## * 23–10 Lensmaker's Equation

A useful equation, known as the **lensmaker's equation**, relates the focal length of a lens to the radii of curvature $R_1$ and $R_2$ of its two surfaces and its index of refraction $n$:

*Lensmaker's equation*

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right). \qquad \textbf{(23–10)}$$

If both surfaces are convex, $R_1$ and $R_2$ are considered positive.† For a concave surface, the radius must be considered *negative.*

Notice that Eq. 23–10 is symmetrical in $R_1$ and $R_2$. Thus, if a lens is turned around so that light impinges on the other surface, the focal length is the same even if the two lens surfaces are different.

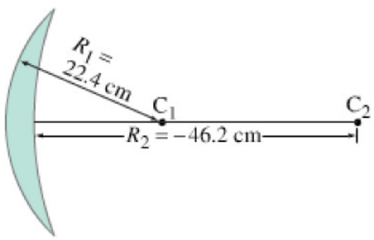


**FIGURE 23–43** Example 23–14.

**EXAMPLE 23–14** **Calculating *f* for a converging lens.** A convex meniscus lens (Figs. 23–29a and 23–43) is made from glass with $n = 1.50$. The radius of curvature of the convex surface is 22.4 cm, and that of the concave surface is 46.2 cm. What is the focal length?

**APPROACH** We use the lensmaker's equation, Eq. 23–10, to find $f$.

**SOLUTION** $R_1 = 22.4\text{ cm}$ and $R_2 = -46.2\text{ cm}$ (concave surface). Then

$$\frac{1}{f} = (1.50 - 1.00)\left(\frac{1}{22.4\text{ cm}} - \frac{1}{46.2\text{ cm}}\right) = 0.0115\text{ cm}^{-1}.$$

So

$$f = \frac{1}{0.0115\text{ cm}^{-1}} = 87\text{ cm},$$

and the lens is converging since $f > 0$.

**NOTE** If we turn the lens around so that $R_1 = -46.2\text{ cm}$ and $R_2 = +22.4\text{ cm}$, we get the same result.

†Some books use a different convention—for example, $R_1$ and $R_2$ are considered positive if their centers of curvature are to the right of the lens, in which case a minus sign replaces the + sign in their equivalent of Eq. 23–10.

## Summary

Light appears to travel in straight-line paths, called **rays**, at a speed $v$ that depends on the **index of refraction**, $n$, of the material; that is

$$n = \frac{c}{v}, \qquad \textbf{(23–4)}$$

where $c$ is the speed of light in vacuum.

When light reflects from a flat surface, the *angle of reflection equals the angle of incidence.* This **law of reflection** explains why mirrors can form **images**.

In a **plane mirror**, the image is virtual, upright, the same size as the object, and is as far behind the mirror as the object is in front.

A **spherical mirror** can be concave or convex. A **concave** spherical mirror focuses parallel rays of light (light from a very distant object) to a point called the **focal point**. The distance of this point from the mirror is the **focal length** $f$ of the mirror and

$$f = \frac{r}{2}, \qquad \textbf{(23–1)}$$

where $r$ is the radius of curvature of the mirror.

Parallel rays falling on a **convex mirror** reflect from the mirror as if they diverged from a common point behind the mirror. The distance of this point from the mirror is the focal length and is considered negative for a convex mirror.

For a given object, the approximate position and size of the image formed by a mirror can be found by ray tracing. Algebraically, the relation between image and object distances, $d_i$ and $d_o$, and the focal length $f$, is given by the **mirror equation:**

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}. \qquad \textbf{(23–2)}$$

The ratio of image height $h_i$ to object height $h_o$, which equals the magnification $m$ of a mirror, is

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}. \qquad \textbf{(23–3)}$$

If the rays that converge to form an image actually pass through the image, so the image would appear on film or a screen placed there, the image is said to be a **real image**. If the light rays do not actually pass through the image, the image is a **virtual image**.