Answer to Essential Question 24.3: Everyone has their own rainbow! The light you see enters your eye only. In addition, the light making up the colors of the rainbow that you see comes from droplets that are at just the right position in the sky to refract and reflect sunlight back toward you. Your neighbor would see a very similar rainbow, but at least some of the droplets responsible for her rainbow are different from the water droplets that create your rainbow.

24-4 Image Formation by Thin Lenses

Lenses, which are important for correcting vision, for microscopes, and for many telescopes, rely on the refraction of light to form images. As with mirrors, we draw ray diagrams to help us to understand how such images are formed. Let's first begin by looking at what a lens does to a set of parallel rays of light, such as the five rays in Figure 24.16.

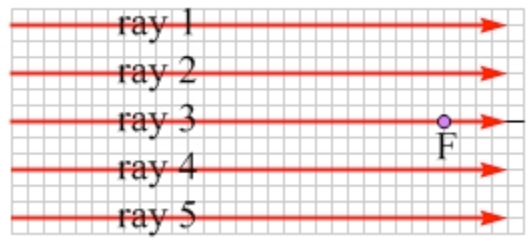

Figure 24.16: Five parallel rays of light.

How can we change the direction of the five rays of light in Figure 24.16 so that they all pass through the point labeled F? Ray 3 already passes through point F, so we don't need to change its direction at all. We can deflect ray 2 with a triangular piece of glass, as shown in Figure 24.17. Passing from air into the glass prism, the ray deflects toward the normal at that surface, while when it emerges back into the air the deflection is away from the normal at the second surface. We can follow a similar process for ray 1, except that we need to produce a larger change in direction for ray 1 compared to ray 2. The glass prism we use for ray 1 thus has its sides at a greater angle from the vertical. For ray 4, we use an identical prism to that used for ray 2, except that we invert it, and for ray 5 the prism is identical to the prism for ray 1, but inverted.

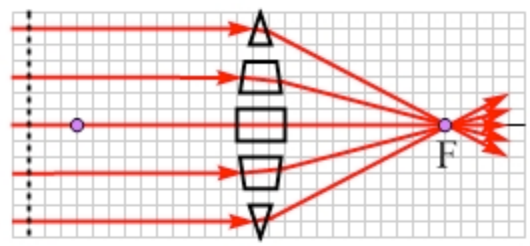

Figure 24.17: We can deflect four of the five rays, so that all five rays meet at point F, by using prisms of the appropriate shapes to produce the deflection required for each beam.

Now, not only do we want all five rays to converge on point F, but we want them to take equal times to travel from the vertical dashed line in Figure 24.17 to point F. Remember that the light travels more slowly in glass than in air. Because rays 1 and 5 travel the greatest distance, they need to pass through the least amount of glass. Ray 3 travels the shortest distance, so we need to delay ray 3 by having it pass through the thickest piece of glass. We can do this without deflecting ray 3 by using a piece of glass with vertical sides, so that ray 3 is incident along the normal. Rather than using various individual glass rectangles and prisms to do the job, we can use a single piece of glass that is thickest in the middle. This piece of glass gets thinner, and its surfaces curve farther away from the vertical, as you move away from ray 3 (that is, as you move away from the principal axis). This is shown in Figure 24.18 – we use a lens. Point F is a focal point of the lens. Lenses allow light to pass through from left-to-right or from right-to-left, so a lens has two focal points, one on each side of the lens.

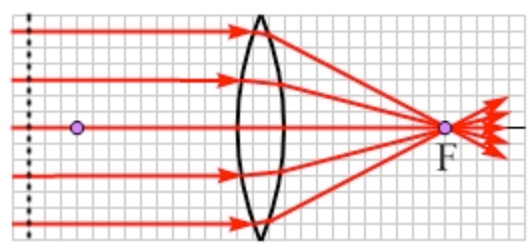

Figure 24.18: A convex lens with surfaces that are spherical arcs brings all parallel rays to one of the focal points, and ensures that the parallel rays take the same time to travel from the vertical line to this focal point.

How does a concave lens, which is thinner in the center than at the edges, affect parallel rays? As shown in Figure 24.19, such lenses generally diverge parallel rays away from the focal point that is on the same side of the lens that the light comes from.

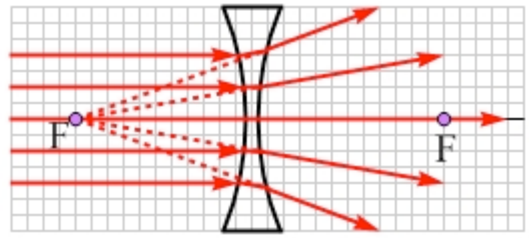

Figure 24.19: The influence of a diverging lens on a set of parallel rays.

EXPLORATION 24.4 – Using a ray diagram to find the location of an image

When drawing ray diagrams for lenses, we follow a process similar to that for mirrors.

Step 1 – ***Figure 24.20 shows an object in front of a converging lens. Sketch two rays of light, which travel in different directions, that leave the tip (the top) of the object and pass through the lens. Show the direction of these rays after they are refracted by the lens.*** Figure 24.21 shows three rays that leave the tip of the object and which are incident on the lens. Because the ray in red is parallel to the principal axis, it is refracted by the lens to pass through the focal point that is to the right of the lens. The ray in green travels along the line connecting the tip of the object to the focal point on the left of the lens. This ray is refracted so that it is parallel to the principal axis. We know this because of the reversibility of light rays – if we reversed the direction of the ray, it would come from the right and be refracted by the lens to pass through the focal point on the right. Finally, the ray in blue passes through the center of the lens without changing direction. This is an approximation, which is valid as long as the lens is thin so the ray enters and exits the lens very close to the principal axis.

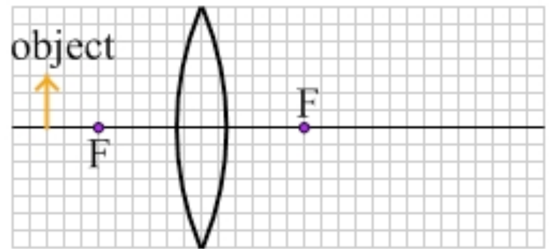

Figure 24.20: An object located some distance in front of a converging lens.

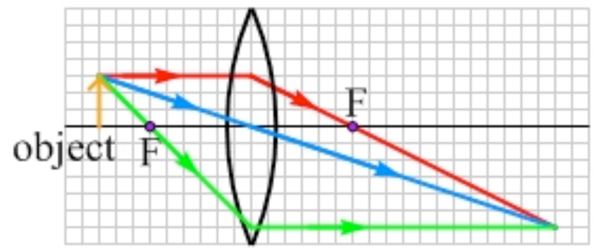

Figure 24.21: Three of the rays that are refracted by the lens. In general, we draw a ray changing direction once, inside the lens. Each ray really changes direction twice, once at each air-glass interface. We are drawing the ray's path incorrectly within the lens, but it is correct outside of the lens, which is where it really matters.

Step 2 – ***The point where the refracted rays meet is where the tip of the image is located. Use this information to sketch the image of the object.*** In this situation, the refracted rays meet at a point to the right of the lens, below the principal axis. Thus, we draw an inverted image between the point where the image of the tip is (where the rays meet) and the principal axis. This is a real image, because the rays pass through the image. All the rays take the same time to travel from the tip of the object to the tip of the image.

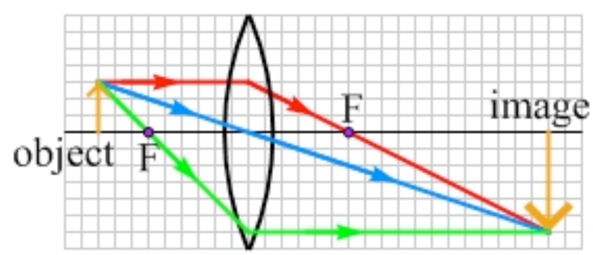

Figure 24.22: Because the rays originate at the tip of the object, the point where the refracted rays meet is the location of the tip of the image of the object. The base of the object is on the principal axis, so the base of the image is on the principal axis, too.

Key idea for ray diagrams: The location of the image of any point on an object, when the image is created by a lens, can be found by drawing rays of light that leave that point on the object and are refracted by the lens. The point where the refracted rays meet (or where they appear to diverge from) is where the image of that point is. **Related End-of-Chapter Exercises: 5, 49**

Essential Question 24.4: Are the three rays in Figure 24.22 the only rays that pass through the tip of the image? Explain.