Chapter 34

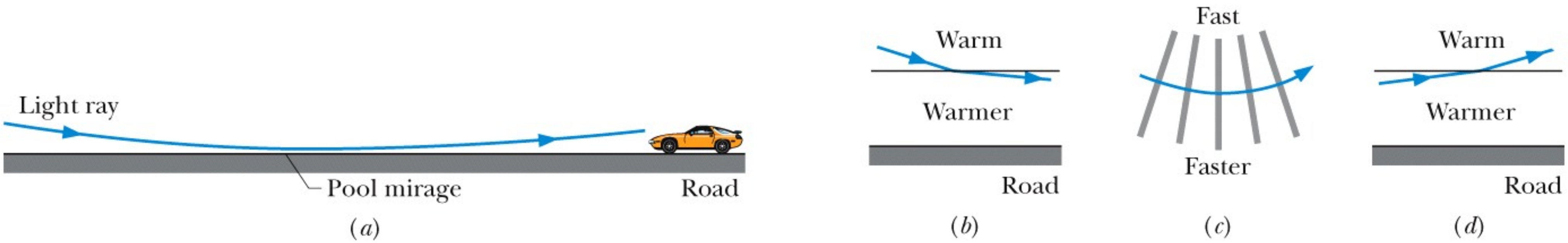
Images

- Images and Plane Mirrors
- Spherical Mirrors
- Spherical Refracting Surface
- Thin Lenses

34-1 Images and Plane Mirrors

An image is a reproduction of an object via light. If the image can form on a surface, it is a real image and can exist even if no observer is present. If the image requires the visual system of an observer, it is a virtual image.

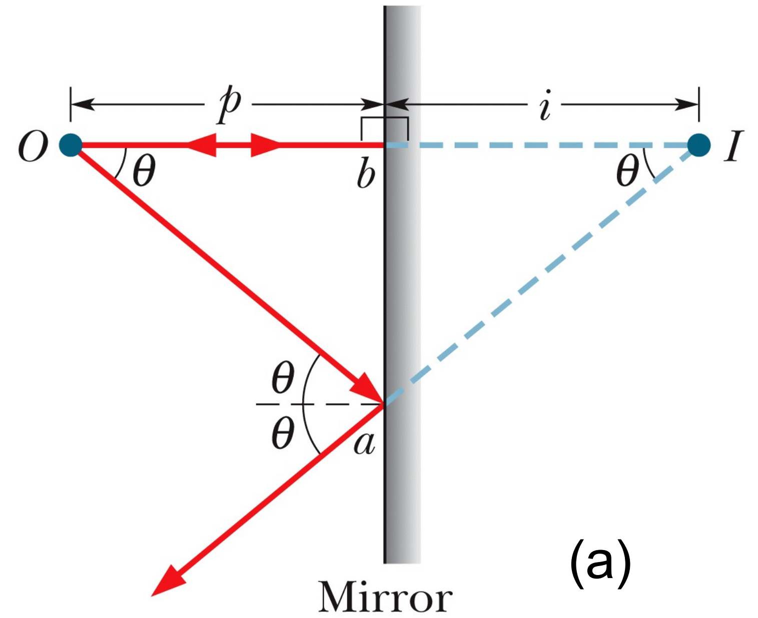
Here are some common examples of virtual image.



(a) A ray from a low section of the sky refracts through air that is heated by a road (without reaching the road). An observer who intercepts the light perceives it to be from a pool of water on the road. (b) Bending (exaggerated) of a light ray descending across an imaginary boundary from warm air to warmer air. (c) Shifting of wavefronts and associated bending of a ray, which occur because the lower ends of wavefronts move faster in warmer air. (d) Bending of a ray ascending across an imaginary boundary to warm air from warmer air.

34-1 Images and Plane Mirrors

As shown in figure (a), a plane (flat) mirror can form a virtual image of a light source (said to be the object, O) by redirecting light rays emerging from the source. The image can be seen where backward extensions of reflected rays pass through one another. The object's distance *p* from the mirror is related to the (apparent) image distance *i* from the mirror by

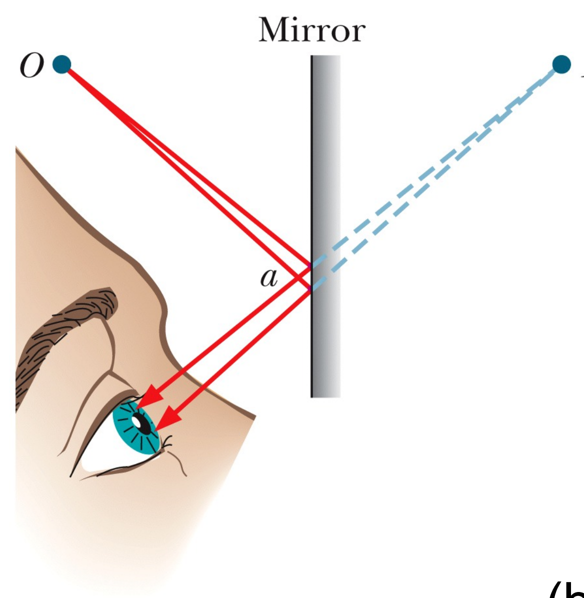


(a)

$$i = -p$$

Object distance *p* is a positive quantity. Image distance *i* for a virtual image is a negative quantity.

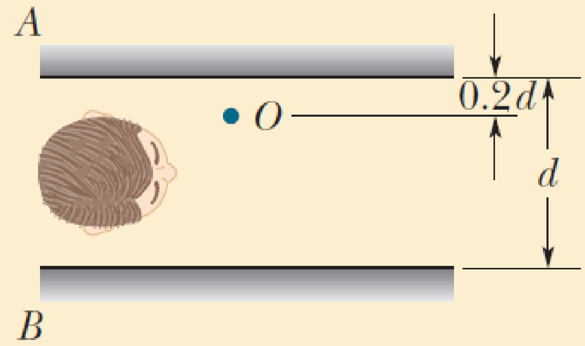
Only rays that are fairly close together can enter the eye after reflection at a mirror. For the eye position shown in Fig. (b), only a small portion of the mirror near point *a* (a portion smaller than the pupil of the eye) is useful in forming the image.



(b)

Checkpoint 1

In the figure you are in a system of two vertical parallel mirrors A and B separated by distance d. A grinning gargoyle is perched at point O, a distance $0.2d$ from mirror A. Each mirror produces a *first* (least deep) image of the gargoyle. Then each mirror produces a *second* image with the object being the first image in the opposite mirror. Then each mirror produces a *third* image with the object being the second image in the opposite mirror, and so on—you might see hundreds of grinning gargoyle images. How deep behind mirror A are the first, second, and third images in mirror A?

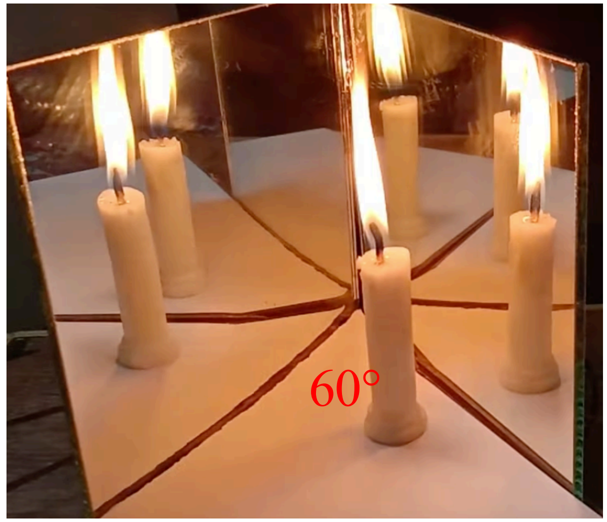


$$0.2d, 1.8d, 2.2d$$

Ex: Two plane mirrors make an angle of 120° with each other. The maximum number of images of an object placed symmetrically between them is:

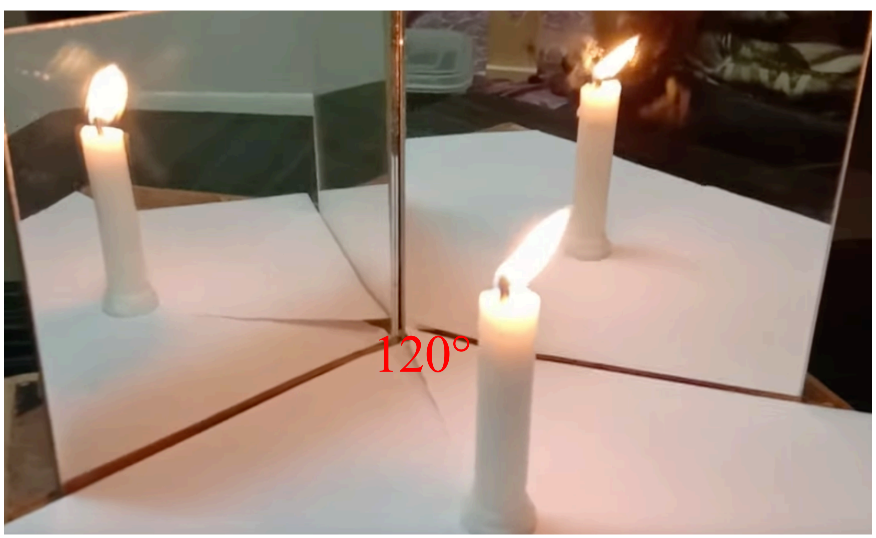
A) one
B) two
C) three
D) four
E) more than four

Number of images = 3



Number of images = 5

Number of images = 7



Number of images = 2 (symmetrically)

Number of images = 3 (unsymmetrically)

Ex: **Two plane mirrors make an angle of 120° with each other. The maximum number of images of an object placed between them is:**

If θ is the angle between two plane mirrors then,

1. Find the ratio $\frac{360^0}{\theta}$ if the ratio is *even* then

   Whether the object is kept on angle bisector (symmetrically) or

   unsymmetrically the number of images 'n' = $\frac{360^0}{\theta}$ -1

2. Find the ratio $\frac{360^0}{\theta}$, if the ratio is *Odd* then

   (a) If object is kept on angle bisector symmetrically then the number of

   images 'n' = $\frac{360^0}{\theta}$ - 1

   (b) If object is not kept on angle bisector or unsymmetrically then the number

   of images

   'n' = $\frac{360^0}{\theta}$

The ratio $\frac{360^0}{120}$ = 3, The ratio is *Odd* then

symmetrically

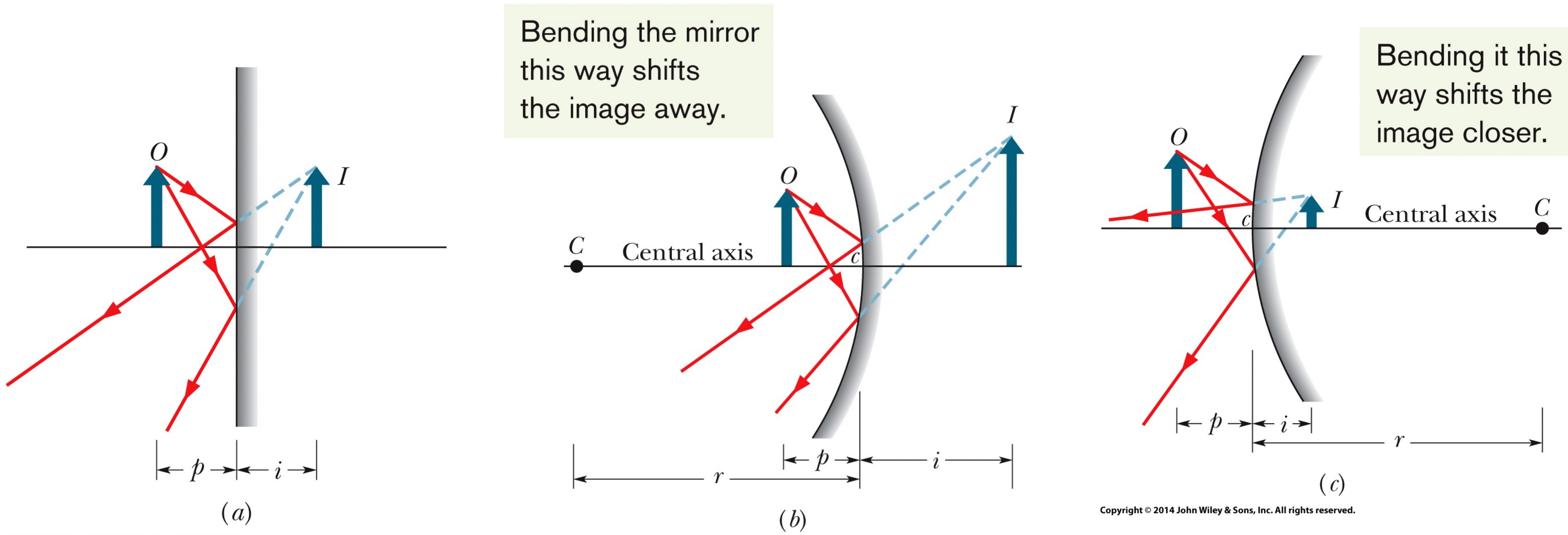
images 'n' = $\frac{360^0}{\theta}$ -1, n=2

unsymmetrically

'n' = $\frac{360^0}{\theta}$, n=3

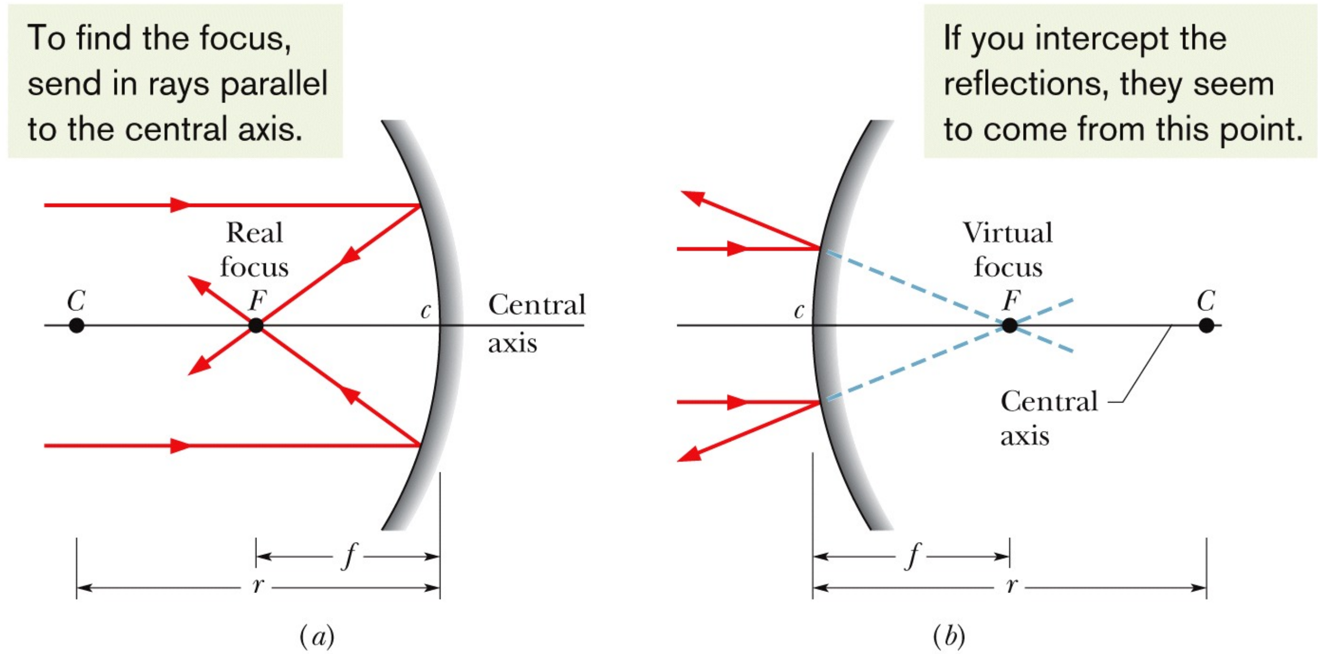
34-2 Spherical Mirrors

A spherical mirror is in the shape of a small section of a spherical surface and can be **concave** (the radius of curvature *r* is a positive quantity), **convex** (*r* is a negative quantity), or **plane** (flat, *r* is infinite).



We make a **concave mirror** by curving the mirror's surface so it is concave ("caved in" to the object) as in Fig. (b). We can make a **convex mirror** by curving a plane mirror so its surface is convex ("flexed out") as in Fig.(c). Curving the surface in this way (1) moves the *center of curvature C* to behind the mirror and (2) increases the field of view. It also (3) moves the image of the object closer to the mirror and (4) shrinks it. These iterated characteristics are the exact opposite for concave mirror.

34-2 Spherical Mirrors



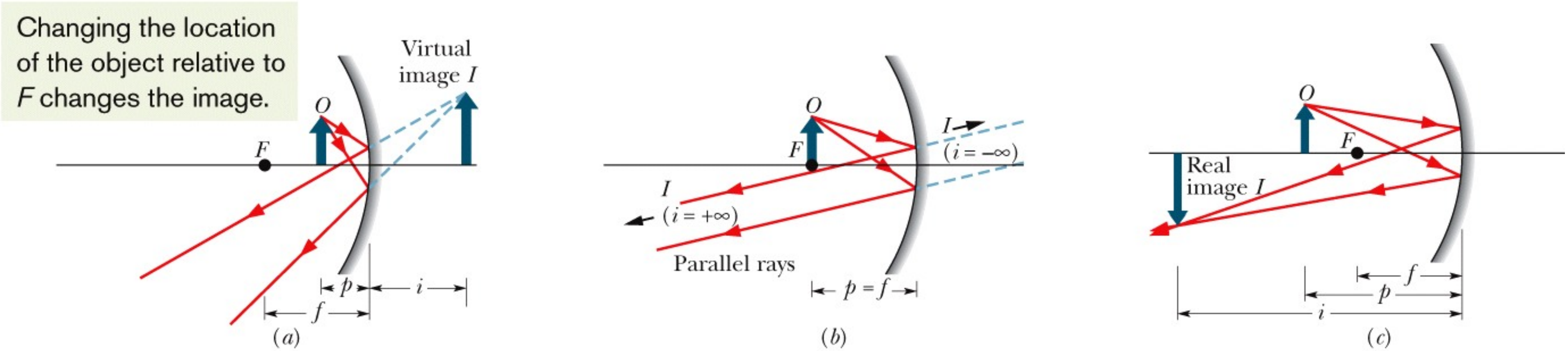
If parallel rays are sent into a (spherical) concave mirror parallel to the central axis, the reflected rays pass through a common point (a real focus *F*) at a distance *f* (a positive quantity) from the mirror (figure a). If they are sent toward a (spherical) convex mirror, backward extensions of the reflected rays pass through a common point (a virtual focus *F*) at a distance f (a negative quantity) from the mirror (figure b).

For mirrors of both types, the focal length *f* is related to the radius of curvature *r* of the mirror by

$$f = \frac{1}{2}r$$

where *r (*and *f)* is positive for a concave mirror and negative for a convex mirror.

34-2 Spherical Mirrors



(a) An object O inside the focal point of a concave mirror, and its virtual image I. (b) The object at the focal point F. (c) The object outside the focal point, and its real image I.

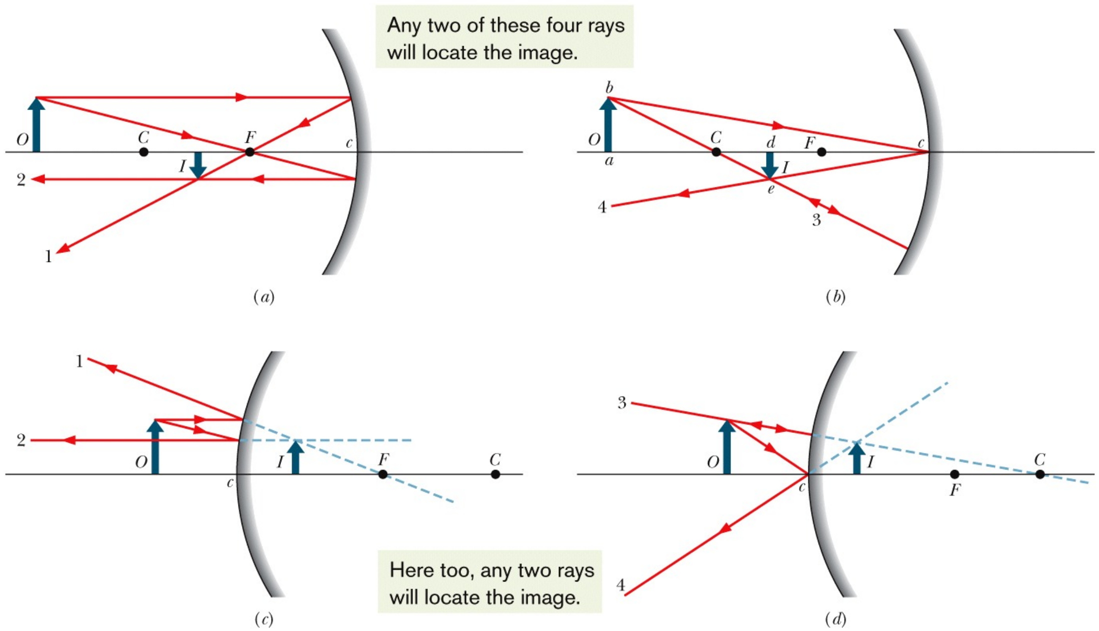
- A concave mirror can form a real image (if the object is outside the focal point) or a virtual image (if the object is inside the focal point).
- A convex mirror can form only a virtual image.
- The mirror equation relates an object distance *p*, the mirror's focal length *f* and radius of curvature *r*, and the image distance *i*:

$$\frac{1}{p}+\frac{1}{i}=\frac{1}{f}$$

- The magnitude of the lateral magnification m of an object is the ratio of the image height h' to object height h,

$$|m|=\frac{h'}{h} \qquad m=-\frac{i}{p}$$

34-2 Spherical Mirrors



Locating Images by Drawing Rays

1. A ray that is initially parallel to the central axis reflects through the focal point *F* (ray 1 in Fig. a).
2. A ray that reflects from the mirror after passing through the focal point emerges parallel to the central axis (Fig. a).
3. A ray that reflects from the mirror after passing through the center of curvature *C* returns along itself (ray 3 in Fig. b).
4. A ray that reflects from the mirror at point *c* is reflected symmetrically about that axis (ray 4 in Fig. b).

The image of the point is at the intersection of the two special rays you choose. The image of the object can then be found by locating the images of two or more of its off-axis points (say, the point most off axis) and then sketching in the rest of the image. You need to modify the descriptions of the rays slightly to apply them to convex mirrors, as in Figs. c and d.

Checkpoint 2

A Central American vampire bat, dozing on the central axis of a spherical mirror, is magnified by $m = -4$. Is its image (a) real or virtual, (b) inverted or of the same orientation as the bat, and (c) on the same side of the mirror as the bat or on the opposite side?

(a) real; (b) inverted; (c) same

Sample Problem 34.01 Image produced by a spherical mirror

A tarantula of height h sits cautiously before a spherical mirror whose focal length has absolute value $|f| = 40$ cm. The image of the tarantula produced by the mirror has the same orientation as the tarantula and has height $h' = 0.20h$.

(a) Is the image real or virtual, and is it on the same side of the mirror as the tarantula or the opposite side?

Reasoning: Because the image has the same orientation as the tarantula (the object), it must be virtual and on the opposite side of the mirror. (You can easily see this result if you have filled out Table 34-1.)

(b) Is the mirror concave or convex, and what is its focal length f, sign included?

KEY IDEA

We *cannot* tell the type of mirror from the type of image because both types of mirror can produce virtual images. Similarly, we cannot tell the type of mirror from the sign of the focal length f, as obtained from Eq. 34-3 or Eq. 34-4, because we lack enough information to use either equation. However, we can make use of the magnification information.

Calculations: From the given information, we know that the ratio of image height h' to object height h is 0.20. Thus, from Eq. 34-5 we have

$$|m| = \frac{h'}{h} = 0.20.$$

Because the object and image have the same orientation, we know that m must be positive: $m = +0.20$. Substituting this into Eq. 34-6 and solving for, say, i gives us

$$i = -0.20p,$$

which does not appear to be of help in finding f. However, it is helpful if we substitute it into Eq. 34-4. That equation gives us

$$\frac{1}{f} = \frac{1}{i} + \frac{1}{p} = \frac{1}{-0.20p} + \frac{1}{p} = \frac{1}{p}(-5 + 1),$$

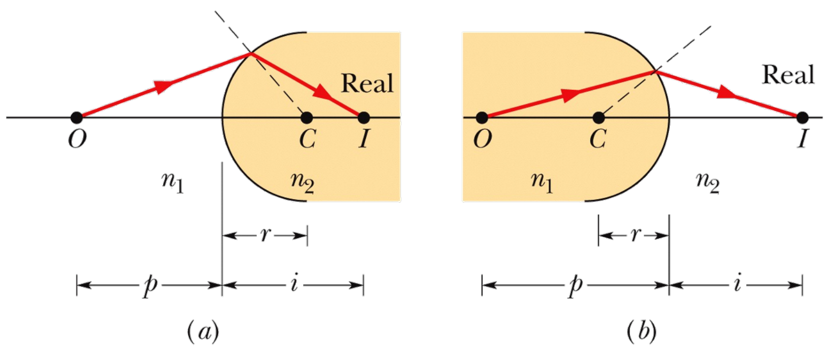
from which we find

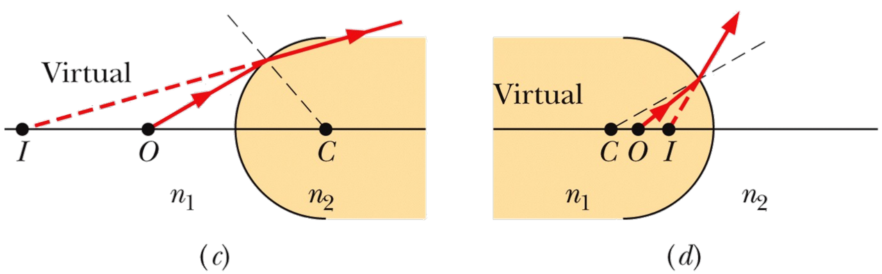
$$f = -p/4.$$

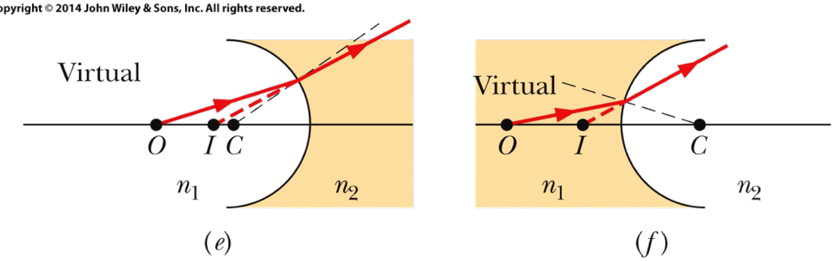
Now we have it: Because p is positive, f must be negative, which means that the mirror is convex with

$$f = -40 \text{ cm.} \qquad \text{(Answer)}$$

34-3 Spherical Refracting Surface







Real images are formed in (a) and (b); virtual images are formed in the other four situations.

- A single spherical surface that refracts light can form an image.
- The object distance p, the image distance i, and the radius of curvature r of the surface are related by

$$\frac{n_1}{p} + \frac{n_2}{i} = \frac{n_2 - n_1}{r}.$$

where n_1 is the index of refraction of the material where the object is located and n_2 is the index of refraction on the other side of the surface.

- If the surface faced by the object is convex, r is positive, and if it is concave, r is negative.

Real images form on the side of a refracting surface that is opposite the object, and virtual images form on the same side as the object.

Be careful: This is just the reverse of the sign convention we have for mirrors.

Checkpoint 3

A bee is hovering in front of the concave spherical refracting surface of a glass sculpture. (a) Which part of Fig. 34-12 is like this situation? (b) Is the image produced by the surface real or virtual, and (c) is it on the same side as the bee or the opposite side?

(a) e; (b) virtual, same

Sample Problem 34.02 Image produced by a refracting surface

A Jurassic mosquito is discovered embedded in a chunk of amber, which has index of refraction 1.6. One surface of the amber is spherically convex with radius of curvature 3.0 mm (Fig. 34-13). The mosquito's head happens to be on the central axis of that surface and, when viewed along the axis, appears to be buried 5.0 mm into the amber. How deep is it really?

KEY IDEAS

The head appears to be 5.0 mm into the amber only because the light rays that the observer intercepts are bent by refraction at the convex amber surface. The image distance i differs from the object distance p according to Eq. 34-8. To use that equation to find the object distance, we first note:

1. Because the object (the head) and its image are on the same side of the refracting surface, the image must be virtual and so $i = -5.0$ mm.
2. Because the object is always taken to be in the medium of index of refraction n_1, we must have $n_1 = 1.6$ and $n_2 = 1.0$.
3. Because the *object* faces a concave refracting surface, the radius of curvature r is negative, and so $r = -3.0$ mm.

Calculations: Making these substitutions in Eq. 34-8,

$$\frac{n_1}{p} + \frac{n_2}{i} = \frac{n_2 - n_1}{r},$$

yields

$$\frac{1.6}{p} + \frac{1.0}{-5.0\text{ mm}} = \frac{1.0 - 1.6}{-3.0\text{ mm}}$$

and

$$p = 4.0\text{ mm}. \qquad \text{(Answer)}$$

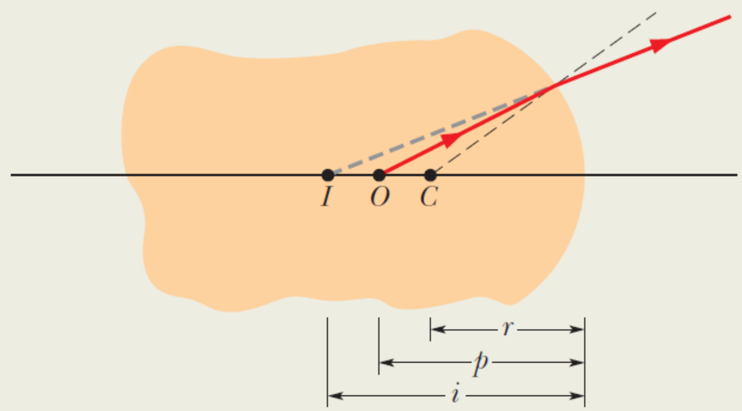


Figure 34-13 A piece of amber with a mosquito from the Jurassic period, with the head buried at point O. The spherical refracting surface at the right end, with center of curvature C, provides an image I to an observer intercepting rays from the object at O.

34-4 Thin Lenses

For an object in front of a lens, object distance p and image distance i are related to the lens's focal length f, index of refraction n, and radii of curvature r_1 and r_2 by

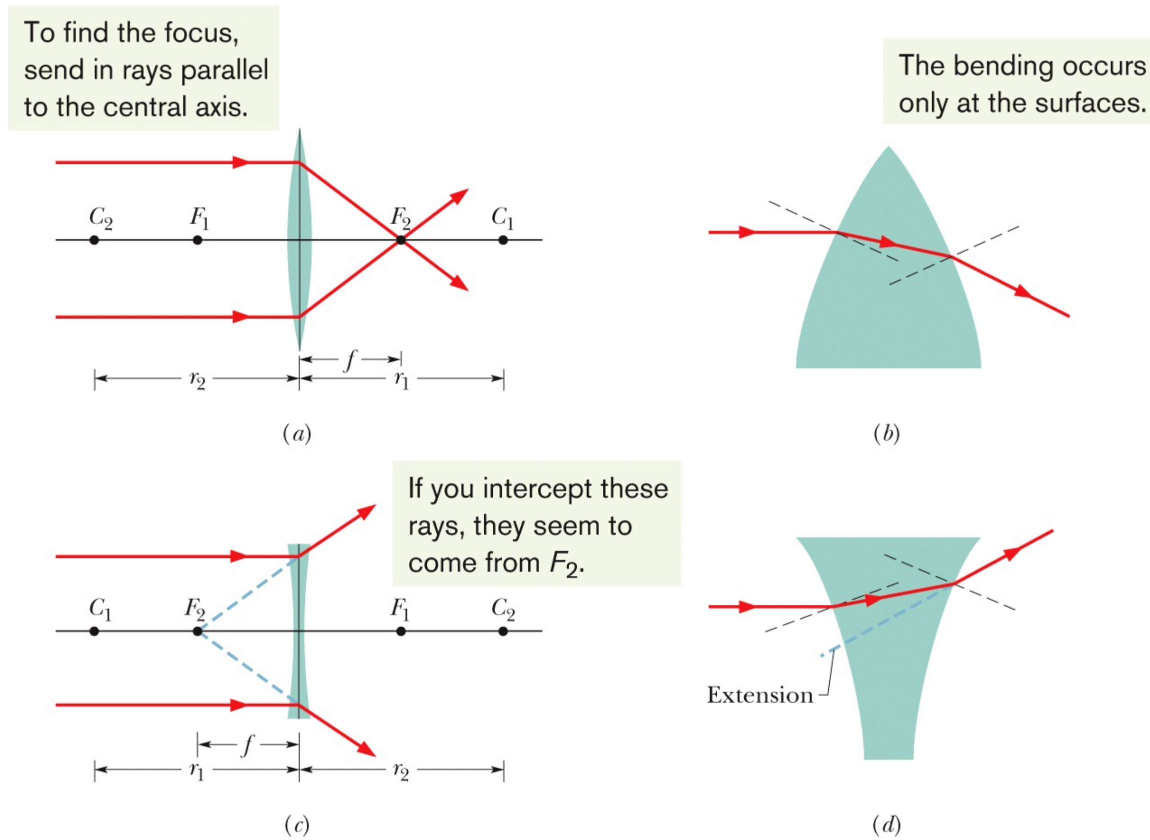
$$\frac{1}{f} = (n-1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \quad \text{(thin lens in air)},$$

which is often called the **lens maker's** equation. Here r_1 is the radius of curvature of the lens surface nearer the object and r_2 is that of the other surface. If the lens is surrounded by some medium other than air (say, corn oil) with index of refraction n_{medium}, we replace n in above Eq. with n/n_{medium}.

A lens can produce an image of an object only because the lens can bend light rays, but it can bend light rays only if its index of refraction differs from that of the surrounding medium.

34-4 Thin Lenses

Forming a Focus. Figure (a) shows a thin lens with convex refracting surfaces, or sides. When rays that are parallel to the central axis of the lens are sent through the lens, they refract twice, as is shown enlarged in Fig.(b). This double refraction causes the rays to converge and pass through a common point F_2 at a distance f from the center of the lens. Hence, this lens is a converging lens; further, a real focal point (or focus) exists at F_2 (because the rays really do pass through it), and the associated focal length is f. When rays parallel to the central axis are sent in the opposite direction through the lens, we find another real focal point at F_1 on the other side of the lens. For a thin lens, these two focal points are equidistant from the lens.



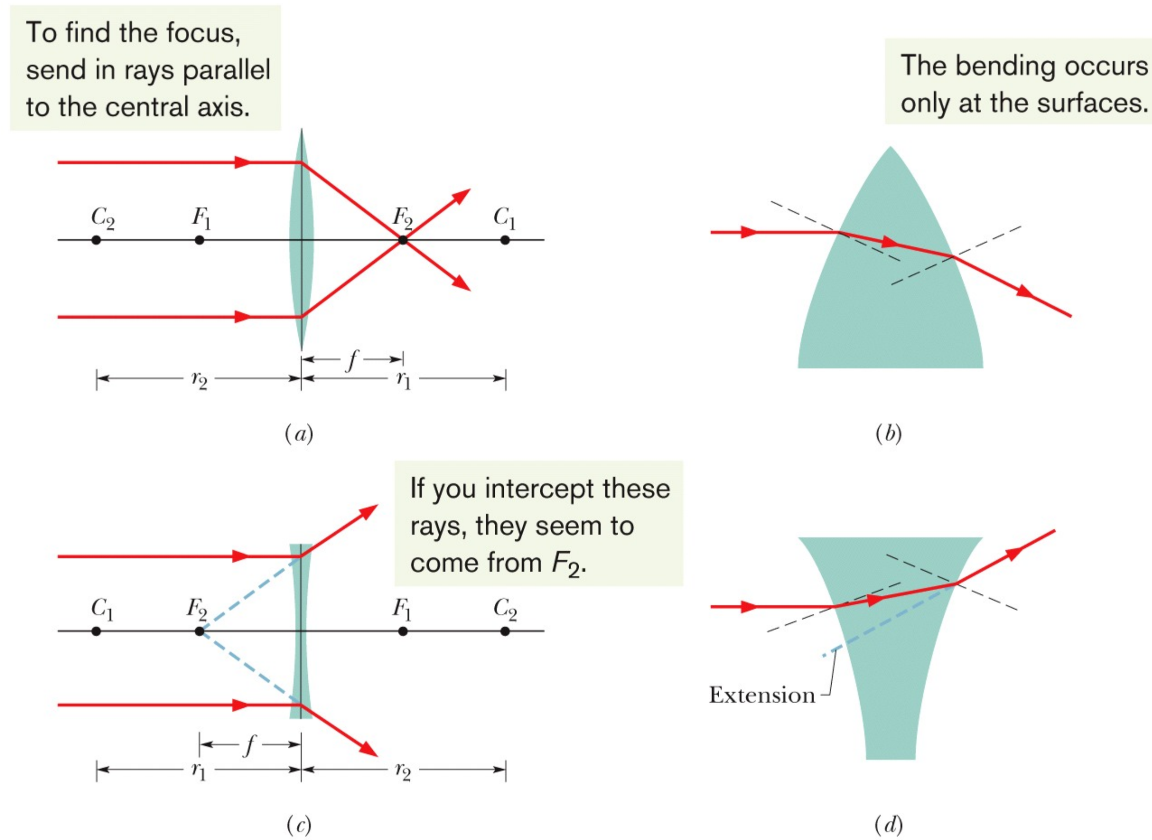
Thin Lenses

is, a lens in which the thickest part is thin relative to the object distance p, the image distance i, and the radii of curvature r_1 and r_2 of the two surfaces of the lens. We shall also consider only light rays that make small angles with the central axis

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{i} \quad \text{(thin lens),}$$

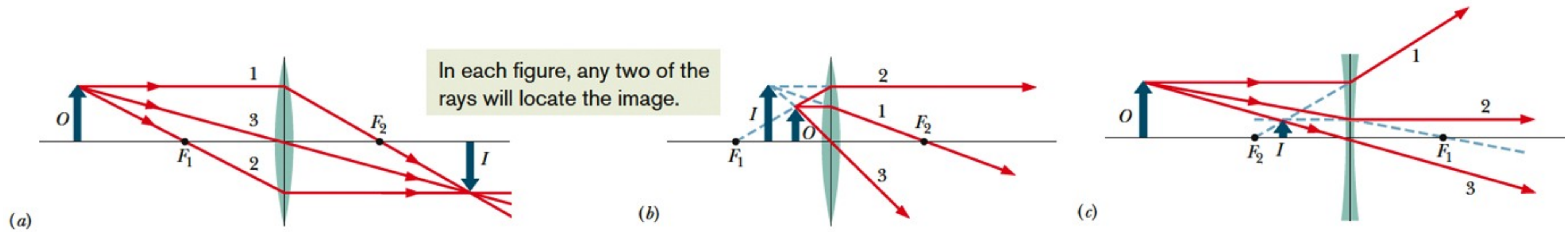
34-4 Thin Lenses

Forming a Focus. Figure (c) shows a thin lens with concave sides. When rays that are parallel to the central axis of the lens are sent through this lens, they refract twice, as is shown enlarged in Fig. (d); these rays diverge, never passing through any common point, and so this lens is a diverging lens. However, extensions of the rays do pass through a common point F_2 at a distance f from the center of the lens. Hence, the lens has a virtual focal point at F_2. (If your eye intercepts some of the diverging rays, you perceive a bright spot to be at F_2, as if it is the source of the light.) Another virtual focus exists on the opposite side of the lens at F_1, symmetrically placed if the lens is thin. Because the focal points of a diverging lens are virtual, we take the focal length f to be negative.



34-4 Thin Lenses

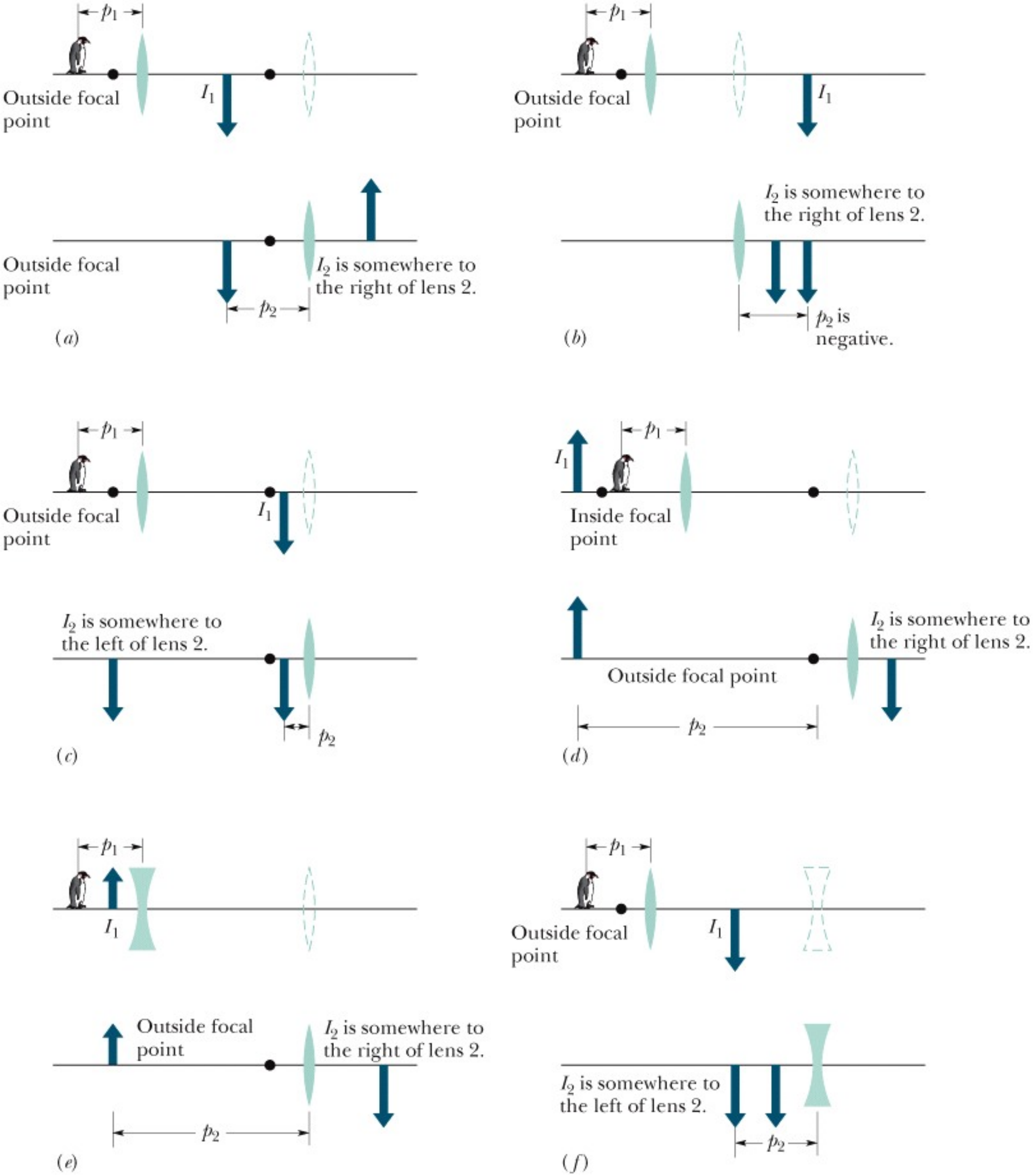
Locating Images of Extended Objects by Drawing Rays



1. A ray that is initially parallel to the central axis of the lens will pass through focal point F_2 (ray 1 in Fig. a).
2. A ray that initially passes through focal point F_1 will emerge from the lens parallel to the central axis (ray 2 in Fig. a).
3. A ray that is initially directed toward the center of the lens will emerge from the lens with no change in its direction (ray 3 in Fig. a) because the ray encounters the two sides of the lens where they are almost parallel.

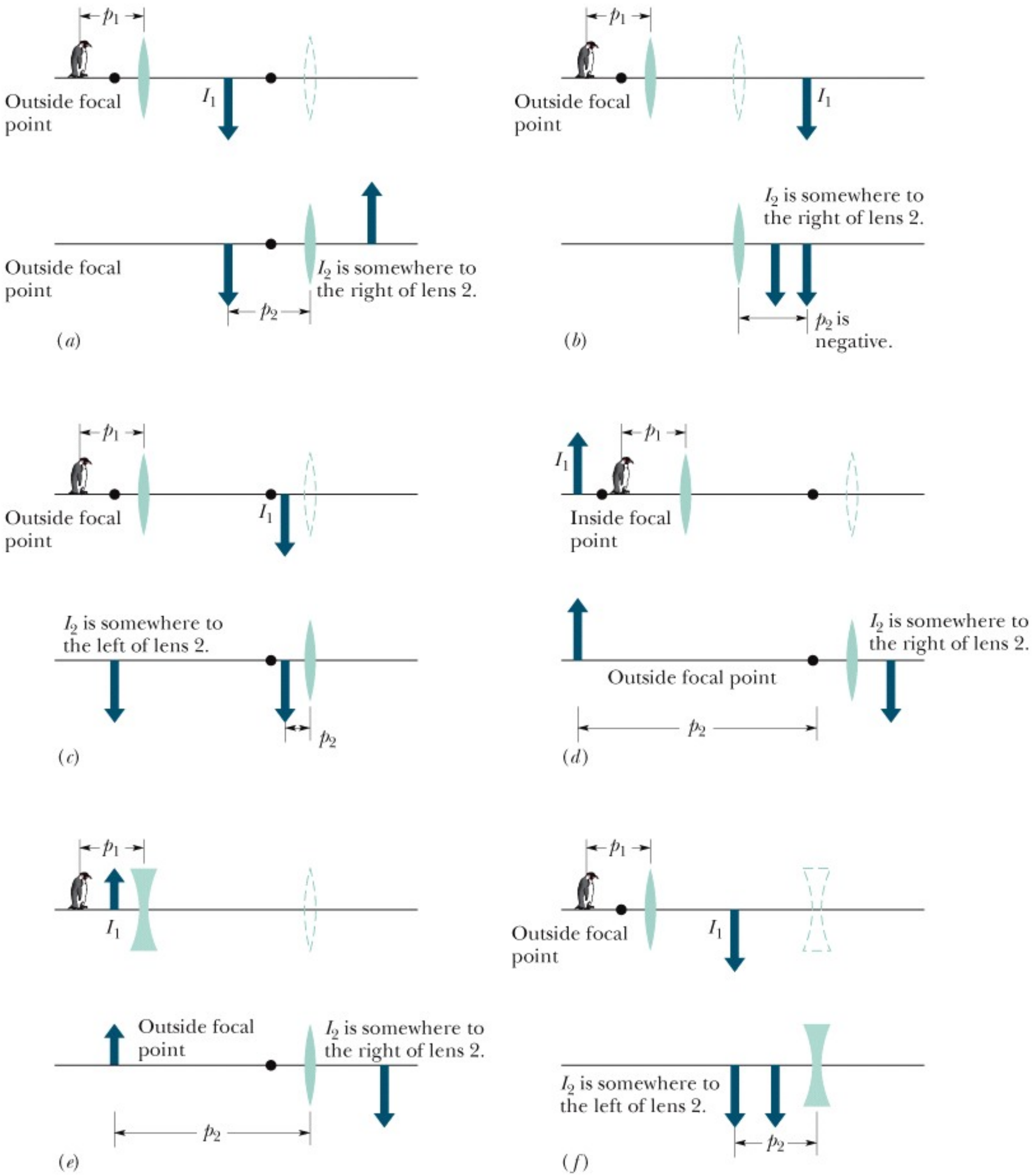
Figure b shows how the extensions of the three special rays can be used to locate the image of an object placed inside focal point F_1 of a converging lens. Note that the description of ray 2 requires modification (it is now a ray whose backward extension passes through F_1).You need to modify the descriptions of rays 1 and 2 to use them to locate an image placed (anywhere) in front of a diverging lens. In Fig. c, for example, we find the point where ray 3 intersects the backward extensions of rays 1 and 2.

Two Lens System



Here we consider an object sitting in front of a system of two lenses whose central axes coincide. Some of the possible two-lens systems are sketched in the figure (left) , but the figures are not drawn to scale. In each, the object sits to the left of lens 1 but can be inside or outside the focal point of the lens. Although tracing the light rays through any such two-lens system can be challenging, we can use the following simple two-step solution:

Two Lens System



Step 1: Neglecting lens *2*, use thin lens equation to locate the image I_1 produced by lens *1*. Determine whether the image is on the left or right side of the lens, whether it is real or virtual, and whether it has the same orientation as the object. Roughly sketch I_1. The top part of Fig. (a) gives an example.

Step 2: Neglecting lens *1*, treat I_1 as though it is the object for lens 2. Use thin lens equation to locate the image I_2 produced by lens 2. This is the final image of the system. Determine whether the image is on the left or right side of the lens, whether it is real or virtual, and whether it has the same orientation as the object for lens *2*. Roughly sketch I_2 . The bottom part of Fig. (a) gives an example.

Checkpoint 4

A thin symmetric lens provides an image of a fingerprint with a magnification of $+0.2$ when the fingerprint is 1.0 cm farther from the lens than the focal point of the lens. What are the (a) type and (b) orientation of the image, and (c) what is the type of lens?

virtual, same as object, diverging

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{i} \quad \text{(thin lens)},$$

Sample Problem 34.03 Image produced by a thin symmetric lens

A praying mantis preys along the central axis of a thin symmetric lens, 20 cm from the lens. The lateral magnification of the mantis provided by the lens is $m = -0.25$, and the index of refraction of the lens material is 1.65.

(a) Determine the type of image produced by the lens, the type of lens, whether the object (mantis) is inside or outside the focal point, on which side of the lens the image appears, and whether the image is inverted.

Reasoning: We can tell a lot about the lens and the image from the given value of m. From it and Eq. 34-6 ($m = -i/p$), we see that

$$i = -mp = 0.25p.$$

Even without finishing the calculation, we can answer the questions. Because p is positive, i here must be positive. That means we have a real image, which means we have a converging lens (the only lens that can produce a real image). The object must be outside the focal point (the only way a real image can be produced). Also, the image is inverted and on the side of the lens opposite the object. (That is how a converging lens makes a real image.)

(b) What are the two radii of curvature of the lens?

KEY IDEAS

1. Because the lens is symmetric, r_1 (for the surface nearer the object) and r_2 have the same magnitude r.
2. Because the lens is a converging lens, the object faces a convex surface on the nearer side and so $r_1 = +r$. Similarly, it faces a concave surface on the farther side; so $r_2 = -r$.
3. We can relate these radii of curvature to the focal length f via the lens maker's equation, Eq. 34-10 (our only equation involving the radii of curvature of a lens).
4. We can relate f to the object distance p and image distance i via Eq. 34-9.

Calculations: We know p, but we do not know i. Thus, our starting point is to finish the calculation for i in part (a); we obtain

$$i = (0.25)(20 \text{ cm}) = 5.0 \text{ cm}.$$

Now Eq. 34-9 gives us

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{i} = \frac{1}{20 \text{ cm}} + \frac{1}{5.0 \text{ cm}},$$

from which we find $f = 4.0$ cm.

Equation 34-10 then gives us

$$\frac{1}{f} = (n-1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right) = (n-1)\left(\frac{1}{+r} - \frac{1}{-r}\right)$$

or, with known values inserted,

$$\frac{1}{4.0 \text{ cm}} = (1.65 - 1)\frac{2}{r},$$

which yields

$$r = (0.65)(2)(4.0 \text{ cm}) = 5.2 \text{ cm}. \qquad \text{(Answer)}$$

Sample Problem 34.04 Image produced by a system of two thin lenses

Figure 34-18*a* shows a jalapeño seed O_1 that is placed in front of two thin symmetrical coaxial lenses 1 and 2, with focal lengths $f_1 = +24$ cm and $f_2 = +9.0$ cm, respectively, and with lens separation $L = 10$ cm. The seed is 6.0 cm from lens 1. Where does the system of two lenses produce an image of the seed?

KEY IDEA

We could locate the image produced by the system of lenses by tracing light rays from the seed through the two lenses. However, we can, instead, calculate the location of that image by working through the system in steps, lens by lens. We begin with the lens closer to the seed. The image we seek is the final one—that is, image I_2 produced by lens 2.

Lens 1: Ignoring lens 2, we locate the image I_1 produced by lens 1 by applying Eq. 34-9 to lens 1 alone:

$$\frac{1}{p_1} + \frac{1}{i_1} = \frac{1}{f_1}.$$

The object O_1 for lens 1 is the seed, which is 6.0 cm from the lens; thus, we substitute $p_1 = +6.0$ cm. Also substituting the given value of f_1, we then have

$$\frac{1}{+6.0\text{ cm}} + \frac{1}{i_1} = \frac{1}{+24\text{ cm}},$$

which yields $i_1 = -8.0$ cm.

This tells us that image I_1 is 8.0 cm from lens 1 and virtual. (We could have guessed that it is virtual by noting that the seed is inside the focal point of lens 1, that is, between the lens and its focal point.) Because I_1 is virtual, it is on the same side of the lens as object O_1 and has the same orientation as the seed, as shown in Fig. 34-18*b*.

Lens 2: In the second step of our solution, we treat image I_1 as an object O_2 for the second lens and now ignore lens 1. We first note that this object O_2 is outside the focal point

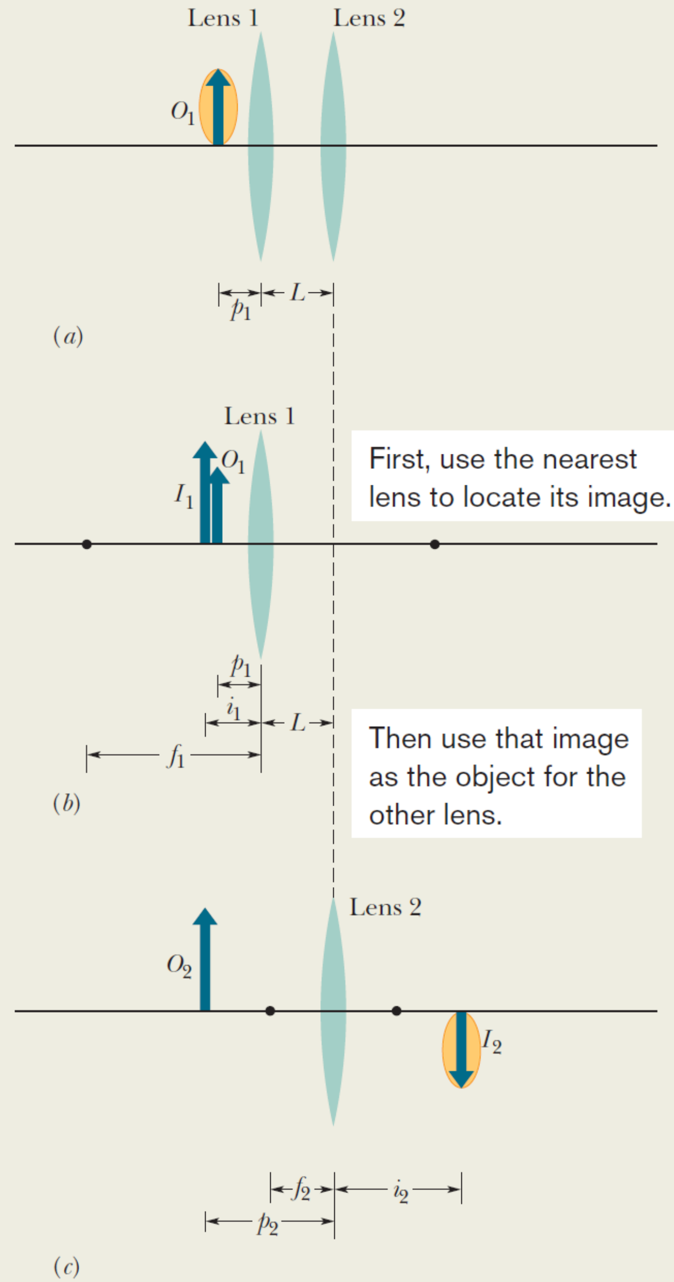


Figure 34-18 (*a*) Seed O_1 is distance p_1 from a two-lens system with lens separation L. We use the arrow to orient the seed. (*b*) The image I_1 produced by lens 1 alone. (*c*) Image I_1 acts as object O_2 for lens 2 alone, which produces the final image I_2.

of lens 2. So the image I_2 produced by lens 2 must be real, inverted, and on the side of the lens opposite O_2. Let us see.

The distance p_2 between this object O_2 and lens 2 is, from Fig. 34-18*c*,

$$p_2 = L + |i_1| = 10 \text{ cm} + 8.0 \text{ cm} = 18 \text{ cm}.$$

Then Eq. 34-9, now written for lens 2, yields

$$\frac{1}{+18 \text{ cm}} + \frac{1}{i_2} = \frac{1}{+9.0 \text{ cm}}.$$

Hence,

$$i_2 = +18 \text{ cm}. \qquad \text{(Answer)}$$

The plus sign confirms our guess: Image I_2 produced by lens 2 is real, inverted, and on the side of lens 2 opposite O_2, as shown in Fig. 34-18*c*. Thus, the image would appear on a card placed at its location.

34-5 Optical Instruments

Simple Magnifying Lens

The angular magnification of a simple magnifying lens is

$$m_\theta \approx \frac{25\text{ cm}}{f} \quad \text{(simple magnifier).}$$

where f is the focal length of the lens and 25 cm is a reference value for the near point value.

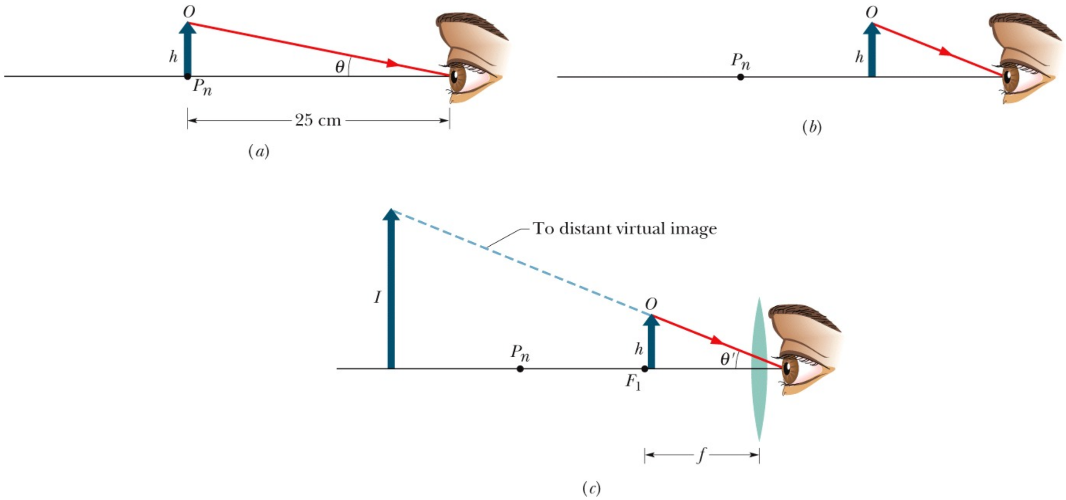


Figure (a) shows an object O placed at the near point P_n of an eye. The size of the image of the object produced on the retina depends on the angle θ that the object occupies in the field of view from that eye. By moving the object closer to the eye, as in Fig.(b), you can increase the angle and, hence, the possibility of distinguishing details of the object. However, because the object is then closer than the near point, it is no longer in focus; that is, the image is no longer clear. You can restore the clarity by looking at O through a converging lens, placed so that O is just inside the focal point F_1 of the lens, which is at focal length f (Fig. c). What you then see is the virtual image of O produced by the lens. That image is farther away than the near point; thus, the eye can see it clearly.

34-5 Optical Instruments

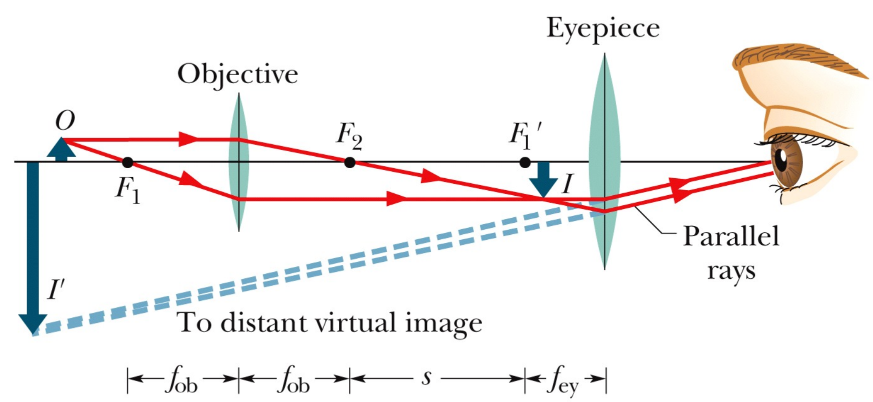
Compound Microscope

Figure shows a thin-lens version of a compound microscope. The instrument consists of an objective (the front lens) of focal length f_{ob} and an eyepiece (the lens near the eye) of focal length f_{ey}. It is used for viewing small objects that are very close to the objective. The object O to be viewed is placed just outside the first focal point F_1 of the objective, close enough to F_1 that we can approximate its distance p from the lens as being f_{ob}. The separation between the lenses is then adjusted so that the enlarged, inverted, real image I produced by the objective is located just inside the first focal point F_1 of the eyepiece. The tube length s shown in the figure is actually large relative to f_{ob}, and therefore we can approximate the distance i between the objective and the image I as being length s.

The overall magnification of a compound microscope is

$$M = mm_\theta = -\frac{s}{f_{ob}}\frac{25\text{ cm}}{f_{ey}},$$

where where m is the lateral magnification of the objective, m_θ is the angular magnification of the eyepiece.



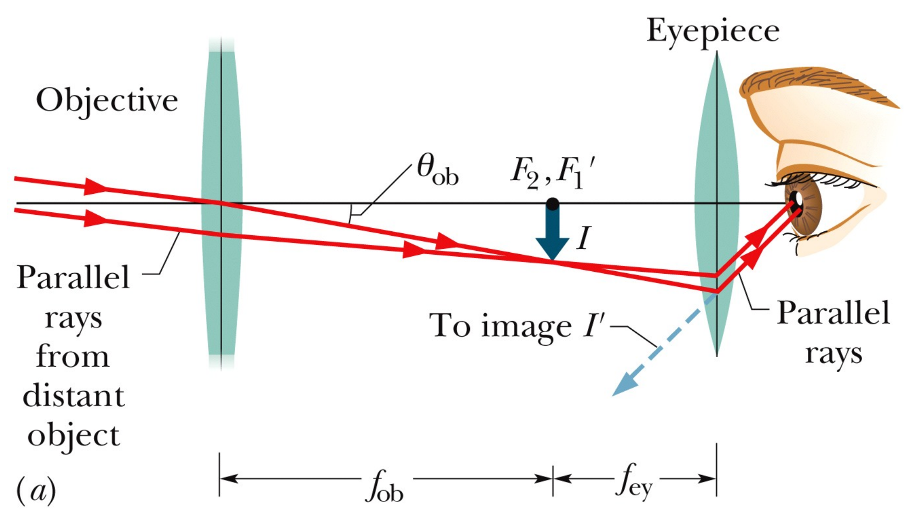
34-5 Optical Instruments

Refracting Telescope

Refracting telescope consists of an objective and an eyepiece; both are represented in the figure with simple lenses, although in practice, as is also true for most microscopes, each lens is actually a compound lens system. The lens arrangements for telescopes and for microscopes are similar, but telescopes are designed to view large objects, such as galaxies, stars, and planets, at large distances, whereas microscopes are designed for just the opposite purpose. This difference requires that in the telescope of the figure the second focal point of the objective F_2 coincide with the first focal point of the eyepiece F'_1, whereas in the microscope these points are separated by the tube length s.

The angular magnification of a refracting telescope is

$$m_\theta = -\frac{f_{ob}}{f_{ey}}.$$



34 Summary

Real and Virtual Images

- If the image can form on a surface, it is a real image and can exist even if no observer is present. If the image requires the visual system of an observer, it is a virtual image.

Image Formation

- Spherical mirrors, spherical refracting surfaces, and thin lenses can form images of a source of light—the object — by redirecting rays emerging from the source.
- **Spherical Mirror:**

$$\frac{1}{p} + \frac{1}{i} = \frac{1}{f} = \frac{2}{r},$$ **Eq. 34-3 & 4**

- **Spherical Refracting Surface:**

$$\frac{n_1}{p} + \frac{n_2}{i} = \frac{n_2 - n_1}{r}$$ **Eq. 34-8**

- **Thin Lens:**

$$\frac{1}{p} + \frac{1}{i} = \frac{1}{f} = (n-1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right),$$ **Eq. 34-9 & 10**

Optical Instruments

- Three optical instruments that extend human vision are:

1. The simple magnifying lens, which produces an angular magnification m_θ given by

$$m_\theta = \frac{25\text{ cm}}{f}$$ **Eq. 34-12**

2. The compound microscope, which produces an overall magnification M given by

$$M = mm_\theta = -\frac{s}{f_{ob}}\frac{25\text{ cm}}{f_{ey}}$$ **Eq. 34-14**

3. The refracting telescope, which produces an angular magnification mu given by $$m_\theta = -\frac{f_{ob}}{f_{ey}}.$$ **Eq. 34-15**