Answer to Essential Question 23.2: Images from plane mirrors are always the same size as the original object. We can see this in the ray diagram in Figure 23.14.

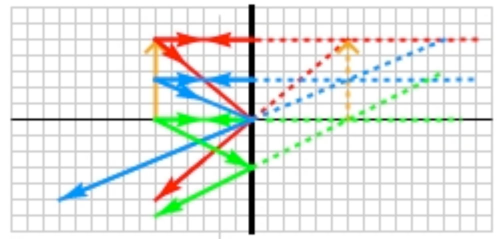


Figure 23.14: Compare this figure to Figure 23.12. Moving the object closer to the mirror moves the image closer to the mirror, but the height of the image is still equal to the height of the object.

23-3 Spherical Mirrors: Ray Diagrams

Let us move now from plane mirrors to spherical mirrors, which curve like the surface of a sphere. Spherical mirrors can be convex, such as the mirrors on the passenger side of cars, or concave, such as shaving or makeup mirrors. Unlike plane mirrors, which always produce an image that is the same size as the object, the image in a convex mirror is always smaller than the object, while the image in a concave mirror can be larger, smaller, or the same size as the object.

The focal point of a spherical mirror is defined by what the mirror does to a set of rays of light that are parallel to one another and to the principal axis of the mirror. As shown in Figure 23.15, a concave mirror reflects the rays so they converge to pass through the focal point, *F*. A convex mirror, in contrast, reflects parallel rays so that they diverge away from the focal point. Note that each ray obeys the law of reflection when it reflects from the mirror. The location of the focal point depends on the curvature of the mirror. The smaller the radius of curvature of the mirror, the closer the focal point is to the mirror's surface.

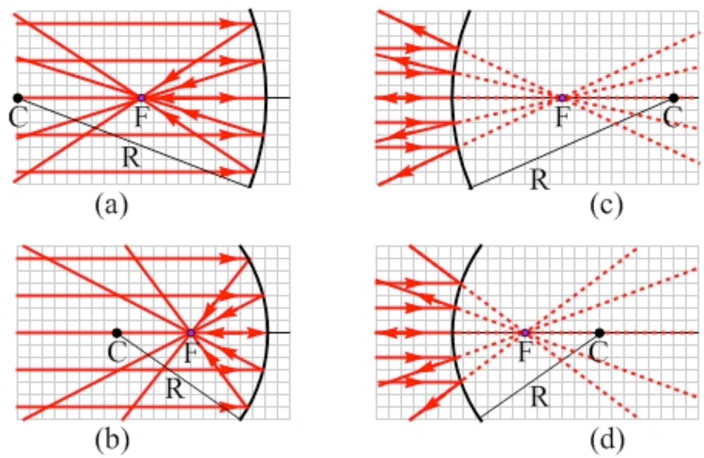


Figure 23.15: Focal points are shown for four different mirrors. In (a) and (b), concave mirrors reflect parallel rays so that they converge to a single point called the focal point. In (c) and (d), convex mirrors reflect parallel rays so that they diverge away from the mirror's focal point. The location of the focal point depends on the mirror's radius of curvature. In each case, *C* is the mirror's center of curvature, *R* is the radius of curvature, and *F* is the focal point.

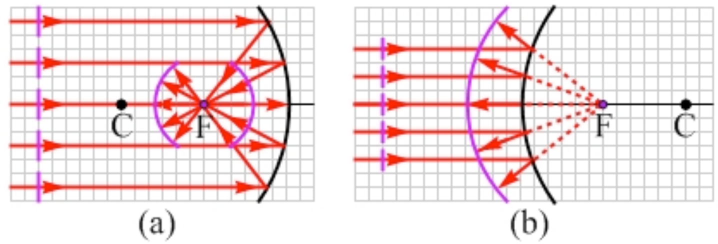
What we show here for spherical mirrors is an approximation, valid for rays that are not too far from the principal axis, in relation to the magnitude of the mirror's focal length. A mirror actually needs to have a parabolic shape to reflect all parallel rays through one point (or away from one point, for a diverging mirror). The fact that spherical mirrors do not really bring all such rays to a point (or diverge them away from a point) is a defect called **spherical aberration**.

Focal length of a spherical mirror: The focal point of a spherical mirror is located halfway between the surface of the mirror and the mirror's center of curvature. Thus, the focal length of a spherical mirror has a magnitude of $R/2$, where R is the radius of curvature of the mirror. By convention, an object that diverges parallel light rays has a negative focal length (f), while an object that converges parallel light rays has a positive focal length. Thus:

For a concave mirror: $f = +\frac{R}{2}$. (Eq. 23.1) For a convex mirror: $f = -\frac{R}{2}$. (Eq. 23.2)

In the limit that the radius of curvature approaches infinity, the mirror becomes a plane mirror and the focal length is either + infinity or – infinity (it does not matter which sign is used).

Figure 23.16: (a) For light rays that are parallel to the principal axis, a converging mirror re-unites the wave front at the focal point. From there, the wave front diverges as if the focal point is a point source. (b) A diverging mirror deflects the parallel rays so the wave fronts appear to diverge from the mirror's focal point.



Following the wave fronts

Figure 23.16 shows what spherical mirrors do to wave fronts. For the converging mirror, the waves take the same time to get from the left to the focal point. For the diverging mirror, once the waves reflect from the mirror, it is as if they left the focal point at the same time.

EXPLORATION 23.3 – Ray diagram for a convex mirror

We will follow a process similar to that for plane mirrors to draw a ray diagram for a convex (diverging) mirror.

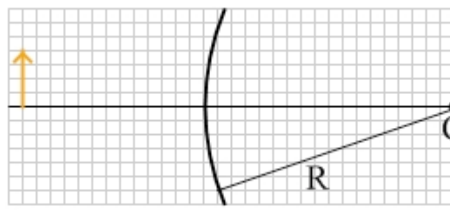


Figure 23.17: An object, represented by an arrow, is placed in front of a convex (diverging) mirror. The mirror's center of curvature is shown.

Step 1 – ***First, locate the mirror's focal point. Then, draw a light ray that leaves the tip of the object (its top) and goes parallel to the principal axis. Show how this parallel ray reflects from the mirror.*** The focal point is halfway between the point where the principal axis intersects the mirror, and the center of curvature. For a convex mirror, all parallel rays appear to diverge from the focal point, so we draw the reflected ray reflecting along a line that takes it directly away from the focal point, as in Figure 23.18.

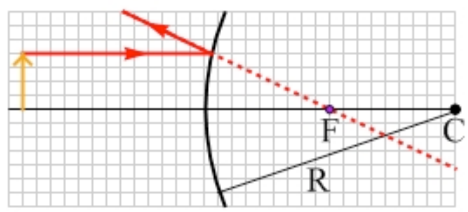


Figure 23.18: The parallel ray reflects from the mirror in such a way that it travels directly away from the focal point.

Step 2 – ***Sketch a second ray that leaves the tip of the object and reflects from the mirror. Using your reflected rays, draw the image.*** One useful ray, the lower ray in Figure 23.19, reflects from the point on the mirror that the principal axis passes through. At that location, the reflection is like that from a vertical plane mirror. Another useful ray goes straight toward the mirror's center of curvature. This ray has a 0° angle of incidence, and thus reflects back along the same line. The reflected rays diverge on the left of the mirror, but we can extend them back to meet on the right side of the mirror, showing us where the tip of the image is. The image, smaller than the object, is drawn from the tip down to the principal axis.

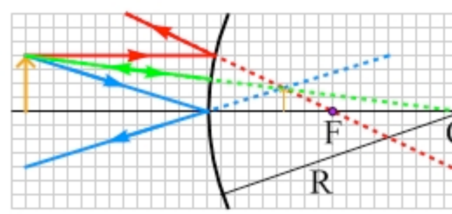


Figure 23.19: In addition to the parallel ray, two other rays are easy to draw the reflection for. The ray that strikes the mirror at the principal axis reflects as if the mirror was a vertical plane mirror. The ray that travels directly toward the center of curvature strikes the mirror at 90° to the surface, and thus reflects straight back.

Key idea: As with a plane mirror, when a number of rays leave the same point on an object and reflect from a spherical mirror, the corresponding point on the image is located at the intersection of the reflected rays. **Related End-of-Chapter Exercises: 6, 9, 22, 60, 61.**

Essential Question 23.3: (a) Modify the ray diagram in Figure 23.19 to show what happens to the image when the object is moved closer to the mirror. (b) Add several more rays (leaving the tip of the object) to your modified ray diagram, showing what the rays do when they reflect from the mirror. How do you know how to draw the reflected rays?