Lenses

Unit: Light & Optics

NGSS Standards/MA Curriculum Frameworks (2016): N/A

AP® Physics 2 Learning Objectives/Essential Knowledge (2024): 13.4.A, 13.4.A.1, 13.4.A.2, 13.4.A.3, 13.4.A.4, 13.4.A.5, 13.4.A.5.i, 13.4.A.5.ii, 13.4.A.6, 13.4.A.7, 13.4.A.7.i, 13.4.A.7.ii

Mastery Objective(s): (Students will be able to…)

- Draw ray tracing diagrams for refraction through convex and concave lenses.
- Numerically calculate the distance from the lens to its focus and the lens to the image.

Success Criteria:

- Ray diagrams correctly show location of object, focus and image.
- Calculations are correct with correct algebra.

Language Objectives:

- Explain when and why images are inverted (upside-down) *vs.* upright.

Tier 2 Vocabulary: light, refraction, virtual image, real image, lens, focus

Labs, Activities & Demonstrations:

- Fresnel lens
- optics bench lab

Notes:

Lenses are similar to curved mirrors in that they change the direction of light rays to produce an image of an object that can have a different size, orientation and distance from the mirror relative to the object.

Lenses are different from mirrors in that light passes through them, which means they operate by refraction instead of reflection.

lens: a usually symmetrical optical device which refracts light in a way that makes the rays of light either converge or diverge.

convex lens: a lens that refracts light so that it converges as it passes through.

concave lens: a lens that refracts light so that it diverges as it passes through.

focus or focal point: the point at which light rays converge after passing through the lens.

principal axis: a line perpendicular to the surface of the lens, such that light passing through it is refracted at an angle of 0° (*i.e.*, the direction is not changed).

The principal axis is often shown as a single horizontal line, but every point on the surface of a lens has a principal axis. Note also that if a lens is asymmetrical, its principal axis may be different on each side.

vertex: the point where the principal axis passes through the center of the lens.

real image: an image produced by light rays that pass through the lens. A ***real image*** will appear on the ***opposite side of the lens*** from the object. A real image is what you are used to seeing through a magnifying glass.

virtual image: an apparent image produced at the point where diverging rays appear to originate. A ***virtual image*** will appear on the ***same side of the lens*** as the object.

A rule of thumb that works for both mirrors and lenses is that a ***real image*** is produced by the convergence of the ***actual rays of light***. A virtual image is our perception of where the rays of light would have come from.

upright image: an image that is oriented in the same direction as the object. ("right-side-up")

inverted image; an image that is oriented in the opposite direction from the object. ("upside-down")

Calculations

The equations for lenses are the same as the equations for curved mirrors. Distances are measured from the vertex.

The magnification (M) is the ratio of the height of the image (h_i) to the height of the object (h_o), which is equal to the ratio of the distance of the image (s_i) to distance of the object (s_o).

$$M = \frac{h_i}{h_o} = -\frac{s_i}{s_o}$$

As with mirrors, the distance to the image is defined to be positive for a real image, and negative for a virtual image. However, note that with lenses the real image is caused by the rays of light that pass through the lens, which means a real image is behind a lens, where as a real image is in front of a mirror.

Note also that for lenses, this means that the positive direction for the object and the positive for the image are opposite.

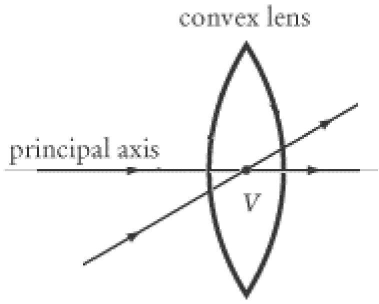
As with mirrors, the distance from the vertex of the lens to the focus (f) is defined by the equation:

$$\frac{1}{s_i} + \frac{1}{s_o} = \frac{1}{f}$$

Ray Tracing

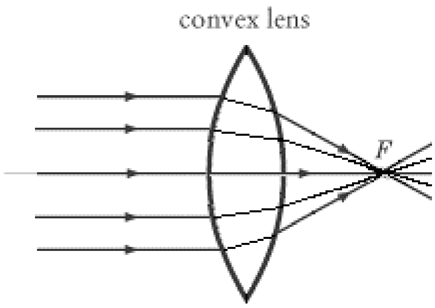
In all lenses:

1. Light passing through the *vertex* of the lens comes out of the lens in the same direction as it entered, as if the lens were not there.

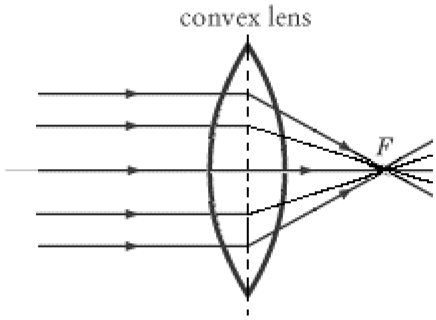


2. Light passing through any part of the lens other than the vertex is refracted through the *focus* .

   Notice that the light is refracted twice, once upon entering the lens and a second time upon entering the air when it exits. For convenience, we usually draw the ray trace as if the light is refracted once when it crosses the center of the lens.



what actually happens



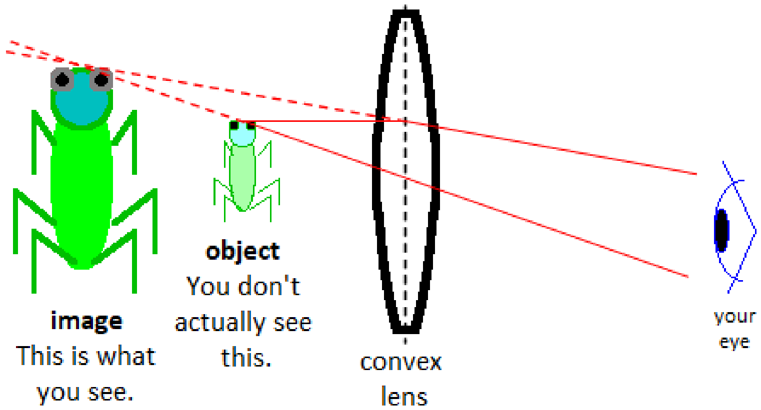
how we usually draw it

Similar to mirrors, the "three principal rays" are the ray that passes through the vertex of the lens (step 1 above), the ray that strikes the lens parallel to the principal axis (step 2 above), and the same ray after being refracted that passes through the focal point of the lens (also step 2 above).

Convex Lenses

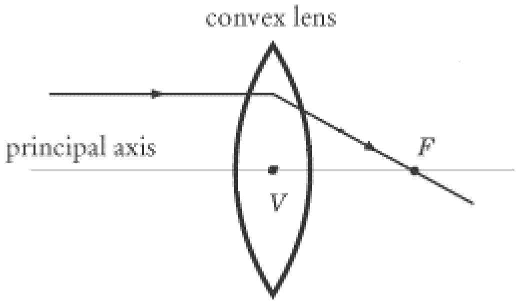
A convex lens causes light rays to converge (bend towards each other) as they pass through.

The most familiar use of convex lenses is as a magnifying glass. Note how the bending of the light rays makes the object appear larger.

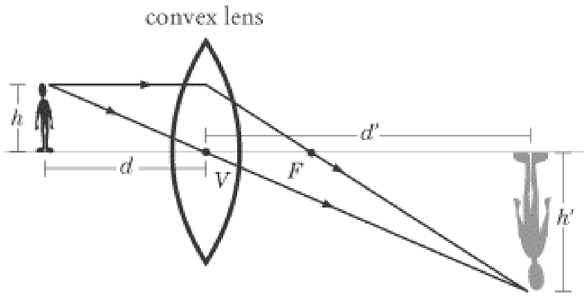


Note also that the lens bends ***all*** of the light. Your eyes cannot see the unbent light rays, which means you cannot see the actual object in its actual location; you *only* see the image.

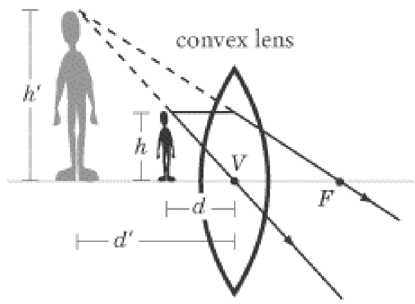
For a convex lens, the focus is always on the opposite side of the lens from the object:



1. If the object is farther away from the lens than the focus, the image is real (on the opposite side of the lens) and inverted (upside-down).

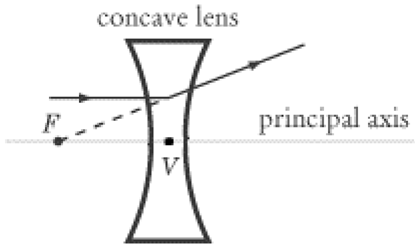


2. If the object is closer than the focus, the image is virtual (on the same side of the lens) and upright (right-side-up).

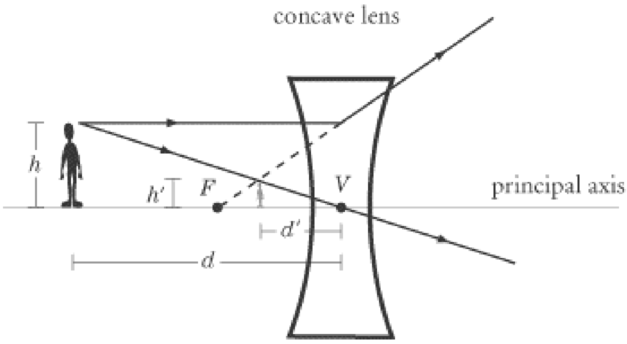


Concave Lenses

A concave lens causes light rays to diverge (bend away from each other). For a concave lens, the focus is on the same side of the lens as the object.

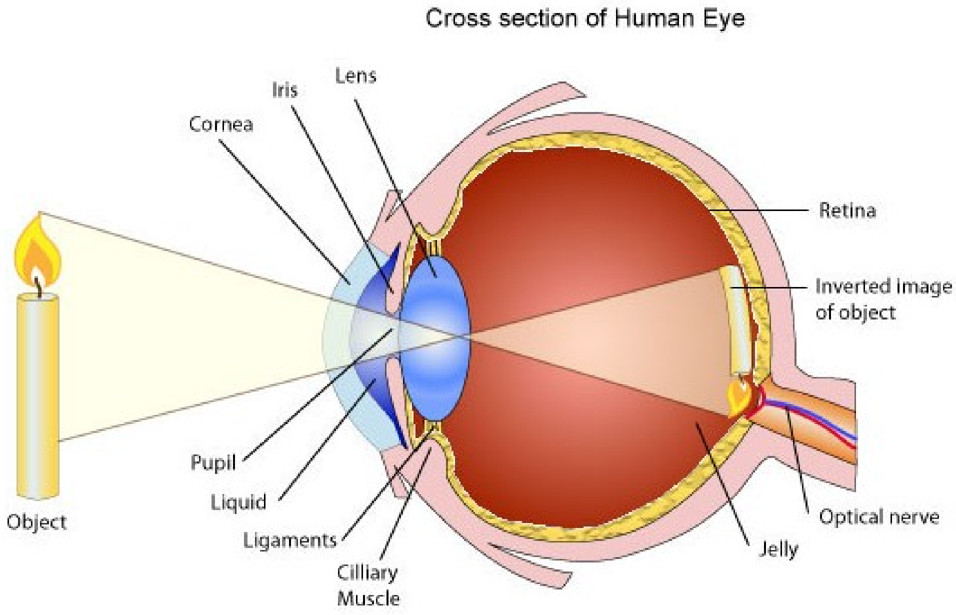


For a concave lens, the image is always virtual (on the same side of the lens) and upright (right-side-up):



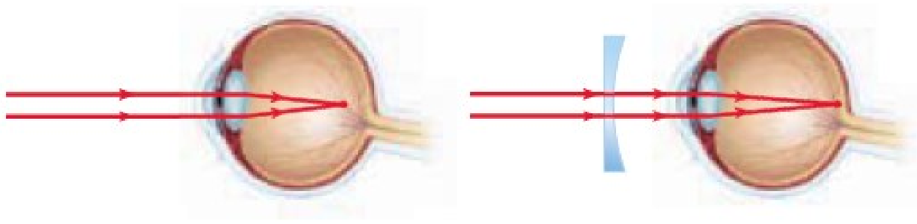
Physiology

In the human eye, the cornea and lens both act as lenses. However, because the action of the ciliary muscles changes the shape of the lens, the lens is responsible for the exact focal point, which determines what we are focusing our eyes on. When the ciliary muscles relax, the images of distant objects are focused on the retina. When these muscles contract, the focal point moves, and closer objects come into focus.



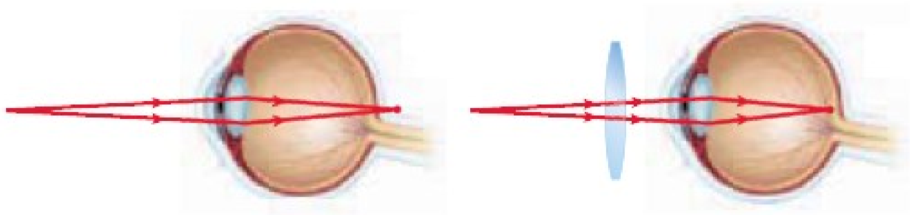
Nearsightedness and Farsightedness

"Nearsighted" means only objects near the eye are in focus; the viewer is unable to focus on distant objects. This happens because the focus of the lens when the ciliary muscles are fully relaxed is in front of the retina. Nearsightedness is corrected by eyeglasses with concave lenses, which move the focal point back to the retina.



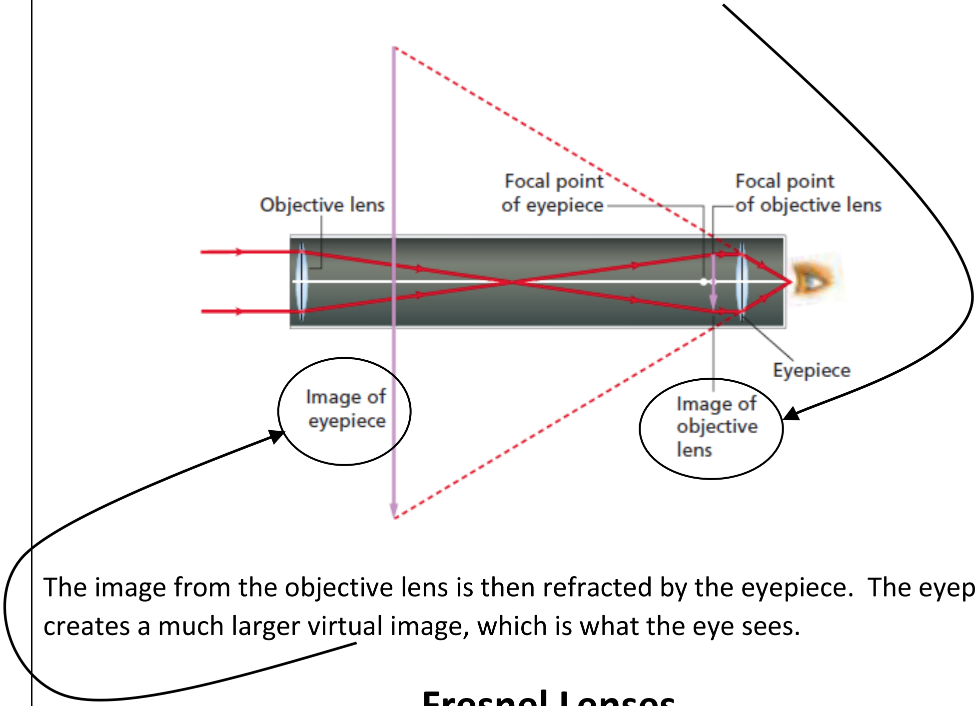
Notice that lenses that correct nearsightedness are concave only on the inside. This helps the lenses avoid the "Coke bottle" look.

"Farsighted" means only objects far away from the eye are in focus; the viewer is unable to focus on close objects. This happens because the ciliary muscles cannot contract enough to bring the focal point of the lens for light coming from nearby objects onto the retina. Farsightedness is corrected by eyeglasses with convex lenses, which move the focal point forward to the retina.



Telescopes

A telescope performs two tasks. The objective lens focuses light from a distant object and creates a virtual image in front of the eyepiece.

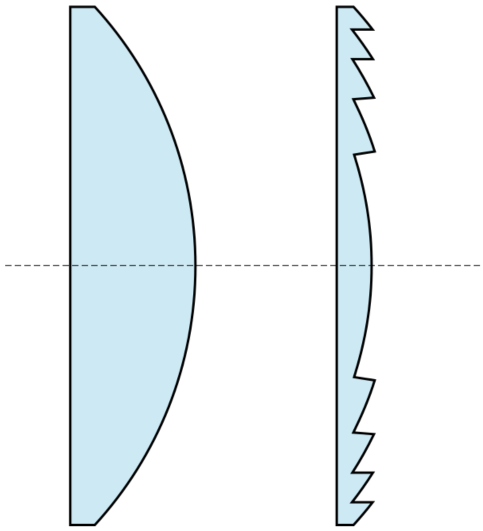


The image from the objective lens is then refracted by the eyepiece. The eyepiece creates a much larger virtual image, which is what the eye sees.

Fresnel Lenses

In the late 1700s, lighthouses were built to warn ships away from hazardous waters. Starting in 1788, in order to make the light more visible to ships from a farther distance, lenses were used to focus the light and make it brighter.

However, one of the challenges of building a lens that has a high magnification is that the lens becomes quite thick, and as the lens becomes thicker, it becomes much more difficult to make the lens optically pure enough to allow the rays of light to focus properly.

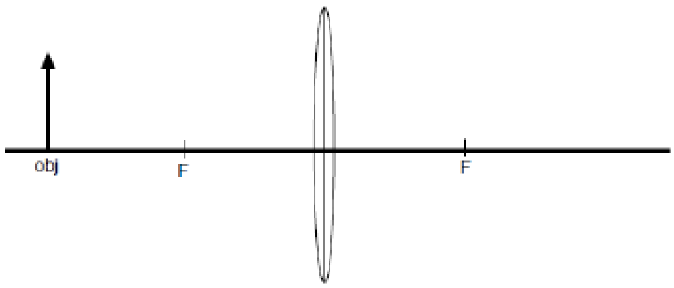


In the mid-1700s French mathematician Georges-Louis Leclerc, the Count of Buffon, designed a lens that was cleverly cut into steps so the lens could be made much thinner. French civil engineer and physicist Augustin-Jean Fresnel improved on the design, and he began manufacturing lenses for lighthouses starting in 1821.

Homework Problems

1. **(M)** A 4.2 cm tall object is placed 12 cm from a convex lens that has a focal length of 6.0 cm.

   a. Show the location and orientation of the image by accurately drawing a ray diagram on the image below.

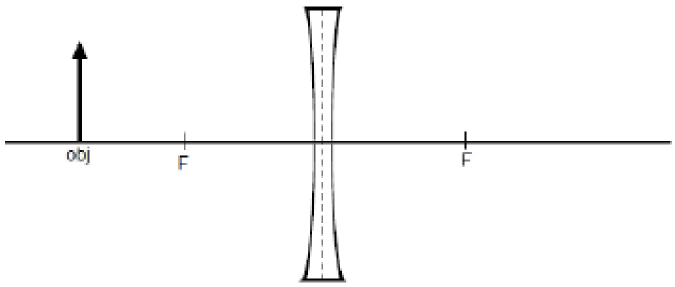


   b. Calculate the height and orientation of the image, and its distance from the lens.

Answers: $s_i = +12$ cm; $h_i = -4.2$ cm

2. **(M)** A 4.2 cm tall object is placed 12 cm from a concave lens that has a focal length of 6.0 cm.

   a. Show the location and orientation of the image by accurately drawing a ray diagram on the image below.

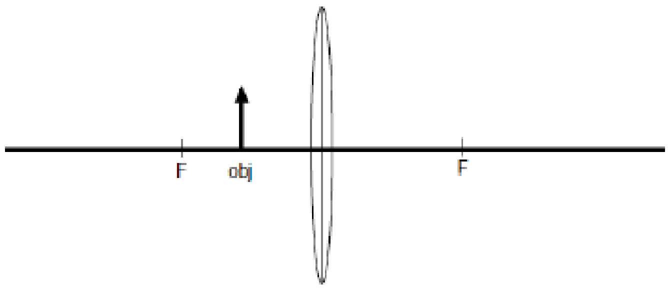


   b. Calculate the height and orientation of the image, and its distance from the lens.

Answers: $s_i = -4$ cm; $h_i = +1.4$ cm

3. **(M)** A 2.7 cm tall object is placed 3.4 cm from a convex lens that has a focal length of 6.0 cm.

   a. Show the location and orientation of the image by accurately drawing a ray diagram on the image below.

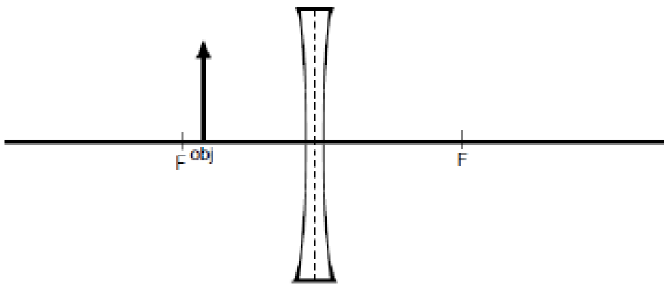


   b. Calculate the height and orientation of the image, and its distance from the lens.

Answers: $s_i = -7.84$ cm; $h_i = +6.23$ cm

4. **(M)** A 2.7 cm tall object is placed 5.1 cm from a concave lens that has a focal length of 6.0 cm.

   a. Show the location and orientation of the image by accurately drawing a ray diagram on the image below.



   b. Calculate the height and orientation of the image, and its distance from the lens.

Answers: $s_i = -2.76$ cm; $h_i = +1.46$ cm