Chapter 34

Images

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34-1 Images and Plane Mirrors

Learning Objectives

34.01 Distinguish virtual images from real images.

34.02 Explain the common roadway mirage.

34.03 Sketch a ray diagram for the reflection of a point source of light by a plane mirror, indicating the object distance and image distance.

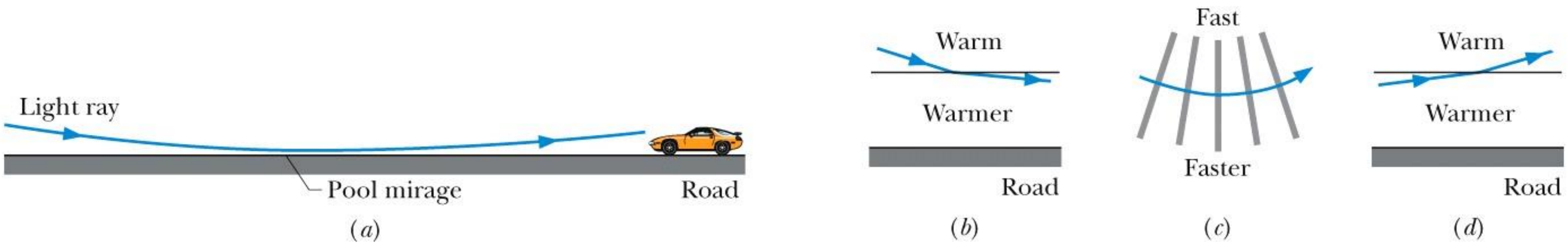
34.04 Using the proper algebraic sign, relate the object distance p to the image distance i.

34.05 Give an example of the apparent hallway that you can see in a mirror maze based on equilateral triangles.

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.

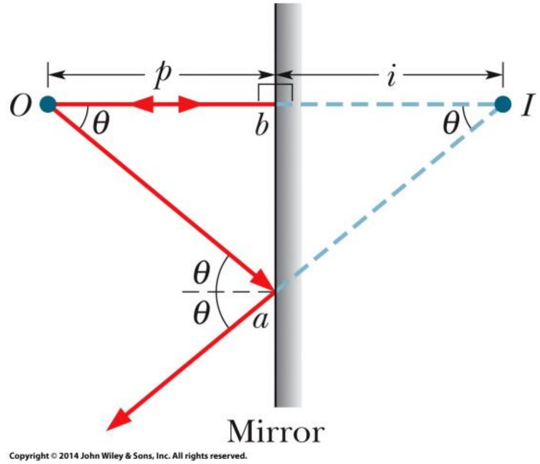
34-1 Images and Plane Mirrors

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

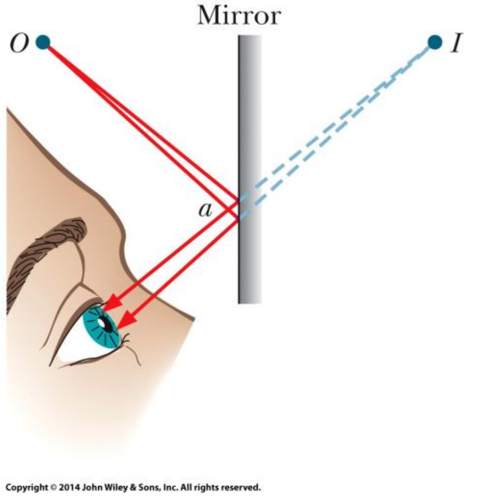
$$i = -p$$

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.



(a)



(b)

34-2 Spherical Mirrors

Learning Objectives

34.06 Distinguish a concave spherical mirror from a convex spherical mirror.

34.07 For concave and convex mirrors, sketch a ray diagram for the reflection of light rays that are initially parallel to the central axis, indicating how they form the focal points, and identifying which is real and which is virtual.

34.08 Distinguish a real focal point from a virtual focal point, identify which corresponds to which type of mirror, and identify the algebraic sign associated with each focal length.

34.09 Relate a focal length of a spherical mirror to the radius.

34.10 Identify the terms “inside the focal point” and “outside the focal point.”

34.11 For an object (a) inside and (b) outside the focal point of a concave mirror, sketch the reflections of at least two rays to find the image and identify the type and orientation of the image..

Learning Objectives (Contd.)

34.12 For a concave mirror, distinguish the locations and orientations of a real image and a virtual image.

34.13 For an object in front of a convex mirror, sketch the reflections of at least two rays to find the image and identify the type and orientation of the image.

34.14 Identify which type of mirror can produce both real and virtual images and which type can produce only virtual images.

34.15 Identify the algebraic signs of the image distance *i* for real images and virtual images.

34.16 For convex, concave, and plane mirrors, apply the relationship between the focal length *f*, object distance *p*, and image distance *i*.

34.17 Apply the relationships between lateral magnification *m*, image height *h'*, object height *h*, image distance *i*, and object distance *p*.

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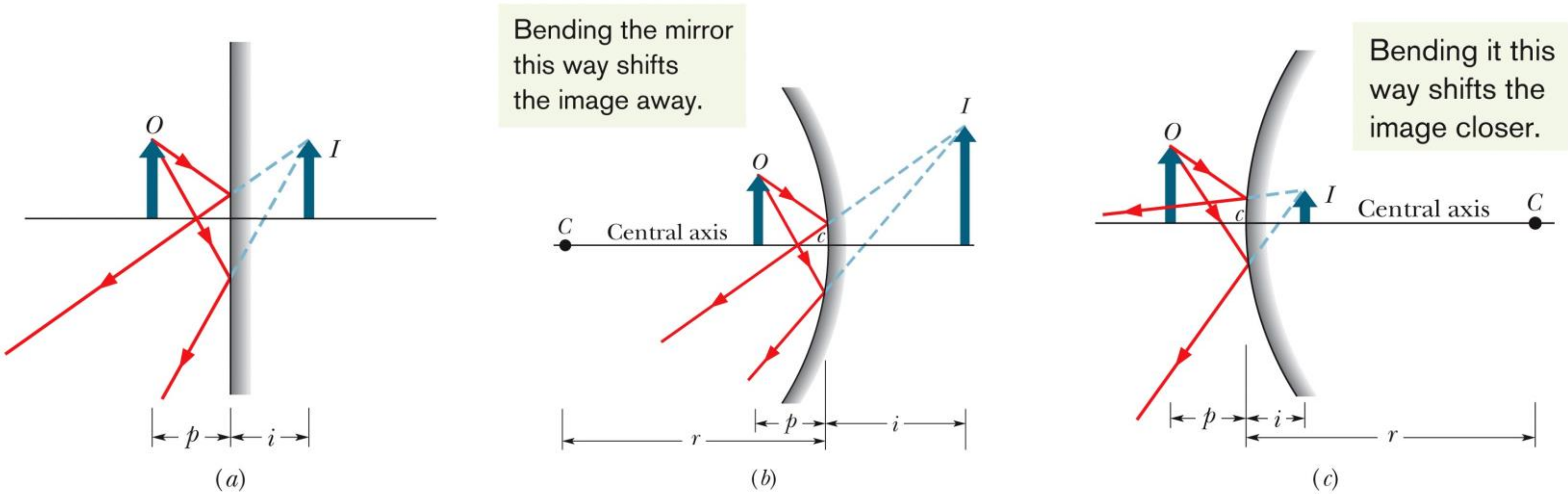
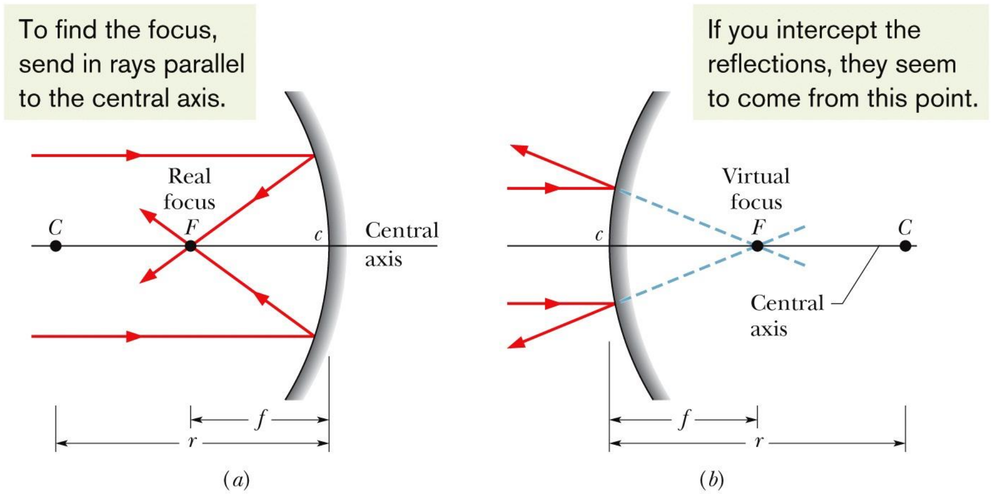
34-2 Spherical Mirrors

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



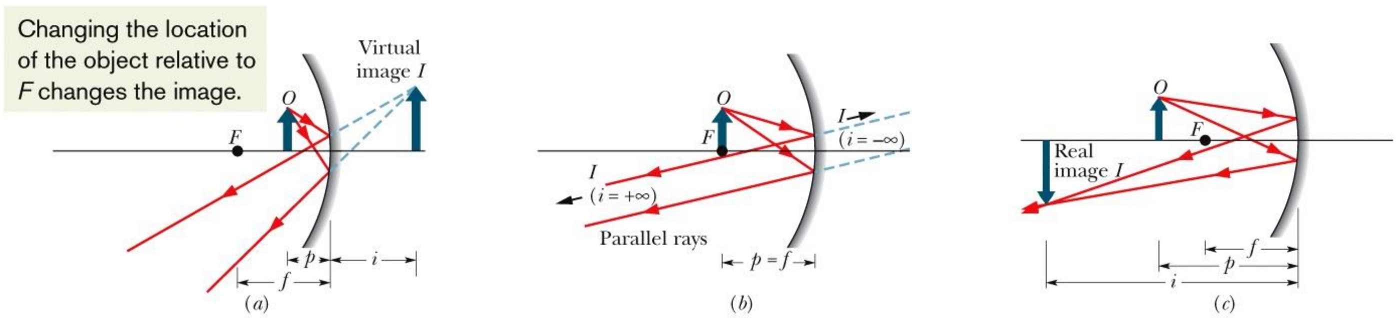
If parallel rays are sent into a (spherical) concave mirror parallel to the central axis, the reflected rays pass through a common point (a real focus *F*) at a distance *f* (a positive quantity) from the mirror (figure a). If they are sent toward a (spherical) convex mirror, backward extensions of the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

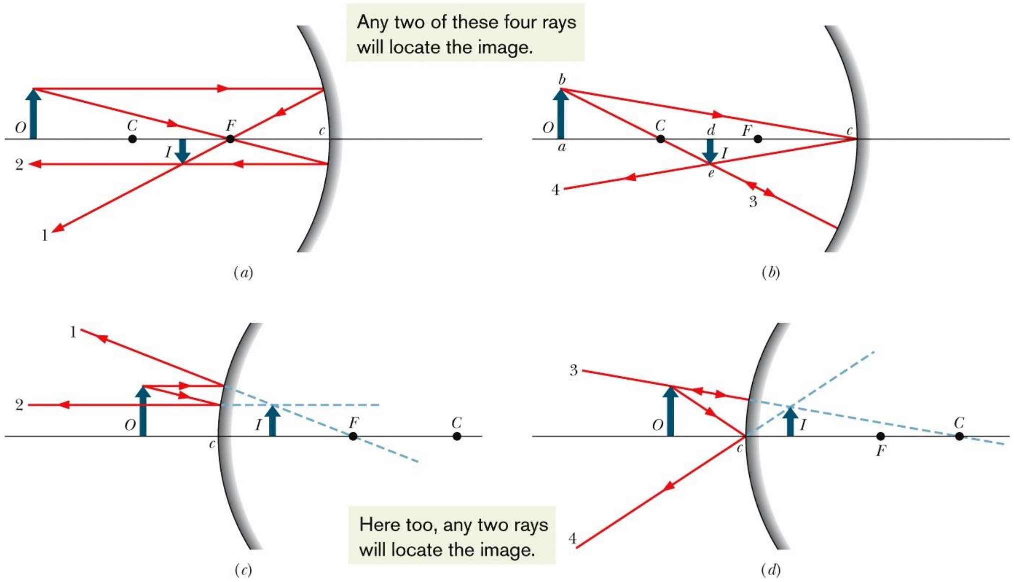
- A concave mirror can form a real image (if the object is outside the focal point) or a virtual image (if the object is inside the focal point).
- A convex mirror can form only a virtual image.
- The mirror equation relates an object distance *p*, the mirror's focal length *f* and radius of curvature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

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

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.

34-3 Spherical Refracting Surface

Learning Objectives

34.18 Identify that the refraction of rays by a spherical surface can produce real images and virtual images of an object, depending on the indexes of refraction on the two sides, the surface's radius of curvature *r*, and whether the object faces a concave or convex surface.

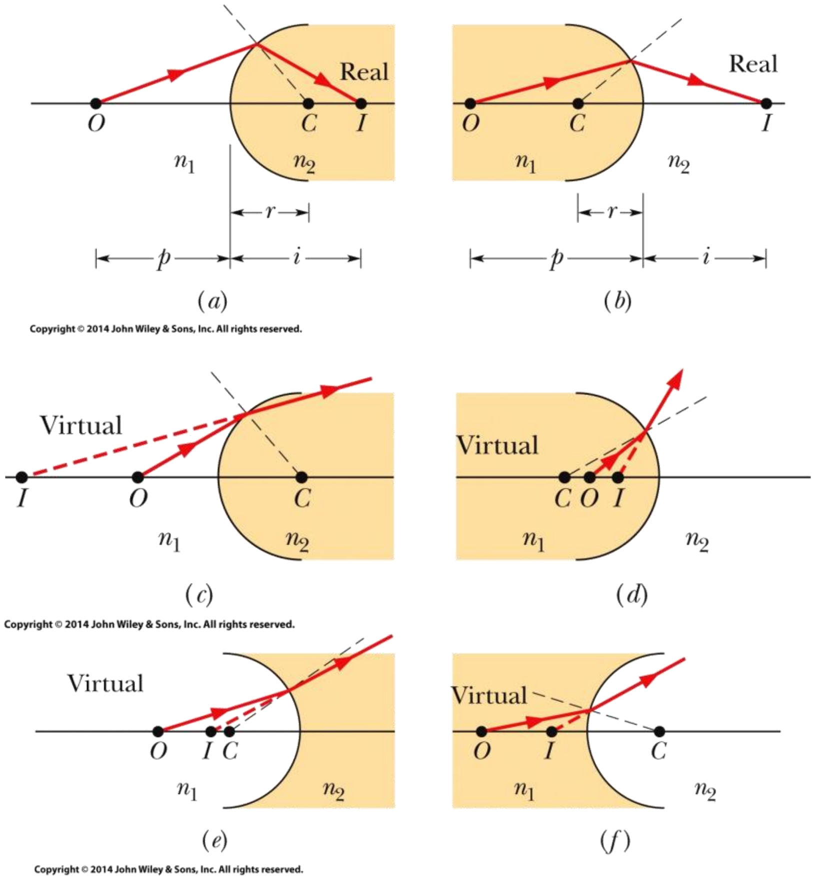
34.19 For a point object on the central axis of a spherical refracting surface, sketch the refraction of a ray in the six general arrangements and identify whether the image is real or virtual.

34.20 For a spherical refracting surface, identify what type of image appears on the same side as the object and what type appears on the opposite side.

34.21 For a spherical refracting surface, apply the relation- ship between the two indexes of refraction, the object distance *p*, the image distance *i*, and the radius of curvature *r*.

34.22 Identify the algebraic signs of the radius *r* for an object facing a concave refracting surface and a convex refracting surface.

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.

34-4 Thin Lenses

Learning Objectives

34.23 Distinguish converging lenses from diverging lenses.

34.24 For converging and diverging lenses, sketch a ray diagram for rays initially parallel to the central axis, indicating how they form focal points, and identifying which is real and which is virtual.

34.25 Distinguish a real focal point from a virtual focal point, identify which corresponds to which type of lens and under which circumstances, and identify the algebraic sign associated with each focal length.

34.26 For an object (a) inside and (b) outside the focal point of a converging lens, sketch at least two rays to find the image and identify the type and orientation of the image.

34.27 For a converging lens, distinguish the locations and orientations of a real image and a virtual image.

34.28 For an object in front of a diverging lens, sketch at least two rays to find the image and identify the type and orientation of the image.

34-4 Thin Lenses

Learning Objectives

34.29 Identify which type of lens can produce both real and virtual images and which type can produce only virtual images.

34.30 Identify the algebraic sign of the image distance i for areal image and for a virtual image.

34.31 For converging and diverging lenses, apply the relationship between the focal length f, object distance p, and image distance i.

34.32 Apply the relationships between lateral magnification *m*, image height *h'*, object height *h*, image and object distance *i*, & *p*.

34.33 Apply the lens maker's equation to relate a focal length to the index of refraction of a lens (assumed to be in air) and the radii of curvature of the two sides of the lens.

34.34 For a multiple-lens system with the object in front of lens 1, find the image produced by lens 1 and then use it as the object for lens 2, and so on.

34.35 For a multiple-lens system, determine the overall magnification (of the final image) from the magnifications produced by each lens.

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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

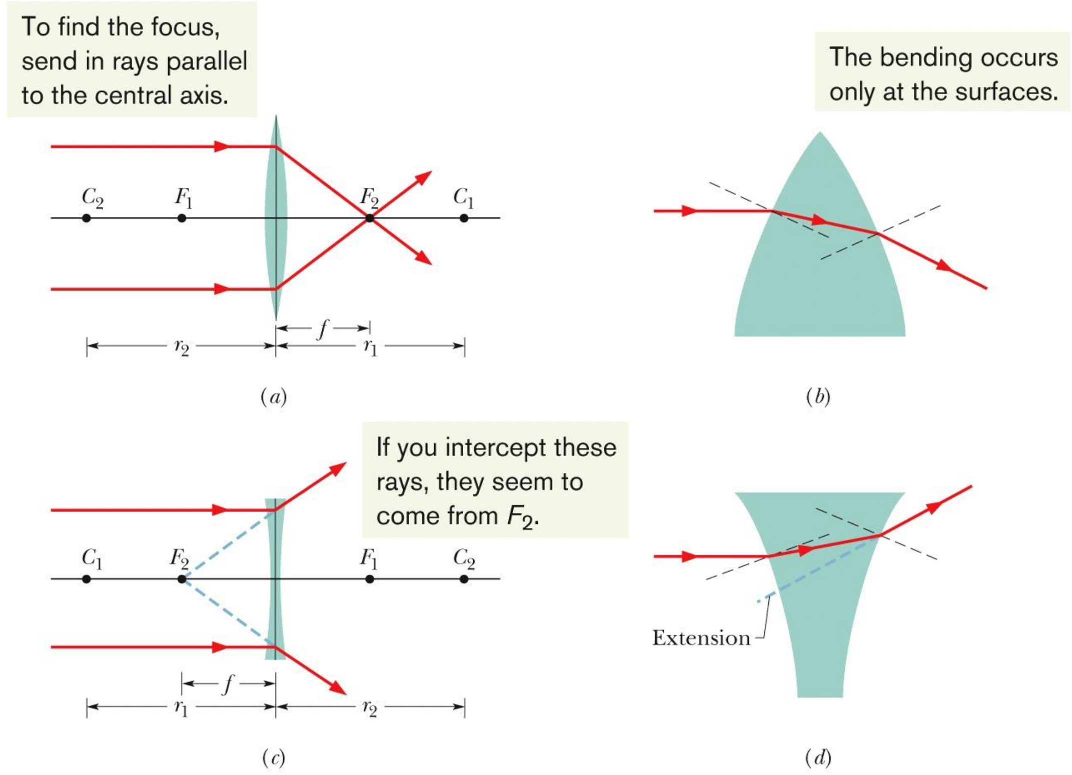
$$\frac{1}{f} = (n-1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \quad \text{(thin lens in air)},$$

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.



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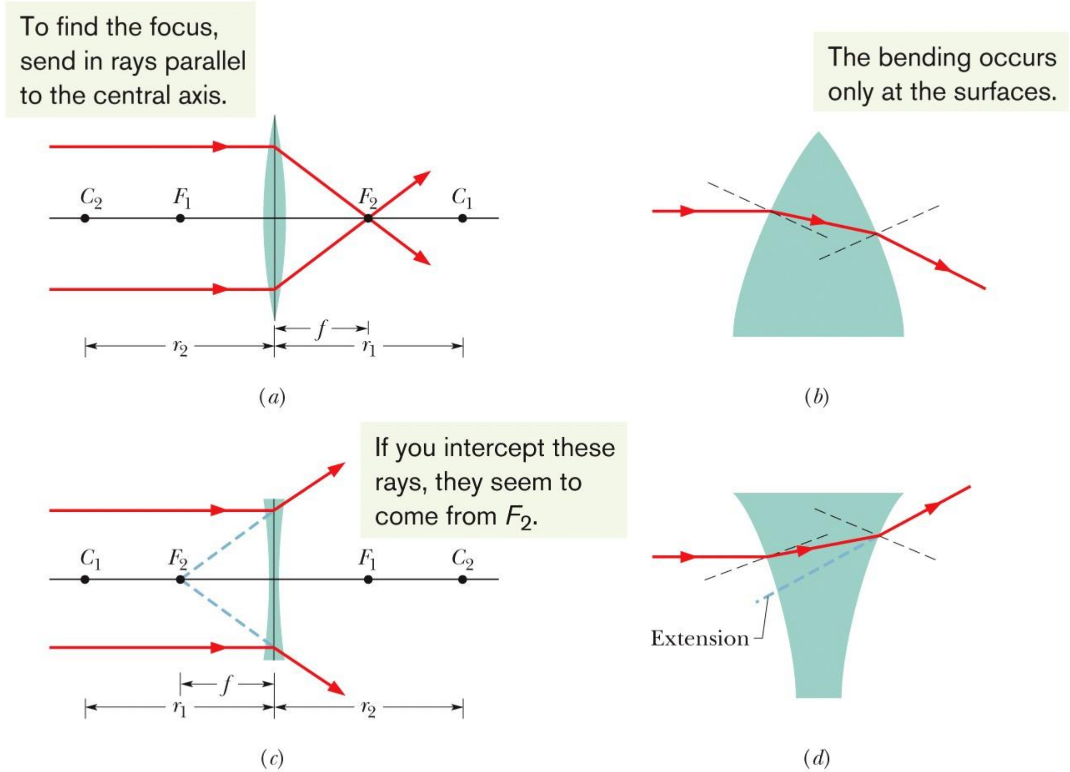
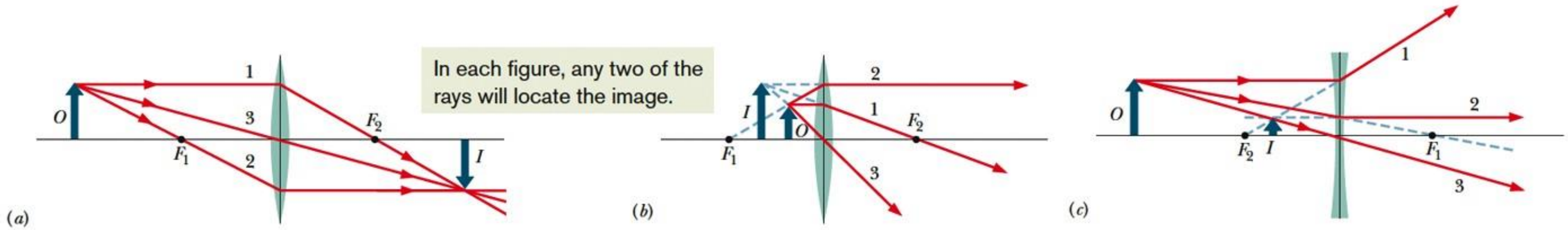
34-4 Thin Lenses



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

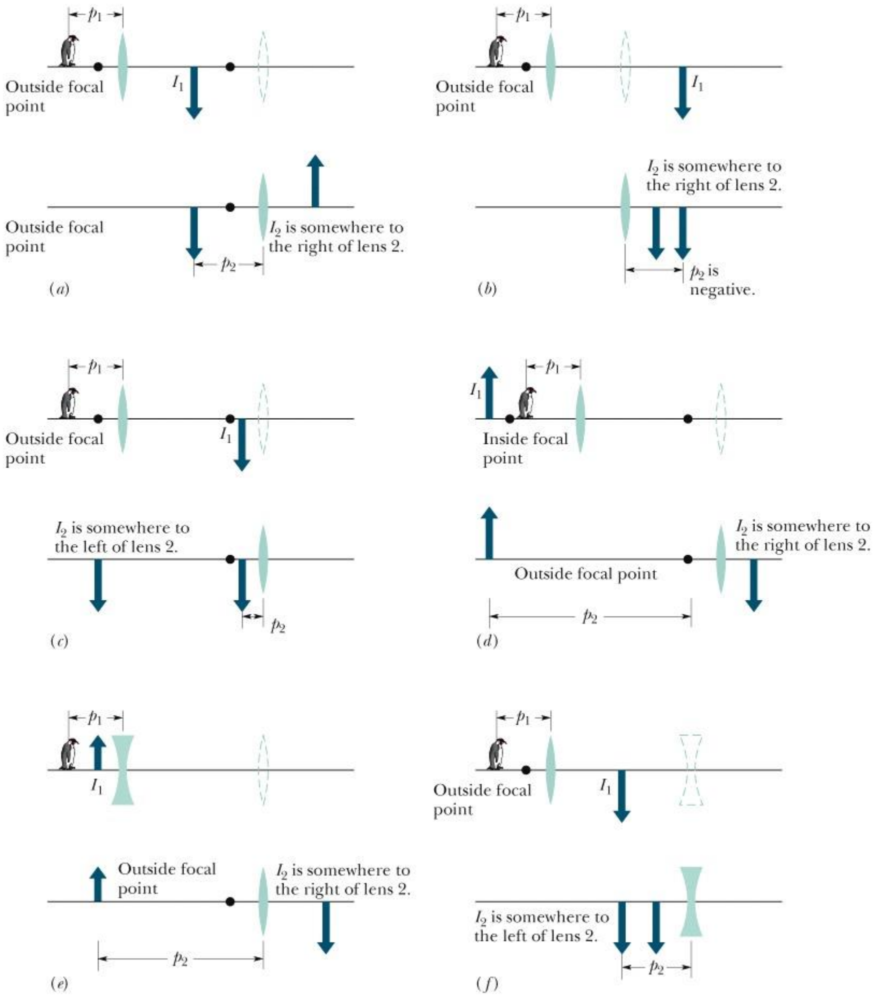


1. A ray that is initially parallel to the central axis of the lens will pass through focal point F_2 (ray 1 in Fig. a).
2. A ray that initially passes through focal point F_1 will emerge from the lens parallel to the central axis (ray 2 in Fig. a).
3. A ray that is initially directed toward the center 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.

34-4 Thin Lenses

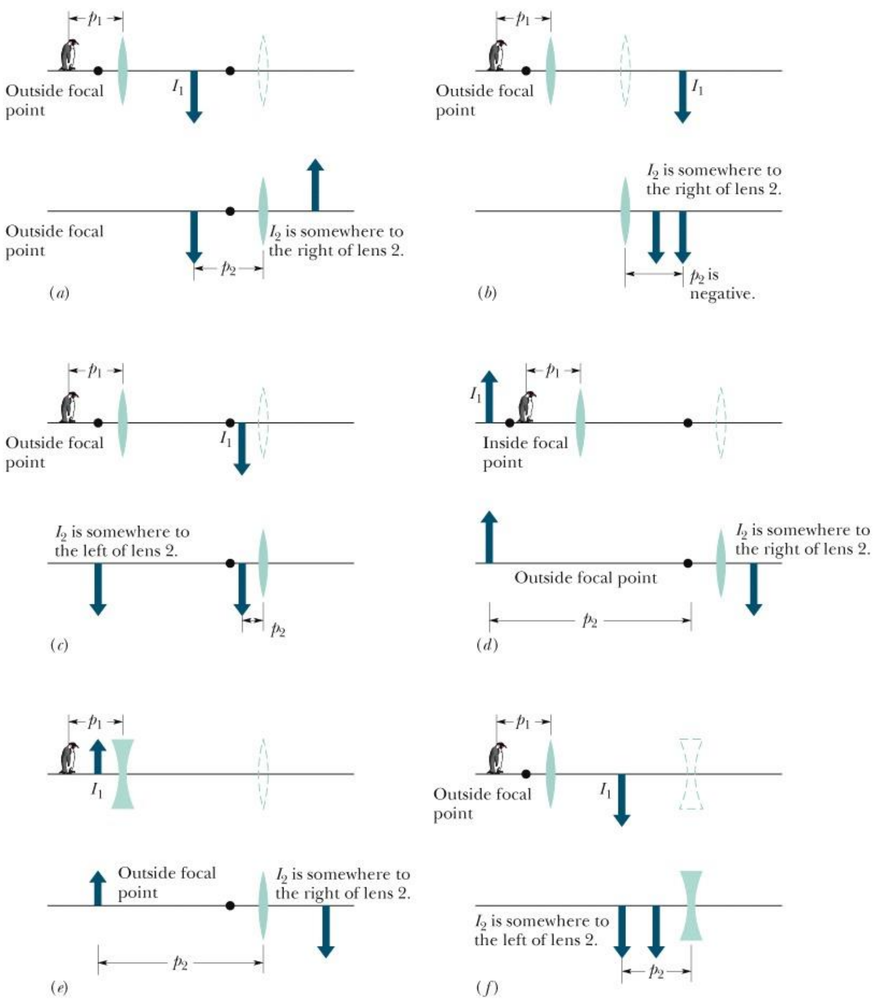
Two Lens System



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:

34-4 Thin Lenses

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.

34-5 Optical Instruments

Learning Objectives

34.36 Identify the near point in vision.

34.37 With sketches, explain the function of a simple magnifying lens.

34.38 Identify angular magnification.

34.39 Determine the angular magnification for an object at the focal point of a simple magnifying lens.

34.40 With a sketch, explain a compound microscope.

34.41 Identify that the overall magnification of a compound microscope is due to the lateral magnification by the objective and the angular magnification by the eyepiece.

34.42 Calculate the overall magnification of a compound microscope.

34.43 With a sketch, explain a refracting telescope.

34.44 Calculate the angular magnification of a refracting telescope.

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.

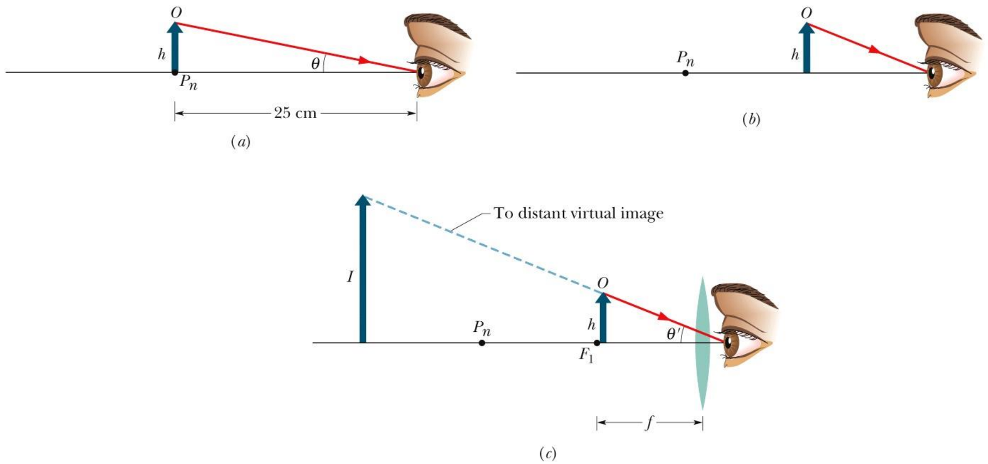


Figure (a) shows an object O placed at the near point P_n of an eye. The size of the image of the object produced on the retina depends on the angle *θ* that the object occupies in the field of view from that eye. By moving the object closer to the eye, as in Fig.(b), you can increase the angle and, 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.

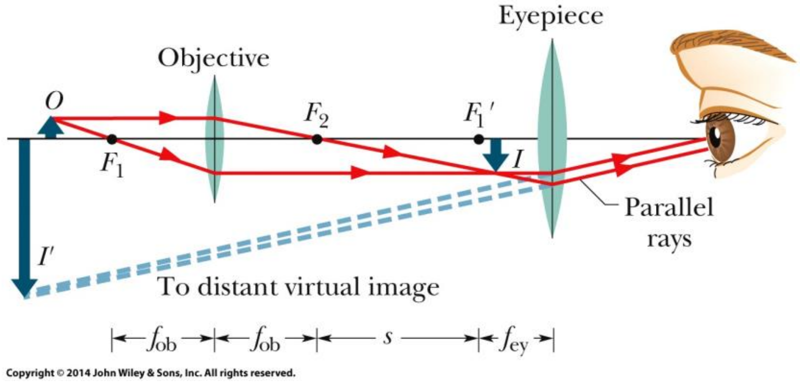
Compound Microscope

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.

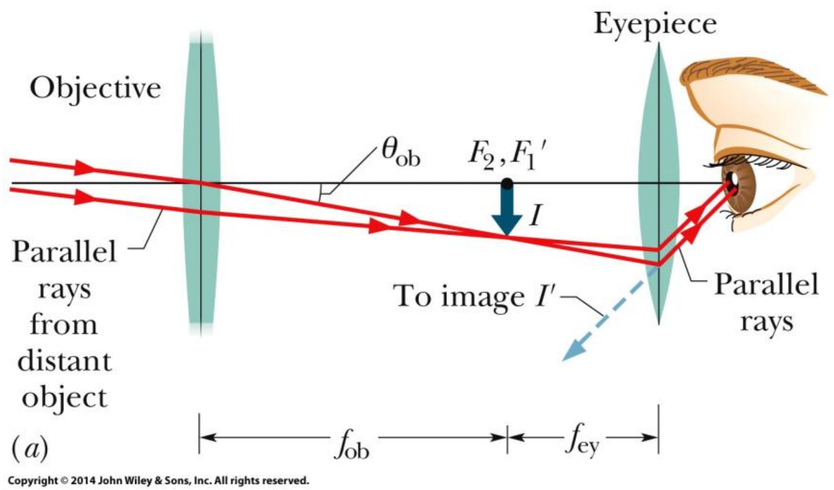


Refracting Telescope

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**