Chapter 36

Image Formation

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.

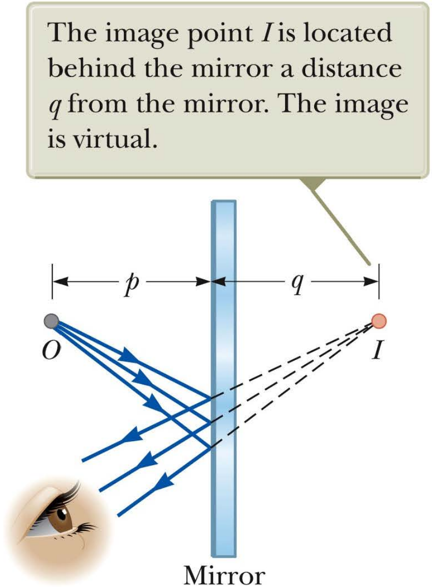
- Denoted by p

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 all light rays pass through and diverge from the image point.

- Real images can be displayed on screens.

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

- Virtual images cannot be displayed on screens.

Images Formed by Flat Mirrors

Simplest possible mirror.

Light rays leave the source and are reflected from the mirror.

Point I is called the **image** of the object at point *O*.

The image is virtual .

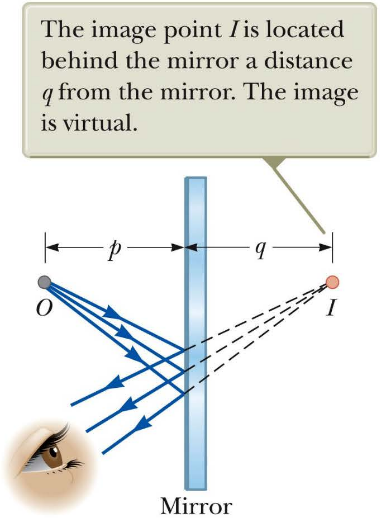
No light ray from the object can exist behind the mirror, so the light rays in front of the mirror only seem to be diverging from *I*.

A flat mirror *always* produces a virtual image.

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

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

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



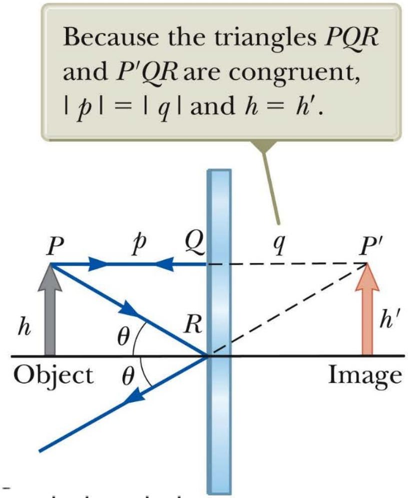
Images Formed by Flat Mirrors, Geometry

One ray starts at point *P*, travels to *Q* and reflects back on itself.

Another ray follows the path *PR* and reflects according to the law of reflection.

An observer in front of the mirror would extend the two reflected rays back to the point at which they appear to have originated, which is point *P* ‘ behind the mirror.

A continuation of this process for points other than *P* on the object would result in a virtual image (represented by a pink arrow) of the entire object behind the mirror.



The triangles *PQR* and *P’QR* are congruent. $PQ = P'Q$, so $|p| = |q|$

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.

Lateral Magnification

Lateral magnification, *M*, is defined as

$$M = \frac{\text{image height}}{\text{object height}} = \frac{h'}{h}$$

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

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
- By upright we mean that if the object arrow points upward as, so does the image arrow.

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.

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

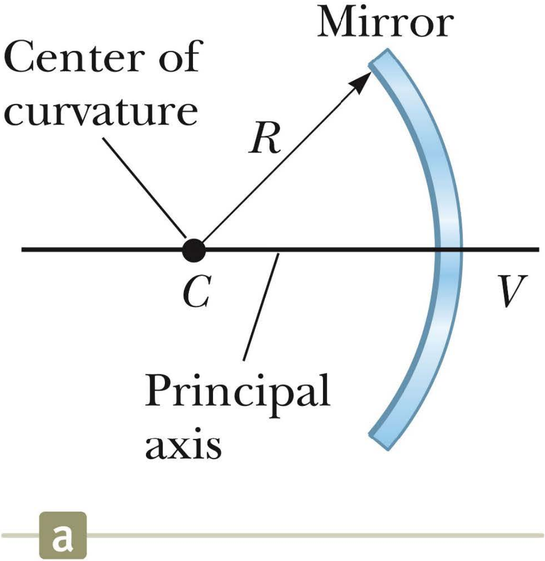
The mirror has a *radius of curvature* of *R.*

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.

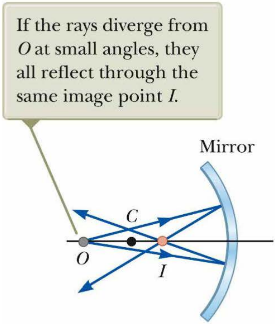


Paraxial Rays

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.



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.

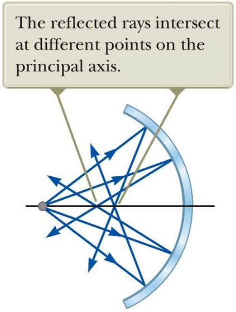


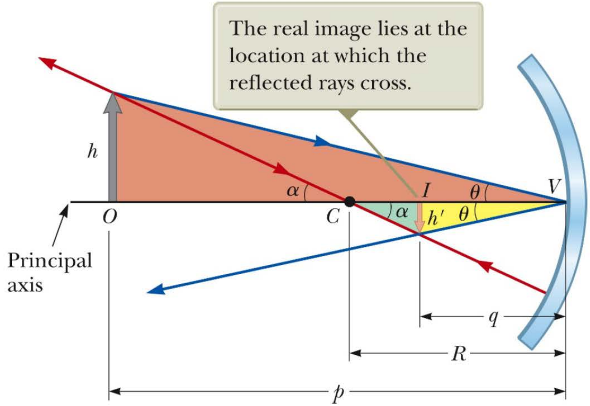
Image Formed by a Concave Mirror

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.



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 → ∞ , then 1/p → 0 and q = R/2.

Focal Length

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

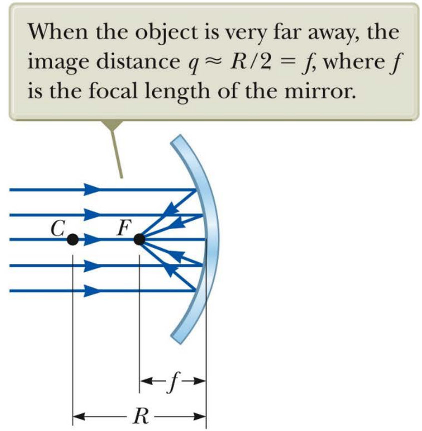
In this special case, the image point is called the **focal point.**

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

- The focal length is ½ the radius of curvature, f = R/2

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

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



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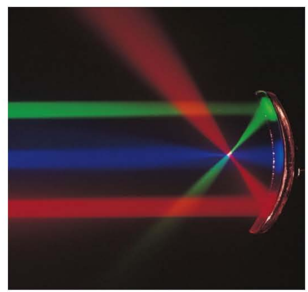

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Convex Mirrors

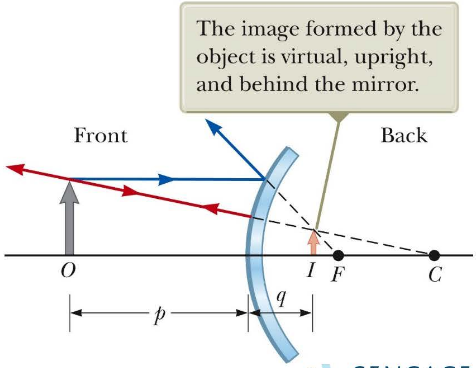
A **convex mirror** is sometimes called a *diverging mirror.*

- The light reflects from the outer, convex side.

The rays from any point on the object diverge after reflection as though they were coming from some point behind the mirror.

The image is virtual because the reflected rays only appear to originate at the image point.

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.

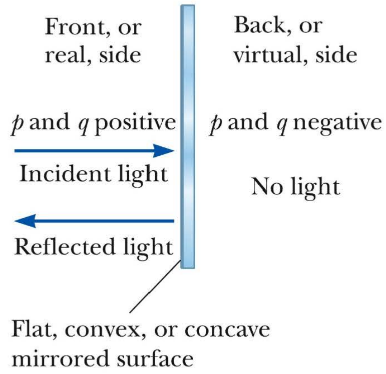


TABLE 36.1 *Sign Conventions for Mirrors*

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.

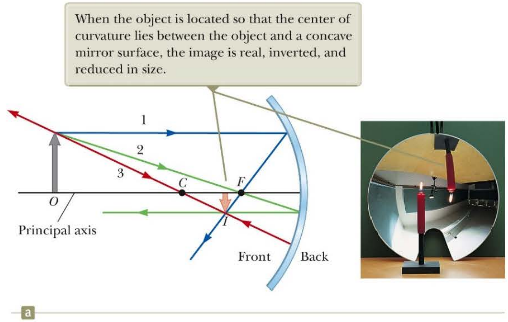
Ray Diagram for a Concave Mirror, p > R

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).



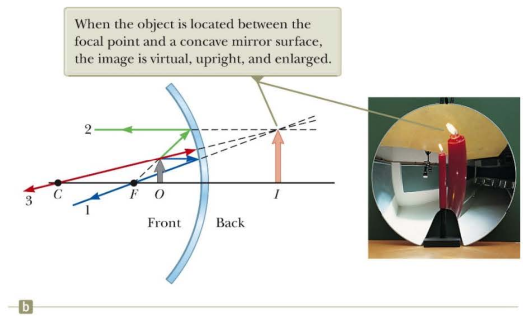
Ray Diagram for a Concave Mirror, *p* < *f*

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).



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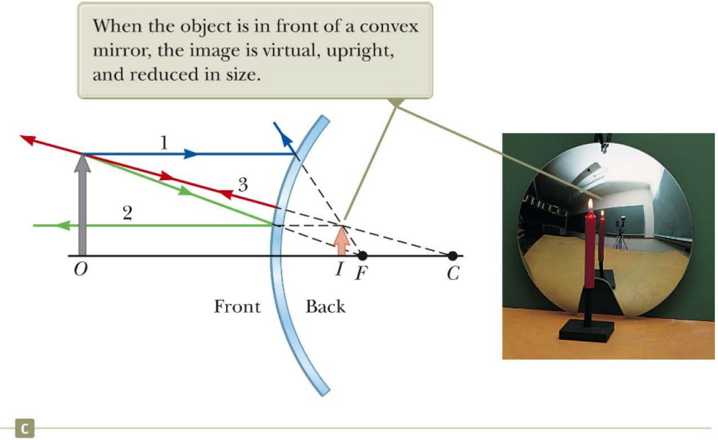
Ray Diagram for a Convex Mirror

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.

Example

An object is placed 20.0 cm from a concave spherical mirror having a focal length of magnitude 40.0 cm. Determine the location of the image and the magnification of the image.

The mirror is concave (converging), so $f = +40.0$ cm.

$$\frac{1}{q} = \frac{1}{f} - \frac{1}{p} = \frac{1}{40.0\text{ cm}} - \frac{1}{20.0\text{ m}} \quad \rightarrow \quad q = -40.0\text{ cm}$$

$$M = \frac{-q}{p} = \frac{-(-40.0\text{ cm})}{20.0\text{ cm}} = +2.00$$

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Example

At an intersection of hospital hallways, a convex spherical mirror is mounted high on a wall to help people avoid collisions. The magnitude of the mirror's radius of curvature is 0.550 m. (a) Locate the image of a patient 10.0 m from the mirror. (b) Determine the magnification of the image.

(a) The mirror is convex (diverging), so

$$f = -\frac{R}{2} = -\frac{0.550\ \text{m}}{2} = -0.275\ \text{m}$$

$$\frac{1}{q} = \frac{1}{f} - \frac{1}{p} = \frac{1}{-0.275\ \text{m}} - \frac{1}{10.0\ \text{m}}$$

$$q = -0.267\ \text{m} = \boxed{-26.7\ \text{cm}}.$$

The image distance is negative; thus, the image is virtual. The image is 26.7 cm behind the mirror.

(b) $M = \frac{-q}{p} = -\frac{-0.267}{10.0\ \text{m}} = +0.026\ 7$ The magnification is positive, so the image is upright.

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Example

A dentist uses a spherical mirror to examine a tooth. The tooth is 1.00 cm in front of the mirror, and the image is formed 10.0 cm behind the mirror. Determine (a) the mirror's radius of curvature and (b) the magnification of the image.

(a) Since the object is in front of the mirror, $p > 0$, and $p = 1.00$ cm. With the image behind the mirror, the image is virtual, so $q < 0$, and $q = -10.0$ cm. The mirror equation gives for the radius of curvature

$$\frac{1}{f} = \frac{2}{R} = \frac{1}{p} + \frac{1}{q} = \frac{1}{1.00\text{ cm}} + \frac{1}{-10.0\text{ cm}} \quad \rightarrow \quad f = \frac{R}{2} = 1.11\text{ cm}$$

$$R = \boxed{+2.22\text{ cm}}$$

A positive radius means the mirror is converging, so it is a concave mirror.

(b) The magnification is $M = -\dfrac{q}{p} = -\dfrac{(-10.0\text{ cm})}{1.00\text{ cm}} = \boxed{+10.0}$.

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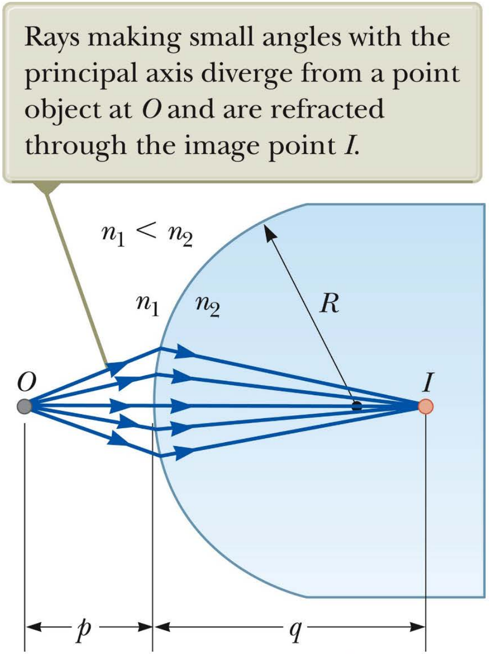
Images Formed by Refraction

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 $n = n_1$.



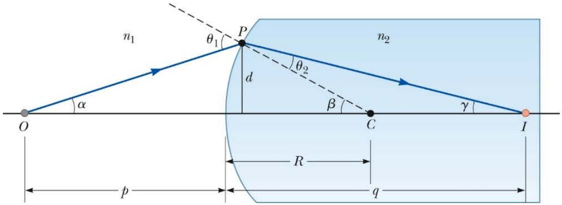
Images Formed by Refraction, 2

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

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



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.

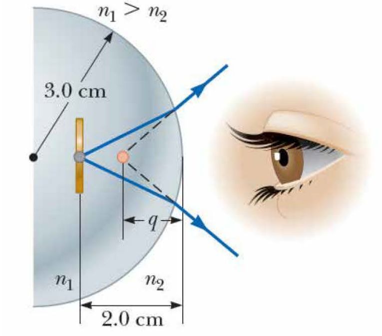
Sign Conventions for Refracting Surfaces

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.

Gaze into the Crystal Ball, Example

A set of coins is embedded in a spherical plastic paperweight having a radius of 3.0 cm. The index of refraction of the plastic is $n_1 = 1.50$. One coin is located 2.0 cm from the edge of the sphere (Fig. 36.19). Find the position of the image of the coin.



Because $n_1 > n_2$, where $n_2 = 1.00$ is the index of refraction for air, the rays originating from the coin are refracted away from the normal at the surface and diverge outward. Extending the outgoing rays backward shows an image point within the sphere.

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

$$\frac{1}{q} = \frac{1.00 - 1.50}{-3.0\text{ cm}} - \frac{1.50}{2.0\text{ cm}}$$

$$q = \boxed{-1.7\text{ cm}}$$

Flat Refracting Surfaces

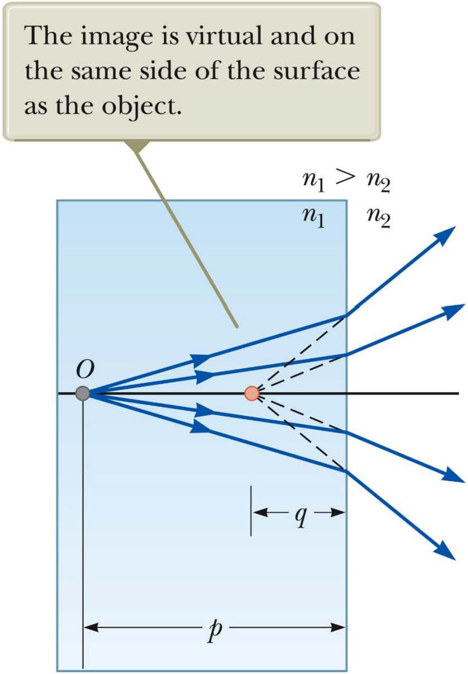
If a refracting surface is flat, then R is infinite.

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.

If n_1 is less than n_2, the rays on the back side diverge from one another at smaller angles. As a result, the virtual image is formed to the left of the object.



Example

A cubical block of ice 50.0 cm on a side is placed over a speck of dust on a level floor. Find the location of the image of the speck as viewed from above. The index of refraction of ice is 1.309.

$$\frac{n_1}{p} + \frac{n_2}{q} = \frac{n_2 - n_1}{R} = 0 \quad \text{and} \quad R \to \infty$$

$$q = -\frac{n_2}{n_1} p = -\frac{1}{1.309}(50.0 \text{ cm}) = -38.2 \text{ cm}$$

Thus, the virtual image of the dust speck is

$\boxed{\text{38.2 cm below the top surface}}$ of the ice.

Images Formed by Thin Lenses

Lenses are commonly used to form images by refraction.

Lenses are used in optical instruments.

- Cameras
- Telescopes
- Microscopes

Light passing through a lens experiences refraction at two surfaces.

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

Locating the Image Formed by a Lens

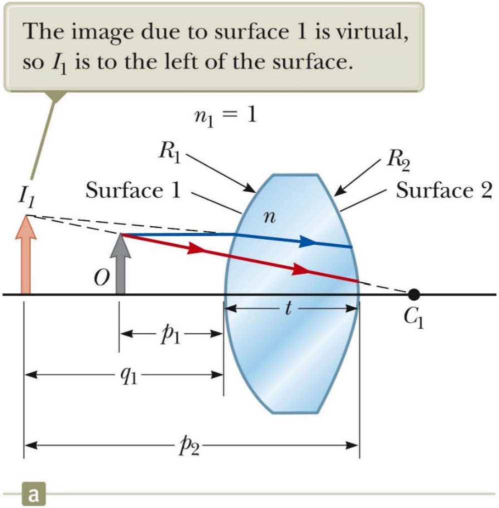
The lens has an index of refraction *n* and two spherical surfaces with radii of R_1 and R_2.

- R_1 is the radius of curvature of the lens surface that the light of the object reaches first.
- R_2 is the radius of curvature of the other surface.

The object is placed at point *O* at a distance of p_1 in front of the first surface.

There is an image formed by surface 1.

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



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

Lens-makers' Equation

If a virtual image is formed from surface 1, then $p_2 = -q_1 + t$

- q_1 is negative
- t is the thickness of the lens

If a real image is formed from surface 1, then $p_2 = -q_1 + t$

- q_1 is positive

Then

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

- This is called the lens-makers' equation.
  - It can be used to determine the values of R_1 and R_2 needed for a given index of refraction and a desired focal length f.
  - n interpreted as the ratio of the index of refraction of the lens material to that of the surrounding fluid.

Example

A contact lens is made of plastic with an index of refraction of 1.50. The lens has an outer radius of curvature of +2.00 cm and an inner radius of curvature of +2.50 cm. What is the focal length of the lens?

Let R_1 = outer radius and R_2 = inner radius:

$$\frac{1}{f}=(n-1)\left[\frac{1}{R_1}-\frac{1}{R_2}\right]=(1.50-1)\left[\frac{1}{2.00\text{ m}}-\frac{1}{2.50\text{ cm}}\right]$$

$$=0.050\ 0\text{ cm}^{-1}$$

$$f=\boxed{20.0\text{ cm}}.$$

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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.

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

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

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Thin Lens Shapes

These are examples of ***converging* lenses.**

They have positive focal lengths.

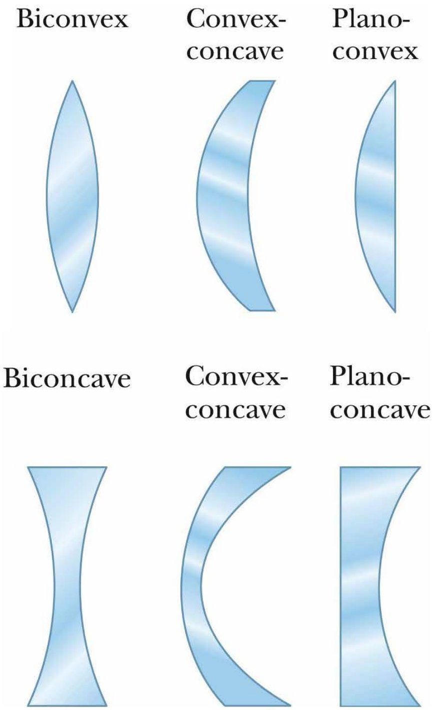
They are thickest in the middle.

These are examples of ***diverging lenses***.

They have negative focal lengths.

They are thickest at the edges.

Notice that a converging lens is thicker at the center than at the edge, whereas a diverging lens is thinner at the center than at the edge.



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.

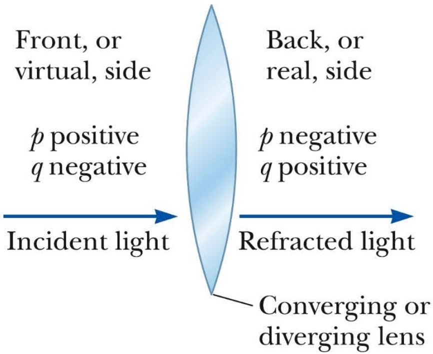


TABLE 36.3 *Sign Conventions for Thin Lenses*

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

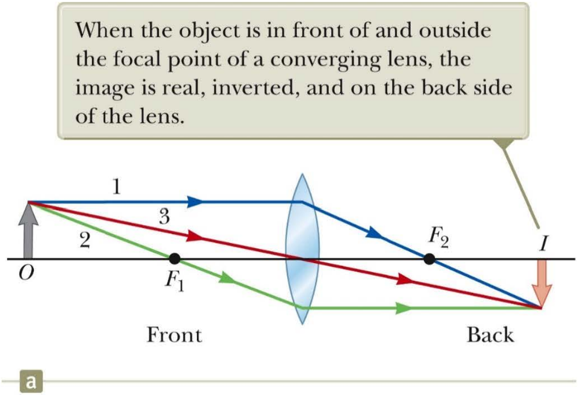
The lateral magnification of the image is

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

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 Diagram for Converging Lens, $p > f$

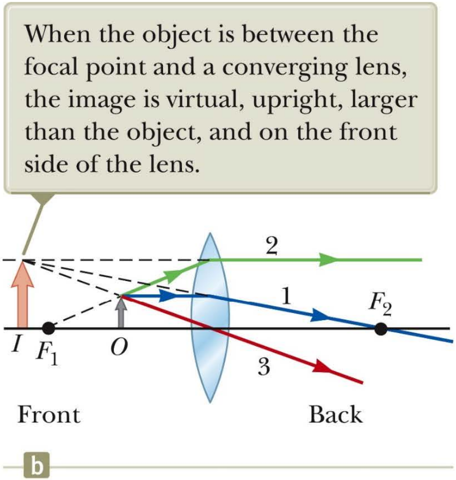


The image is real.

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.

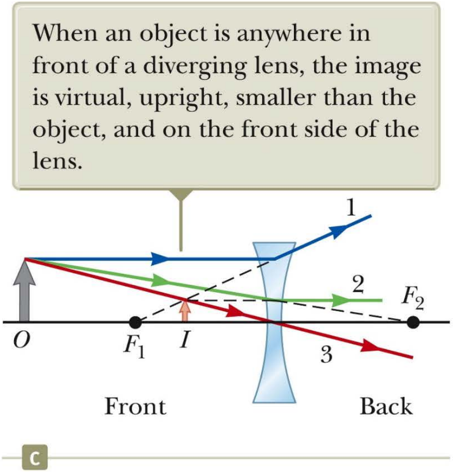
The image is larger than the object.

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.



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.

Overall magnification: $M = M_1 M_2$

Images Formed by a Diverging Lens, Example

A diverging lens has a focal length of 10.0 cm.

(A) An object is placed 30.0 cm from the lens. Construct a ray diagram, find the image distance, and describe the image.

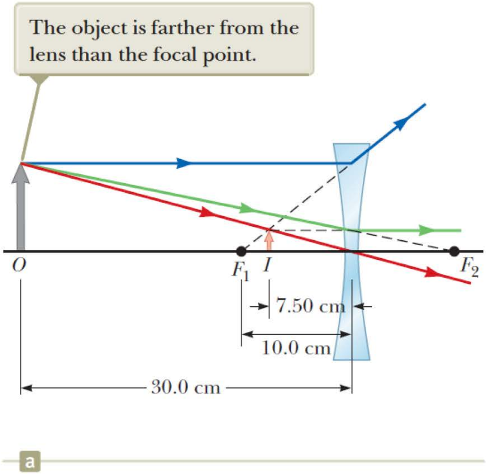
Because the lens is diverging, the focal length is negative (see Table). The ray diagram for this situation is shown in Figure a.

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

$$\frac{1}{q} = \frac{1}{-10.0 \text{ cm}} - \frac{1}{30.0 \text{ cm}}$$

$$q = \boxed{-7.50 \text{ cm}}$$

$$M = -\frac{q}{p} = -\left(\frac{-7.50 \text{ cm}}{30.0 \text{ cm}}\right) = \boxed{+0.250}$$



Images Formed by a Diverging Lens, Example, Cont'd

(B) An object is placed 10.0 cm from the lens. Construct a ray diagram, find the image distance, and describe the image.

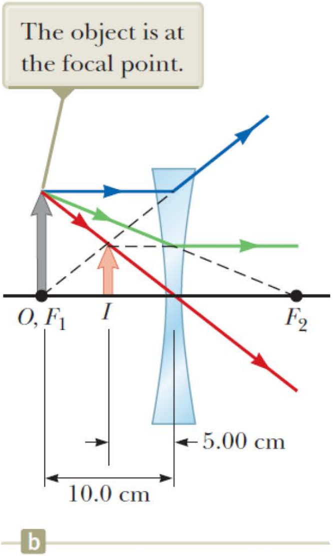
The ray diagram for this situation is shown in Figure b.

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

$$\frac{1}{q} = \frac{1}{-10.0\text{ cm}} - \frac{1}{10.0\text{ cm}}$$

$$q = \boxed{-5.00\text{ cm}}$$

$$M = -\frac{q}{p} = -\left(\frac{-5.00\text{ cm}}{10.0\text{ cm}}\right) = \boxed{+0.500}$$



Images Formed by a Diverging Lens, Example, Cont'd

(C) An object is placed 5.00 cm from the lens. Construct a ray diagram, find the image distance, and describe the image.

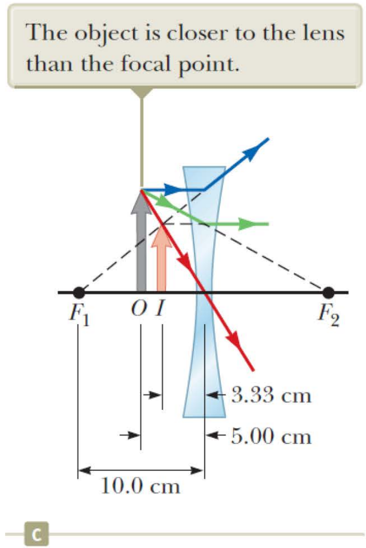
The ray diagram for this situation is shown in Figure c.

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

$$\frac{1}{q} = \frac{1}{-10.0 \text{ cm}} - \frac{1}{5.0 \text{ cm}}$$

$$q = \boxed{-3.33 \text{ cm}}$$

$$M = -\left(\frac{-3.33 \text{ cm}}{5.00 \text{ cm}}\right) = \boxed{+0.667}$$



Example

A thin lens has a focal length of 25.0 cm. Locate and describe the image when the object is placed (a) 26.0 cm and (b) 24.0 cm in front of the lens.

(a) From $\frac{1}{q} = \frac{1}{f} - \frac{1}{p} = \frac{1}{25.0\text{ cm}} - \frac{1}{26.0\text{ cm}}$, we obtain

$\boxed{q = 650\text{ cm}}$.

$\boxed{\text{real, inverted, and enlarged}}$.

$$\frac{1}{q} = \frac{1}{f} - \frac{1}{p} = \frac{1}{25.0\text{ cm}} - \frac{1}{24.0\text{ cm}},$$

$\boxed{q = -600\text{ cm}}$.

(b) $\boxed{\text{virtual, upright, and enlarged}}$.

Example

(a) A converging lens has a focal length of 10.0 cm. Locate the object if a real image is located at a distance from the lens of 20.0. (b) Redo the calculations if the images are virtual and located at a distance from the lens of 20.0 cm.

In part (a), the images are real, so the image distances are positive.

(a) $q = +20.0$ cm:

$$\frac{1}{p}+\frac{1}{q}=\frac{1}{f}: \quad \frac{1}{p}+\frac{1}{20.0\text{ cm}}=\frac{1}{10.0\text{ cm}} \quad \rightarrow \quad p=+20.0\text{ cm}$$

The object distance is positive, so the object is real.

The object is 20.0 cm from the lens on the front side.

(b) Now, the image is virtual, so the image distances are negative.

q = –20.0 cm:

$$\frac{1}{p}+\frac{1}{q}=\frac{1}{f}: \quad \frac{1}{p}+\frac{1}{-20.0\text{ cm}}=\frac{1}{10.0\text{ cm}}$$

$$p=+6.67\text{ cm}$$

The object distance is positive, so the object is real.
The object is 6.67 cm from the lens on the front side.

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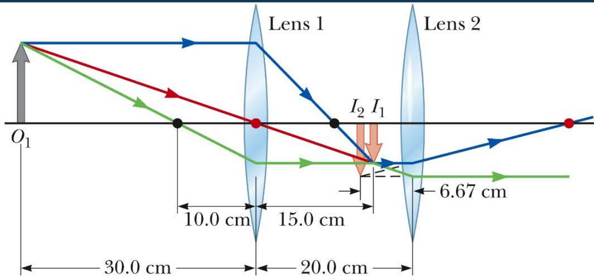
Where Is the Final Image? example

Two thin converging lenses of focal lengths $f_1 = 10.0$ cm and $f_2 = 20.0$ cm are separated by 20.0 cm as illustrated in Figure 36.30. An object is placed 30.0 cm to the left of lens 1. Find the position and the magnification of the final image.



Imagine light rays passing through the first lens and forming a real image (because $p > f$) in the absence of a second lens. Figure shows these light rays forming the inverted image I_1. Once the light rays converge to the image point, they do not stop. They continue through the image point and interact with the second lens. The rays leaving the image point behave in the same way as the rays leaving an object. Therefore, the image of the first lens serves as the object of the second lens.

$$\frac{1}{q_1} = \frac{1}{f} - \frac{1}{p_1}$$

$$\frac{1}{q_1} = \frac{1}{10.0 \text{ cm}} - \frac{1}{30.0 \text{ cm}}$$

$$q_1 = +15.0 \text{ cm}$$

$$M_1 = -\frac{q_1}{p_1} = -\frac{15.0 \text{ cm}}{30.0 \text{ cm}} = -0.500$$

The image formed by this lens acts as the object for the second lens. Therefore, the object distance for the second lens is 20.0 cm - 15.0 cm = 5.00 cm.

$$\frac{1}{q_2} = \frac{1}{20.0 \text{ cm}} - \frac{1}{5.00 \text{ cm}}$$

$$q_2 = \boxed{-6.67 \text{ cm}}$$

$$M_2 = -\frac{q_2}{p_2} = -\frac{(-6.67 \text{ cm})}{5.00 \text{ cm}} = +1.33$$

$$M = M_1 M_2 = (-0.500)(1.33) = \boxed{-0.667}$$

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Lens Aberrations

Assumptions have been:

- Rays make small angles with the principal axis.
- The lenses are thin.
- All rays leaving a point source focus at a single point, producing a sharp image.

The rays from a point object do not focus at a single point.

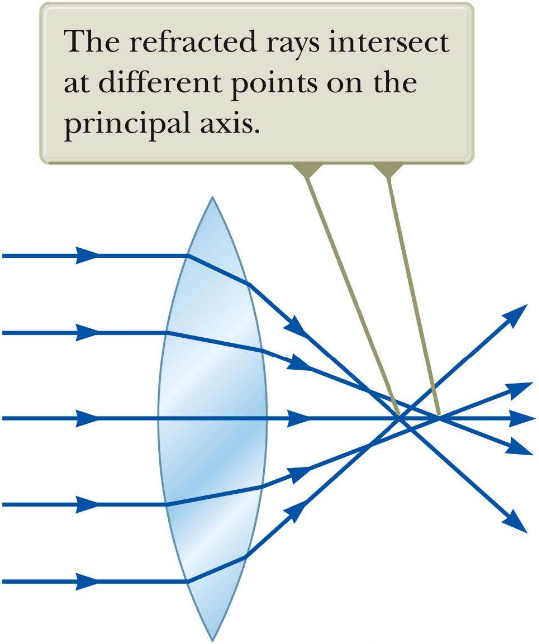
- The result is a blurred image.
- This is a situation where the approximations used in the analysis do not hold.

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

Spherical Aberration

Rays passing through points near the center of the lens are imaged farther from the lens than rays passing through points near the edges.

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.

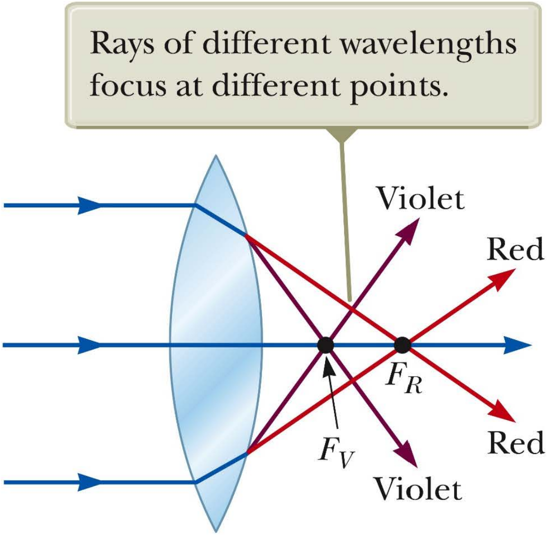


Chromatic Aberration

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.

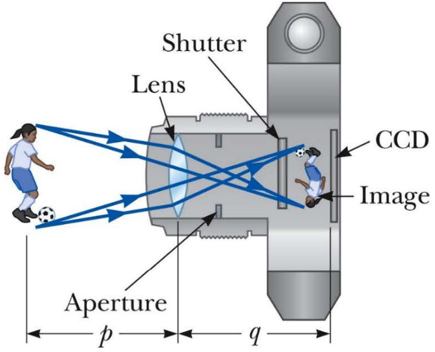


The Camera

The photographic camera is a simple optical instrument.

Components

- Light-tight chamber
- Converging lens
  - Produces a real image
- Light sensitive component behind the lens
  - Where the image is formed
  - Could be a charge-coupled device (CCD) or film
  - CCD digitizes the image, turning it into binary code.



The camera is focused by varying the distance between the lens and the CCD.

An aperture is an opening that controls the amount of light passing through the lens and reduce spherical aberration

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.*

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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 (D is the diameter of the lens)
- 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: $I \propto 1/(f\text{-number})^2$.

The lower the *f*-number, the wider the aperture and the higher the rate at which energy from the light exposes the CCD; therefore, a lens with a low *f*-number is a "fast" lens.

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.

Finding the Correct Exposure Time, Example

The lens of a digital camera has a focal length of 55 mm and a speed (an *f*-number) of $f/1.8$. The correct exposure time for this speed under certain conditions is known to be $\frac{1}{500}$ s.

(A) Determine the diameter of the lens.

$$D = \frac{f}{f\text{-number}} = \frac{55 \text{ mm}}{1.8} = \boxed{31 \text{ mm}}$$

(B) Calculate the correct exposure time if the *f*-number is changed to $f/4$ under the same lighting conditions.

The total light energy hitting the CCD is proportional to the product of the intensity and the exposure time. If I is the light intensity reaching the CCD, the energy per unit area received by the CCD in a time interval Δt is proportional to $I \Delta t$. Comparing the two situations, we require that $I_1 \Delta t_1 = I_2 \Delta t_2$, where Δt_1 is the correct exposure time for $f/1.8$ and Δt_2 is the correct exposure time for $f/4$.

$$I_1 \Delta t_1 = I_2 \Delta t_2 \rightarrow \frac{\Delta t_1}{(f_1\text{-number})^2} = \frac{\Delta t_2}{(f_2\text{-number})^2}$$

$$\Delta t_2 = \left(\frac{f_2\text{-number}}{f_1\text{-number}}\right)^2 \Delta t_1 = \left(\frac{4}{1.8}\right)^2 \left(\tfrac{1}{500} \text{ s}\right) \approx \boxed{\tfrac{1}{100} \text{ s}}$$

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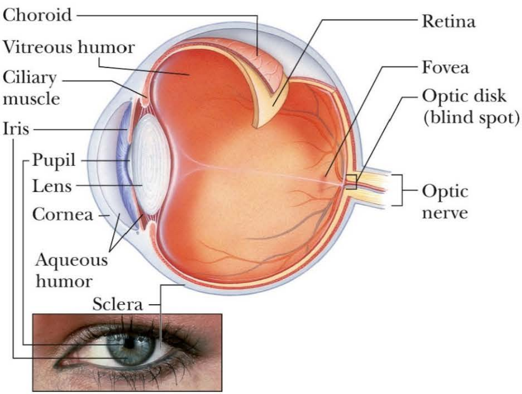
The Eye – Near and Far Points

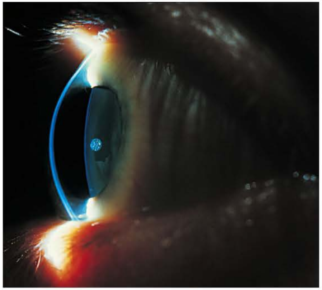
The *near point* is the closest distance for which the lens can accommodate to focus light on the retina.

- 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.





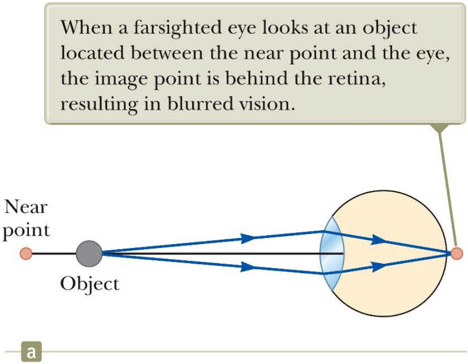
Conditions of the Eye

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 (image behind retina).
- Nearsighted
  - Person can focus on nearby objects but not those far away

Farsightedness



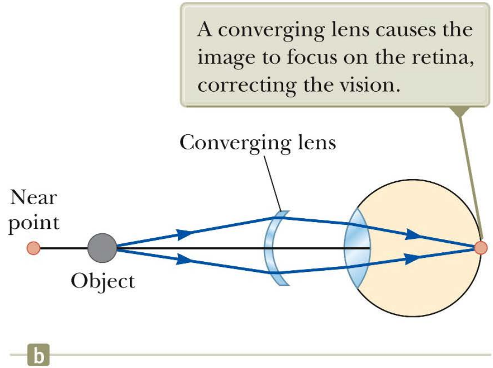
Also called *hyperopia*

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

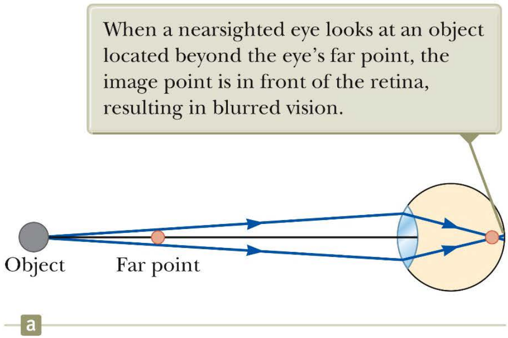


A converging lens placed in front of the eye can correct the condition.

The lens refracts the incoming rays more toward the principal axis before entering the eye.

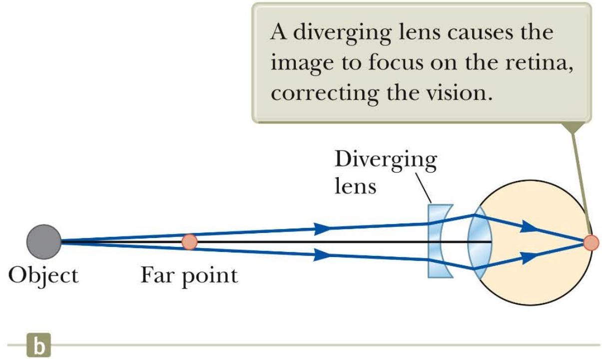
- This allows the rays to converge and focus on the retina.

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.

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.
  - $P = 1/f$

For example, a converging lens of focal length +20 cm has a power of +5.0 diopters, and a diverging lens of focal length -40 cm has a power of -2.5 diopters.

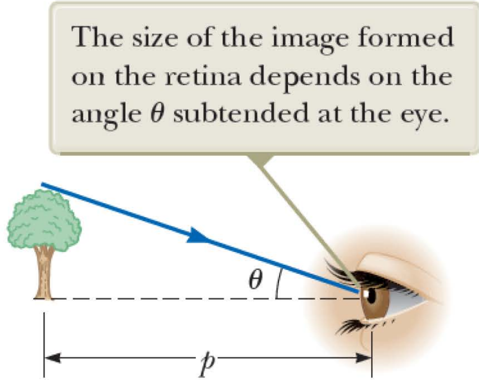
Simple Magnifier

A simple magnifier consists of a single converging lens.

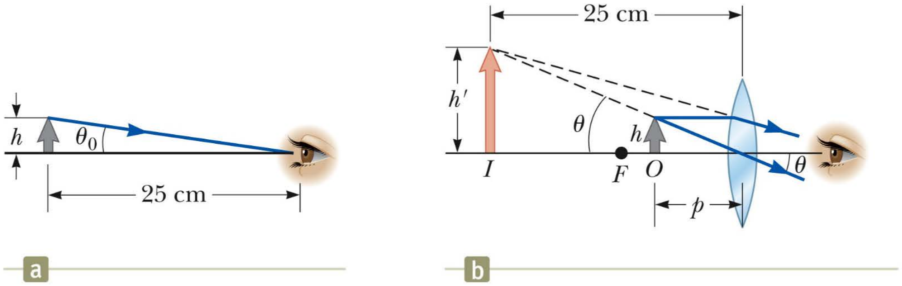
This device is used to increase the apparent size of an object.

The size of an image formed on the retina depends on the angle subtended by the eye.

As the object moves closer to the eye, θ increases and a larger image is observed. An average normal human eye, however, cannot focus on an object closer than about 25 cm, the near point. Therefore, θ is maximum at the near point.



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

The object distance corresponding to this image distance can be calculated from the thin lens equation:

$$\frac{1}{p} + \frac{1}{-25\text{ cm}} = \frac{1}{f} \rightarrow p = \frac{25f}{25 + f}$$

And the magnification becomes

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

Angular Magnification, cont.

For the image formed by a magnifying glass to appear at infinity, the object has to be at the focal point of the lens.

$$\theta_0 \approx \frac{h}{25} \quad \text{and} \quad \theta \approx \frac{h}{f}$$

The angular magnification is

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

Magnification of a Lens, Example

What is the maximum magnification that is possible with a lens having a focal length of 10 cm, and what is the magnification of this lens when the eye is relaxed?

$$m_{\max} = 1 + \frac{25 \text{ cm}}{f} = 1 + \frac{25 \text{ cm}}{10 \text{ cm}} = \boxed{3.5}$$

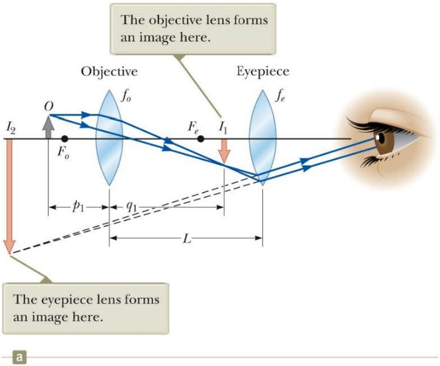
$$m_{\min} = \frac{25 \text{ cm}}{f} = \frac{25 \text{ cm}}{10 \text{ cm}} = \boxed{2.5}$$

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.



The lenses are separated by a distance *L.*

- L is much greater than either focal length.

The object is placed just outside the focal point of the objective.

- This forms a real, inverted image.
- This image is located at or close to the focal point of the eyepiece.

This image acts as the object for the eyepiece.

- The image seen by the eye, I_2, is virtual, inverted and very much enlarged.

Magnifications of the Compound Microscope

The lateral magnification by the objective is

- $M_o = - L / f_o$

The angular magnification by the eyepiece of the microscope is

- $m_e = 25\ cm / f_e$

The overall magnification of the microscope is the product of the individual magnifications.

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

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

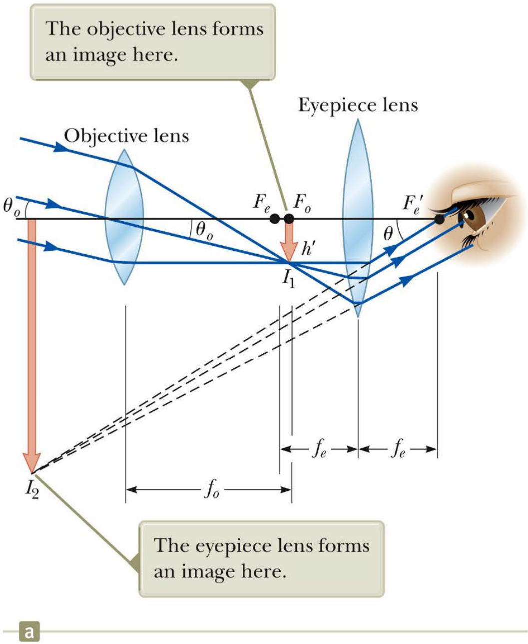
The two lenses are arranged so that the objective forms a real, inverted image of a distant object.

The image is formed very near the focal point of the eyepiece, at the focal point of the objective.

- 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.



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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.

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

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.*