Mirrors and Lenses

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. A flat mirror *always* produces a virtual image.

No light ray from the object can exist behind the mirror, so the light rays in front of the mirror only seem to be diverging from I.

There are an infinite number of choices of direction in which light rays could leave each point on the object.

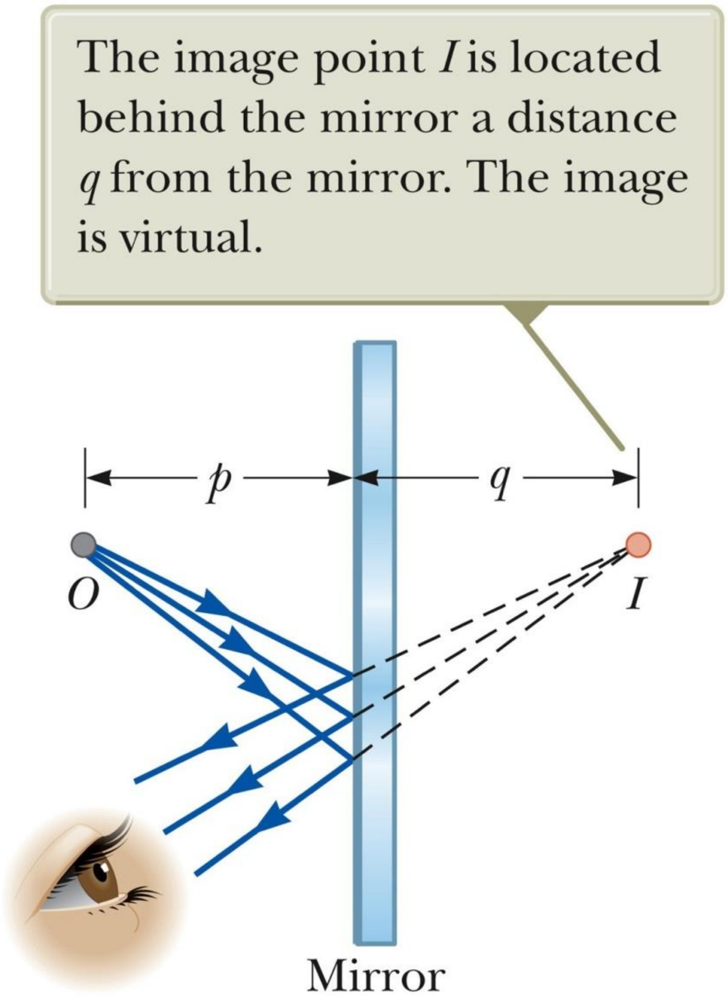


Image of Formation

Images can result when light rays encounter flat or curved surfaces between two media.

Images can be formed either by reflection or refraction due to these surfaces.

Mirrors and lenses can be designed to form images with desired characteristics.

Notation for Mirrors and Lenses

The **object distance** is the distance from the object to the mirror or lens.

- Denoted by p

The **image distance** is the distance from the image to the mirror or lens.

- Denoted by q

The **lateral magnification** of the mirror or lens is the ratio of the image height to the object height.

- Denoted by M

Images

Images are always located by extending diverging rays back to a point at which they intersect.

Images are located either at a point from which the rays of light *actually* diverge or at a point from which they *appear* to diverge.

A *real image* is formed when light rays pass through and diverge from the image point.

- Real images can be displayed on screens.

A *virtual image* is formed when light rays do not pass through the image point but only appear to diverge from that point.

- Virtual images cannot be displayed on screens.

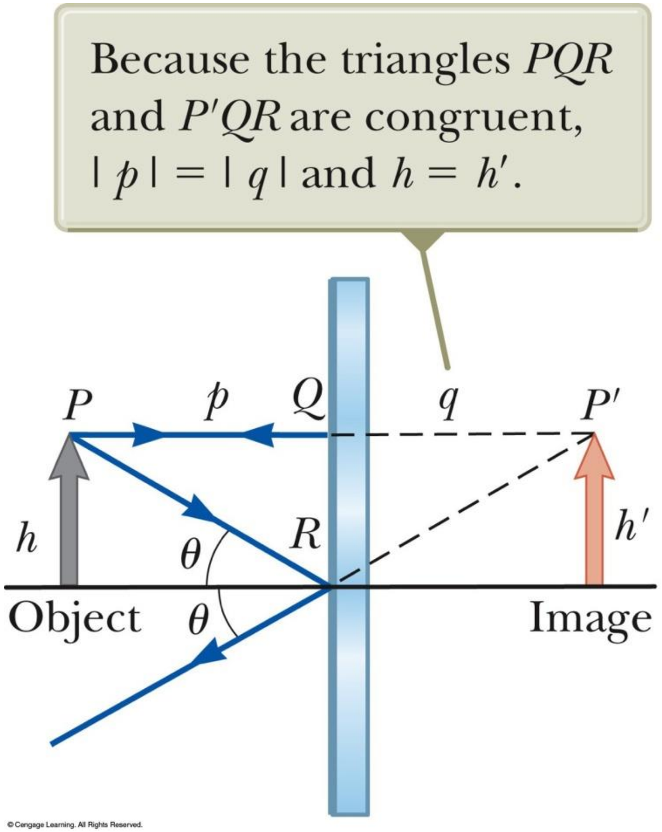
Images Formed by Flat Mirrors, Geometry

Two rays are needed to determine where an image is formed.

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.



Images Formed by Flat Mirrors, final

To observe the image, the observer would trace back the two reflected rays to *P'.*

Point *P'* is the point where the rays appear to have originated.

The image formed by an object placed in front of a flat mirror is as far behind the mirror as the object is in front of the mirror.

- $|p| = |q|$

Reversals in a Flat Mirror

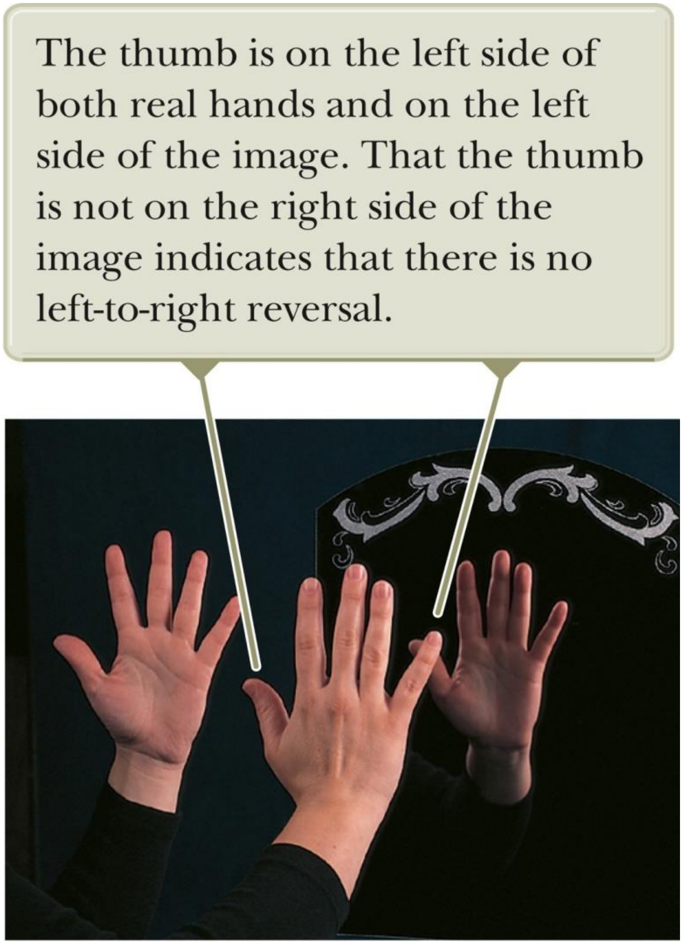
A flat mirror produces an image that has an *apparent* left-right reversal.

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

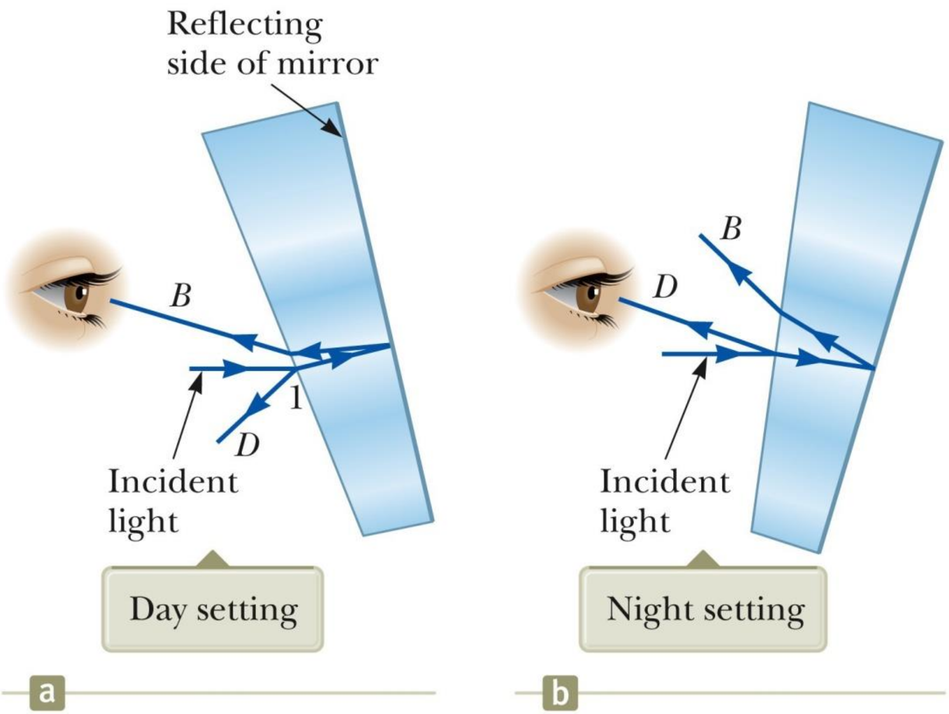
The reversal is not *actually* a left-right reversal.

The reversal is actually a *front-back* reversal.

- It is caused by the light rays going forward toward the mirror and then reflecting back from it.



Application – Day and Night Settings on Auto Mirrors



With the daytime setting, the bright beam (B) of reflected light is directed into the driver's eyes.

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

Spherical Mirrors

A **spherical mirror** has the shape of a section of a sphere.

The mirror focuses incoming parallel rays to a point.

A *concave* spherical mirror has the silvered surface of the mirror on the inner, or concave, side of the curve.

A *convex* spherical mirror has the silvered surface of the mirror on the outer, or convex, side of the curve.

Concave Mirror, Notation

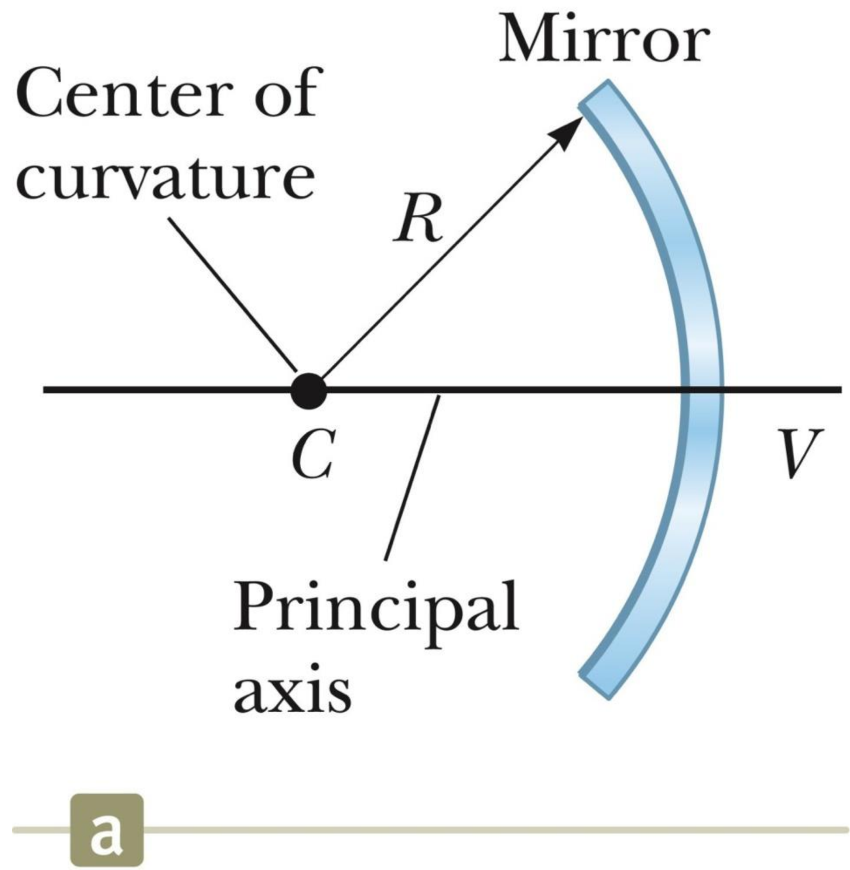
The mirror has a *radius of curvature* of *R.*

Its *center of curvature* is the point *C*

Point *V* is the center of the spherical segment.

A line drawn from *C* to *V* is called the *principal axis* of the mirror.

The blue band represents the structural support for the silvered surface.

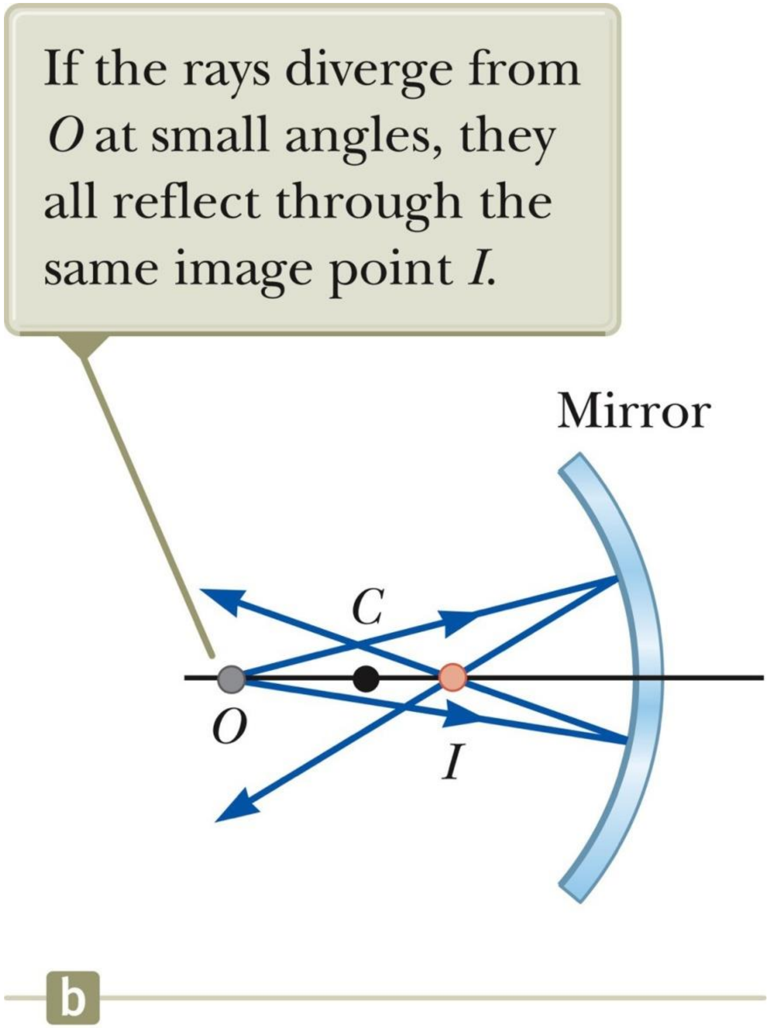


Paraxial Rays

We use only rays that diverge from the object and make a small angle with the principal axis.

Such rays are called **paraxial rays.**

All paraxial rays reflect through the image point.



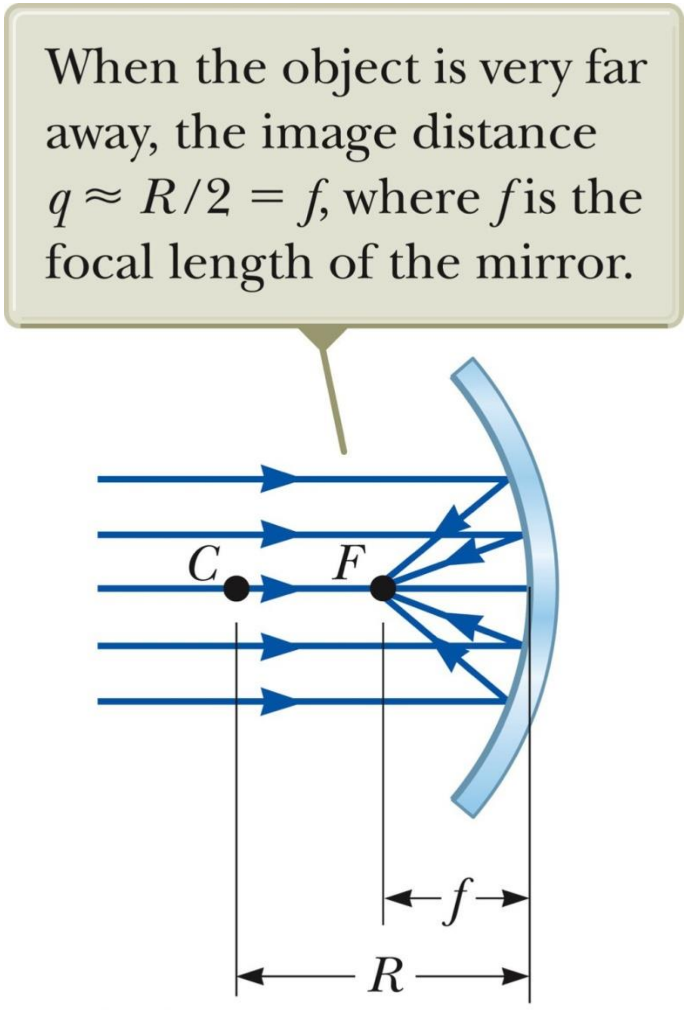
Focal Length

When the object is very far away, then p → ∞ and the incoming rays are essentially parallel.

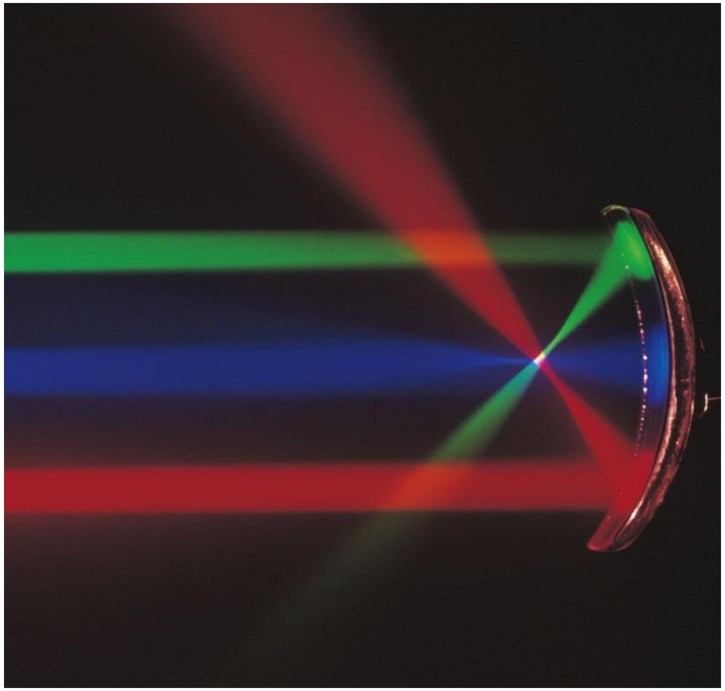
In this special case, the image point is called the **focal point.**

The distance from the mirror to the focal point is called the **focal length.**

- The focal length is ½ the radius of curvature.



Focal Point, cont.



The colored beams are traveling parallel to the principal axis.

The mirror reflects all three beams to the focal point.

The focal point is where all the beams intersect.

- The colors add to white.

Image Formed by a Concave Mirror

Distances are measured from V

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

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

- *h*’ is negative when the image is inverted with respect to the object.

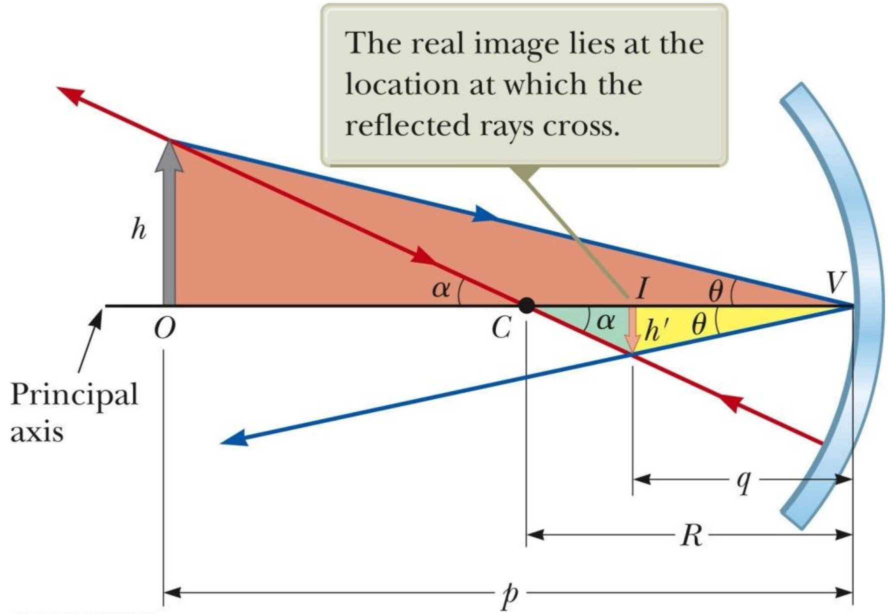


Image Formed by a Concave Mirror

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

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

- This is called the **mirror equation.**

If p is much greater than R, then the image point is half-way between the center of curvature and the center point of the mirror.

- $p \rightarrow \infty$, then $1/p \approx 0$ and $q \approx R/2$

Focal 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.

Since the focal length is related to the radius of curvature by f = R / 2, the mirror equation can be expressed as

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

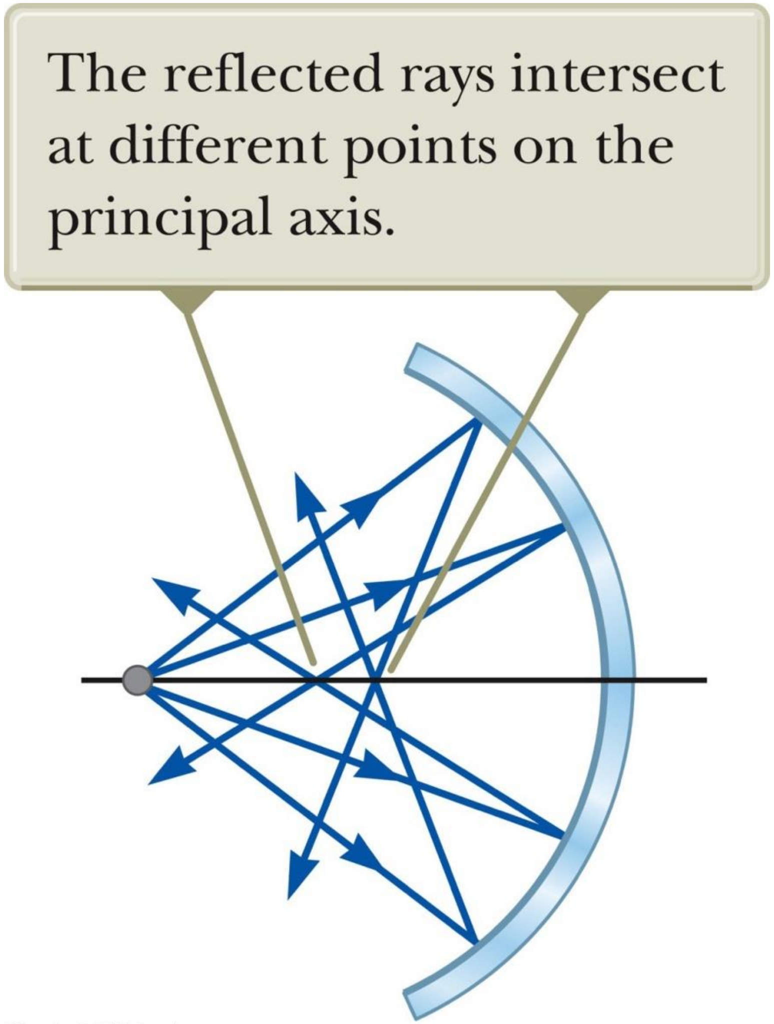
Spherical Aberration

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

- The light rays make large angles with the principal axis.

This produces a blurred image.

The effect is called **spherical aberration.**



Convex Mirrors

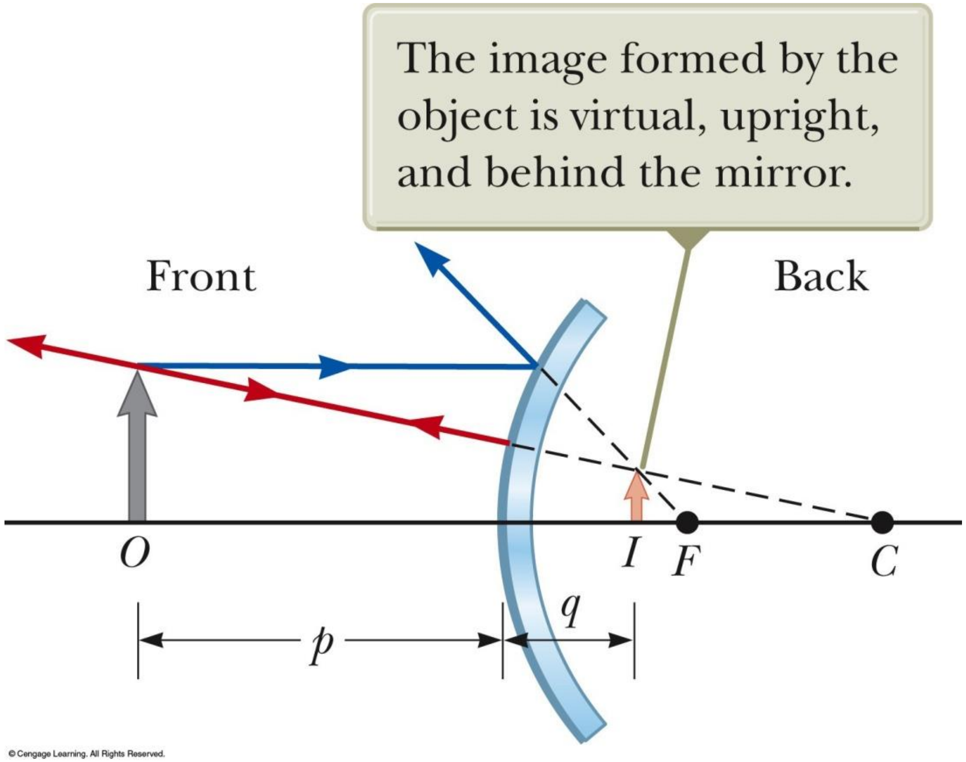
A **convex mirror** is sometimes called a *diverging mirror.*

- 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



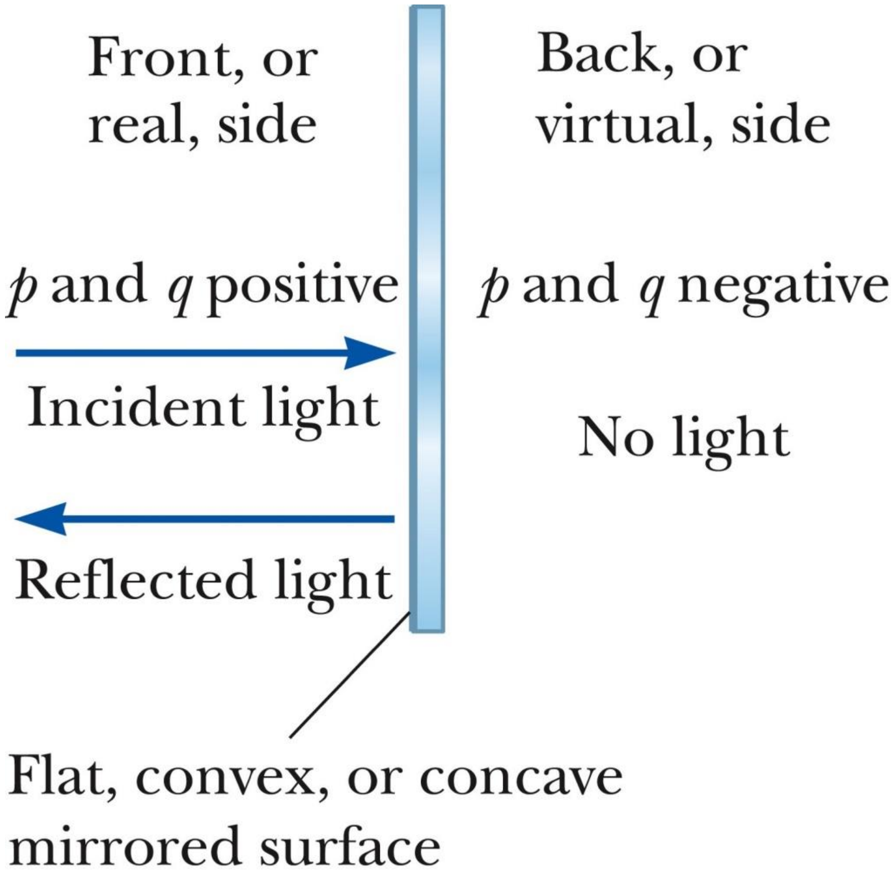
In general, the image formed by a convex mirror is upright, virtual, and smaller than the object.

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.

Be sure to use proper sign choices when substituting values into the equations.



Sign Conventions, Summary Table

Table 36.1 Sign Conventions for Mirrors

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

Ray Diagrams

A *ray diagram* can be used to determine the position and size of an image.

They are graphical constructions which reveal the nature of the image.

They can also be used to check the parameters calculated from the mirror and magnification equations.

To draw a ray diagram, you need to know:

- The position of the object
- The locations of the focal point and the center of curvature.

Three rays are drawn.

- They all start from the same position on the object.

The intersection of any two of the rays at a point locates the image.

- The third ray serves as a check of the construction.

The Rays in a Ray Diagram – Concave Mirrors

Ray 1 is drawn from the top of the object parallel to the principal axis and is reflected through the focal point, *F.*

Ray 2 is drawn from the top of the object through the focal point and is reflected parallel to the principal axis.

Ray 3 is drawn through the center of curvature, C, and is reflected back on itself.

- Draw as if coming from the center C is p $< f$

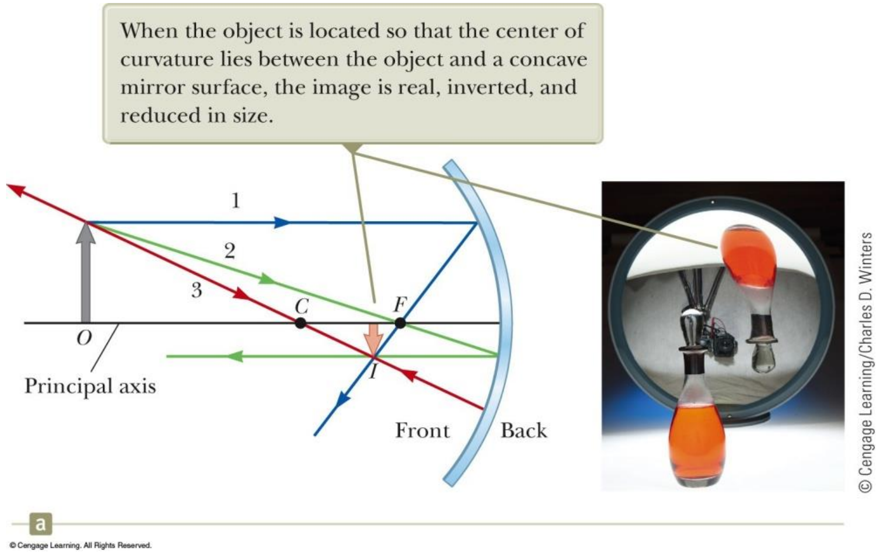
Notes About the Rays

A huge number of rays actually go in all directions from the object.

The three rays were chosen for their ease of construction.

The image point obtained by the ray diagram must agree with the value of q calculated from the mirror equation.

Ray Diagram for a Concave Mirror, p > R



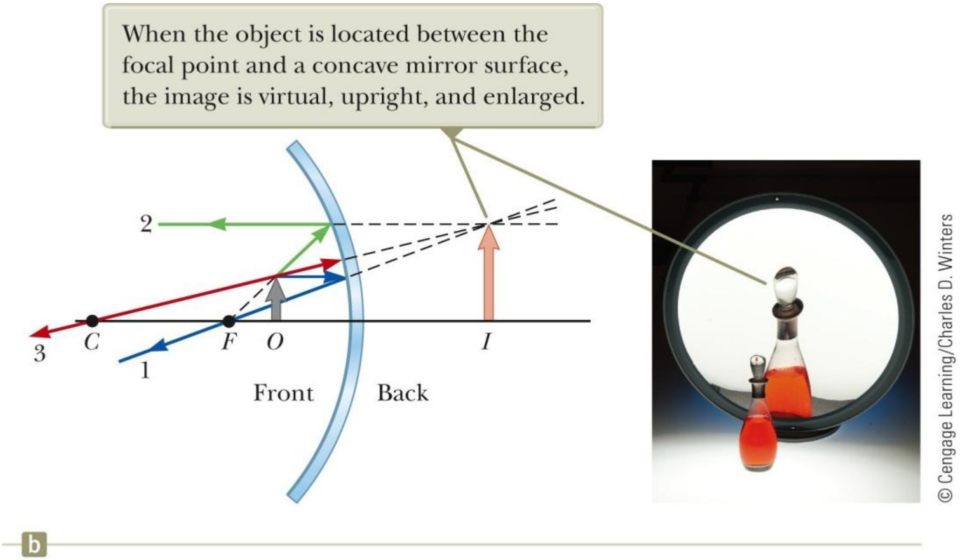
The center of curvature is between the object and the concave mirror surface.

The image is real.

The image is inverted.

The image is smaller than the object (reduced).

Ray Diagram for a Concave Mirror, *p* < *f*



The object is between the mirror surface and the focal point.

The image is virtual.

The image is upright.

The image is larger than the object (enlarged).

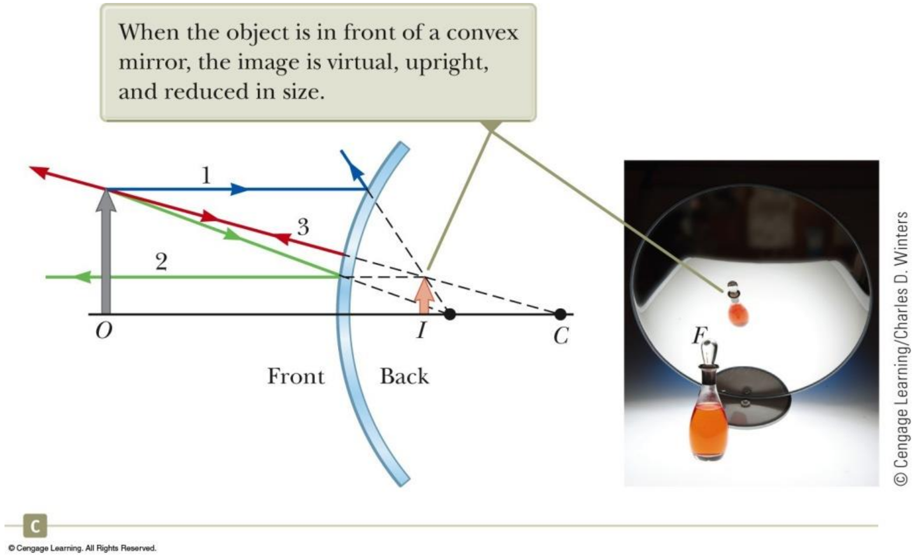
The Rays in a Ray Diagram – Convex Mirrors

Ray 1 is drawn from the top of the object parallel to the principal axis and is reflected away from the focal point, *F.*

Ray 2 is drawn from the top of the object toward the focal point and is reflected parallel to the principal axis.

Ray 3 is drawn through the center of curvature, C, on the back side of the mirror and is reflected back on itself.

Ray Diagram for a Convex Mirror



The object is in front of a convex mirror.

The image is virtual.

The image is upright.

The image is smaller than the object (reduced).

Notes on Images

With a concave mirror, the image may be either real or virtual.

- When the object is outside the focal point, the image is real.
- When the object is at the focal point, the image is infinitely far away.
- When the object is between the mirror and the focal point, the image is virtual.

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

- As the object distance decreases, the virtual image increases in size.

Images Formed by Refraction

Consider two transparent media having indices of refraction n_1 and n_2.

The boundary between the two media is a spherical surface of radius *R.*

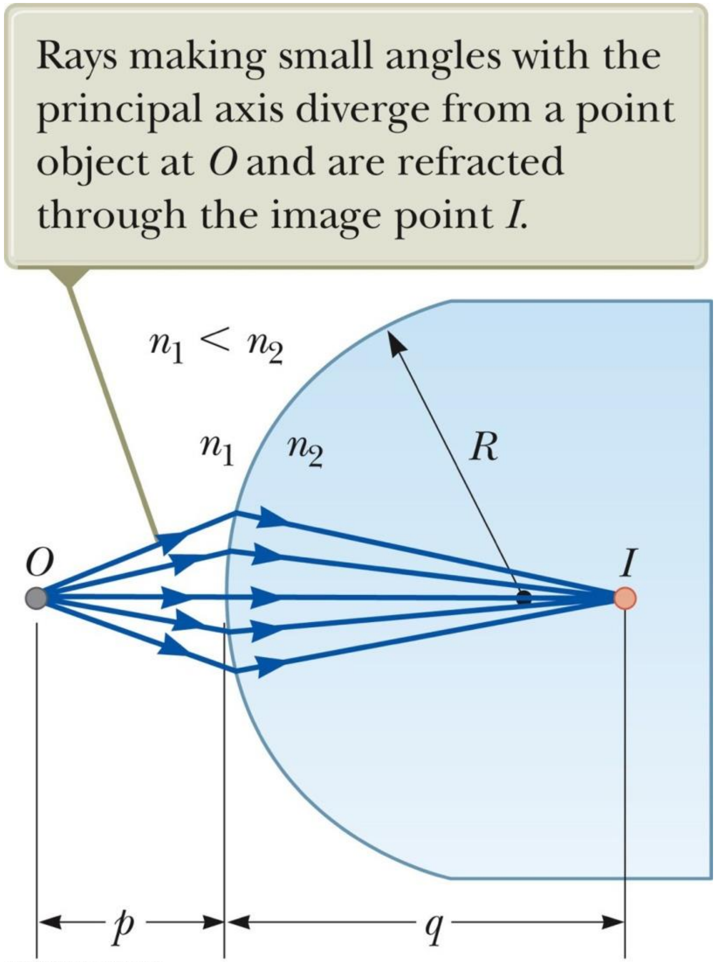
Rays originate from the object at point *O* in the medium with $n = n_1$.

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

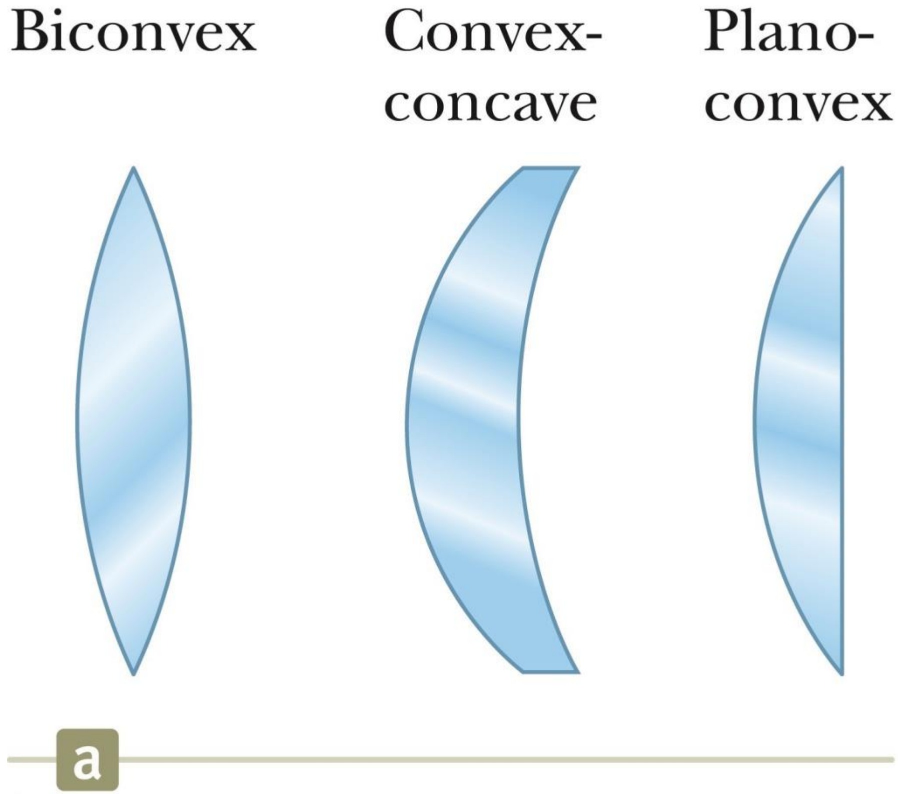
Quantity	Positive When . . .	Negative When . . .
Object location (p)	object is in front of surface (real object).	object is in back of surface (virtual object).
Image location (q)	image is in back of surface (real image).	image is in front of surface (virtual image).
Image height (h')	image is upright.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

Thin Lens Shapes - *converging* lenses.

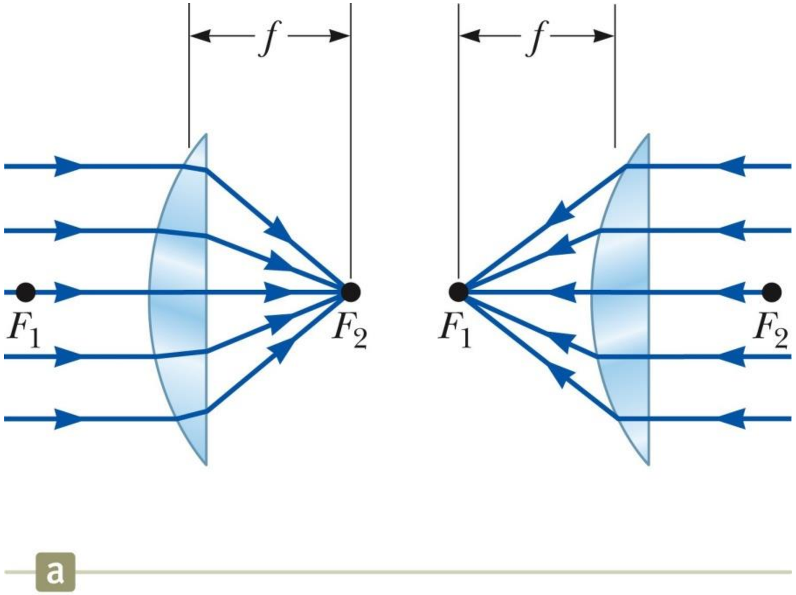
These are examples of *converging* lenses.

They have positive focal lengths.

They are thickest in the middle.



Focal Length of a Converging Lens



The parallel rays pass through the lens and converge at the focal point.

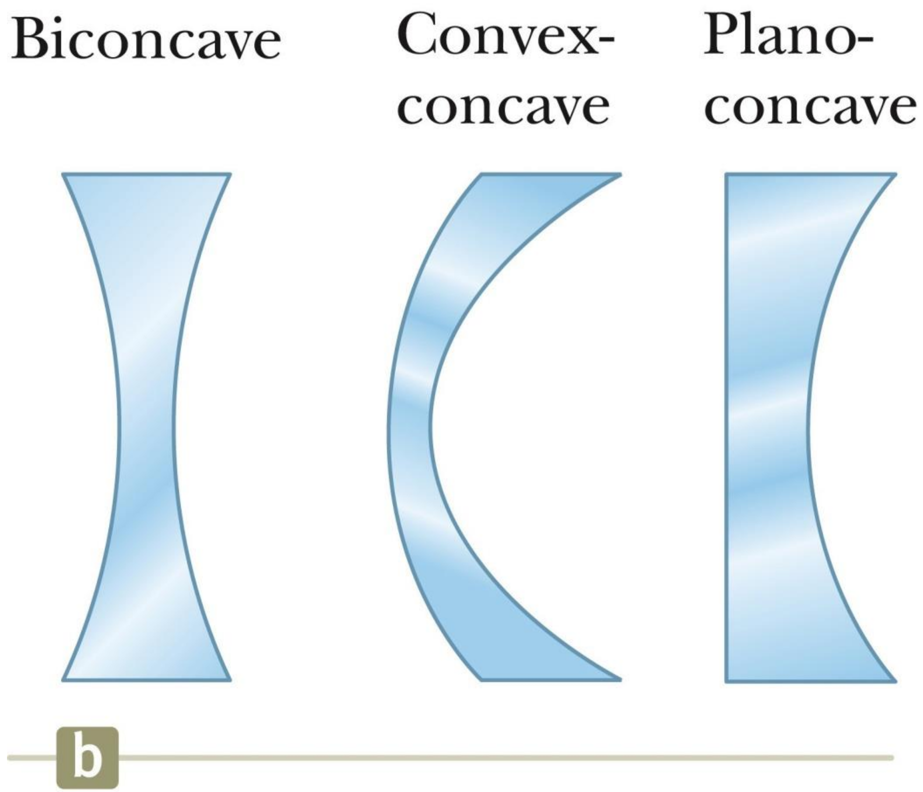
The parallel rays can come from the left or right of the lens.

More Thin Lens Shapes - *diverging* lenses.

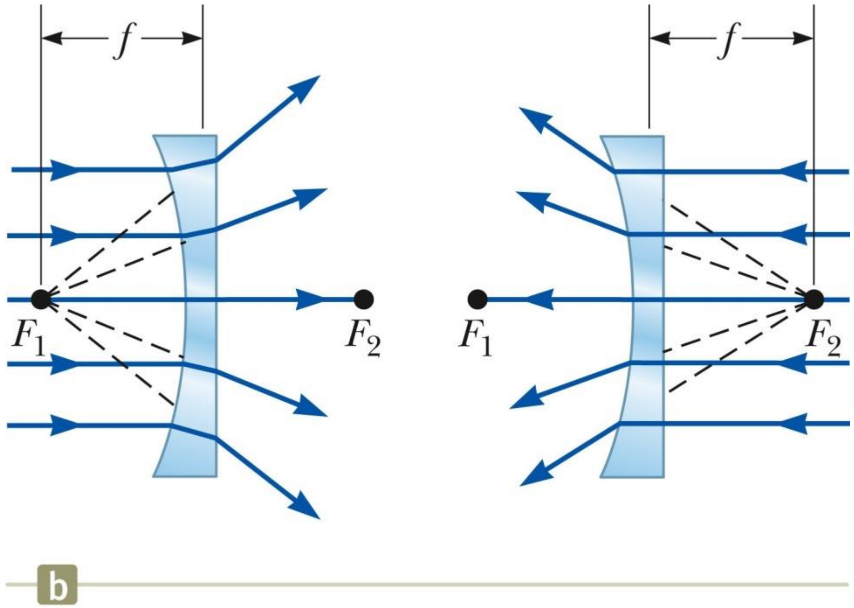
These are examples of *diverging* lenses.

They have negative focal lengths.

They are thickest at the edges.



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.

Images Formed by Lenses

Lenses are commonly used to form images by refraction.

Lenses are used in optical instruments.

- Cameras
- Telescopes
- Microscopes

Light passing through a lens experiences refraction at two surfaces.

The image formed by one refracting surface serves as the object for the second surface.

Lens-makers' Equation

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

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

Image Formed by a Thin Lens

A thin lens is one whose thickness is small compared to the radii of curvature.

For a thin lens, the thickness of the lens can be neglected.

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.

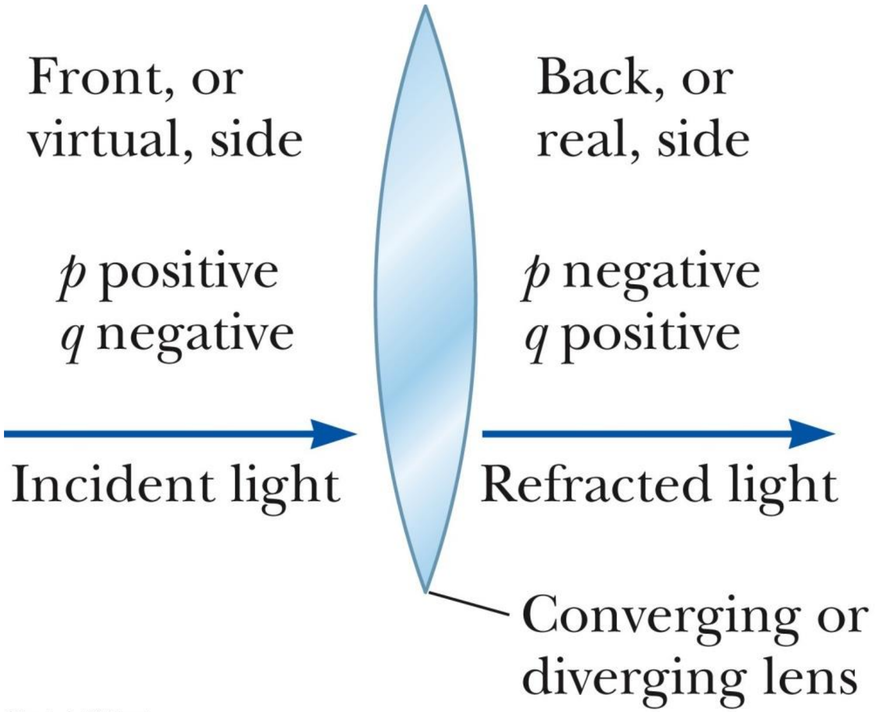
Each focal point is located the same distance from the lens.

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.

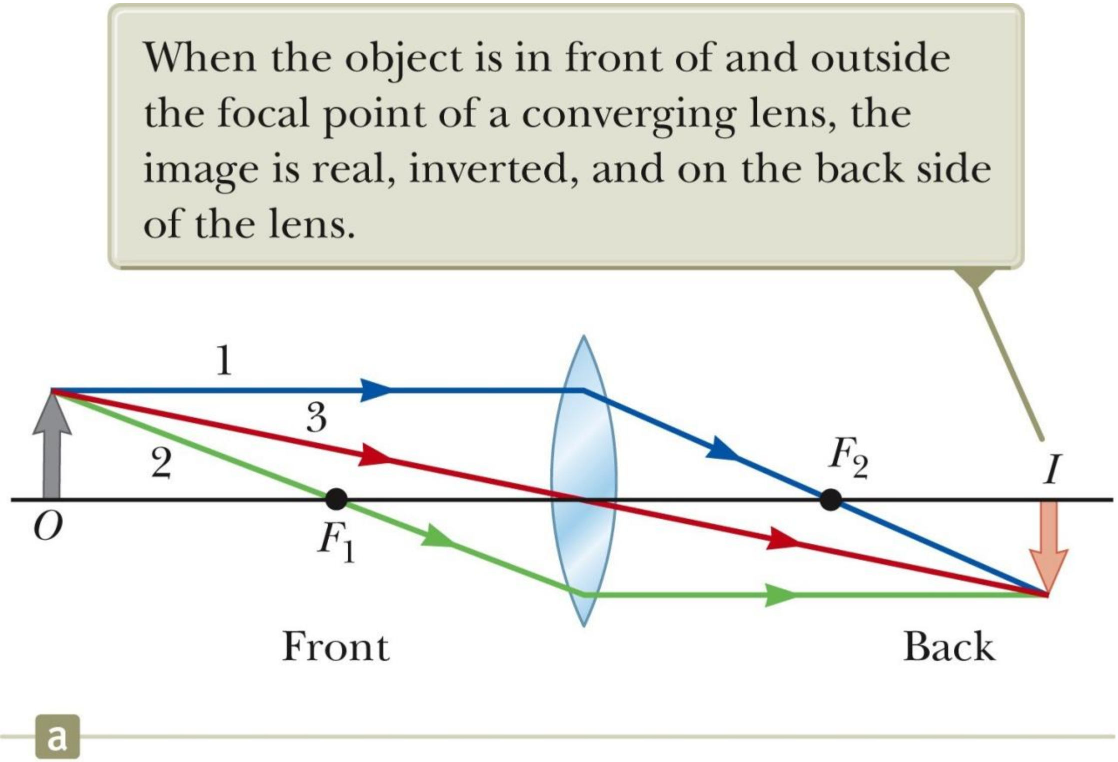
Ray Diagrams for Thin Lenses – Converging

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, $p > f$

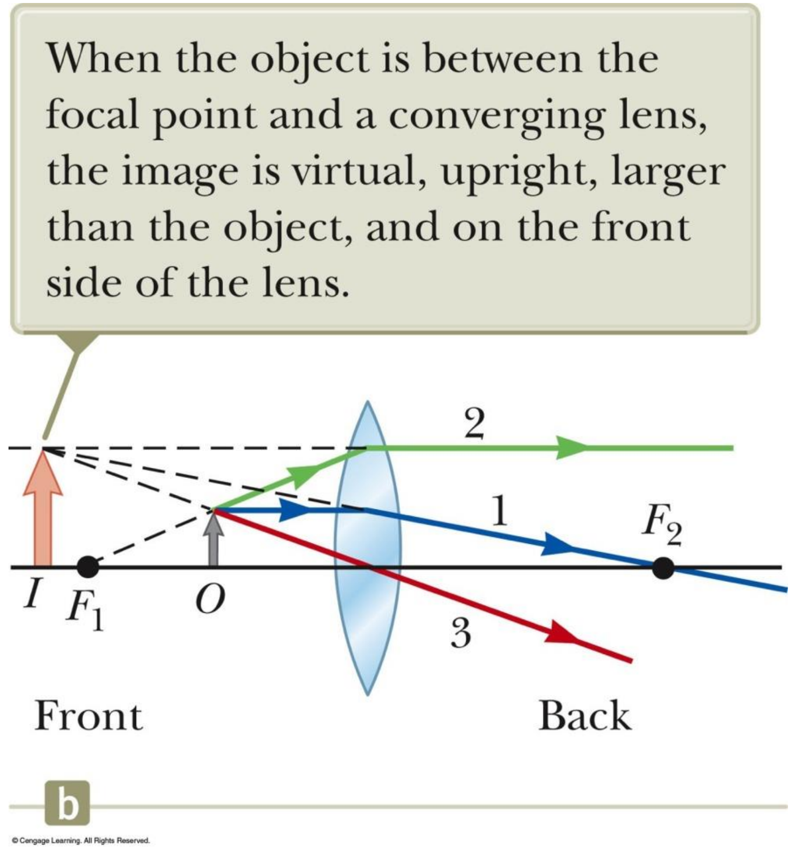


The image is real.

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.

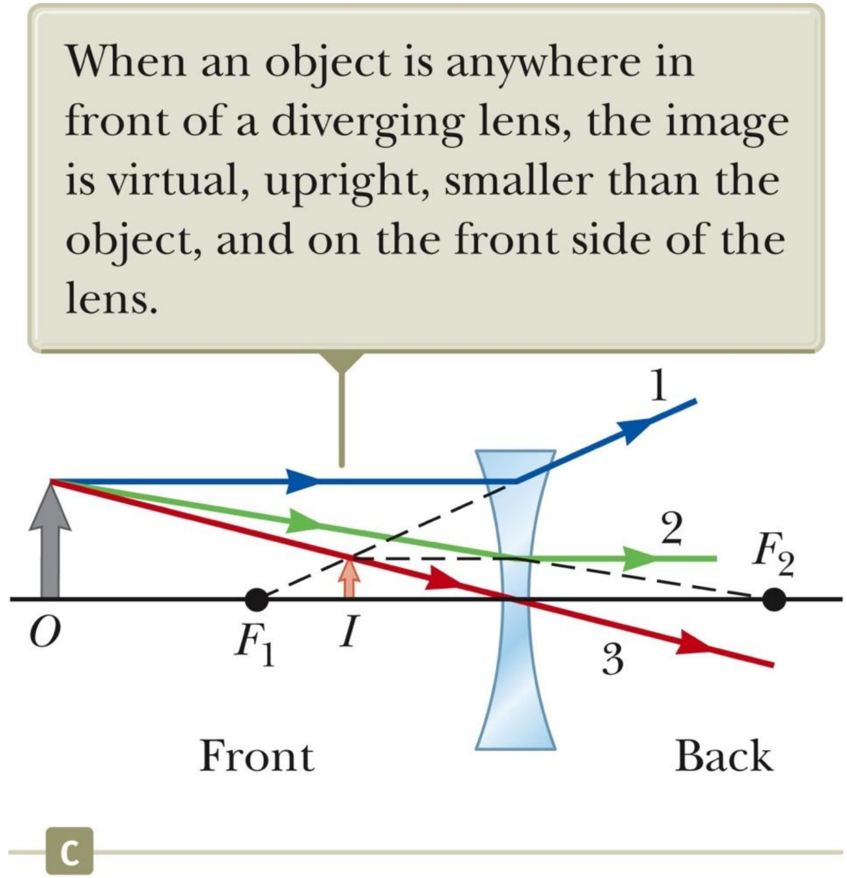
The image is on the front side of the lens.

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.

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.

Combinations of Thin Lenses

The image formed by the first lens is located as though the second lens were not present.

Then a ray diagram is drawn for the second lens.

The image of the first lens is treated as the object of the second lens.

The image formed by the second lens is the final image of the system.

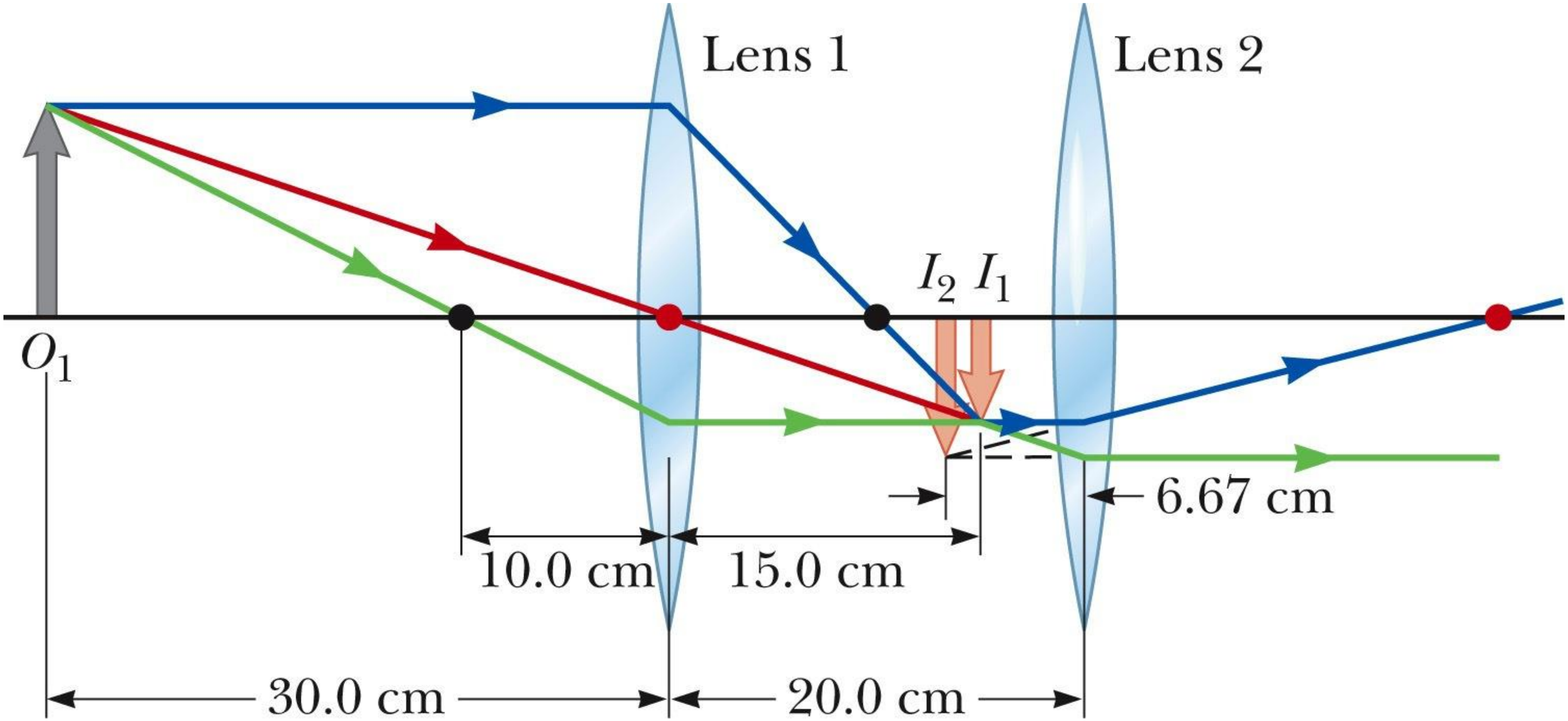
If the image formed by the first lens lies on the back side of the second lens, then the image is treated as a *virtual object* for the second lens.

- p will be negative

The same procedure can be extended to a system of three or more lenses.

The overall magnification is the product of the magnification of the separate lenses.

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.

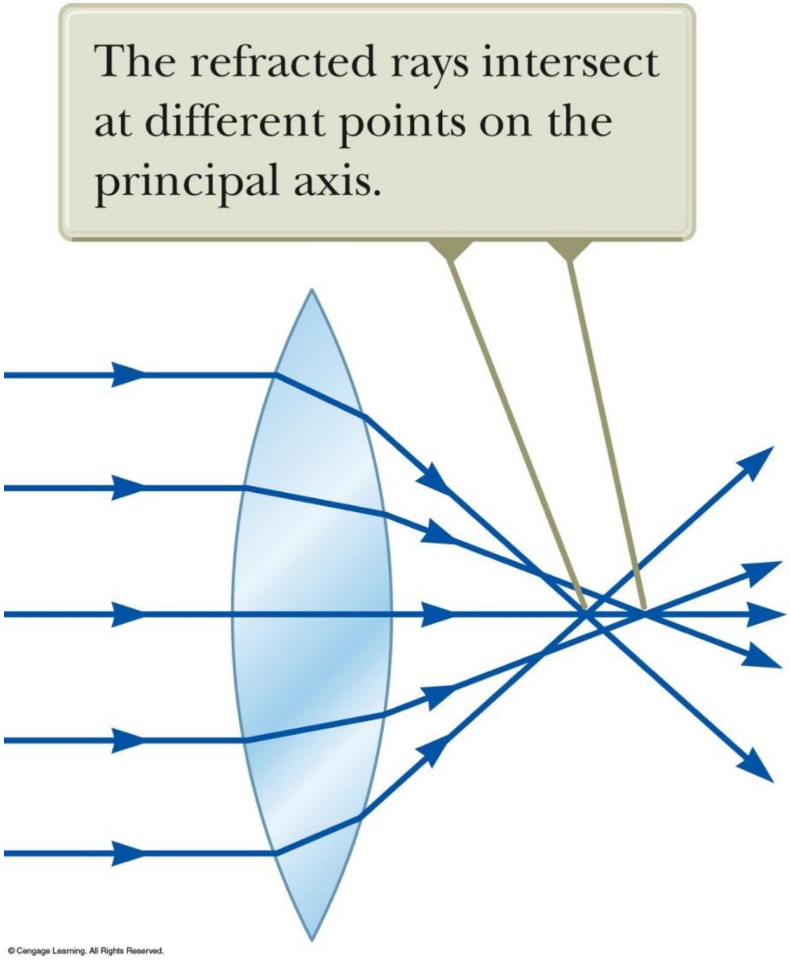
The departures of actual images from the ideal predicted by our model are called **aberrations.**

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.

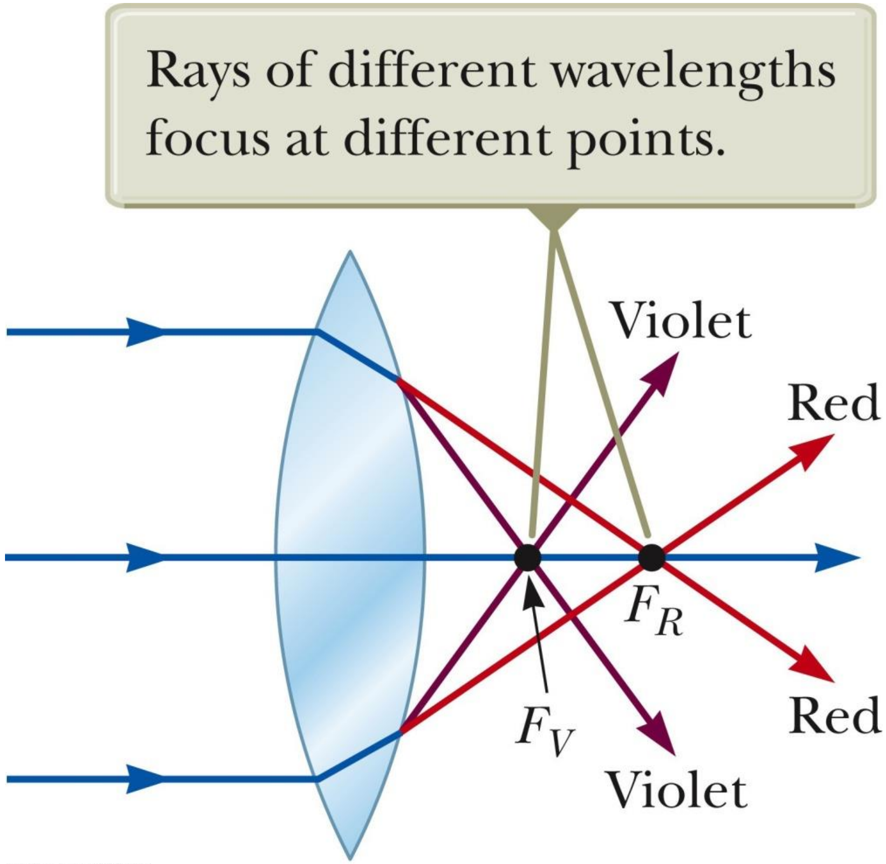


Chromatic Aberration

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.



Fresnel Lens

Refraction occurs only at the surfaces of the lens.

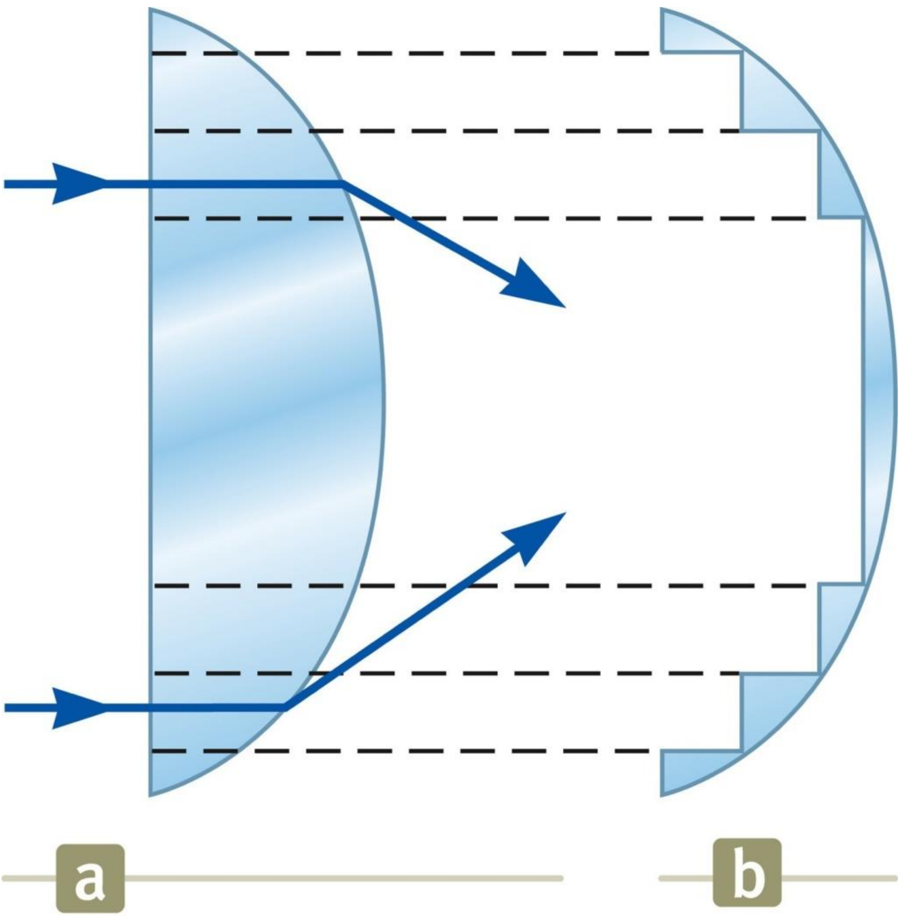
A *Fresnel lens* is designed to take advantage of this fact.

It produces a powerful lens without great thickness.

Only the surface curvature is important in the refracting qualities of the lens.

The material in the middle of the Fresnel lens is removed.

Because the edges of the curved segments cause some distortion, Fresnel lenses are usually used only in situations where image quality is less important than reduction of weight.



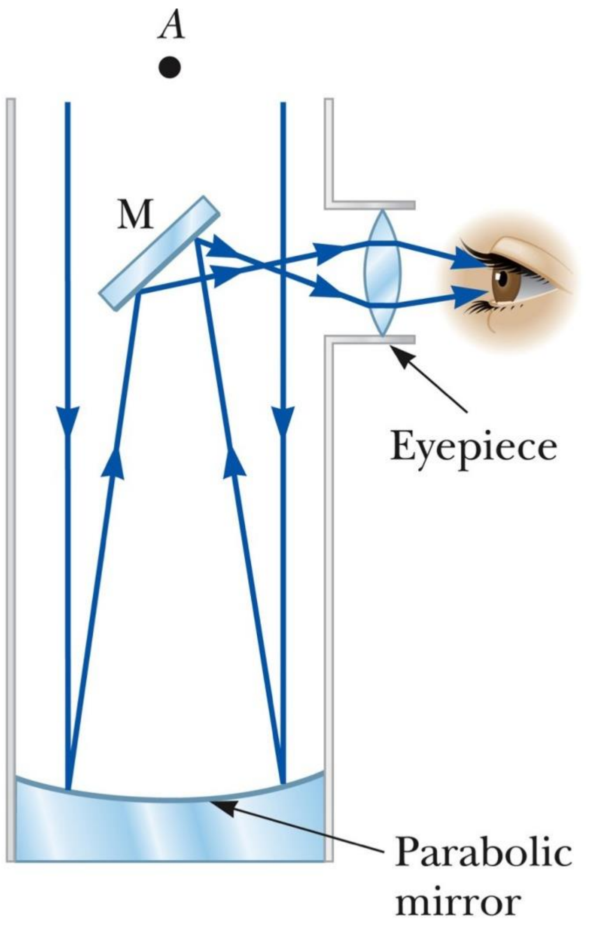
Reflecting Telescope, Newtonian Focus

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.*



Summary

- Flat mirrors
- Spherical mirrors
- Thin lenses
- Combination of lenses
- Lens aberrations