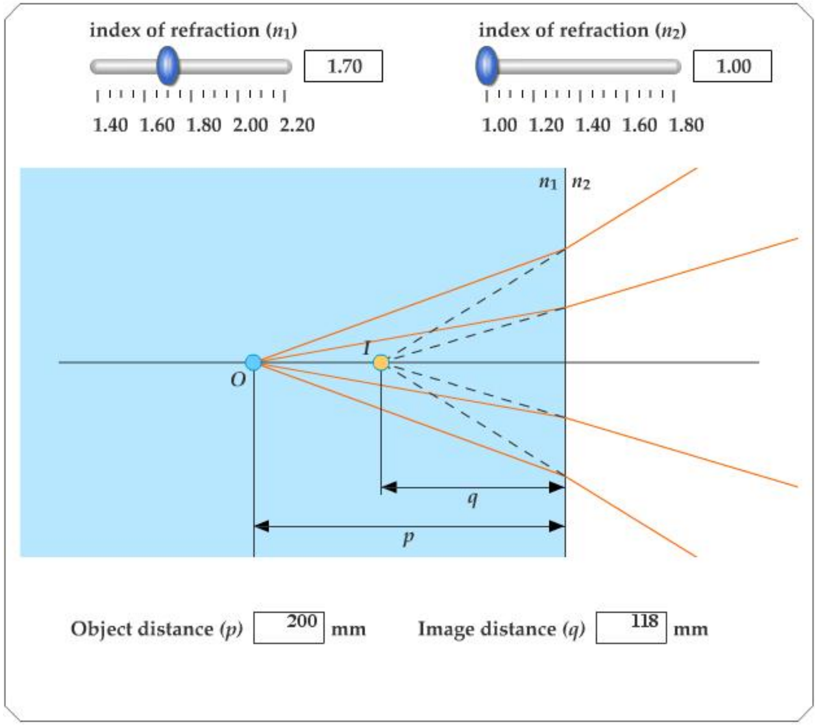
Flat Refracting Surfaces

- 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



Active Figure 36.18

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



PLAY ACTIVE FIGURE

Lenses

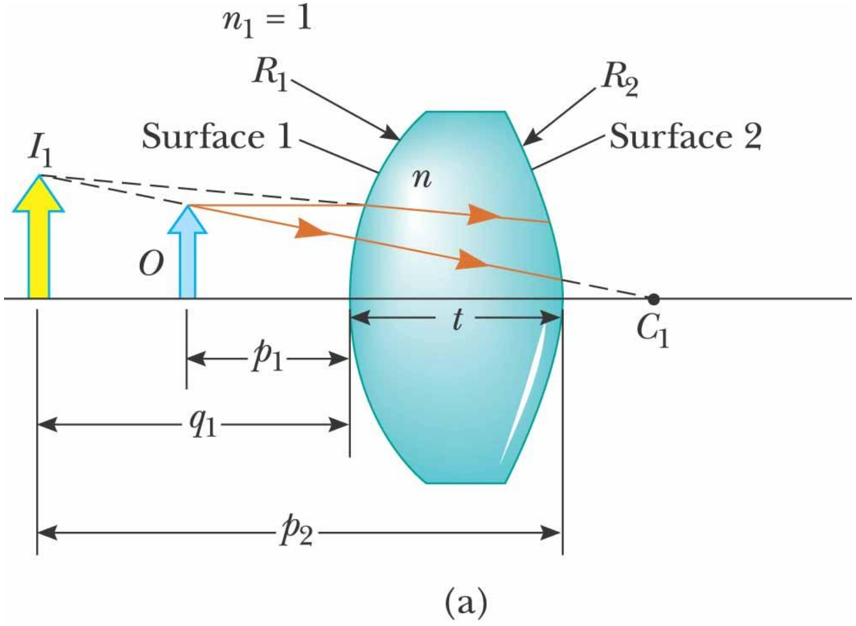
- Lenses are commonly used to form images by refraction
- Lenses are used in optical instruments
  - Cameras
  - Telescopes
  - Microscopes

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



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

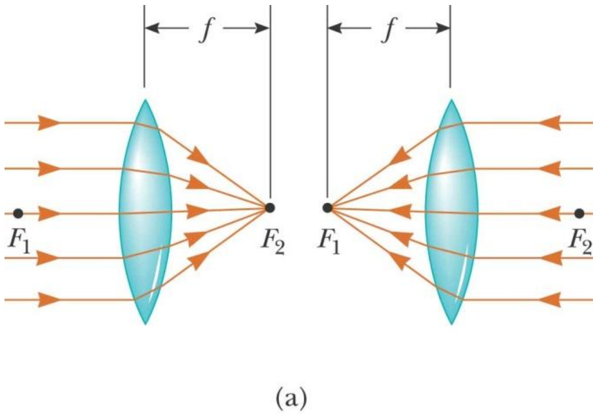
- The relationship among the focal length, the object distance and the image distance is the same as for a mirror

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

Notes on Focal Length and Focal Point of a Thin Lens

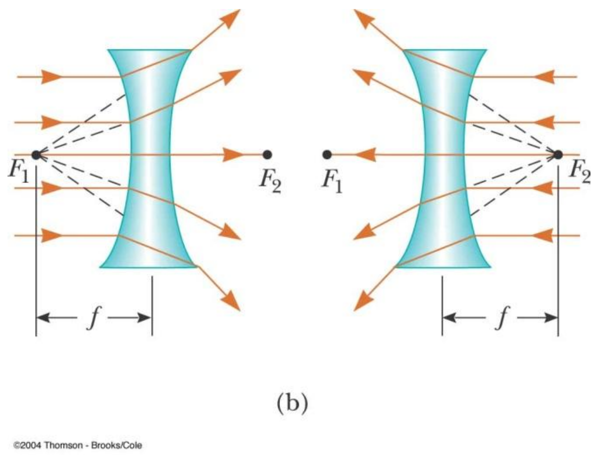
- Because light can travel in either direction through a lens, each lens has two focal points
  - One focal point is for light passing in one direction through the lens and one is for light traveling in the opposite direction
- However, there is only one focal length
- Each focal point is located the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

Focal Length of a Converging Lens



- 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

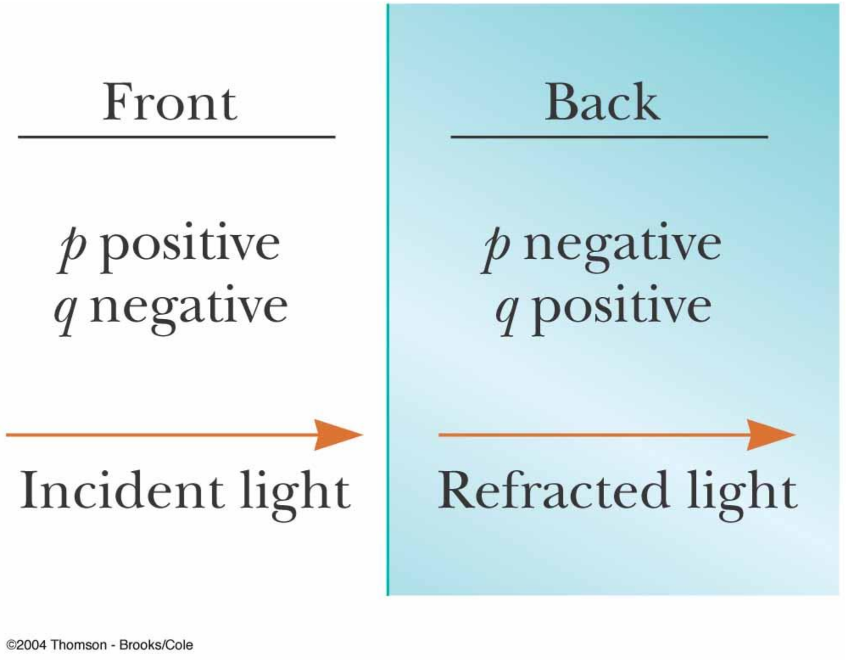
Focal Length of a Diverging Lens



- 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

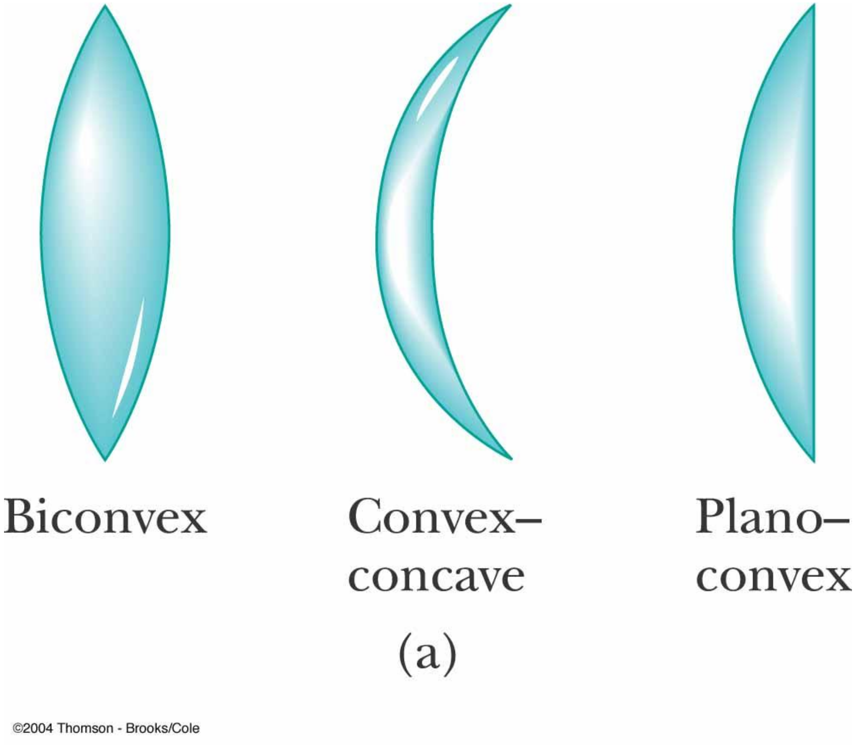
- The lateral magnification of the image is

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

- 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

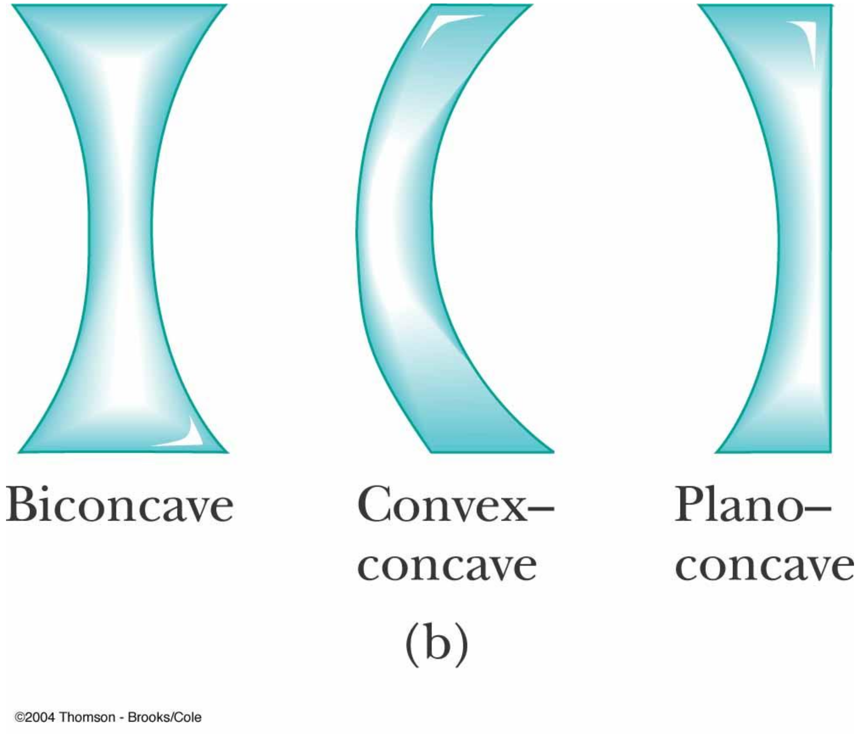
Thin Lens Shapes

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



More Thin Lens Shapes

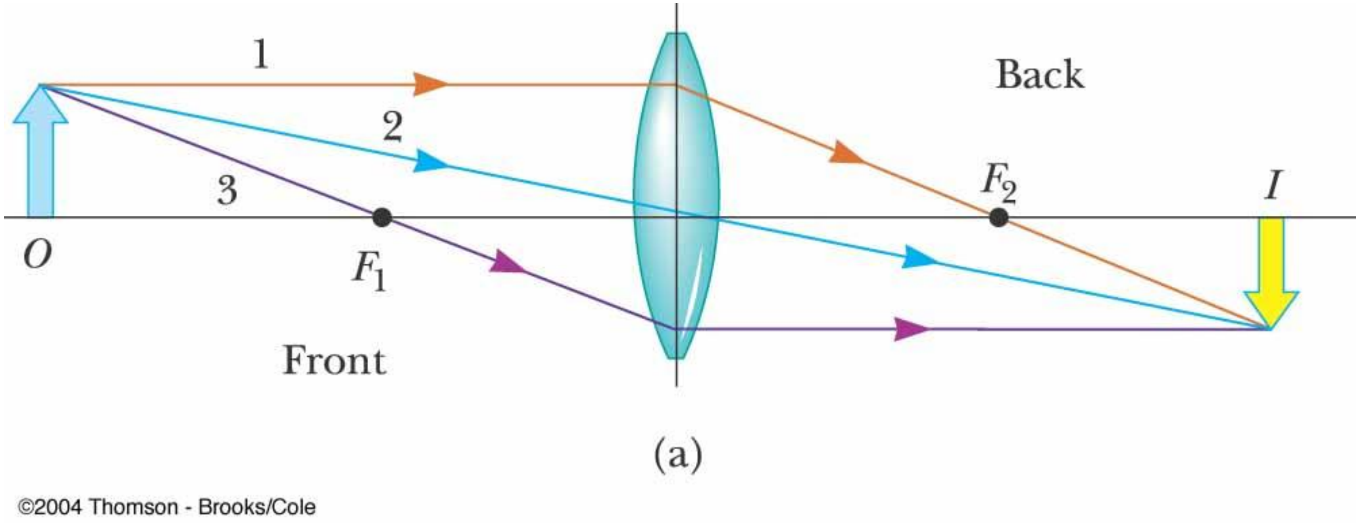
- These are examples of *diverging* lenses
- They have negative focal lengths
- They are thickest at the edges



Ray Diagrams for Thin Lenses – Converging

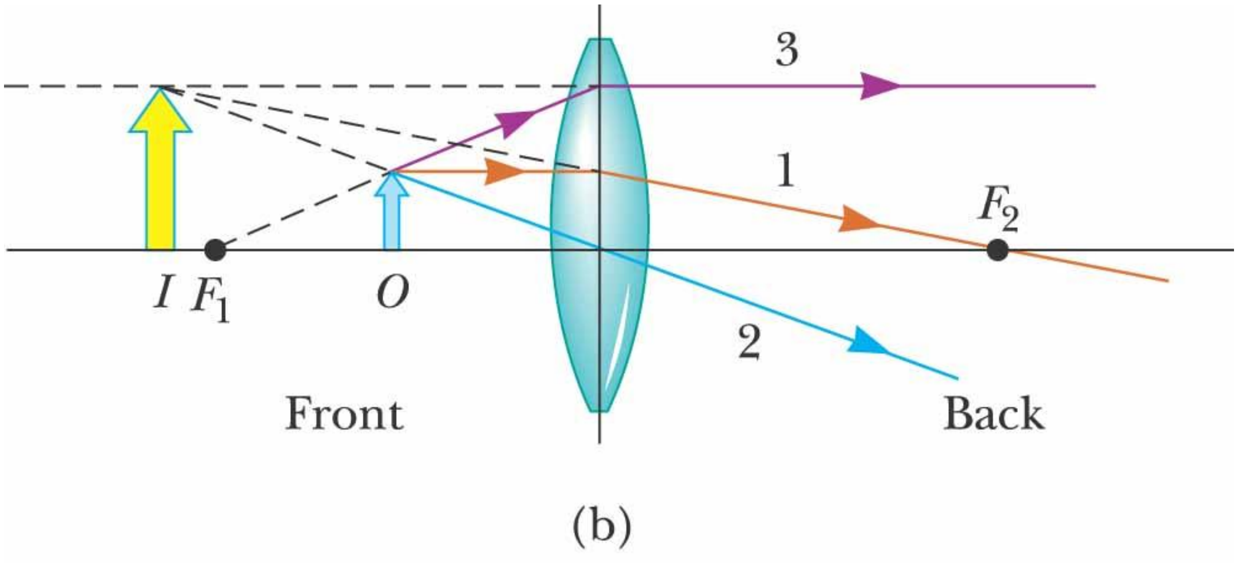
- Ray diagrams are convenient for locating the images formed by thin lenses or systems of lenses
- For a converging lens, the following three rays are drawn:
  - Ray 1 is drawn parallel to the principal axis and then passes through the focal point on the back side of the lens
  - Ray 2 is drawn through 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*



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

Ray Diagram for Converging Lens, $p < f$

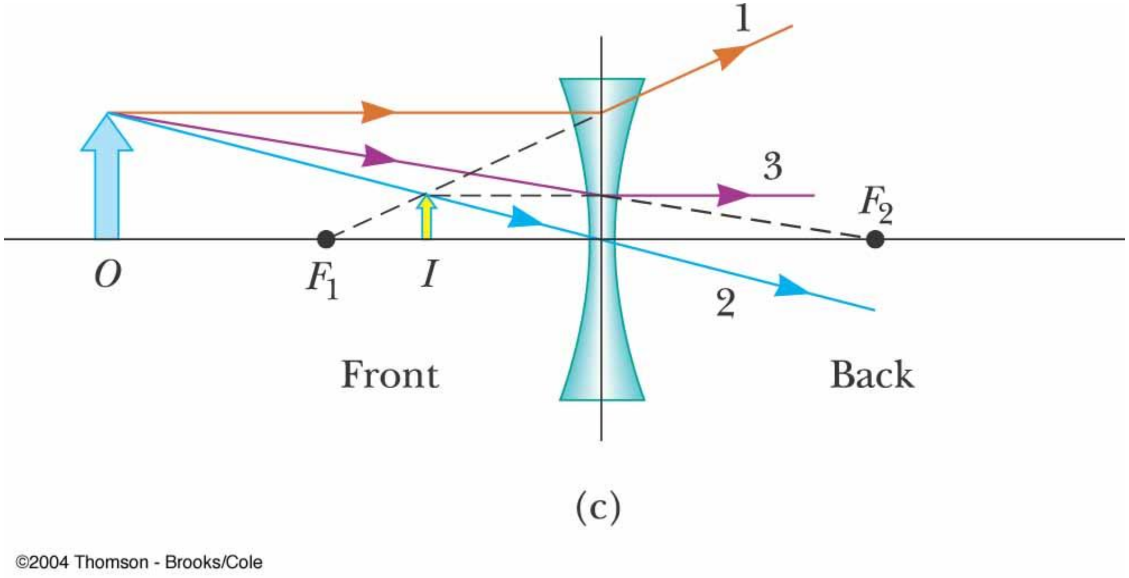


- The image is virtual
- The image is upright
- The image is larger than the object
- The image is on the front side of the lens

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

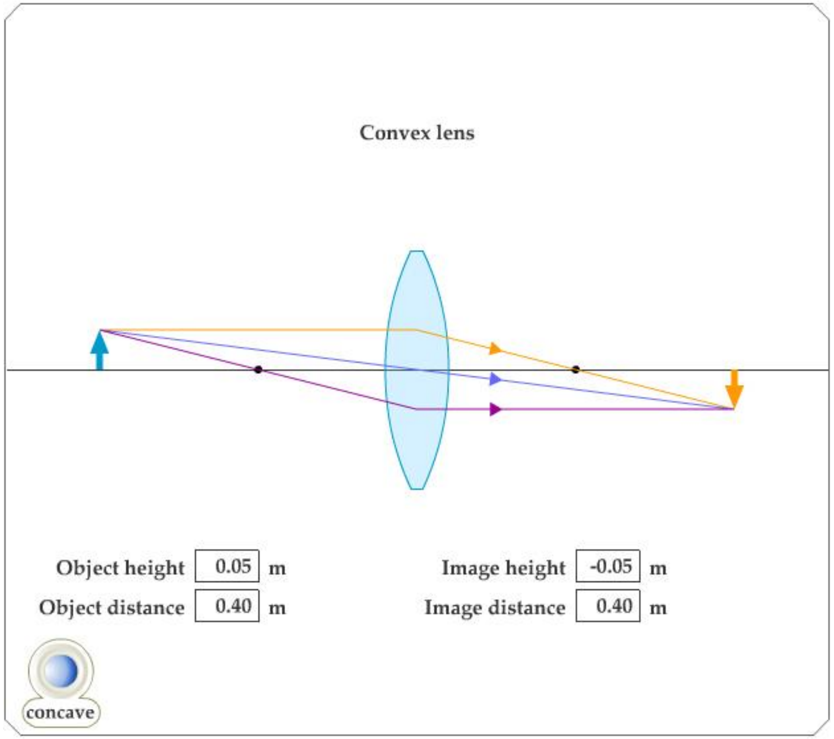
Ray Diagram for Diverging Lens



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

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



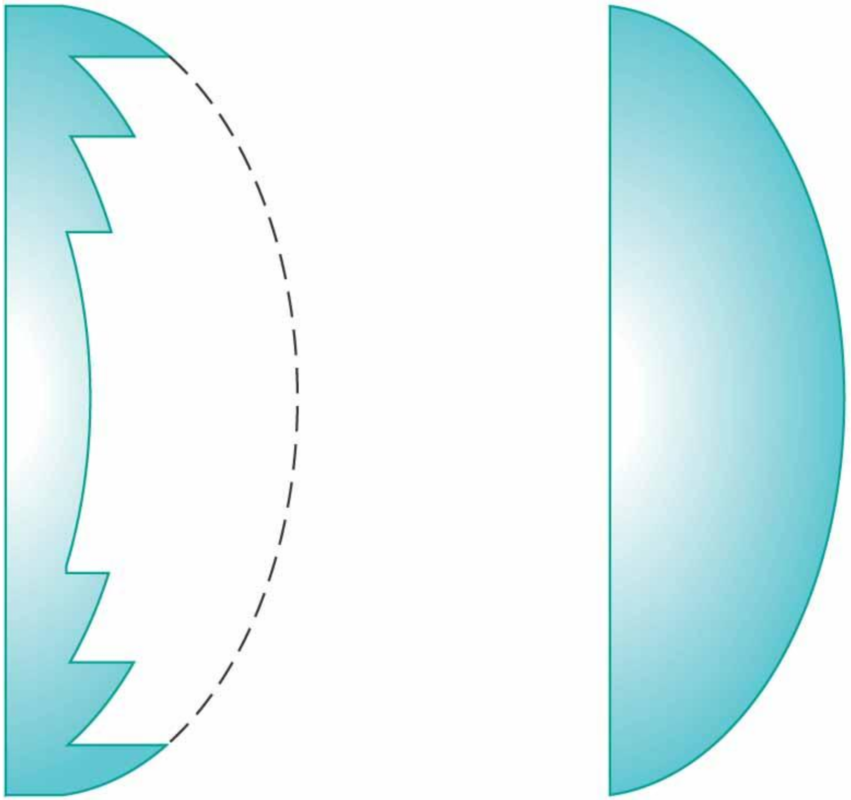
PLAY ACTIVE FIGURE

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



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,

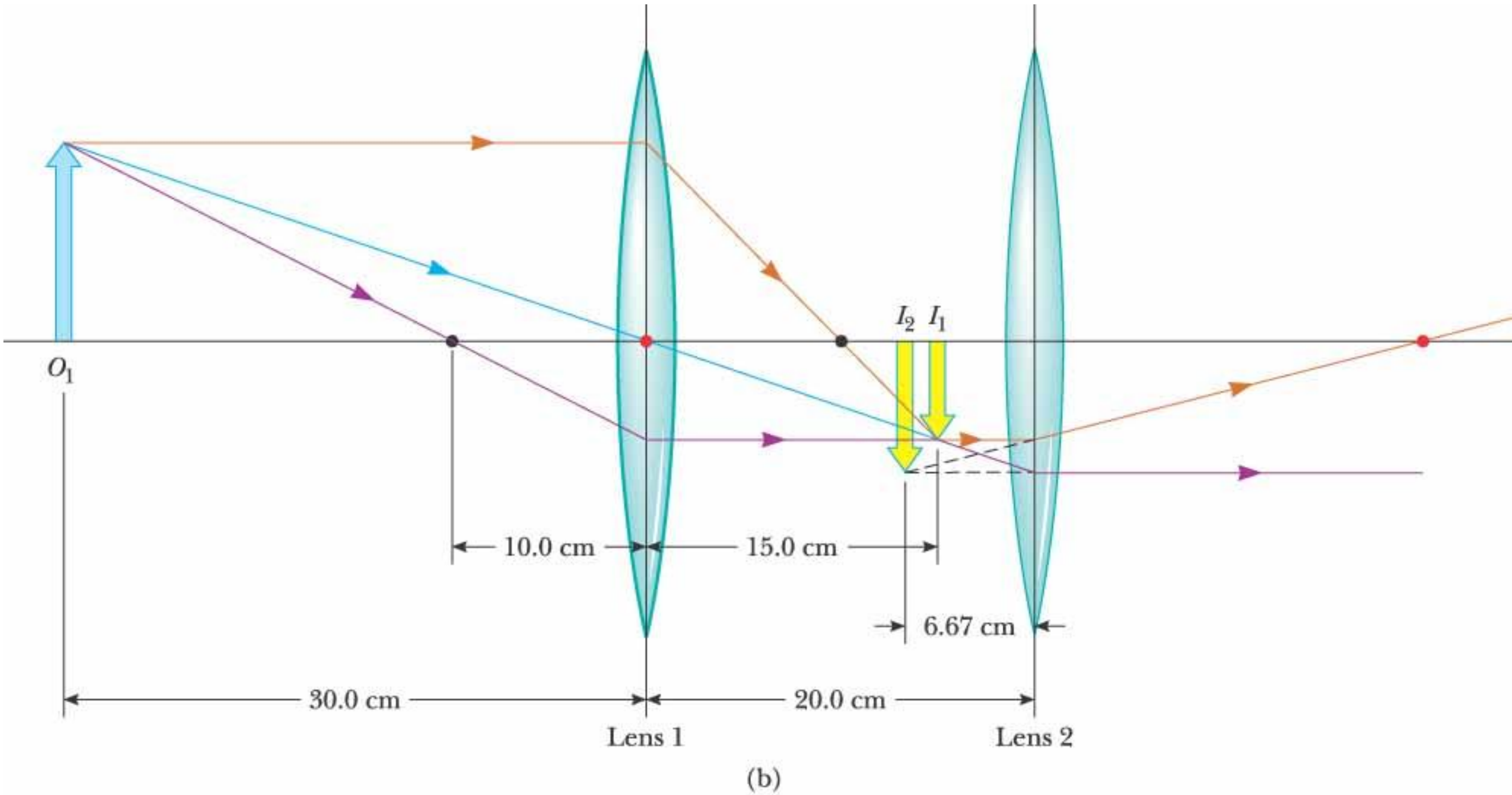
$$\frac{1}{p_2}+\frac{1}{q_2}=\frac{1}{f_2}=-\frac{1}{q_1}+\frac{1}{q}$$

- 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



Combination of Thin Lenses, example

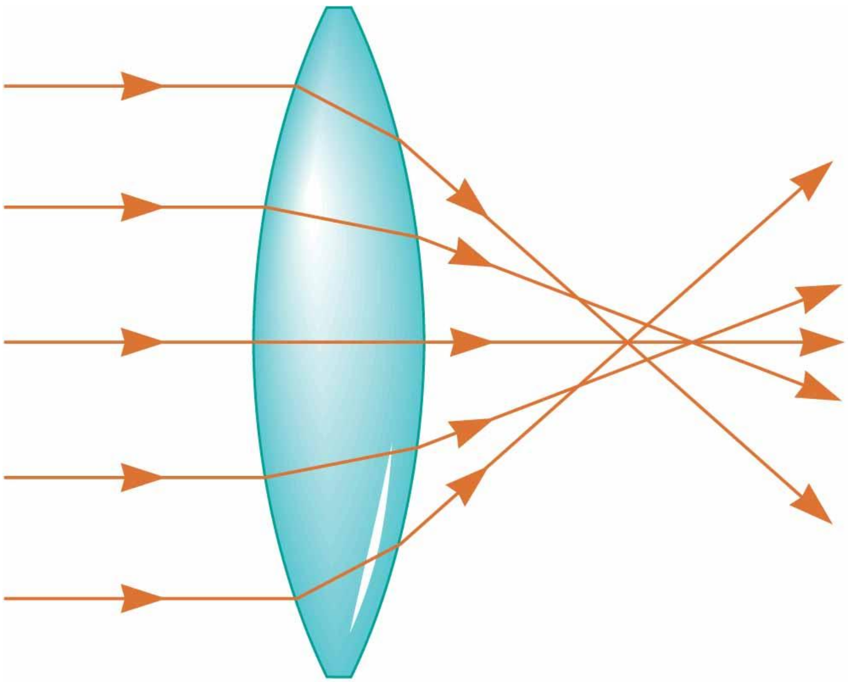
- Find the location of the image formed by lens 1
- Find the magnification of the image due to lens 1
- Find the object distance for the second lens
- Find the location of the image formed by lens 2
- Find the magnification of the image due to lens 2
- Find the overall magnification of the system

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**

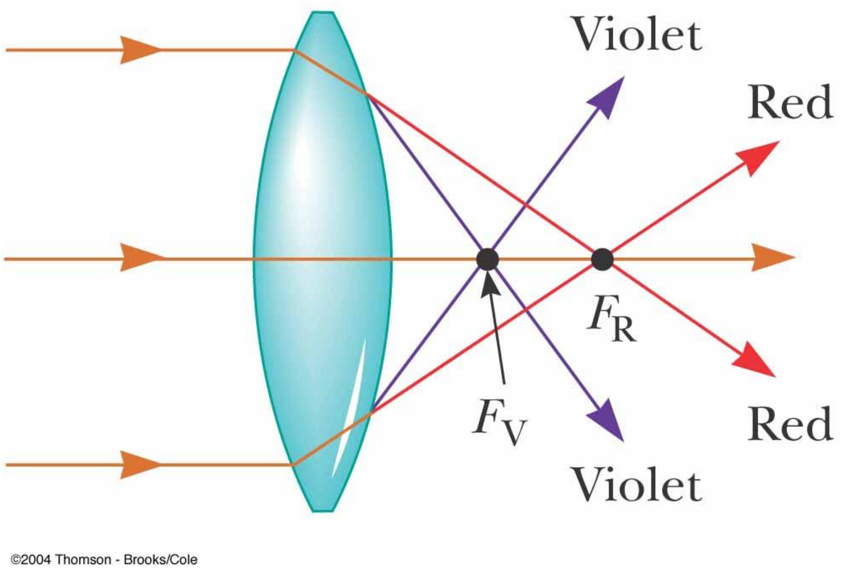
Spherical Aberration

- 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



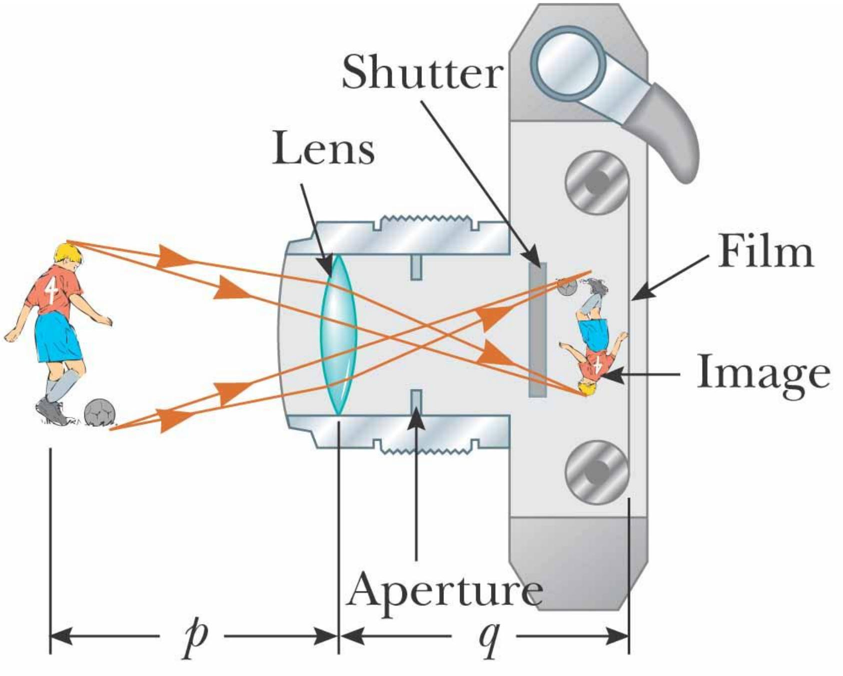
Chromatic Aberration

- 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



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



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 *ƒ*-number to the next higher value decreases the area of the aperture by a factor of 2
- The lowest *ƒ*-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 *ƒ*-number of about 11
  - Most cameras with variable *ƒ*-numbers adjust them automatically

Camera, Depth of Field

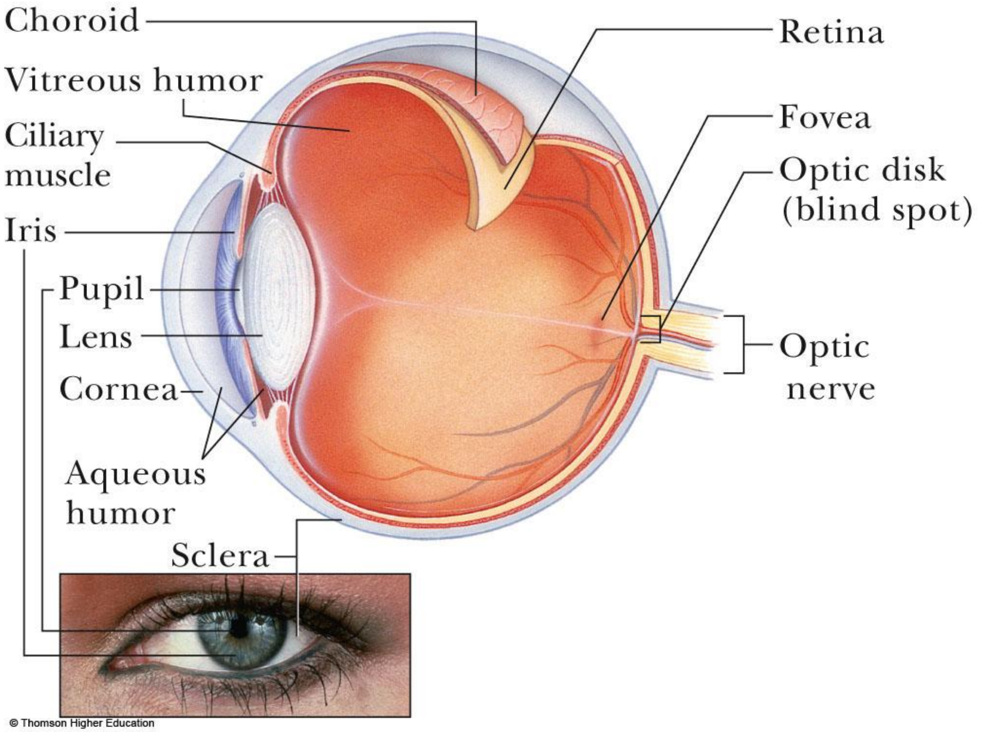
- A high value for the *f*-number allows for a large depth of field
  - This means that objects at a wide range of distances from the lens form reasonably sharp images on the film
  - The camera would not have to be focused for various objects

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

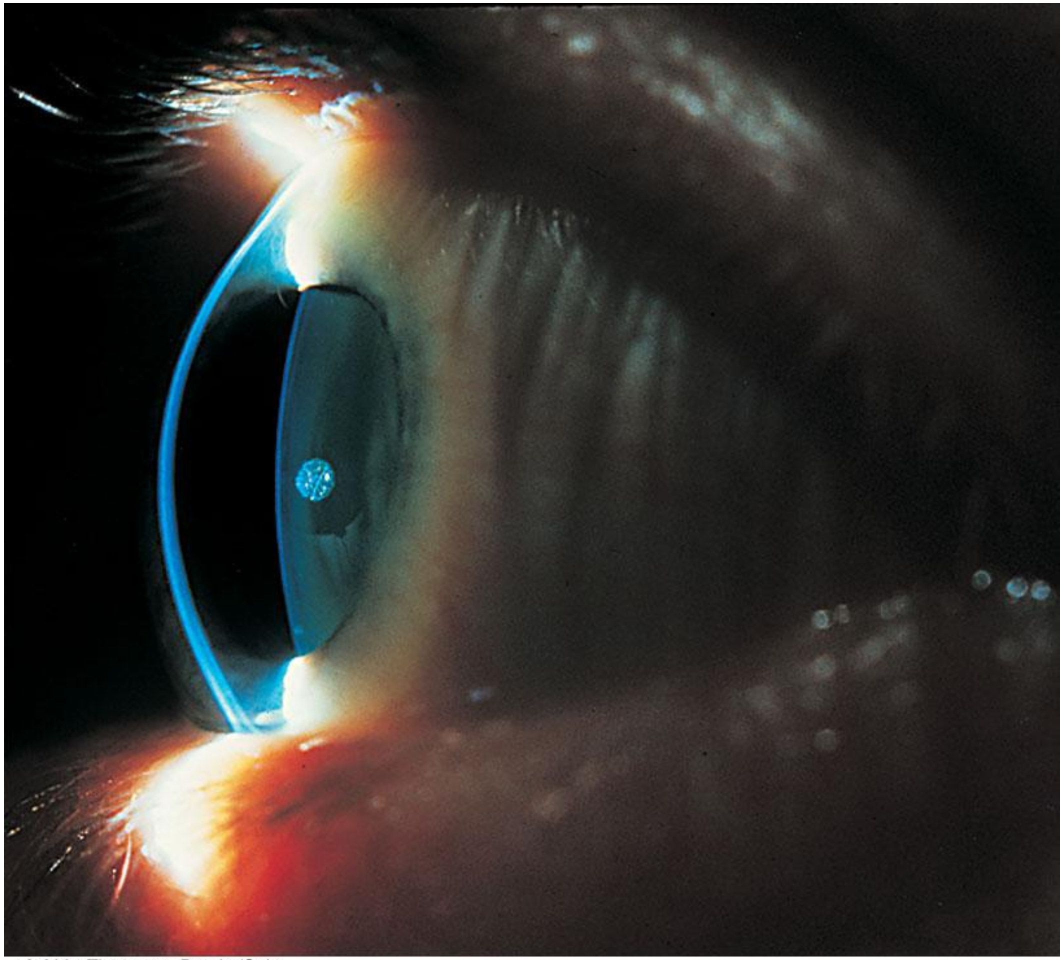
- The normal eye focuses light and produces a sharp image
- Essential parts of the eye:
  - Cornea – light passes through this transparent structure
  - Aqueous Humor – clear liquid behind the cornea



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



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.

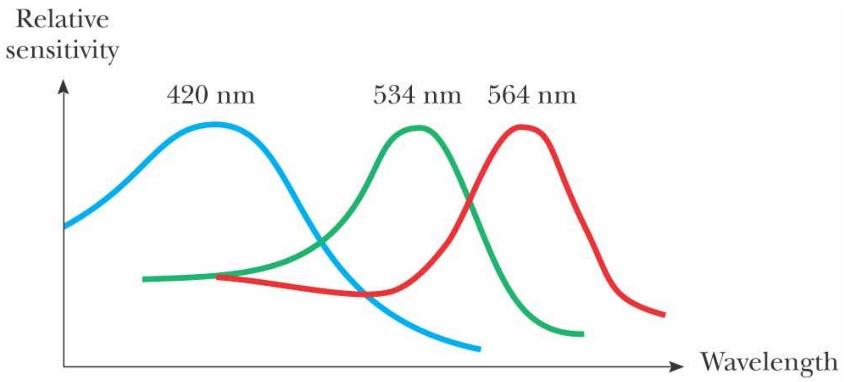
- Accommodation
  - The eye focuses on an object by varying the shape of the pliable crystalline lens through this process
  - Takes place very quickly
  - Limited in that objects very close to the eye produce blurred images

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

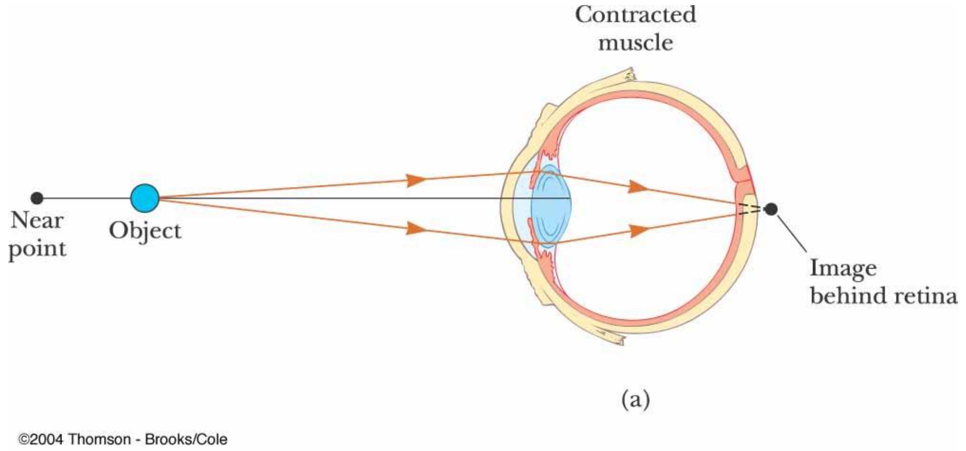
- Only three types of color-sensitive cells are present in the retina
  - They are called red, green and blue cones
- What color is seen depends on which cones are stimulated



Conditions of the Eye

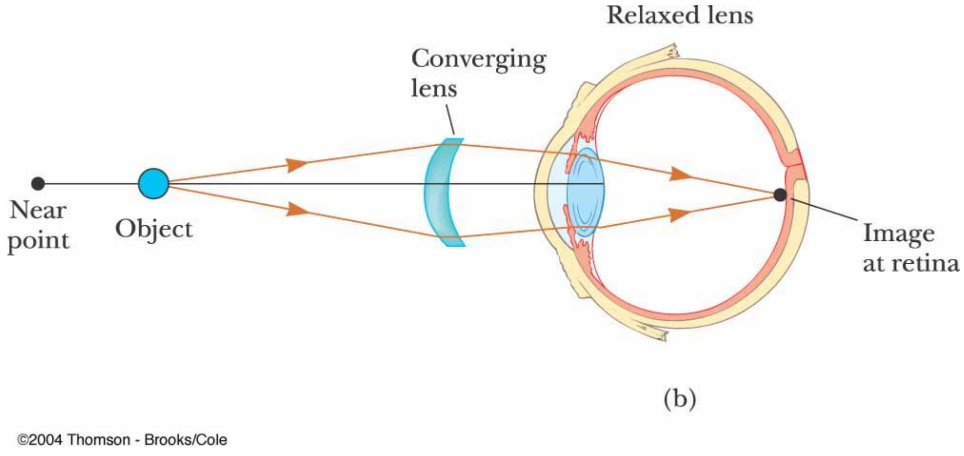
- Eyes may suffer a mismatch between the focusing power of the lens-cornea system and the length of the eye
- Eyes may be:
  - Farsighted
    - Light rays reach the retina before they converge to form an image
  - Nearsighted
    - Person can focus on nearby objects but not those far away

Farsightedness



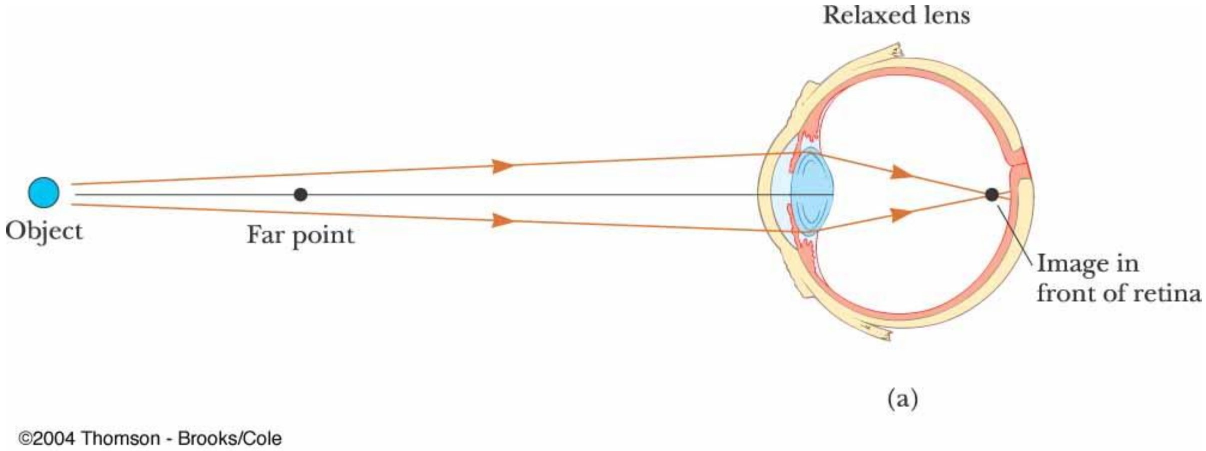
- Also called *hyperopia*
- The near point of the farsighted person is much farther away than that of the normal eye
- The image focuses behind the retina
- Can usually see far away objects clearly, but not nearby objects

Correcting Farsightedness



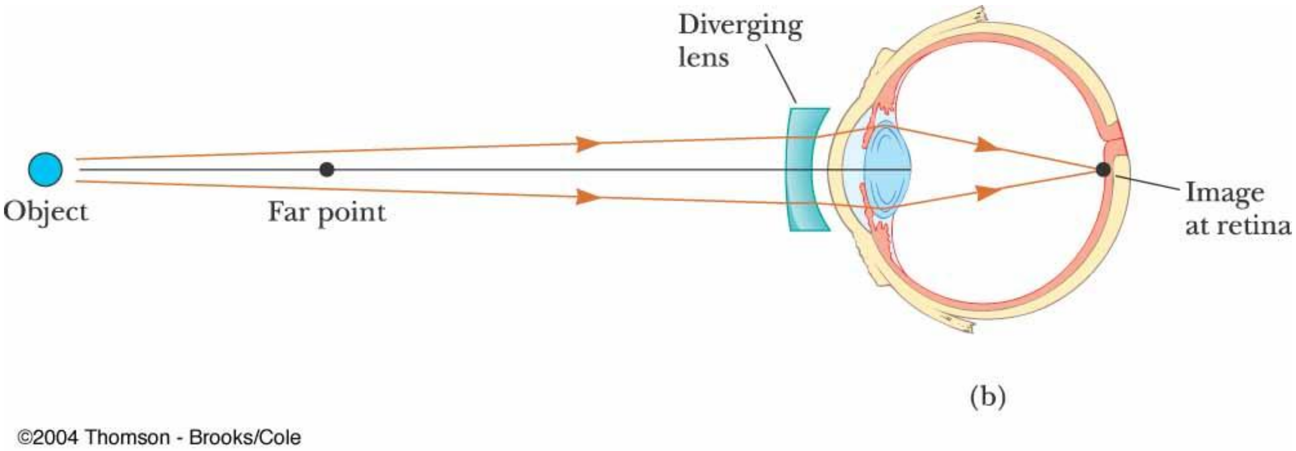
- A converging lens placed in front of the eye can correct the condition
- The lens refracts the incoming rays more toward the principal axis before entering the eye
  - This allows the rays to converge and focus on the retina

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

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

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

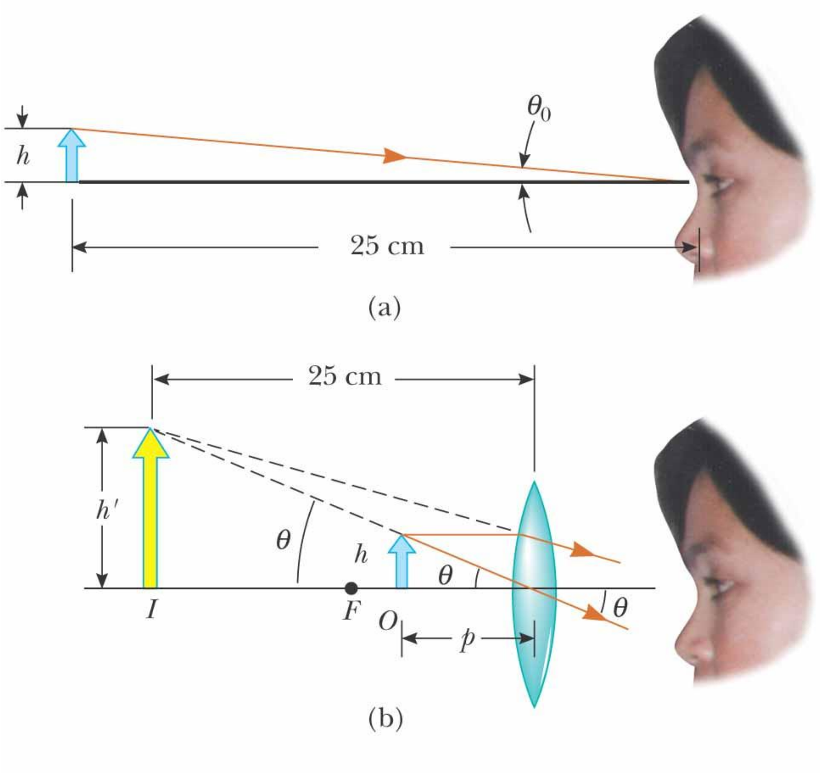
- Optometrists and ophthalmologists usually prescribe lenses measured in *diopters*
  - The power *P* of a lens in diopters equals the inverse of the focal length in meters
    - $P = 1/f$

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

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

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

Angular Magnification, cont.

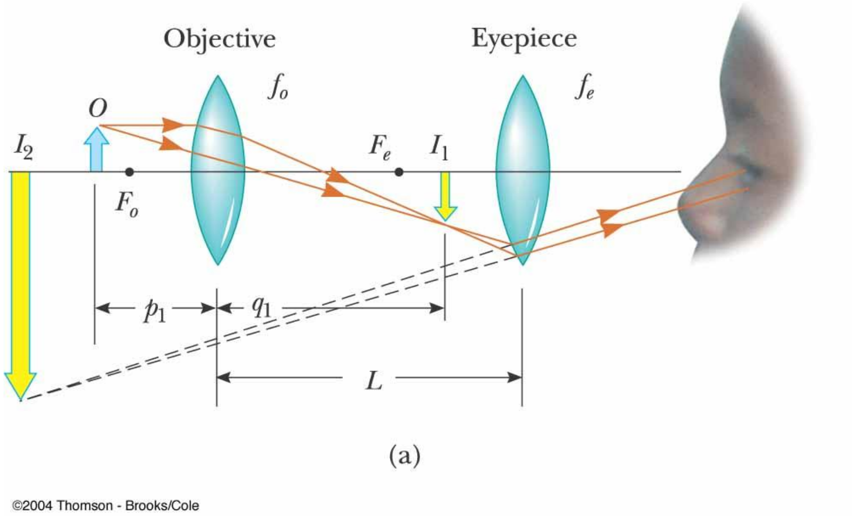
- The eye is most relaxed when the image is at infinity
  - Although the eye can focus on an object anywhere between the near point and infinity
- For the image formed by a magnifying glass to appear at infinity, the object has to be at the focal point of the lens
- The angular magnification is $m_{\text{min}} = \dfrac{\theta}{\theta_o} = \dfrac{25\text{ cm}}{f}$

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

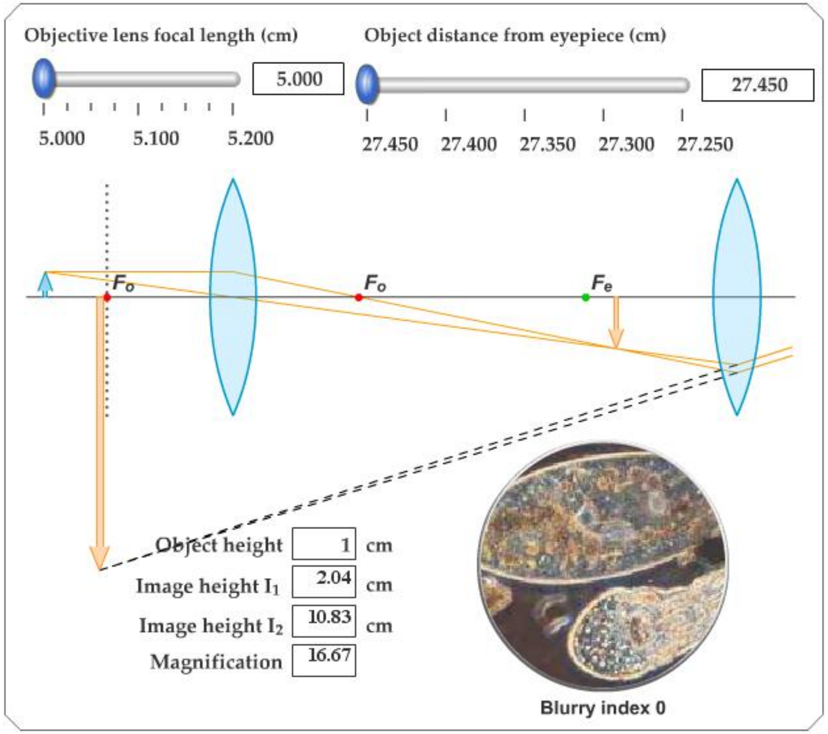


Compound Microscope, cont.

- 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

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

Other Considerations with a Microscope

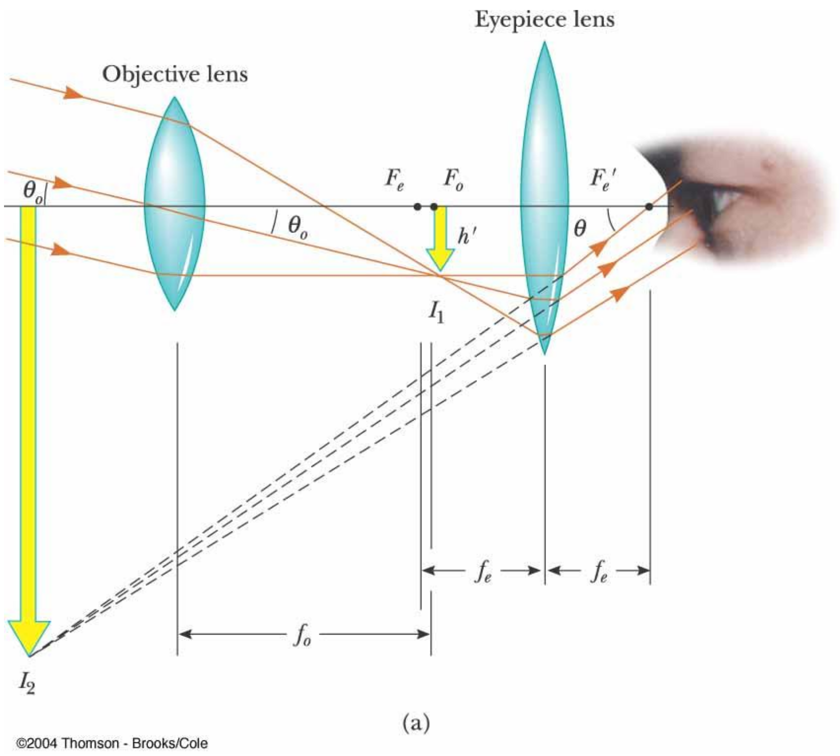
- The ability of an optical microscope to view an object depends on the size of the object relative to the wavelength of the light used to observe it
  - For example, you could not observe an atom ($d \approx$ 0.1 nm) with visible light ($\lambda \approx$ 500 nm)

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

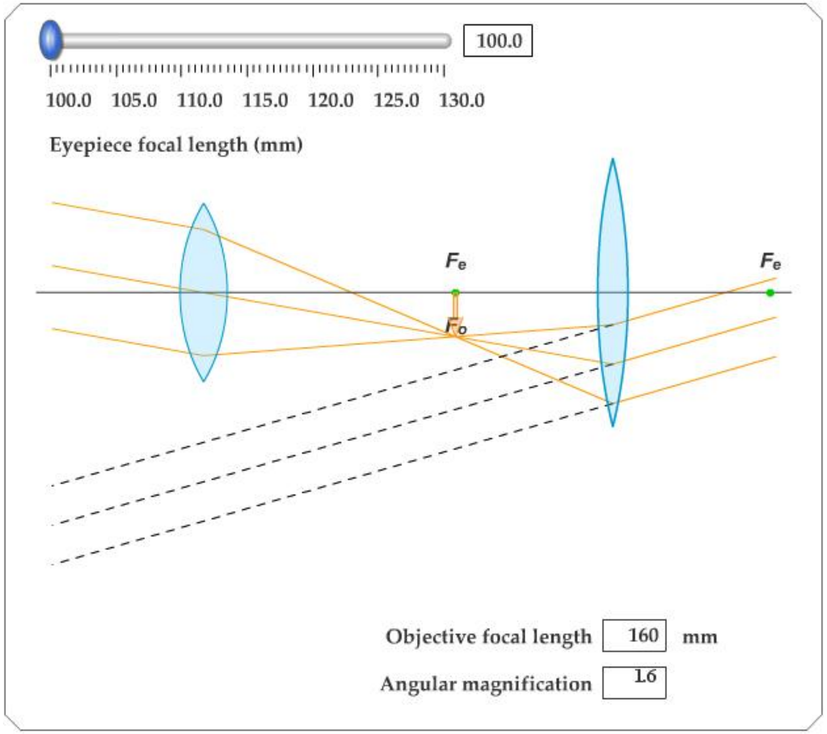
Refracting Telescope

- 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



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

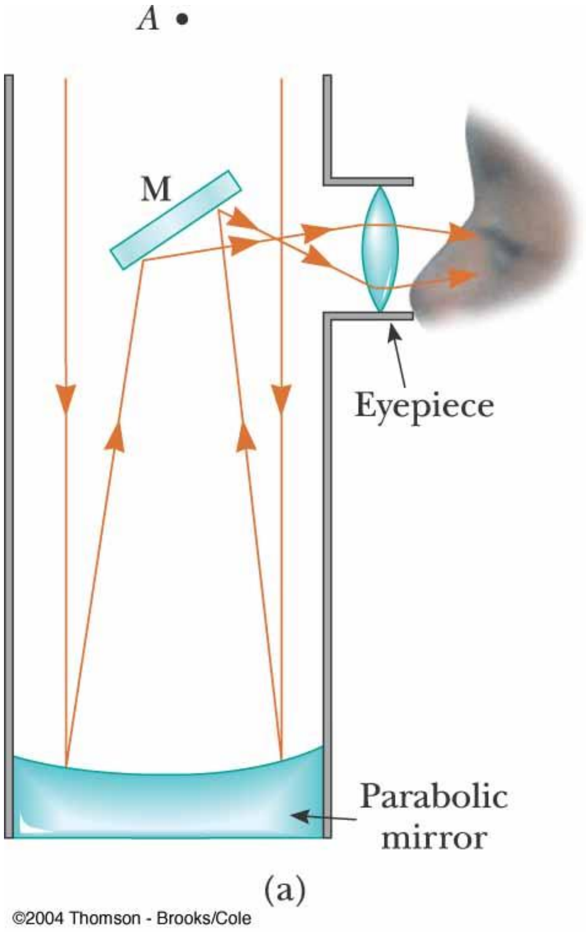
- Large diameters are needed to study distant objects
- Large lenses are difficult and expensive to manufacture
- The weight of large lenses leads to sagging which produces aberrations

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*



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