Answer to Essential Question 24.4: The three rays in Figure 24.21 are easy to draw, because we know what they do after passing through the lens. However, as shown in Figure 24.23, all rays that leave the tip of the object and which are refracted by the lens will converge at the tip of the image.

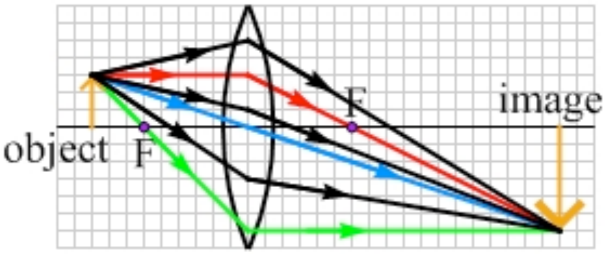

Figure 24.23: All rays that leave the tip of the object and pass through the lens will converge at the tip of the image.

24-5 Lens Concepts

In general, a lens has a larger index of refraction than the medium that surrounds it. In that case, a lens that is thicker in the center than the ends is a converging lens (it converges parallel rays toward a focal point), while a lens that is thinner in the middle than at the ends is a diverging lens (it diverges parallel rays away from a focal point). Like a concave mirror, converging lenses can produce a real image or a virtual image, and the image can be larger, smaller, or the same size as the object. Like a convex mirror, diverging lenses can only produce a virtual image that is smaller than the object.

As with mirrors, the focal point of a lens is defined by what the lens does to a set of rays of light that are parallel to one another and to the principal axis of the mirror. As we discussed in Section 24-4, a converging lens generally refracts the rays so they converge to pass through a focal point, *F*. A diverging lens, in contrast, refracts parallel rays so that they diverge away from a focal point.

Because of dispersion (the fact that the index of refraction of the lens material depends on wavelength), a lens generally has slightly different focal points for different colors of light. This range of focal points is a defect called **chromatic aberration**.

Focal length of a lens with spherical surfaces: The focal length of a lens depends on the curvature of the two surfaces of the lens, the index of refraction of the lens material, and on the index of refraction of the surrounding medium. The focal length is given by:

$$\frac{1}{f} = \left(\frac{n_{lens}}{n_{medium}} - 1\right)\left(\frac{1}{R_1} + \frac{1}{R_2}\right),$$ (Equation 24.5: **The lensmaker's equation**)

where the two *R*'s represent the radii of curvature of the two lens surfaces. A radius is positive if the surface is convex, and negative if the surface is concave.

Companies that make eyeglasses exploit the lensmaker's equation in creating lenses of the desired focal length. By choosing a lens material that has a high index of refraction, a smaller radius of curvature (and thus a thinner and lighter lens) can be used, compared to a lens made from glass with a smaller index of refraction.

The factor of $[(n_{lens}/n_{medium}) - 1]$ in Equation 24.5 has an interesting implication. First, consider the diagram in Figure 24.24, which shows a familiar situation of a lens, made from material with an index of refraction larger than that of air, surrounded by air. This lens causes the parallel rays to change direction so that they pass through the focal point on the right, and $[(n_{lens}/n_{medium}) - 1]$ is positive, so the focal length of the lens is positive.

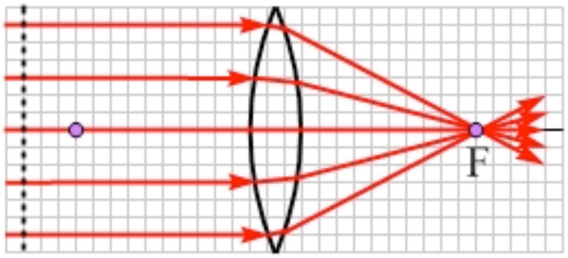

Figure 24.24: A ray diagram for a set of parallel rays encountering a convex lens, made of plastic, surrounded by air.

What happens to the light if the medium around the lens has the same index of refraction as the lens material (perhaps we immerse the lens in some kind of oil)? In this case, the factor of [(n_{lens}/n_{medium}) -1] is zero - this means that the lens does no focusing at all, which we would expect if the lens and the medium have the same index of refraction. Going further, if the surrounding medium has a larger index of refraction than the lens material, [(n_{lens}/n_{medium}) -1] is negative and so is the focal length: parallel rays would be *diverged* in this situation.

Thus, depending on the situation, a lens with a convex shape can be a converging lens, a diverging lens, or neither. To minimize any ambiguity, for the rest of this chapter we will refer to lenses by their function (converging or diverging) rather than their shape (convex or concave).

EXPLORATION 24.5 – Ray diagram for a diverging lens

We will follow a process similar to that of mirrors to draw a ray diagram for a diverging lens, starting with the situation in Figure 24.25. The ray diagram will show us where the image of an object is.

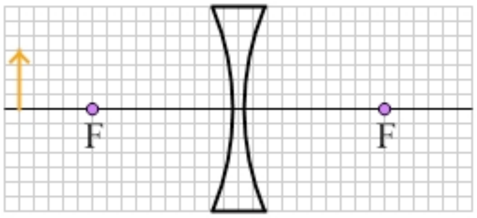

Figure 24.25: An object in front of a diverging lens.

Step 1 – ***Draw a ray of light that leaves the tip of the object (the top of the arrow) and goes parallel to the principal axis (this is known as the parallel ray). Show how this ray is refracted by the lens.*** For a diverging lens, all parallel rays appear to diverge from the focal point on the side of the lens that the light comes from, so we draw the refracted ray (see Figure 24.26) refracting along a line that takes it directly away from that focal point.

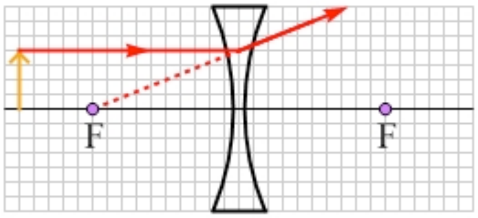

Figure 24.26: The parallel ray refracts to travel directly away from the focal point on the side of the lens the light came from.

Step 2 – ***Sketch a second ray that leaves the tip of the object and is refracted by the lens. Using the refracted rays, draw the image.*** One useful ray, shown in Figure 24.27, passes through the center of the lens without changing direction. This is something of an approximation, but the thinner the lens, the more accurate this is. Another useful ray goes straight toward the focal point on the right of the lens. This ray refracts so as to emerge from the lens going parallel to the principal axis. The refracted rays diverge to the right of the lens, but we can extend them back to meet on the left side of the lens, showing us where the tip of the image is.

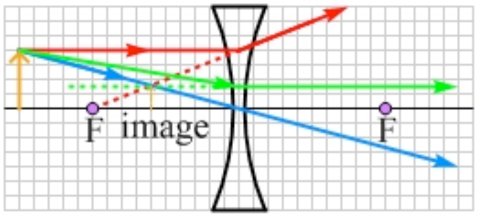

Figure 24.27: In addition to the parallel ray, two other rays are easy to draw the refracted rays for. The ray that passes through the center of the lens is undeflected, approximately. The ray that travels directly toward the focal point on the far side of the lens is refracted so it emerges from the lens traveling parallel to the principal axis. If you look at the object through the lens, your brain interprets the light as coming from the image.

Key idea: When a number of rays leave the same point on an object and are refracted by a lens, the corresponding point on the image is located at the intersection of the refracted rays.
Related End-of-Chapter Exercises: 3, 4, 52.

Essential Question 24.5: Starting with Figure 24.27, show a few more rays of light leaving the tip of the object and being refracted by the lens. How do you know how to draw the refracted rays?