Types of lenses

- Shown below are various types of lenses, both converging and diverging.
- Any lens that is thicker at its center than at its edges is a *converging* lens with positive \( f \); and any lens that is thicker at its edges than at its center is a *diverging* lens with negative \( f \).

![Diagram of lens types](image)

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Lenses

- In an actual lens, rays refract twice, at spherical surfaces having radii of curvature \( R_1 \) and \( R_2 \).

<table>
<thead>
<tr>
<th>TABLE 34.3 Sign convention for thin lenses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
</tr>
<tr>
<td>Negative</td>
</tr>
<tr>
<td>( R_1, R_2 )</td>
</tr>
<tr>
<td>Convex toward the object</td>
</tr>
<tr>
<td>Concave toward the object</td>
</tr>
<tr>
<td>( f )</td>
</tr>
<tr>
<td>Converging, lens, thicker in center</td>
</tr>
<tr>
<td>Diverging, lens, thinner in center</td>
</tr>
<tr>
<td>( x' )</td>
</tr>
<tr>
<td>Real image, opposite side from object</td>
</tr>
<tr>
<td>Virtual image, same side as object</td>
</tr>
</tbody>
</table>

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Lensmaker's equation

The image formed by the first surface of a lens serves as the object for the second surface.

![Diagram of lensmaker's equation](image)

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Example 1 – The radius of curvature for the surfaces of a double convex lens is 10 cm and the index of refraction is 1.52. What is the focal length \( f \) of the lens? Repeat the calculation for a double concave lens.

Example 2 – For each thin lens shown in the figure, calculate the location of the image of an object that is 18.5 cm to the left of the lens. The lens material has a refractive index of 1.50, and the radii of curvature shown are only the magnitudes.
In-class Activity #1

What is focal length of the glass meniscus lens shown? Is this a converging or diverging lens?

\[ R_1 = 40 \text{ cm} \quad n = 1.50 \quad R_2 = 20 \text{ cm} \]

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Lenses in Combination

- The analysis of multi-lens systems requires only one new rule: The image of the first lens acts as the object for the second lens.
- Below is a ray-tracing diagram of a simple astronomical telescope.

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Example 3 – Converging lenses A and B, of focal lengths 8.0 cm and 6.0 cm, respectively, are placed 36.0 cm apart. Both lenses have the same optic axis. An object 8.0 cm high is placed 12.0 cm to the left of lens A. Find the position, size, and orientation of the image produced by the combination.
The Camera

- A camera “takes a picture” by using a lens to form a real, inverted image on a light-sensitive detector in a light-tight box.
- We can model a combination lens as a single lens with an **effective focal length** (usually called simply “the focal length”).
- A zoom lens changes the effective focal length by varying the spacing between the converging lens and the diverging lens.

A Simple Camera Lens Is a Combination Lens

![Diagram: A Simple Camera Lens Is a Combination Lens](image)

The parallel light rays will be focused at a point _______ the second lens than would light focused by the second lens acting alone.

A. closer to  
B. the same distance from  
C. farther from

QuickCheck
Example 4

Your digital camera lens, with an effective focal length of 10.0 mm, is focused on a flower 20.0 cm away. You then turn to take a picture of a distant landscape. How far, and in which direction, must the lens move to bring the landscape into focus?

Controlling the Exposure

- The amount of light passing through the lens is controlled by an adjustable aperture, shown in the photos.
- The aperture sets the effective diameter $D$ of the lens.
- The light-gathering ability of a lens is specified by its $f$-number, defined as
  \[ f\text{-number} = \frac{f}{D} \]
- The light intensity on the detector is related to the lens’s $f$-number by
  \[ I = \frac{D^2}{f^2} = \frac{1}{(f\text{-number})^2} \]

QuickCheck

If the $f$-number of a camera lens is doubled, say from $F4.0$ to $F8.0$, that means the diameter of the lens aperture is

A. Quadrupled (increased by a factor of 4).
B. Doubled (increased by a factor of 2).
C. Halved (decreased by a factor of 2).
D. Quartered (decreased by a factor of 4).
Example 5 – A common telephoto lens for a 35-mm film camera has a focal length of 200 mm; its f-stops range from f/2.8 to f/22. (a) What is the corresponding range of aperture diameters? (b) What is the corresponding range of image intensities on the film?

Vision

- The human eye is roughly spherical, about 2.4 cm in diameter.
- The transparent cornea and the lens are the eye’s refractive elements.
- The eye is filled with a clear, jellylike fluid called the aqueous humor and the vitreous humor.

Vision

- The indices of refraction of the aqueous and vitreous humors are 1.34, only slightly different from water.
- The lens has an average index of 1.44.
- The pupil, a variable-diameter aperture in the iris, automatically opens and closes to control the light intensity.
- The f-number varies from roughly f/3 to f/16, very similar to a camera!
Focusing and Accommodation

- The eye focuses by changing the focal length of the lens by using the ciliary muscles to change the curvature of the lens surface.
- Tensing the ciliary muscles causes accommodation, which decreases the lens's radius of curvature and thus decreases its focal length.

Focusing and Accommodation

- The farthest distance at which a relaxed eye can focus is called the eye's far point (FP).
- The far point of a normal eye is infinity; that is, the eye can focus on objects extremely far away.

Focusing and Accommodation

- The closest distance at which an eye can focus, using maximum accommodation, is the eye's near point (NP).
QuickCheck

If the near point of your eye is at 75 cm, you are

A. Nearsighted.
B. Farsighted.
C. Sharp-sighted.

Corrective Lenses

- Corrective lenses are prescribed not by their focal length but by their power.
- The power of a lens is the inverse of its focal length:
  \[ P = \frac{1}{f} \]
- The SI unit of lens power is the diopter, abbreviated D, defined as 1 D = 1 m\(^{-1}\).
- Thus a lens with \( f = 50 \text{ cm} = 0.50 \text{ m} \) has power \( P = 2.0 \text{ D} \).

Hyperopia

- The cause of farsightedness—called hyperopia—is an eyeball that is too short for the refractive power of the cornea and lens.

![Diagram of hyperopia](image)
Hyperopia

- A person who is **farsighted** can see faraway objects (but even then must use some accommodation rather than a relaxed eye), but his near point is larger than 25 cm, often much larger, so he cannot focus on nearby objects.

![Maximum accommodation](image)

This is the closest point at which the eye can focus.

- With hyperopia, the eye needs assistance to focus the rays from a near object onto the closer-than-normal retina.
- This assistance is obtained by adding refractive power with the positive (i.e., converging) lens.

![This is the actual object the eye wants to see](image)

A converging lens forms a virtual image at the eye's near point. This image acts as the object for the eye and is what the eye actually focuses on.

Example 6

Gregory has hyperopia. The near point of his left eye is 150 cm. What prescription lens will restore normal vision?
Myopia

- Nearsightedness—called myopia—is caused by an eyeball that is too long.
- Rays from a distant object come to a focus in front of the retina and have begun to diverge by the time they reach the retina.

Myopia

- A person who is nearsighted can clearly see nearby objects when the eye is relaxed (and extremely close objects by using accommodation), but no amount of relaxation allows her to see distant objects.

Myopia

- To correct myopia, we needed a diverging lens to slightly defocus the rays and move the image point back to the retina.
Example 7

Mark has myopia. The far point of his left eye is 200 cm. What prescription lens will restore normal vision?

QuickCheck

If your vision is improved with lenses that look like this:
then you must have

A. Presbyopia.
B. Hyperopia.
C. Transopia.
D. Myopia.

The Microscope

- A microscope, whose major parts are shown in the figure, can attain a magnification of up to 1000 × by a two-step magnification process.
- A specimen to be observed is placed on the stage of the microscope, directly beneath the objective, a converging lens with a relatively short focal length.
- The objective creates a magnified real image that is further enlarged by the eyepiece.
The Microscope

- This is a simple two-lens model of a microscope.
- The object is placed just outside the focal point of the objective, which creates a highly magnified real image with lateral magnification 
  \[ m = \frac{-s'}{s} \]

- The lateral magnification of the objective is
  \[ m_{\text{obj}} = \frac{s'}{s} = \frac{L}{f_{\text{obj}}} \]
- Together, the objective and eyepiece produce a total angular magnification:
  \[ M = m_{\text{obj}}M_{\text{eye}} = -\frac{L}{f_{\text{obj}}} \cdot \frac{25 \text{ cm}}{f_{\text{eye}}} \]
- The minus sign shows that the image seen in a microscope is inverted.
- Most biological microscopes are standardized with a tube length \( L = 160 \text{ mm} \).

Example 8

A pathologist inspects a sample of 7-μm-diameter human blood cells under a microscope. She selects a 40x objective and a 10x eyepiece. What size object, viewed from 25 cm, has the same apparent size as a blood cell seen through the microscope?
The Telescope

- A simple telescope contains a large-diameter objective lens that collects parallel rays from a distant object and forms a real, inverted image at distance $s' = f_{\text{obj}}$.
- The focal length of a telescope objective is very nearly the length of the telescope tube.
- The eyepiece functions as a simple magnifier.
- The viewer observes an inverted image.
- The angular magnification of a telescope is

$$M = \frac{\theta_{\text{eye}}}{\theta_{\text{obj}}} = \frac{f_{\text{obj}}}{f_{\text{eye}}}$$

QuickCheck

You are choosing lenses for a telescope that you will use to look at the moon and planets. You should select

A. an objective lens with a long focal length and an eyepiece lens with an even longer focal length.
B. an objective lens with a long focal length and an eyepiece lens with a shorter focal length.
C. an objective lens with a short focal length and an eyepiece lens with a longer focal length.
D. an objective lens with a short focal length and an eyepiece lens with an even shorter focal length.

A Refracting Telescope
Telescopes

- Large light-gathering power requires a large-diameter objective lens, but large lenses are not practical; they begin to sag under their own weight.
- Thus refracting telescopes, with two lenses, are relatively small.
- Serious astronomy is done with a reflecting telescope, such as the one shown in the figure.

QuickCheck

If you increase the diameter of a telescope’s objective lens (and, of course, increase the diameter of the tube) with no other changes, then the telescope will have

A. A larger magnification; more light-collecting power.
B. The same magnification; more light-collecting power.
C. A smaller magnification; more light-collecting power.
D. A larger magnification; the same light-collecting power.
E. A smaller magnification; the same light-collecting power.