Light: Geometric Optics

Units of Chapter 23

Units of Chapter 23

- **Total Internal Reflection; Fiber Optics**

- **Thin Lenses; Ray Tracing**

- **The Thin Lens Equation; Magnification**

- **Combinations of Lenses**

- **Lensmaker's Equation**

23.1 The Ray Model of Light

Light very often travels in straight lines. We represent light using rays, which are straight lines emanating from an object. This is an idealization, but is very useful for geometric optics.

This bundle enters the eye
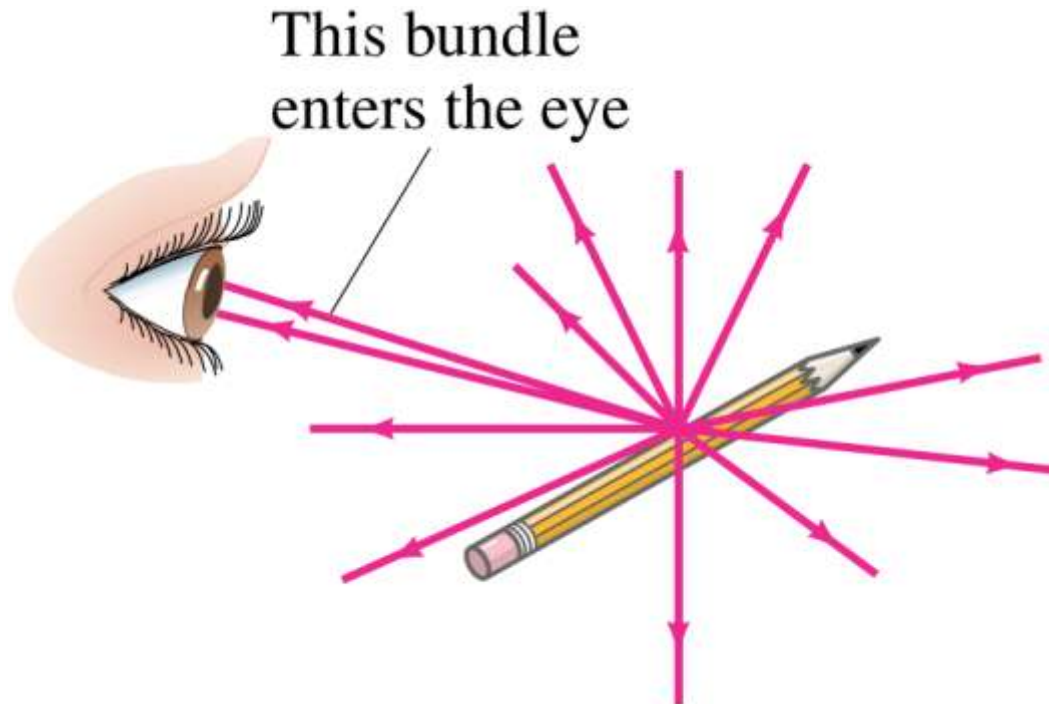
23.2 Reflection; Image Formation by a Plane Mirror

Law of reflection: the angle of reflection (that the ray makes with the normal to a surface) equals the angle of incidence.

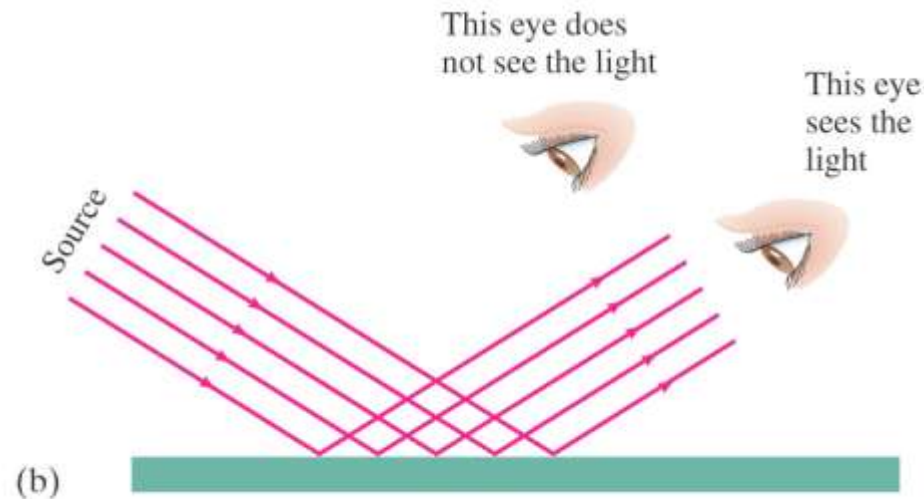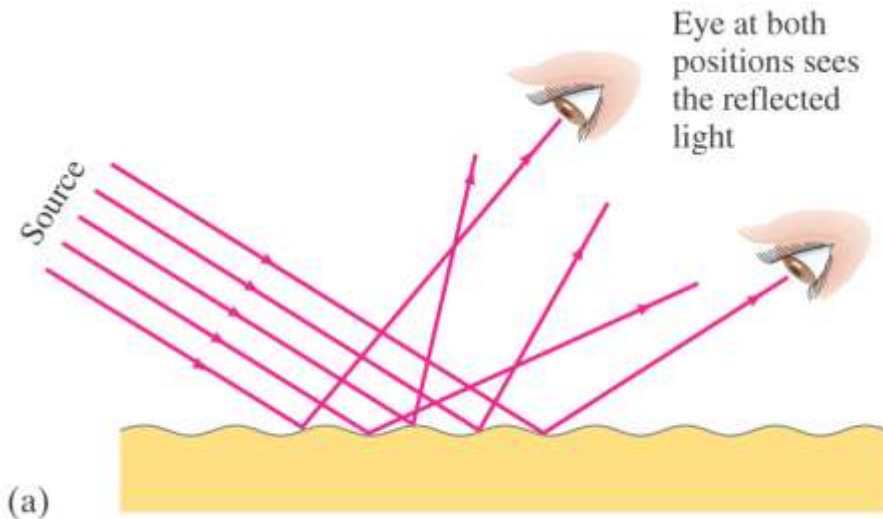Copyright © 2005 Pearson Prentice Hall, Inc.
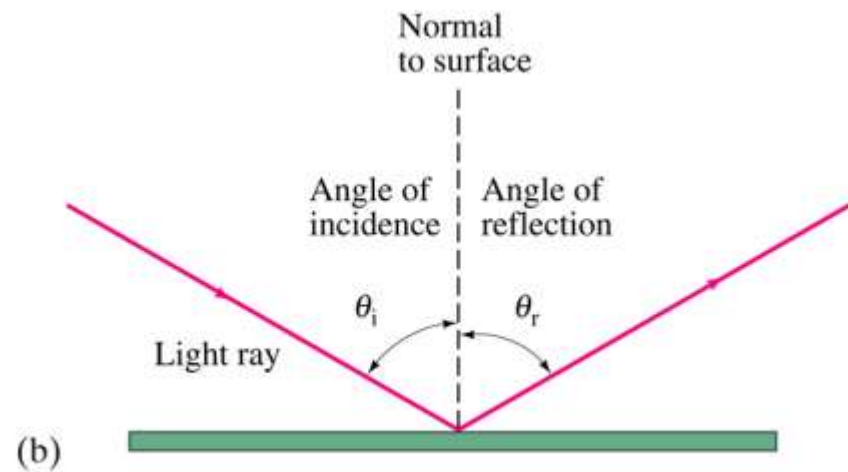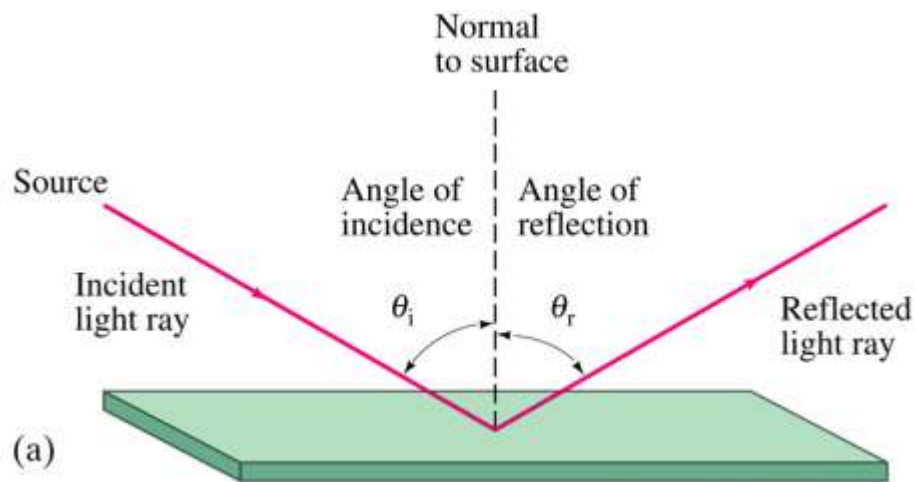
23.2 Reflection; Image Formation by a Plane Mirror

When light reflects from a rough surface, the law of reflection still holds, but the angle of incidence varies. This is called diffuse reflection.
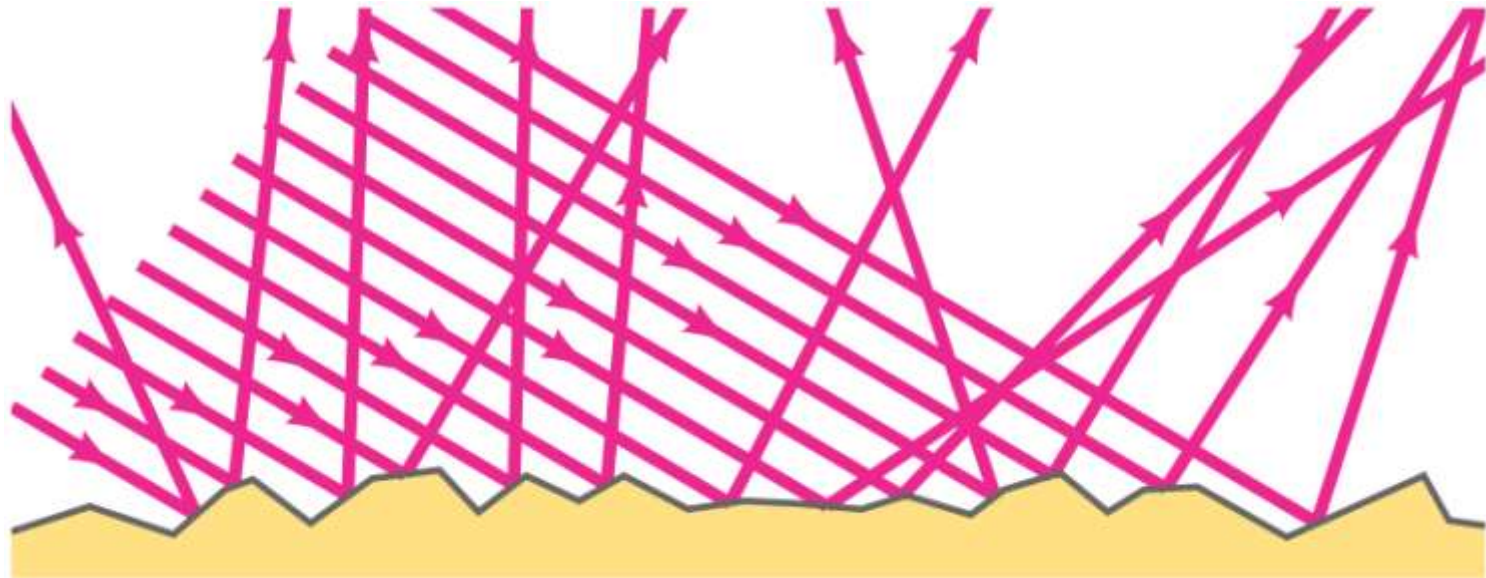
23.2 Reflection; Image Formation by a Plane Mirror

With diffuse reflection, your eye sees reflected light at all angles. With specular reflection (from a mirror), your eye must be in the correct position.

Eye at both positions sees the reflected light

Source

(a)

This eye does not see the light

This eye sees the light

Source

(b)

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23.2 Reflection; Image Formation by a Plane Mirror

What you see when you look into a plane (flat) mirror is an image, which appears to be behind the mirror.
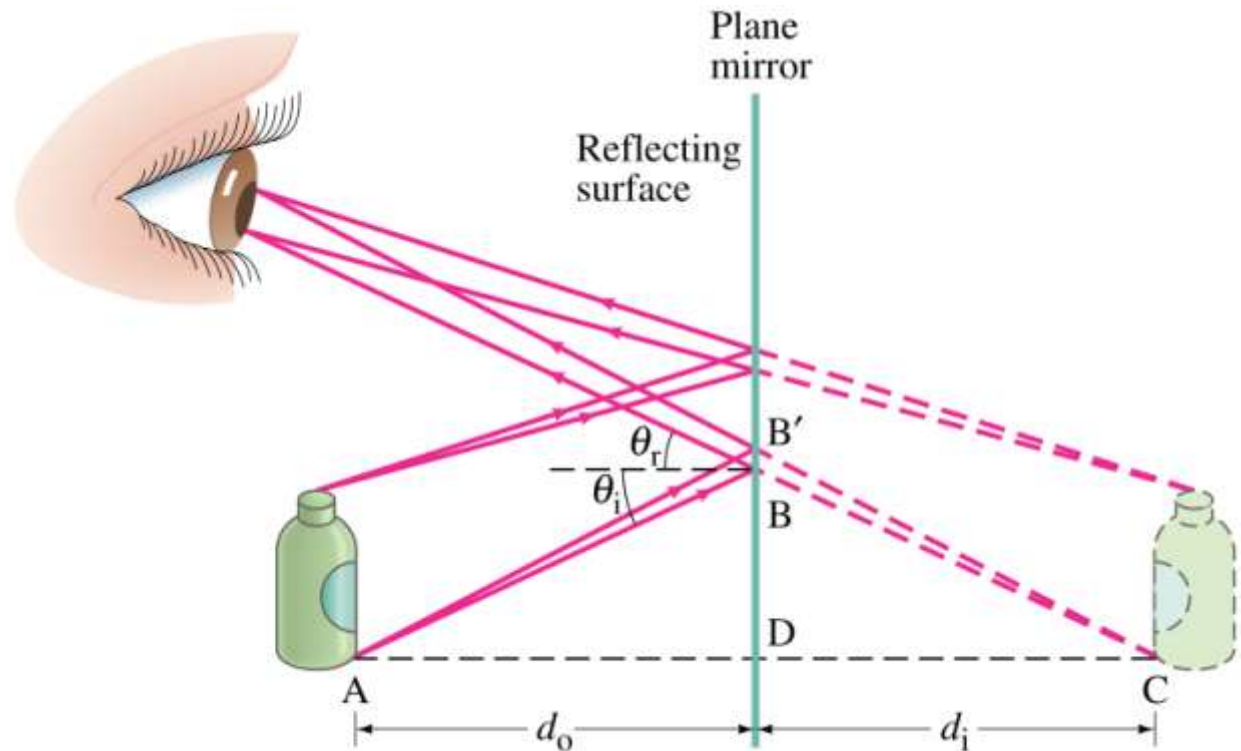
23.2 Reflection; Image Formation by a Plane Mirror
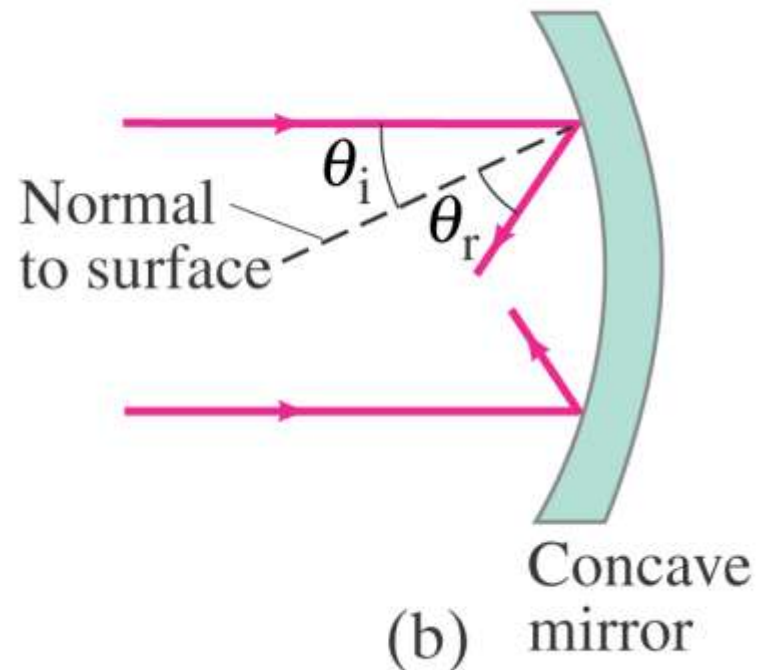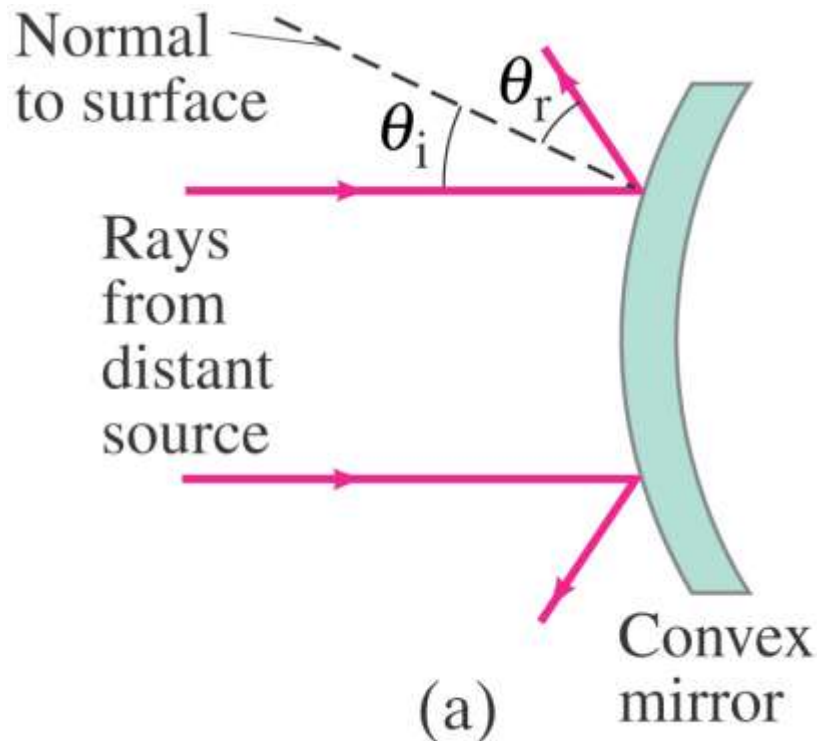
This is called a virtual image, as the light does not go through it. The distance of the image from the mirror is equal to the distance of the object from the mirror.

23.3 Formation of Images by Spherical Mirrors

Spherical mirrors are shaped like sections of a sphere, and may be reflective on either the inside (concave) or outside (convex).

Normal to surface

θ_i θ_r

Rays from distant source

(a) Convex mirror

Normal to surface

θ_i θ_r

(b) Concave mirror

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23.3 Formation of Images by Spherical Mirrors

Rays coming from a faraway object are effectively parallel.

Mirror

These rays strike the mirror, and they are essentially parallel.
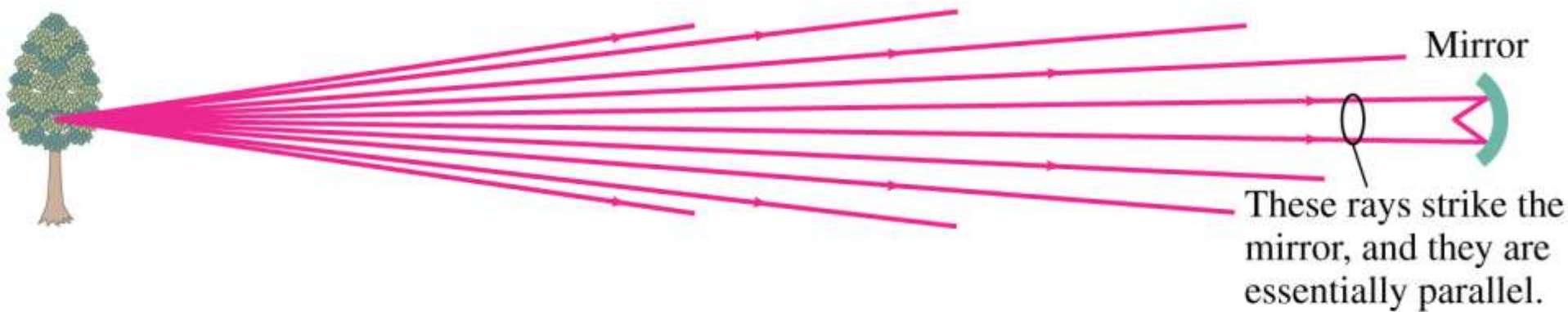
23.3 Formation of Images by Spherical Mirrors
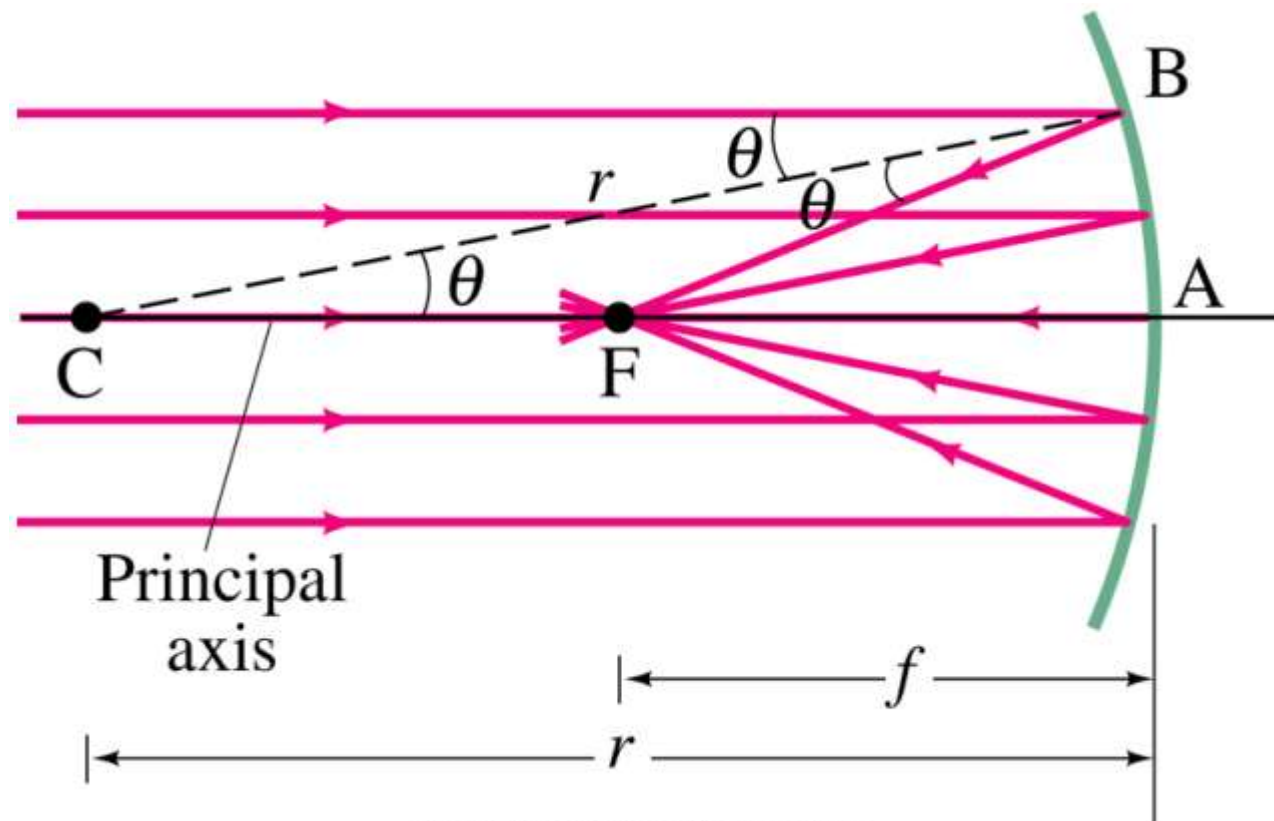
Parallel rays striking a spherical mirror do not all converge at exactly the same place if the curvature of the mirror is large; this is called spherical aberration.
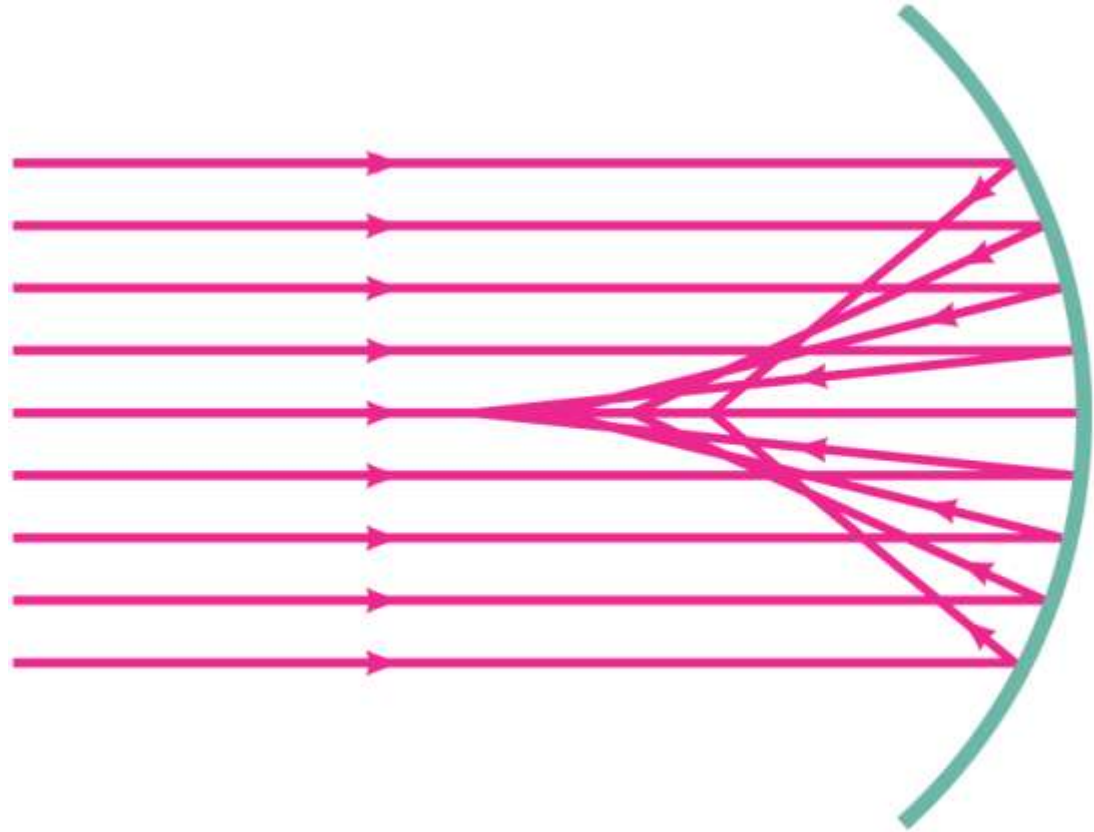
23.3 Formation of Images by Spherical Mirrors

If the curvature is small, the focus is much more precise; the focal point is where the rays converge.

23.3 Formation of Images by Spherical Mirrors

Using geometry, we find that the focal length is half the radius of curvature:

$$f = \frac{r}{2} \qquad \textbf{(23-1)}$$

Spherical aberration can be avoided by using a parabolic reflector; these are more difficult and expensive to make, and so are used only when necessary, such as in research telescopes.
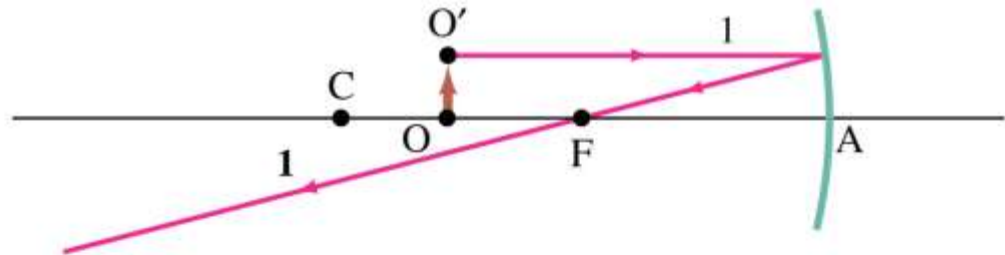
23.3 Formation of Images by Spherical Mirrors

We use ray diagrams to determine where an image will be. For mirrors, we use three key rays, all of which begin on the object:

1. A ray parallel to the axis; after reflection it passes through the focal point

2. A ray through the focal point; after reflection it is parallel to the axis

3. A ray perpendicular to the mirror; it reflects back on itself
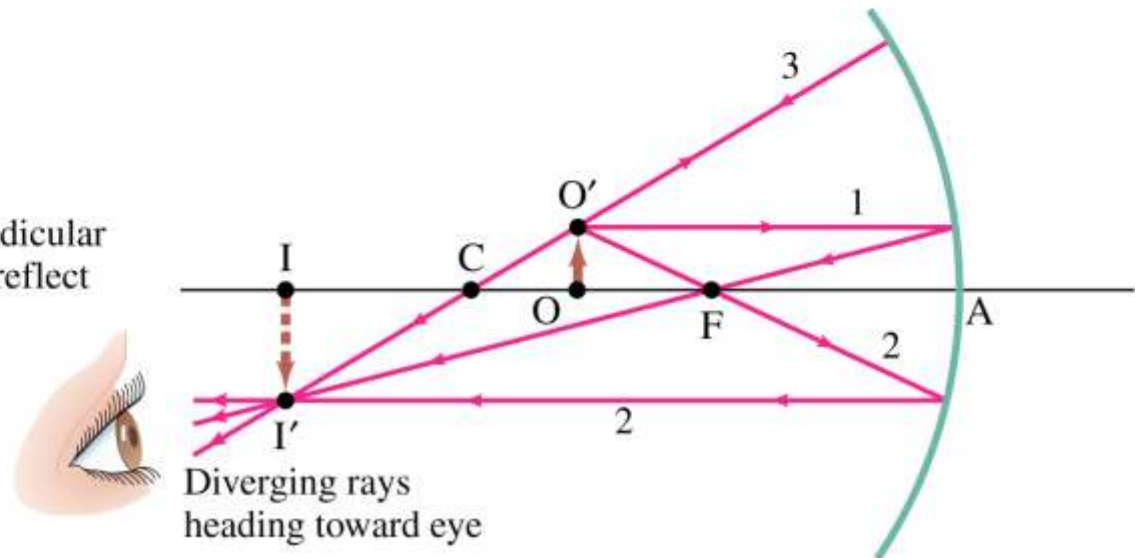
23.3 Formation of Images by Spherical Mirrors

(a) Ray 1 goes out from O′ parallel to the axis and reflects through F.

(b) Ray 2 goes through F and then reflects back parallel to the axis.
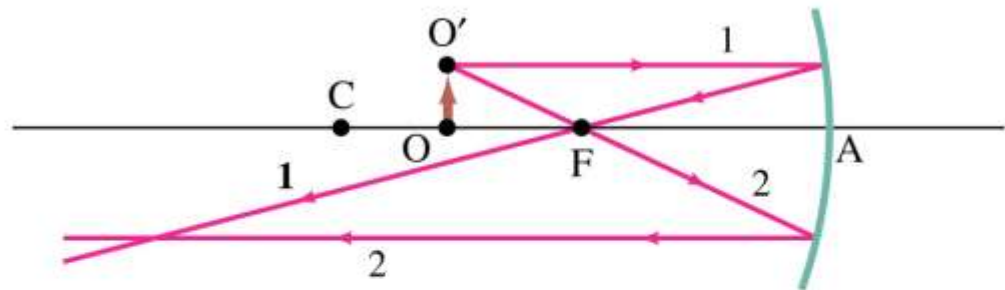
(c) Ray 3 is chosen perpendicular to mirror, and so must reflect back on itself and go through C (center of curvature).

Diverging rays heading toward eye

23.3 Formation of Images by Spherical Mirrors

The intersection of these three rays gives the position of the image of that point on the object. To get a full image, we can do the same with other points (two points suffice for many purposes).

23.3 Formation of Images by Spherical Mirrors

Geometrically, we can derive an equation that relates the object distance, image distance, and focal length of the mirror:

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

(23-2)
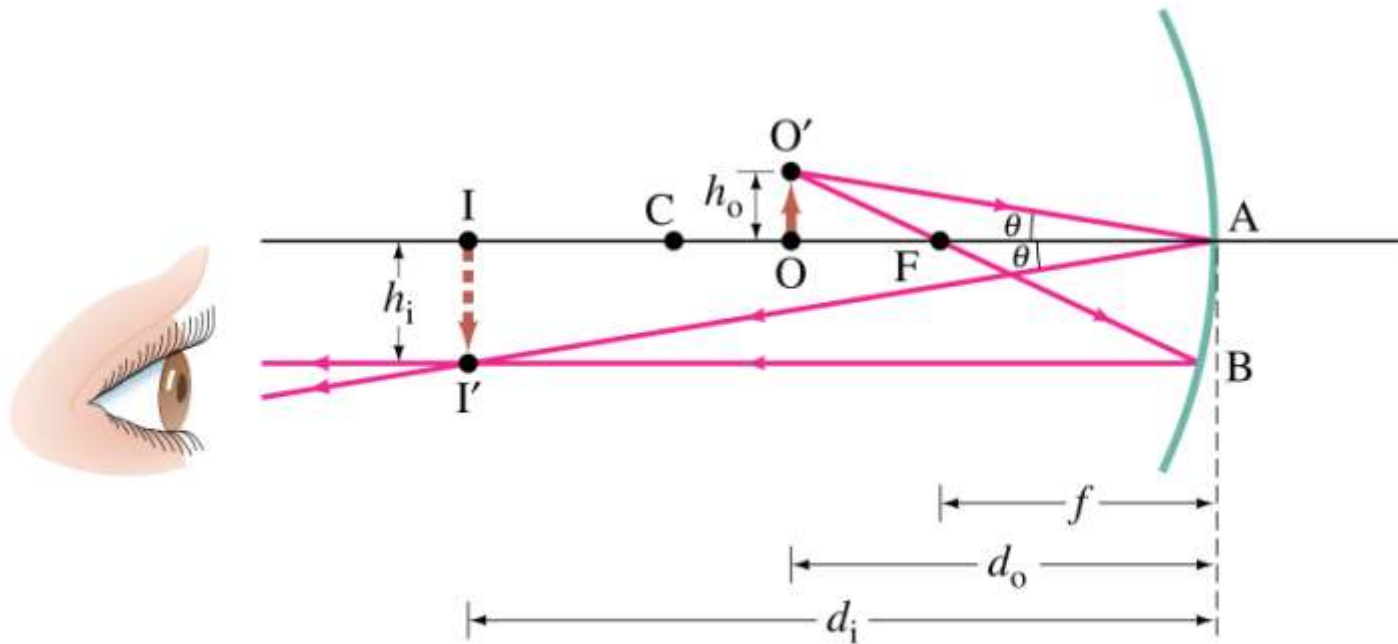
23.3 Formation of Images by Spherical Mirrors

We can also find the magnification (ratio of image height to object height).

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$ (23-3)

The negative sign indicates that the image is inverted. This object is between the center of curvature and the focal point, and its image is larger, inverted, and real.
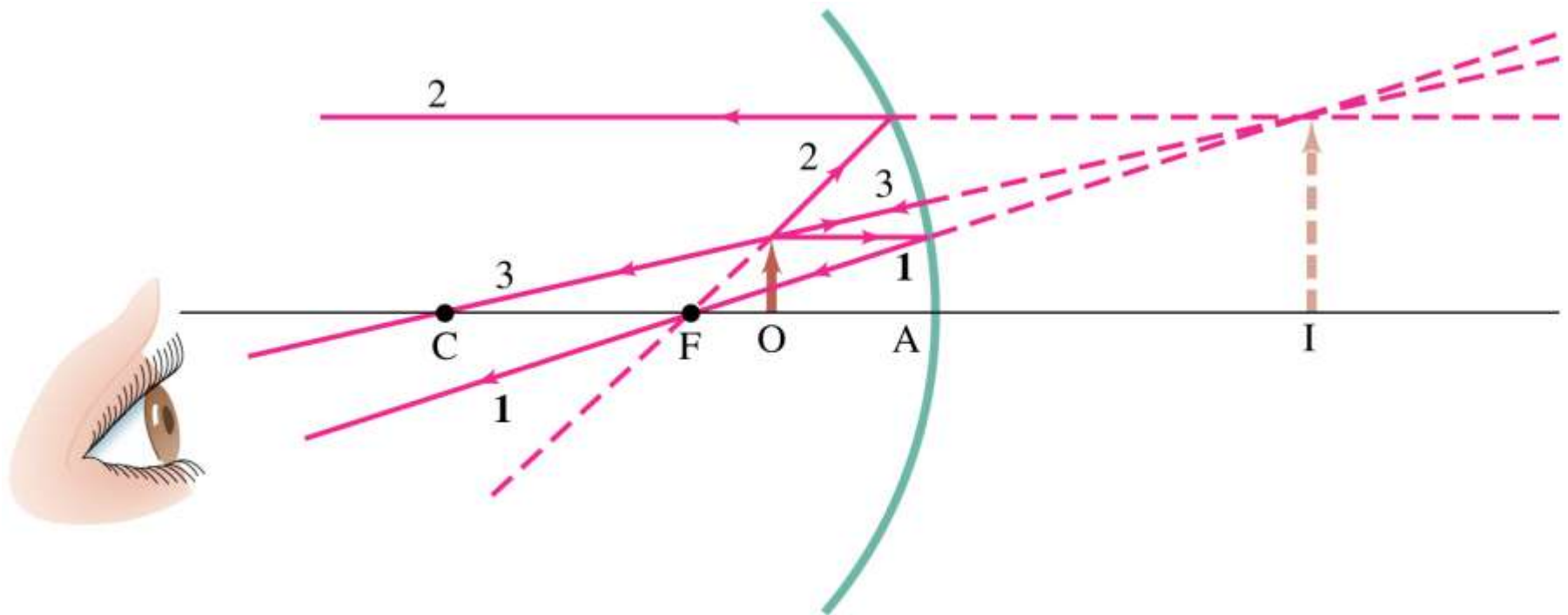
23.3 Formation of Images by Spherical Mirrors

If an object is outside the center of curvature of a concave mirror, its image will be inverted, smaller, and real.

Image of your nose

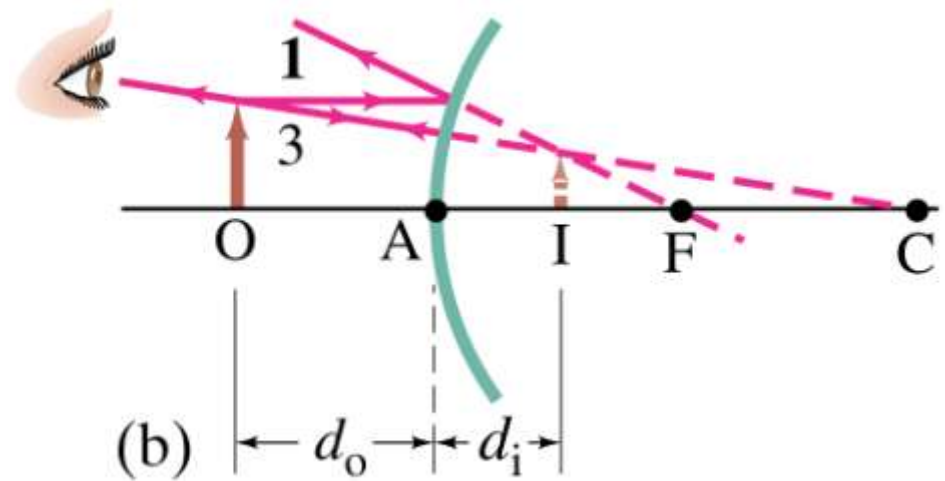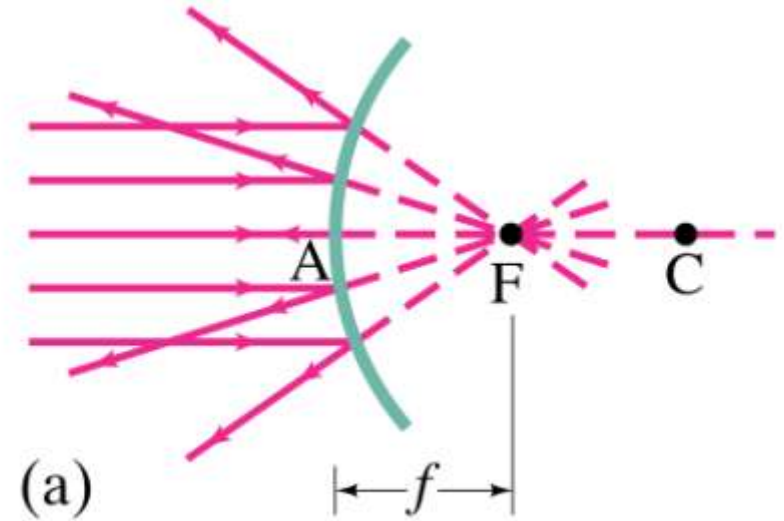Copyright © 2005 Pearson Prentice Hall, Inc.
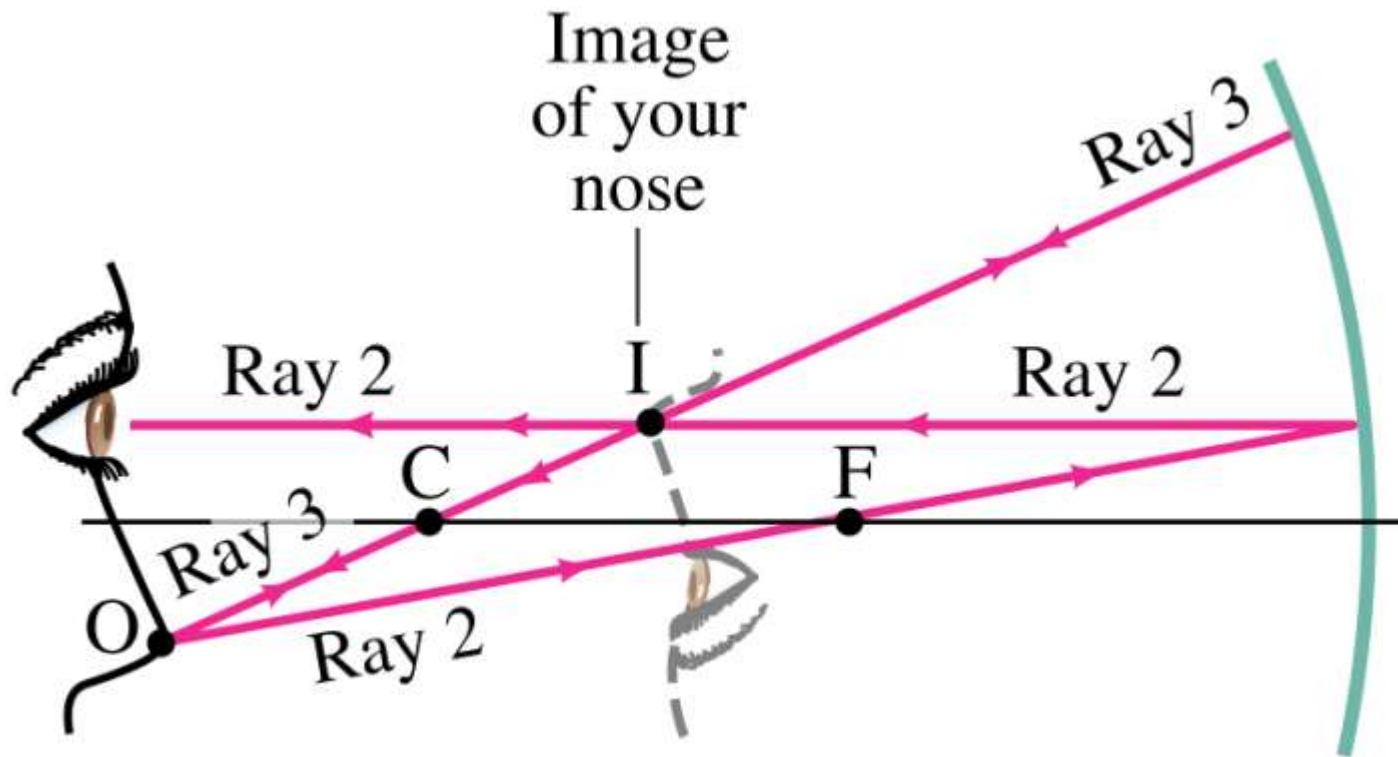
23.3 Formation of Images by Spherical Mirrors

If an object is inside the focal point, its image will be upright, larger, and virtual.

23.3 Formation of Images by Spherical Mirrors

For a convex mirror, the image is always virtual, upright, and smaller.

23.3 Formation of Images by Spherical Mirrors

Problem Solving: Spherical Mirrors

1. Draw a ray diagram; the image is where the rays intersect.

2. Apply the mirror and magnification equations.

3. Sign conventions: if the object, image, or focal point is on the reflective side of the mirror, its distance is positive, and negative otherwise. Magnification is positive if image is upright, negative otherwise.

4. Check that your solution agrees with the ray diagram.

23.4 Index of Refraction

In general, light slows somewhat when traveling through a medium. The index of refraction of the medium is the ratio of the speed of light in vacuum to the speed of light in the medium:

$$n = \frac{c}{v}$$ **(23-4)**

TABLE 23–1
Indices of Refraction†

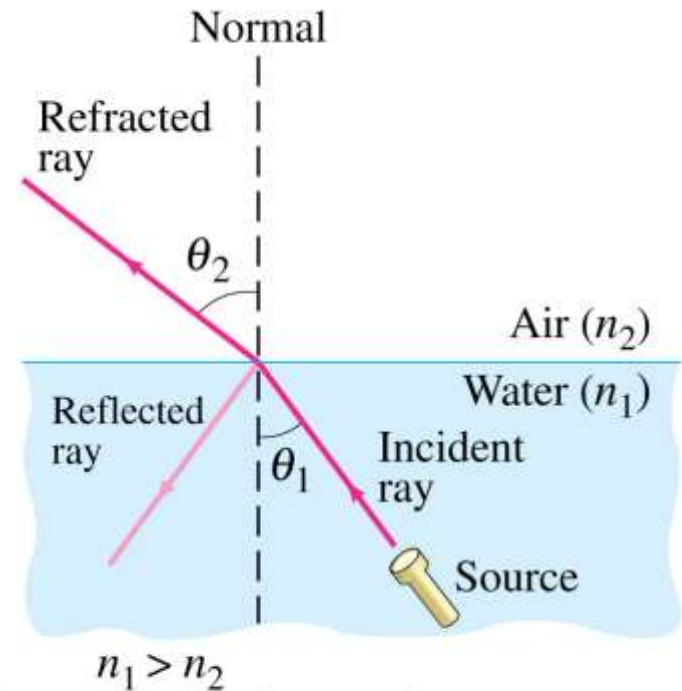| Medium	$n = c/v$
Vacuum	1.0000
Air (at STP)	1.0003
Water	1.33
Ethyl alcohol	1.36
Glass	
Fused quartz	1.46
Crown glass	1.52
Light flint	1.58
Lucite or Plexiglas	1.51
Sodium chloride	1.53
Diamond	2.42

†$\lambda = 589$ nm.

23.5 Refraction: Snell's Law

Light changes direction when crossing a boundary from one medium to another. This is called refraction, and the angle the outgoing ray makes with the normal is called the angle of refraction.

(a) $n_2 > n_1$
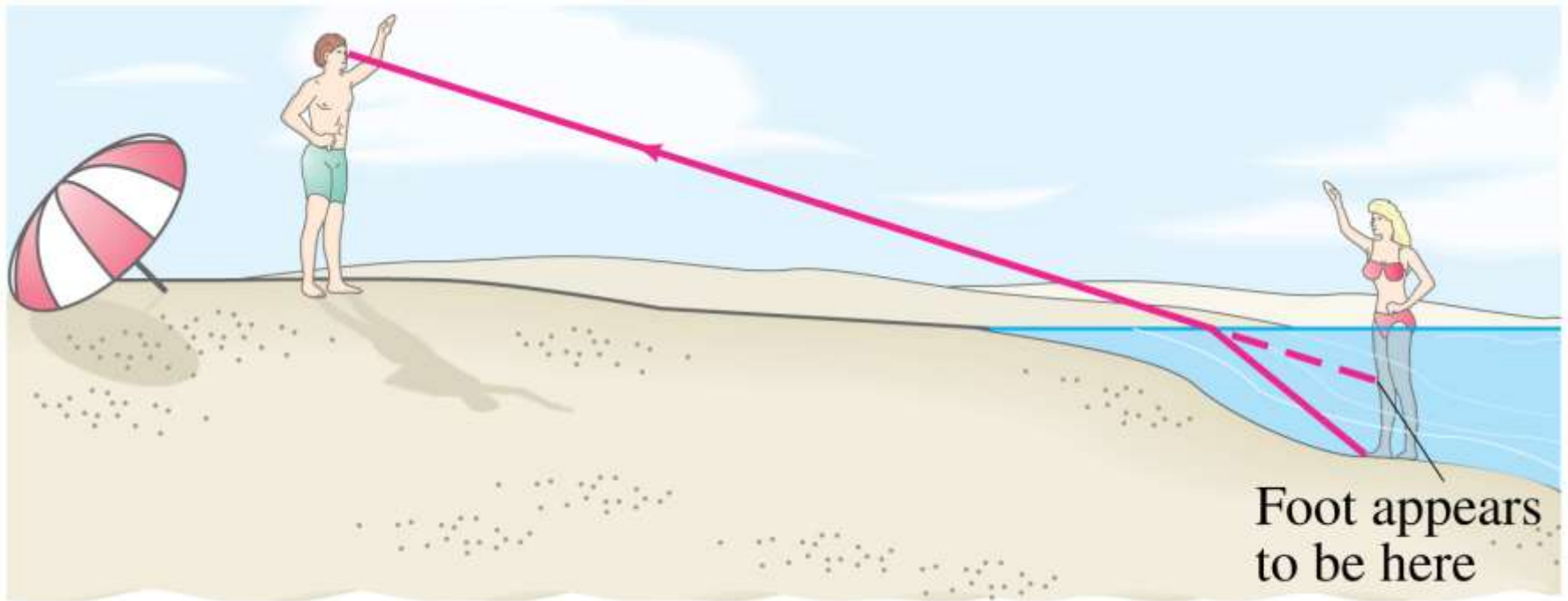Ray bends toward $\perp$

(b) $n_1 > n_2$
Ray bends away from $\perp$

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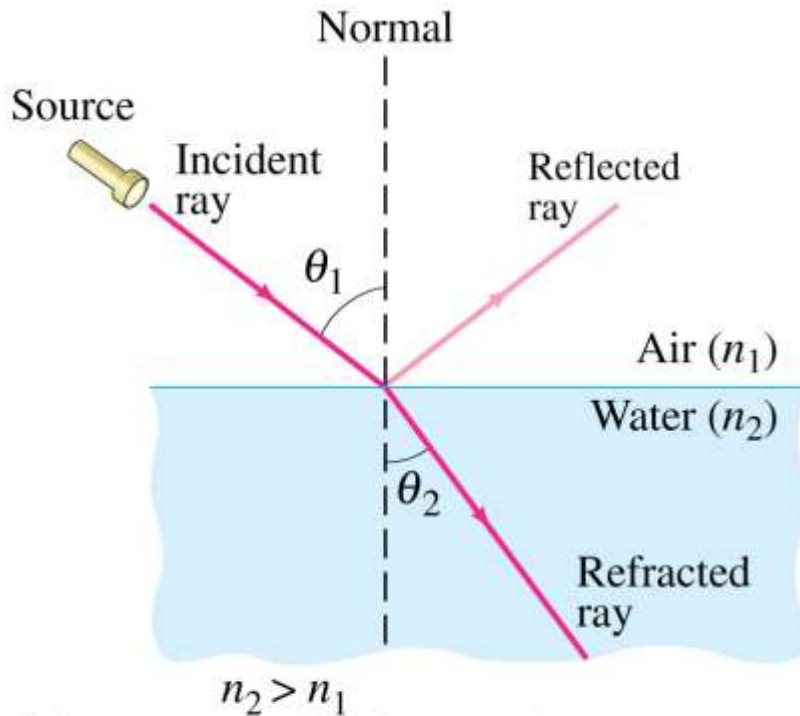
23.5 Refraction: Snell's Law

Refraction is what makes objects half-submerged in water look odd.

Foot appears to be here

23.5 Refraction: Snell's Law

The angle of refraction depends on the indices of refraction, and is given by Snell's law:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \qquad \textbf{(23-5)}$$

Air   Glass   Air

θ_B

θ_A

θ_A

$60°$

Ray from object

"Image" (where object appears to be)
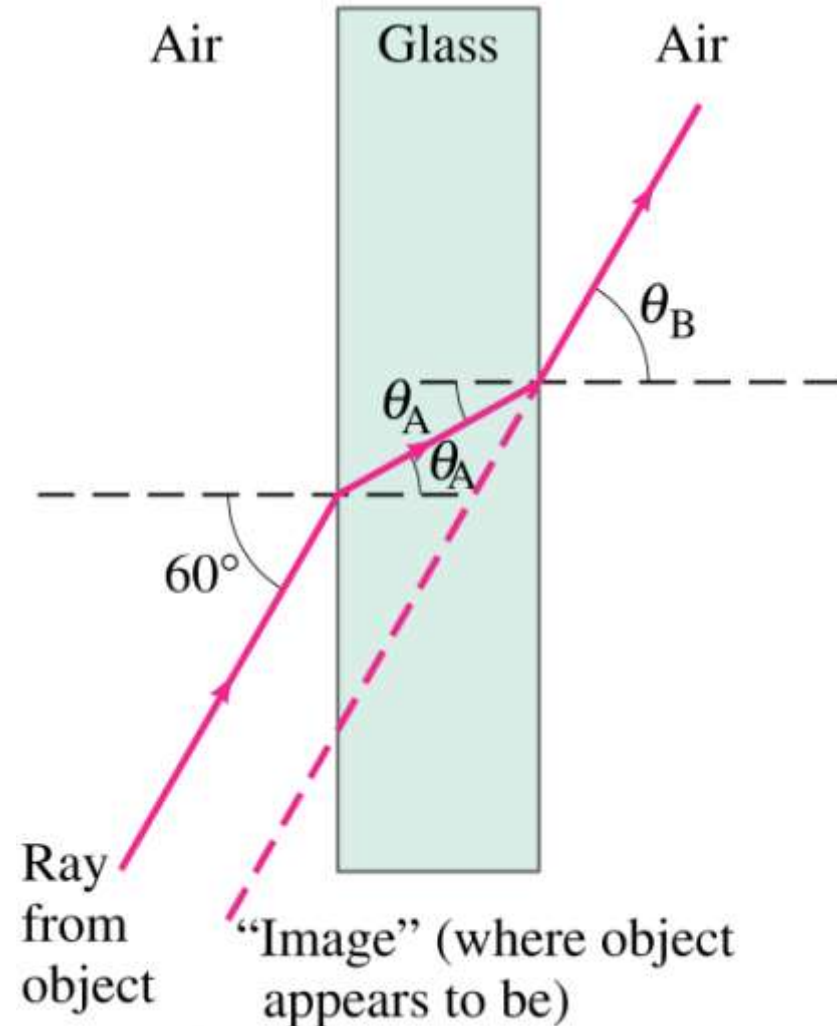
23.6 Total Internal Reflection; Fiber Optics

If light passes into a medium with a smaller index of refraction, the angle of refraction is larger. There is an angle of incidence for which the angle of refraction will be 90°; this is called the critical angle:

$$\sin \theta_C = \frac{n_2}{n_1} \sin 90° = \frac{n_2}{n_1} \qquad \textbf{(23-5)}$$
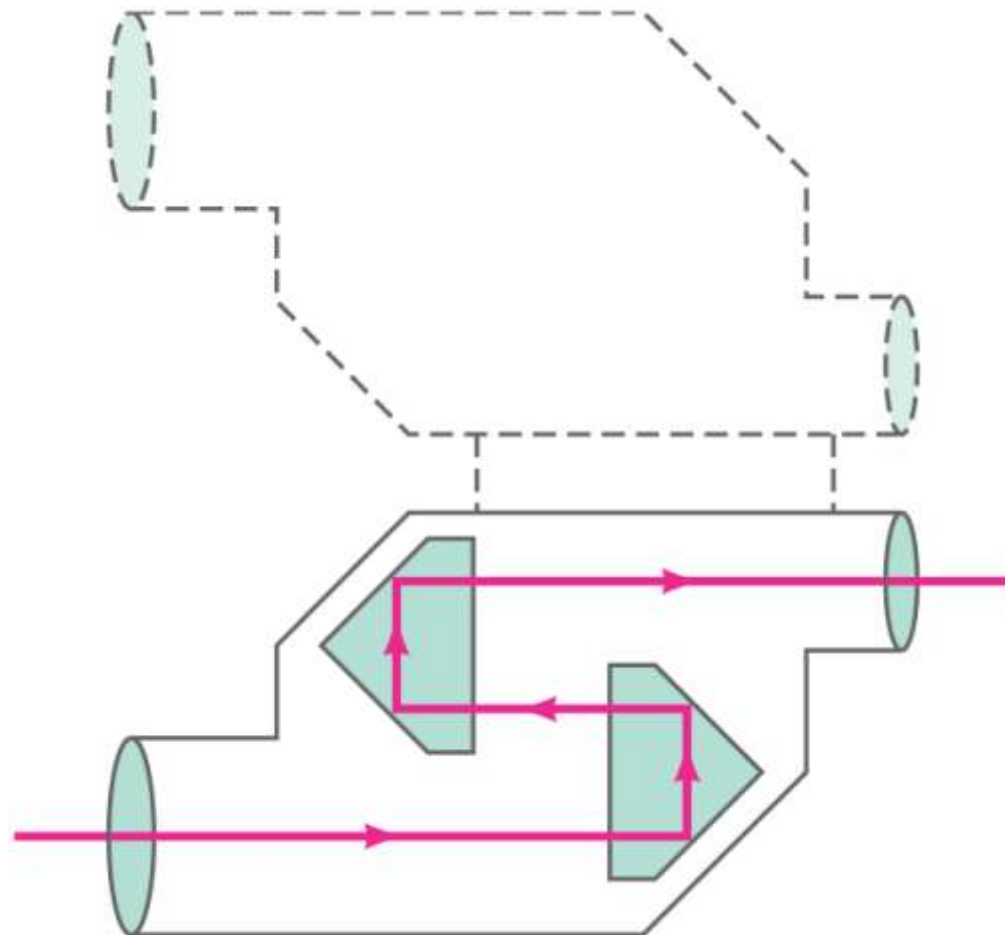
23.6 Total Internal Reflection; Fiber Optics

If the angle of incidence is larger than this, no transmission occurs. This is called total internal reflection.

$n_2 (< n_1)$

n_1

I J K L
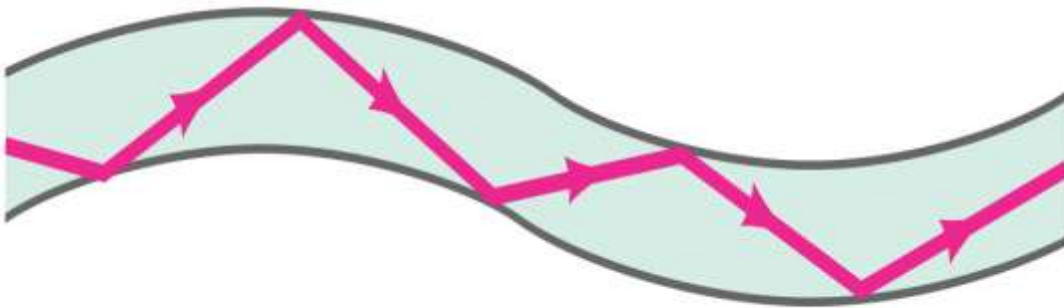
θ_1 θ_1 θ_C

Source
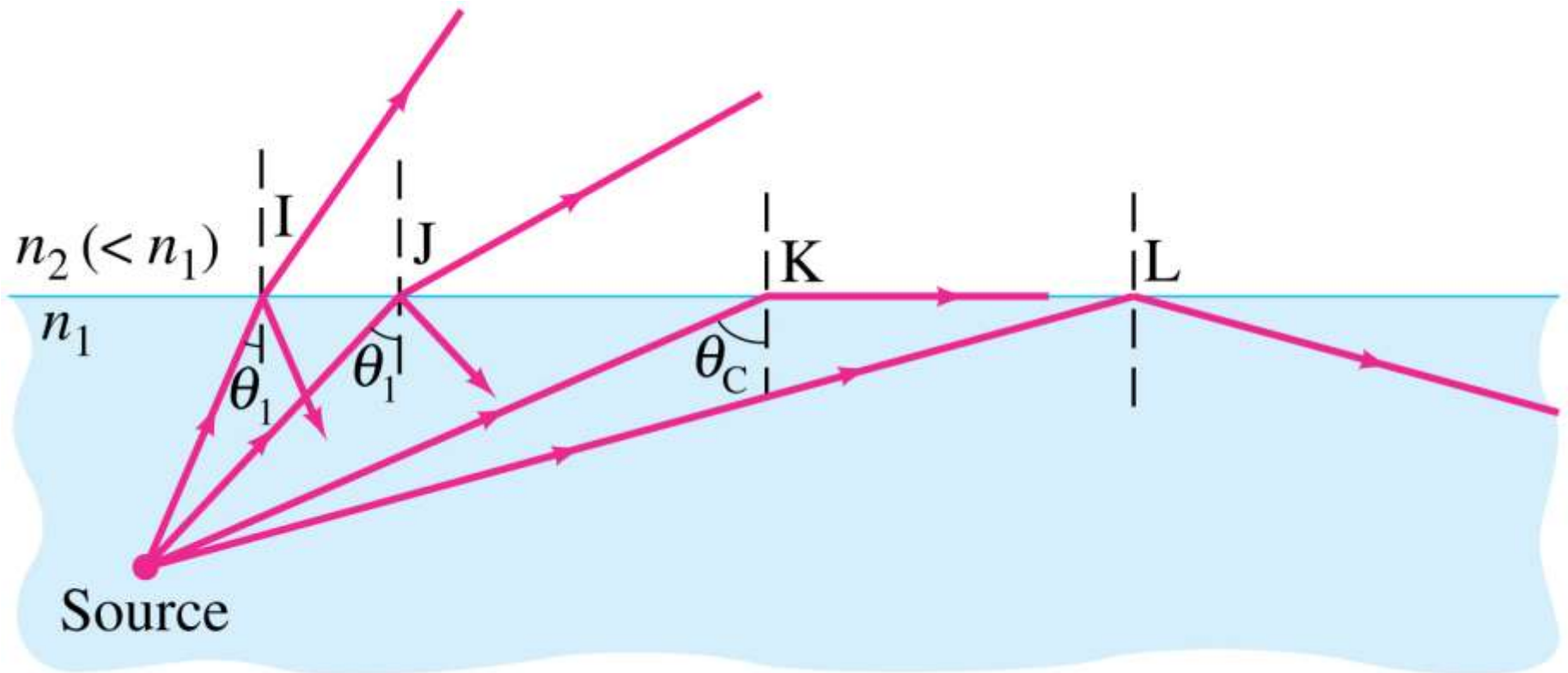
23.6 Total Internal Reflection; Fiber Optics

Binoculars often use total internal reflection; this gives true 100% reflection, which even the best mirror cannot do.
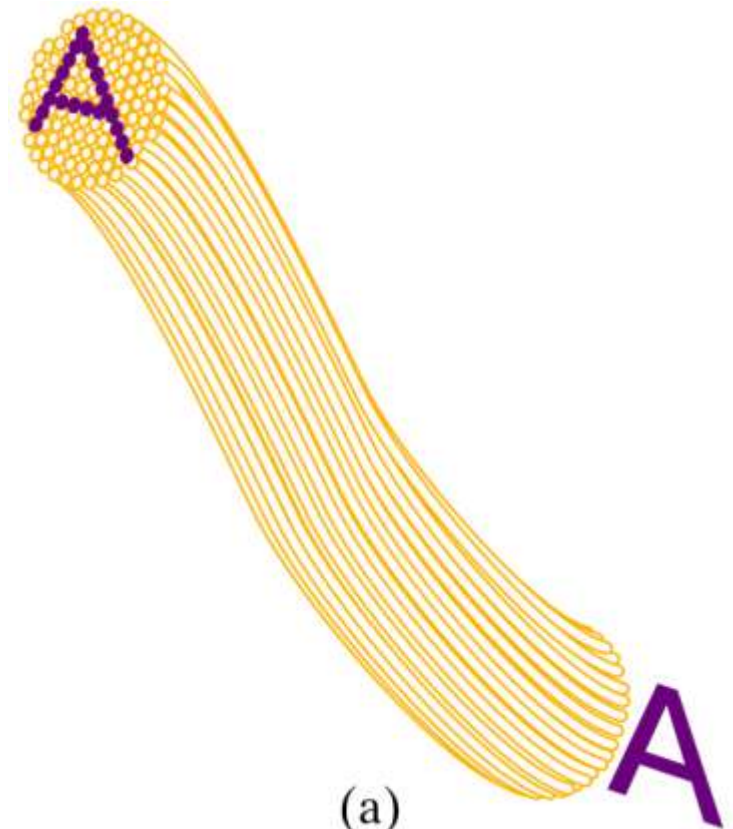
23.6 Total Internal Reflection; Fiber Optics

Total internal reflection is also the principle behind fiber optics. Light will be transmitted along the fiber even if it is not straight. An image can be formed using multiple small fibers.

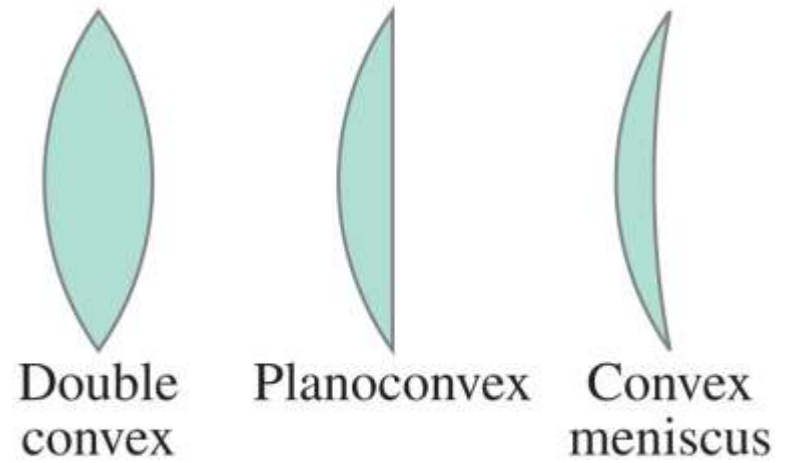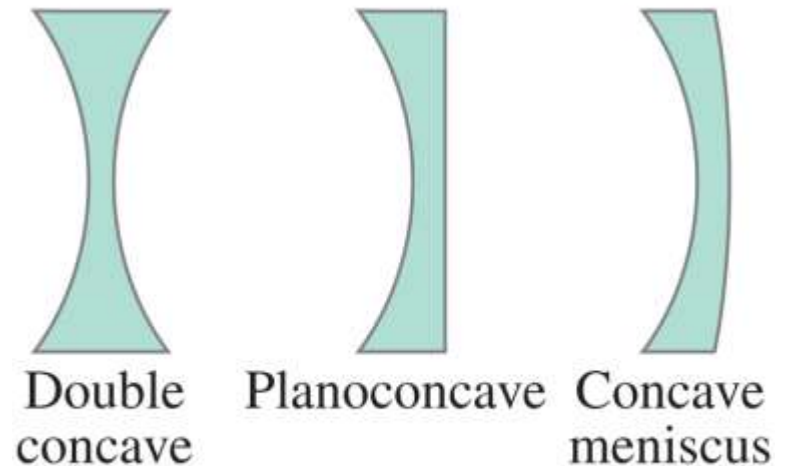Copyright © 2005 Pearson Prentice Hall, Inc.

(a)

23.7 Thin Lenses; Ray Tracing

Thin lenses are those whose thickness is small compared to their radius of curvature. They may be either converging (a) or diverging (b).

Double convex   Planoconvex   Convex meniscus

(a) Converging lenses

Double concave   Planoconcave   Concave meniscus

(b) Diverging lenses

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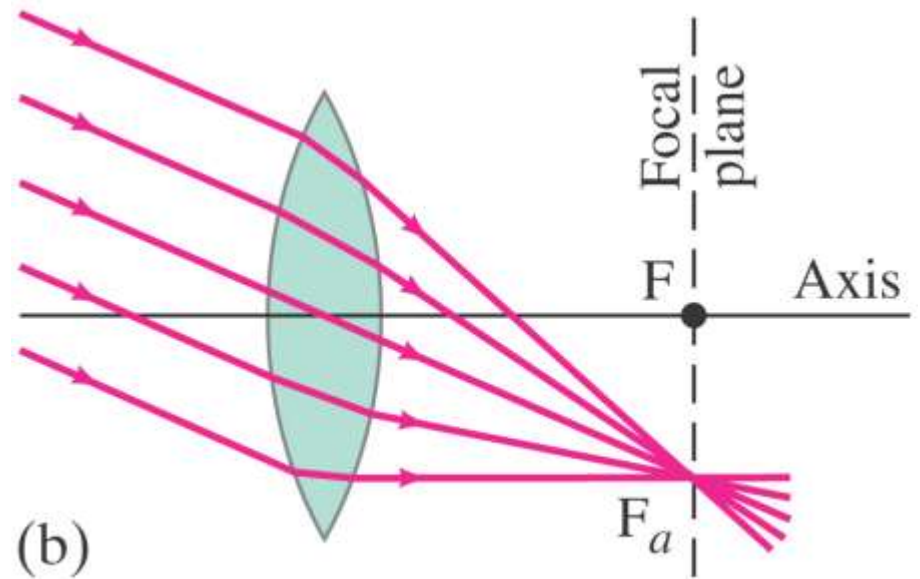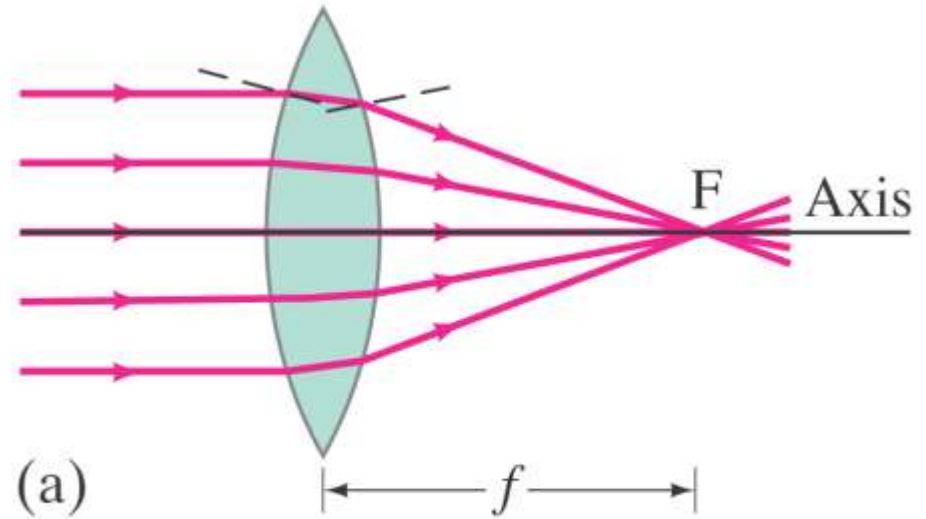
23.7 Thin Lenses; Ray Tracing

Parallel rays are brought to a focus by a converging lens (one that is thicker in the center than it is at the edge).

(a)

(b)

23.7 Thin Lenses; Ray Tracing

A diverging lens (thicker at the edge than in the center) make parallel light diverge; the focal point is that point where the diverging rays would converge if projected back.
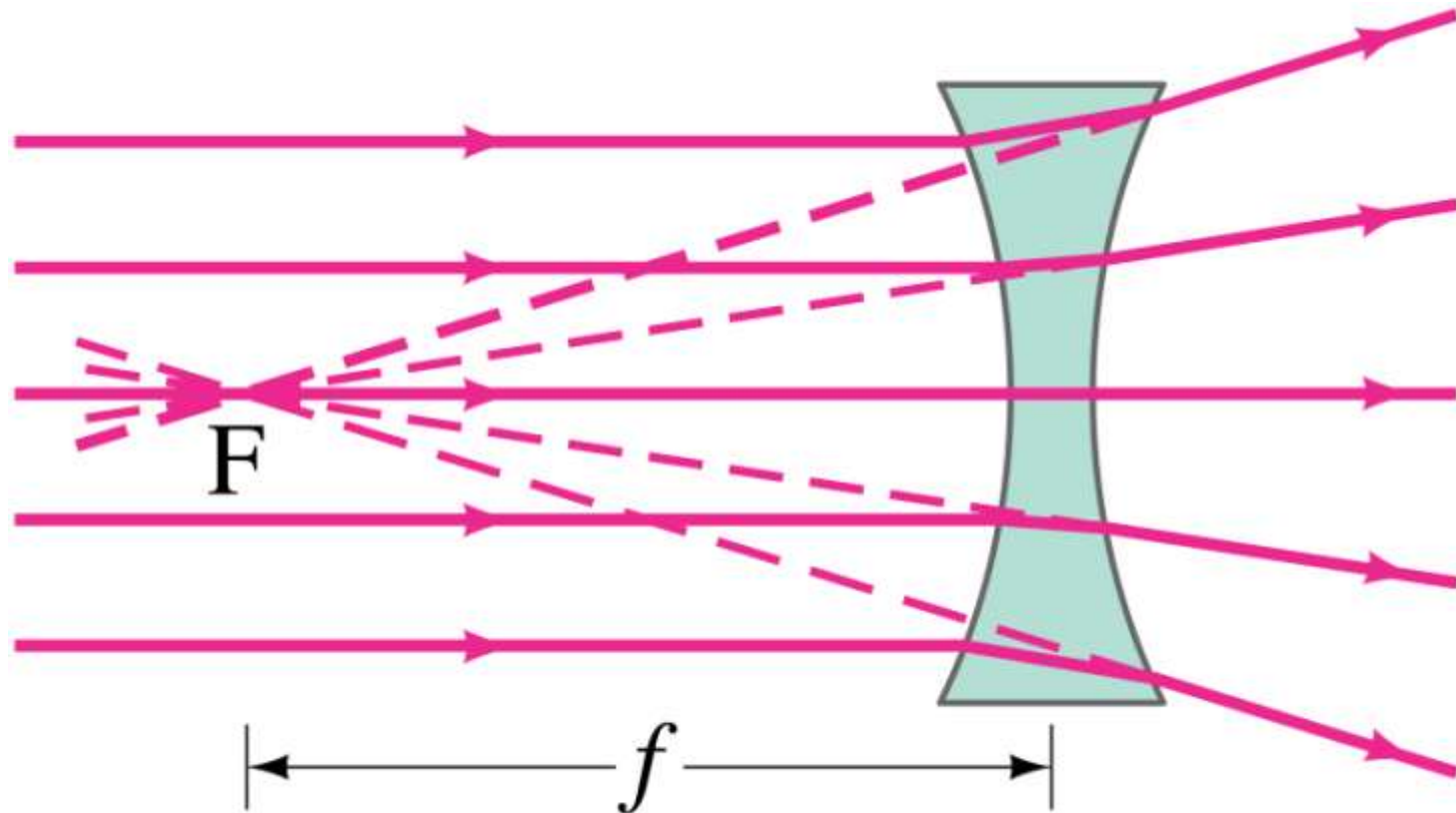
23.7 Thin Lenses; Ray Tracing

The power of a lens is the inverse of its focal length.

$$P = \frac{1}{f}$$ (23-7)

Lens power is measured in diopters, D.

$1\ D = 1\ m^{-1}$

23.7 Thin Lenses; Ray Tracing

Ray tracing for thin lenses is similar to that for mirrors. We have three key rays:

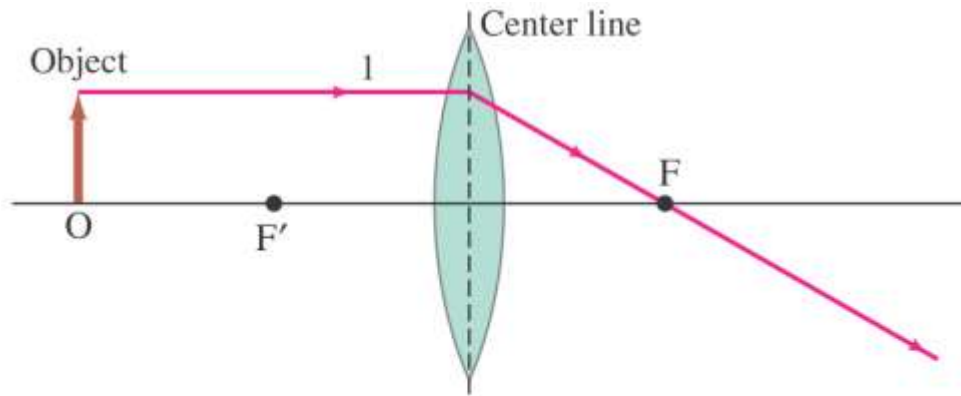1. This ray comes in parallel to the axis and exits through the focal point.

2. This ray comes in through the focal point and exits parallel to the axis.

3. This ray goes through the center of the lens and is undeflected.

23.7 Thin Lenses; Ray Tracing

Center line

Object

1

F

O   F′

(a) Ray 1 leaves one point on object going parallel to the axis, then refracts through focal point behind.

1

1

F   I

F′

2

2
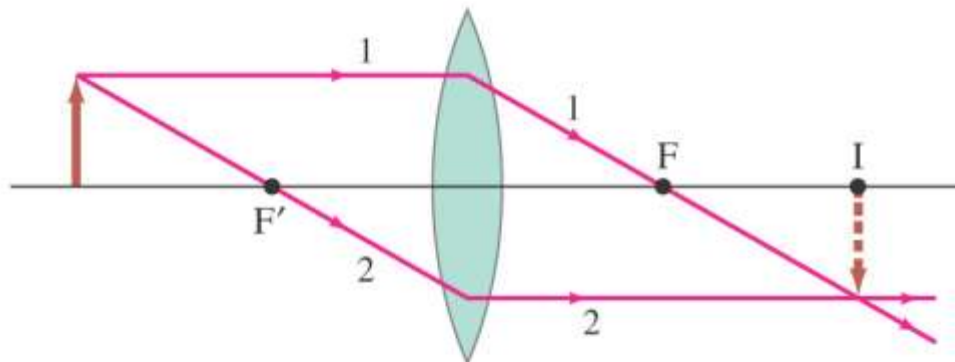
(b) Ray 2 passes through F′ in front of the lens; therefore it is parallel to the axis behind the lens.

Object

1

3

F   I

O   F′

2
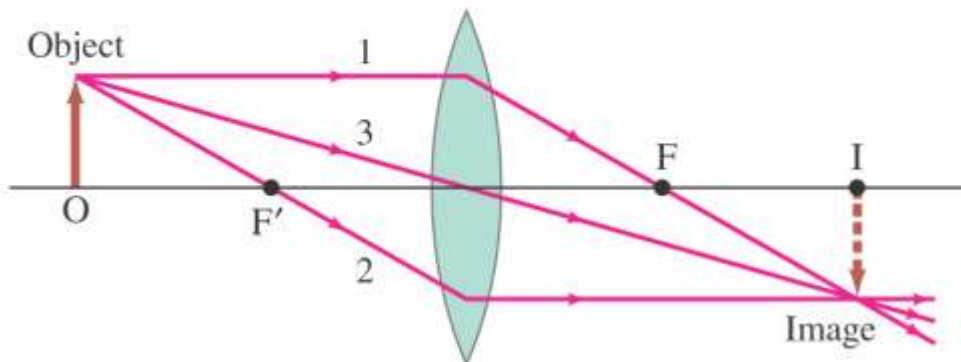
Image

(c) Ray 3 passes straight through the center of the lens (assumed very thin).

23.7 Thin Lenses; Ray Tracing

For a diverging lens, we can use the same three rays; the image is upright and virtual.

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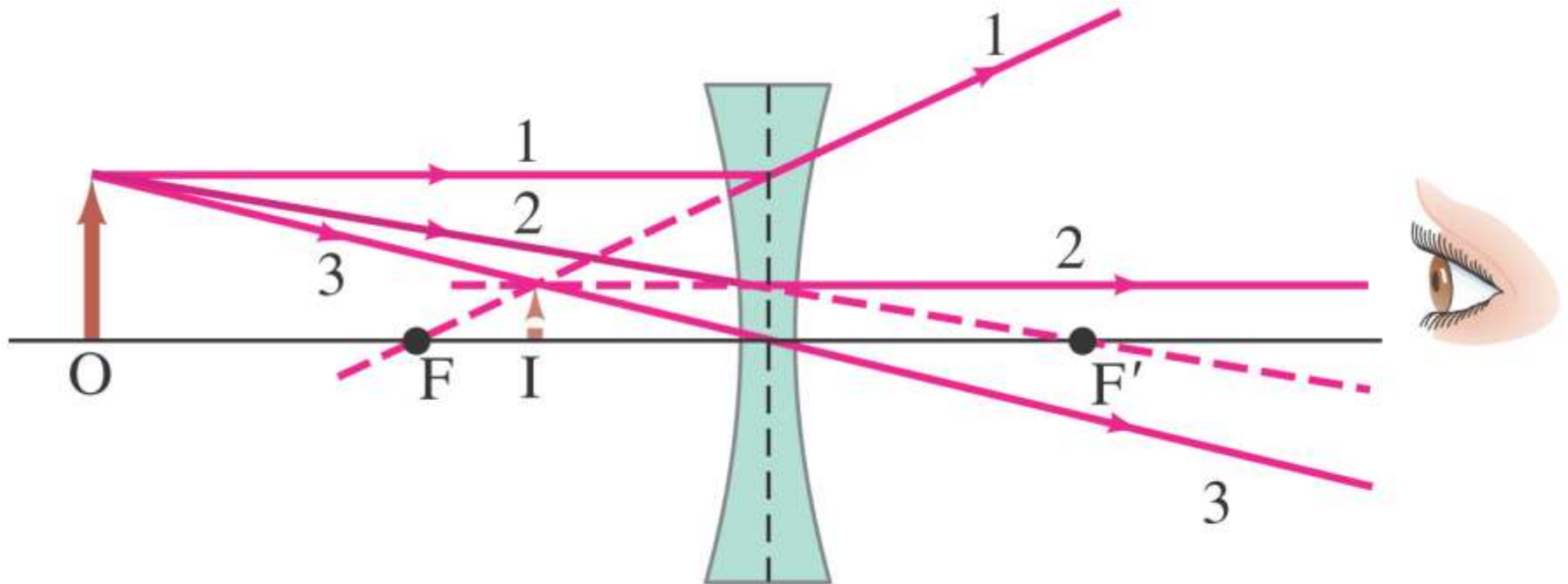
23.8 The Thin Lens Equation; Magnification

The thin lens equation is the same as the mirror equation:

$$\frac{1}{d_\text{o}} + \frac{1}{d_\text{i}} = \frac{1}{f}$$

(23-8)

23.8 The Thin Lens Equation; Magnification

The sign conventions are slightly different:

1. The focal length is positive for converging lenses and negative for diverging.

2. The object distance is positive when the object is on the same side as the light entering the lens (not an issue except in compound systems); otherwise it is negative.

3. The image distance is positive if the image is on the opposite side from the light entering the lens; otherwise it is negative.

4. The height of the image is positive if the image is upright and negative otherwise.

23.8 The Thin Lens Equation; Magnification

The magnification formula is also the same as that for a mirror:

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o} \qquad \textbf{(23-9)}$$

The power of a lens is positive if it is converging and negative if it is diverging.

23.8 The Thin Lens Equation; Magnification

Problem Solving: Thin Lenses

1. Draw a ray diagram. The image is located where the key rays intersect.

2. Solve for unknowns.

3. Follow the sign conventions.

4. Check that your answers are consistent with the ray diagram.

23.9 Combinations of Lenses

In lens combinations, the image formed by the first lens becomes the object for the second lens (this is where object distances may be negative).

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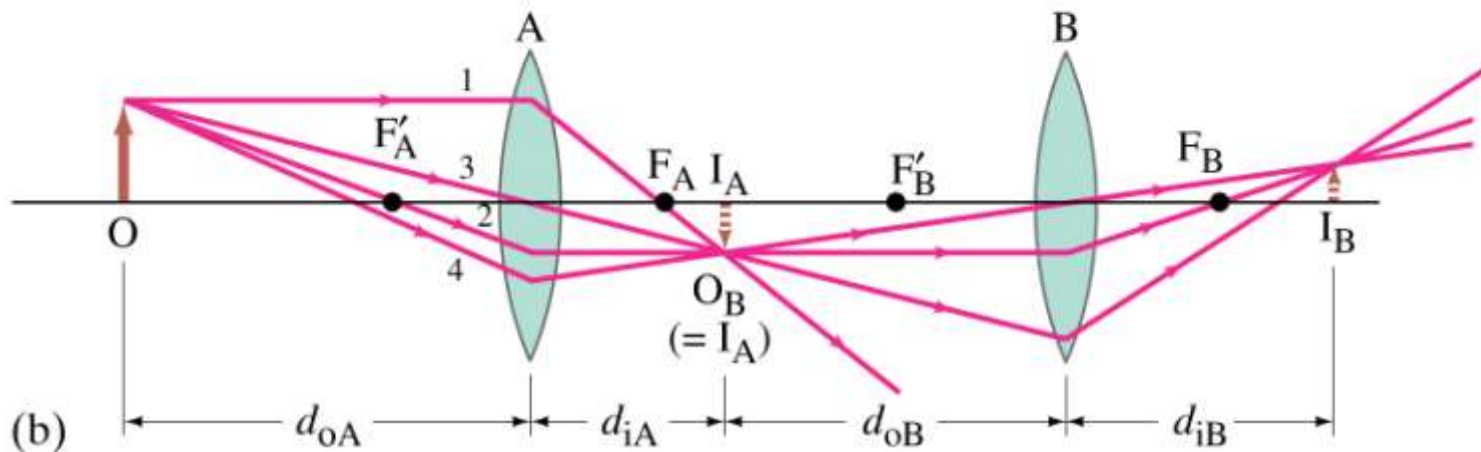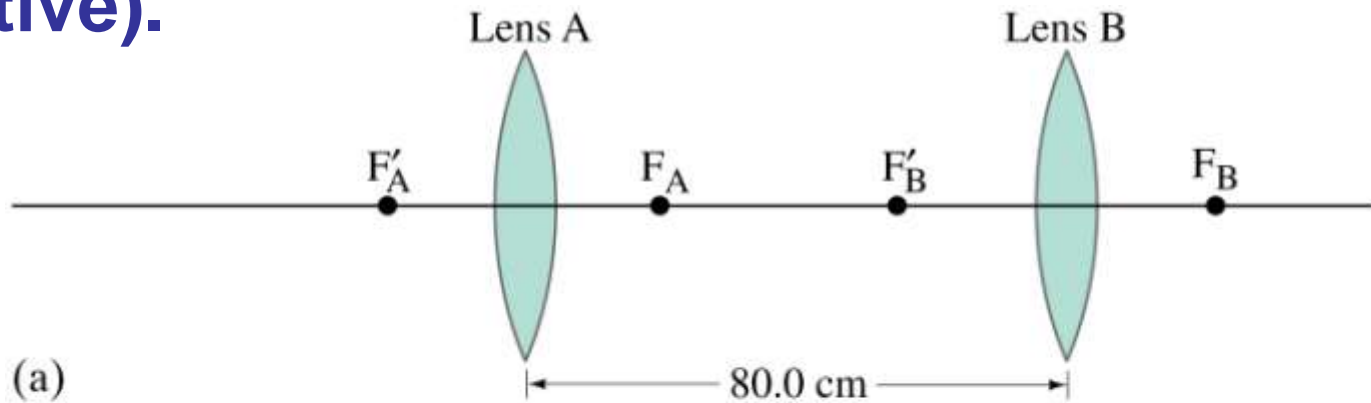
23.10 Lensmaker's Equation

This useful equation relates the radii of curvature of the two lens surfaces, and the index of refraction, to the focal length.

$$\frac{1}{f} = (n - 1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \qquad \textbf{(23-10)}$$

$R_1 = 22.4$ cm

C_1 C_2

$R_2 = -46.2$ cm
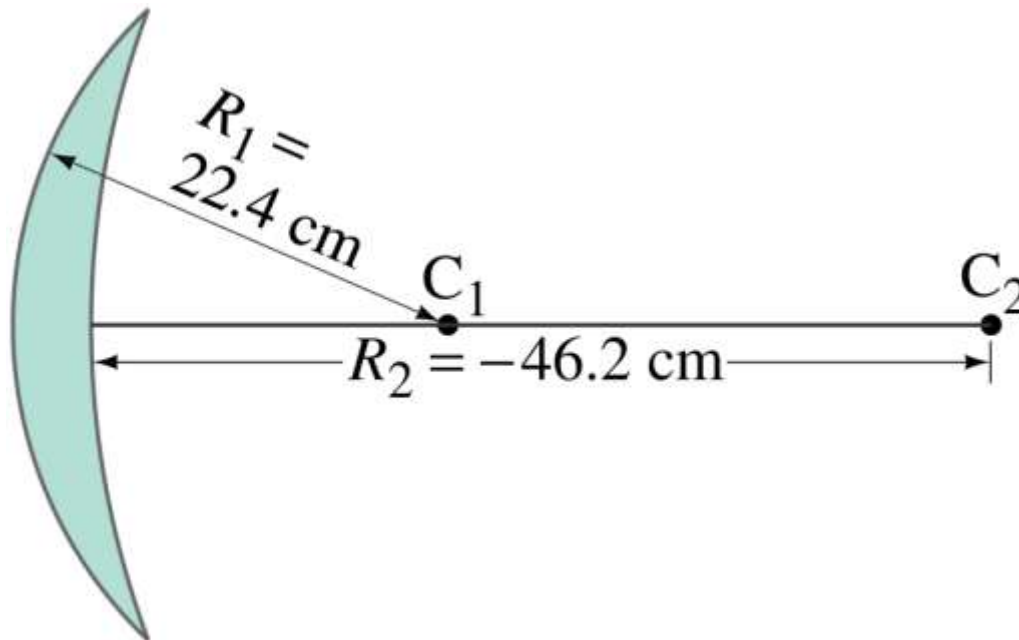
Summary of Chapter 23

- **Light paths are called rays**

- **Index of refraction:** $n = \dfrac{c}{v}$

- **Angle of reflection equals angle of incidence**

- **Plane mirror: image is virtual, upright, and the same size as the object**

- **Spherical mirror can be concave or convex**

- **Focal length of the mirror:** $f = \dfrac{r}{2}$

Summary of Chapter 23

- **Mirror equation:**

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

- **Magnification:**

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

- **Real image: light passes through it**

- **Virtual image: light does not pass through**

Summary of Chapter 23

- **Law of refraction (Snell's law):**

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

- **Total internal reflection occurs when angle of incidence is greater than critical angle:**

$$\sin \theta_C = \frac{n_2}{n_1}$$

- **A converging lens focuses incoming parallel rays to a point**

Summary of Chapter 23

• A diverging lens spreads incoming rays so that they appear to come from a point

• Power of a lens: $P = 1/f$

• Thin lens equation:

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

• Magnification:

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