Answer to Essential Question 24.10: In an astronomical telescope, the object (such as a distant galaxy) is very far away, so the first lens (the objective) creates an image at the focal point of that lens. To produce as large a final image as possible, the second lens (the eyepiece) should create an image at infinity, so the first image needs to be located at the eyepiece's focal point. Because the focal points coincide, the distance between the lenses is the sum of the focal lengths.

Chapter Summary

Essential Idea: Refraction and Lenses.

When light passes from one medium to a second medium in which the speed of light is different, the change in speed is generally associated with refraction (a change in direction of the light). The phenomenon of refraction is exploited in optical fibers and corrective lenses.

Index of Refraction

The index of refraction of a medium is a unitless parameter that is equal to the ratio of the speed of light in vacuum to the speed of light in the medium. In general, the speed of light in vacuum represents the maximum speed of light, so we expect $n \geq 1$.

$$n = \frac{c}{v}.$$ (Equation 24.1: **Index of refraction**)

The index of refraction is also equal to the ratio of the wavelength of light in vacuum to the wavelength of light in the medium.

$$n = \frac{\lambda_{vacuum}}{\lambda_{medium}}.$$ (Equation 24.2: **Index of refraction, in terms of wavelength**)

Snell's Law

When light is transmitted from one medium to another, the angle of incidence, θ_1, in the first medium is related to the angle of refraction, θ_2, in the second medium by:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$ (Equation 24.3: **Snell's Law**)

These angles are measured from the normal (perpendicular) to the surface. The n's represent the indices of refraction of the two media.

Total Internal Reflection

Optical fibers are an important application of total internal reflection. When light traveling in a medium encounters an interface separating that medium from a medium with a lower index of refraction, 100% of the light will be reflected back into the first medium if the angle of incidence exceeds a particular critical angle given by:

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right).$$ (Eq. 24.4: **The critical angle beyond which total internal reflection occurs**)

Ray Diagrams

To draw a ray diagram, we show rays leaving the tip of an object and being refracted by a lens. The tip of the image is where the refracted rays meet. If the rays leaving a single point on the object are refracted so they pass through a single point, a real image is formed. If, instead, such refracted rays appear to diverge from a single point behind the lens, a virtual image is formed. A summary of three rays that are particularly easy to draw is given in section 24-7.

Thin Lenses

Type of lens	Focal length	Image characteristics
Diverging (usually concave)	Negative	The image is virtual, upright, smaller than the object, and between the lens and the focal point on the side of the lens the object is on.
Converging (usually convex)	Positive	The image can be real or virtual, and larger than, smaller than, or the same size as the object. See the table below for details.

Table 24.2: A summary of the lenses we investigated in this chapter.

Images formed by a Converging Lens

Object position	Image position	Image characteristics
∞	At the focal point.	Real image with height of zero.
Moving from ∞ toward twice the focal length.	Moving from the focal point toward twice the focal length.	The image is real, inverted, and smaller than the object. The image moves closer to twice the focal length, and increases in height, as the object is moved closer to twice the focal length from the lens.
At twice the focal length.	At twice the focal length.	The image is real, inverted, and the same size as the object.
Moving from twice the focal length toward the focal point.	Moving from twice the focal length toward infinity.	The image is real, inverted, and larger than the object. The image moves farther from the lens, and increases in height, as the object is moved closer to the focal point.
At the focal point.	At infinity.	The image is at infinity, and is infinitely tall.
Closer to the lens than the focal point.	On the same side of the lens as the object.	The image is virtual, upright, and larger than the object. The image moves closer to the lens, and decreases in height, as the object is moved closer to the lens.

Table 24.3: A summary of the image positions and characteristics for a converging lens.

The thin-lens equation (same as the mirror equation from Chapter 23)

The thin-lens equation relates the object distance, d_o, the image distance, d_i, and the focal length, f. The mnemonic "If I do I di" can help you to remember the equation.

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} .$$ (Equation 24.7: **The thin-lens equation**)

$$d_i = \frac{d_o \times f}{d_o - f}$$ (Equation 24.8: **The thin-lens equation, solved for the image distance**)

Sign conventions

The image distance is positive if the image is on the reflective side of the mirror (a real image), and negative if the image is behind the mirror (a virtual image).

The image height is positive when the image is upright, and negative when the image is inverted. A similar rule applies to the object height.

Magnification

The magnification, m, is the ratio of the image height (h_i) to the object height (h_o).

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o} .$$ (Equation 24.9: **Magnification**)

The image is larger than the object if $|m| > 1$, smaller if $|m| < 1$, and of the same size if $|m| = 1$. The magnification is positive if the image is upright, and negative if the image is inverted.