the projections at angle 2. We calculate the difference between the measured projections at angle 2 (6 and 14) and the projections based on the previous estimate (top row: $3\frac{1}{2} + 6\frac{1}{2} = 10$; same for bottom row). Then we distribute this difference equally to the squares in that row. For the top row, we have

$$3\tfrac{1}{2} + \frac{6-10}{2} = 1\tfrac{1}{2} \quad \text{and} \quad 6\tfrac{1}{2} + \frac{6-10}{2} = 4\tfrac{1}{2};$$

and for the bottom row,

$$3\tfrac{1}{2} + \frac{14-10}{2} = 5\tfrac{1}{2} \quad \text{and} \quad 6\tfrac{1}{2} + \frac{14-10}{2} = 8\tfrac{1}{2}.$$

These values are inserted as shown in Fig. 25–46c. Next, the projection at angle 3 gives

$$\text{(upper left)}\ 1\tfrac{1}{2} + \frac{11-10}{2} = 2 \quad \text{and} \quad \text{(lower right)}\ 8\tfrac{1}{2} + \frac{11-10}{2} = 9;$$

and that for angle 4 gives

$$\text{(lower left)}\ 5\tfrac{1}{2} + \frac{9-10}{2} = 5 \quad \text{and} \quad \text{(upper right)}\ 4\tfrac{1}{2} + \frac{9-10}{2} = 4.$$

The result, shown in Fig. 25–46d, corresponds exactly to the true values. (In real situations, the true values are not known, which is why these computer techniques are required.) To obtain these numbers exactly, we used six pieces of information (two each at angles 1 and 2, one each at angles 3 and 4). For the much larger number of pixels used for actual images, exact values are generally not attained. Many iterations may be needed, and the calculation is considered sufficiently precise when the difference between calculated and measured projections is sufficiently small. The above example illustrates the "convergence" of the process: the first iteration (b to c in Fig. 25–46) changed the values by 2, the last iteration (c to d) by only $\frac{1}{2}$.

Summary

A **camera** lens forms an image on film, or on a charge-coupled device in a digital camera, by allowing light in through a shutter. The lens is focused by moving it relative to the film, and its ***f*-stop** (or lens opening) must be adjusted for the brightness of the scene and the chosen shutter speed. The f-stop is defined as the ratio of the focal length to the diameter of the lens opening.

The human **eye** also adjusts for the available light—by opening and closing the iris. It focuses not by moving the lens, but by adjusting the shape of the lens to vary its focal length. The image is formed on the retina, which contains an array of receptors known as rods and cones.

Diverging eye-glass or contact lenses are used to correct the defect of a nearsighted eye, which cannot focus well on distant objects. Converging lenses are used to correct for defects in which the eye cannot focus on close objects.

A **simple magnifier** is a converging lens that forms a virtual image of an object placed at (or within) the focal point. The **angular magnification**, when viewed by a relaxed normal eye, is

$$M = \frac{N}{f}, \qquad \textbf{(25–2a)}$$

where f is the focal length of the lens and N is the near point of the eye (25 cm for a "normal" eye).

An **astronomical telescope** consists of an **objective lens** or mirror, and an **eyepiece** that magnifies the real image formed by the objective. The **magnification** is equal to the ratio of the objective and eyepiece focal lengths, and the image is inverted:

$$M = -\frac{f_o}{f_e}. \qquad \textbf{(25–3)}$$

[*A compound **microscope** also uses objective and eyepiece lenses, and the final image is inverted. The total magnification is the product of the magnifications of the two lenses and is approximately

$$M \approx \frac{Nl}{f_e f_o}, \qquad \textbf{(25–6b)}$$

where l is the distance between the lenses, N is the near point of the eye, and f_o and f_e are the focal lengths of objective and eyepiece, respectively.]

Microscopes, telescopes, and other optical instruments are limited in the formation of sharp images by **lens aberrations**. These include **spherical aberration**, in which rays passing through the edge of a lens are not focused at the same point as those that pass near the center; and **chromatic aberration**, in which different colors are focused at different points. Compound lenses, consisting of several elements, can largely correct for aberrations.

The wave nature of light also limits the sharpness, or **resolution**, of images. Because of diffraction, it is *not possible to discern details smaller than the wavelength* of the radiation being used. This limits the useful magnification of a light microscope to about 500×.

[***X-rays** are a form of electromagnetic radiation of very short wavelength. They are produced when high-speed electrons, accelerated by high voltage in an evacuated tube, strike a glass or metal target.]

[***Computed tomography** (CT or CAT scans) uses many narrow X-ray beams through a section of the body to construct an image of that section.]

Questions

1. Why is the depth of field greater, and the image sharper, when a camera lens is "stopped down" to a larger f-number? Ignore diffraction.
2. Describe how diffraction affects the statement of Question 1. [*Hint*: see Eq. 24–3 or 25–7.]
3. Why must a camera lens be moved farther from the film to focus on a closer object?
4. Why are bifocals needed mainly by older persons and not generally by younger people?
5. Will a nearsighted person who wears corrective lenses in her glasses be able to see clearly underwater when wearing those glasses? Use a diagram to show why or why not.
6. You can tell whether a person is nearsighted or farsighted by looking at the width of the face through their glasses. If the person's face appears narrower through the glasses (Fig. 25–47), is the person farsighted or nearsighted?

FIGURE 25–47 Question 6.

7. In attempting to discern distant details, people will sometimes squint. Why does this help?
8. Is the image formed on the retina of the human eye upright or inverted? Discuss the implications of this for our perception of objects.
9. The human eye is much like a camera—yet, when a camera shutter is left open and the camera is moved, the image will be blurred; but when you move your head with your eyes open, you still see clearly. Explain.
10. Reading glasses use converging lenses. A simple magnifier is also a converging lens. Are reading glasses therefore magnifiers? Discuss the similarities and differences between converging lenses as used for these two different purposes.

* 11. Inexpensive microscopes for children's use usually produce images that are colored at the edges. Why?

* 12. Spherical aberration in a thin lens is minimized if rays are bent equally by the two surfaces. If a planoconvex lens is used to form a real image of an object at infinity, which surface should face the object? Use ray diagrams to show why.

* 13. Which aberrations present in a simple lens are not present (or are greatly reduced) in the human eye?

* 14. Explain why chromatic aberration occurs for thin lenses but not for mirrors.

15. By what factor can you improve resolution, other things being equal, if you use blue light ($\lambda = 450$ nm) rather than red (700 nm)?
16. Give at least two advantages for the use of large reflecting mirrors in astronomical telescopes.
17. Which color of visible light would give the best resolution in a microscope? Explain.
18. Atoms have diameters of about 10^{-8} cm. Can visible light be used to "see" an atom? Explain.

Problems

25–1 Camera

1. (I) A 55-mm-focal-length lens has f-stops ranging from $f/1.4$ to $f/22$. What is the corresponding range of lens diaphragm diameters?
2. (I) A television camera lens has a 14-cm focal length and a lens diameter of 6.0 cm. What is its f-number?
3. (I) A light meter reports that a camera setting of $\frac{1}{250}$ s at $f/5.6$ will give a correct exposure. But the photographer wishes to use $f/11$ to increase the depth of field. What should the shutter speed be?
4. (I) A properly exposed photograph is taken at $f/16$ and $\frac{1}{60}$ s. What lens opening would be required if the shutter speed were $\frac{1}{1000}$ s?
5. (II) If an $f = 135$-mm telephoto lens is designed to cover object distances from 1.2 m to ∞, over what distance must the lens move relative to the plane of the film?
6. (II) A 200-mm-focal-length lens can be adjusted so that it is 200.0 mm to 206.0 mm from the film. For what range of object distances can it be adjusted?
7. (II) A nature photographer wishes to photograph a 28-m-tall tree from a distance of 58 m. What focal-length lens should be used if the image is to fill the 24-mm height of the film?
8. (II) A "pinhole" camera uses a tiny pinhole instead of a lens. Show, using ray diagrams, how reasonably sharp images can be formed using such a pinhole camera. In particular, consider two point objects 2.0 cm apart that are 1.0 m from a 1.0-mm-diameter pinhole. Show that on a piece of film 7.0 cm behind the pinhole the two objects produce two separate circles that do not overlap.
9. (III) Suppose that a correct exposure is $\frac{1}{250}$ s at $f/11$. Under the same conditions, what exposure time would be needed for a pinhole camera (Problem 8) if the pinhole diameter is 1.0 mm and the film is 7.0 cm from the hole?

25–2 Eye and Corrective Lenses

10. (I) A human eyeball is about 2.0 cm long, and the pupil has a maximum diameter of about 8.0 mm. What is the "speed" of this lens?

11. (I) If the nearsighted person in Example 25–6 wore contact lenses corrected for the far point ($=\infty$), show that the near point would be 41 cm. (Would glasses be better in this case?)

12. (II) Reading glasses of what power are needed for a person whose near point is 115 cm, so that he can read a computer screen at 55 cm? Assume a lens–eye distance of 1.8 cm.

13. (II) A person has a far point of 14 cm. What power glasses would correct this vision if the glasses were placed 2.0 cm from the eye? What power contact lenses, placed on the eye, would the person need?

14. (II) A person struggles to read by holding a book at arm's length, a distance of 45 cm away (= near point). What power of reading glasses should be prescribed for him, assuming they will be placed 2.0 cm from the eye and he wants to read at the normal near point of 25 cm?

15. (II) A person's left eye is corrected by a −3.50-diopter lens, 2.0 cm from the eye. (*a*) Is this person's left eye near- or farsighted? (*b*) What is this eye's far point without glasses?

16. (II) A person's right eye can see objects clearly only if they are between 25 cm and 75 cm away. (*a*) What power of contact lens is required so that objects far away are sharp? (*b*) What will be the near point with the lens in place?

17. (II) About how much longer is the nearsighted eye in Example 25–6 than the 2.0 cm of a normal eye?

18. (II) One lens of a nearsighted person's eyeglasses has a focal length of −22.0 cm, and the lens is 1.8 cm from the eye. If the person switches to contact lenses that are placed directly on the eye, what should be the focal length of the corresponding contact lens?

19. (II) What is the focal length of the eye–lens system when viewing an object (*a*) at infinity, and (*b*) 33 cm from the eye? Assume that the lens–retina distance is 2.0 cm.

20. (III) A nearsighted person has near and far points of 10.0 and 20.0 cm, respectively. If she puts on contact lenses with power $P = -4.00\text{ D}$, what are her new near and far points?

25–3 Magnifying Glass

21. (I) What is the magnification of a lens used with a relaxed eye if its focal length is 12 cm?

22. (I) What is the focal length of a magnifying glass of 3.5× magnification for a relaxed normal eye?

23. (I) A magnifier is rated at 2.5× for a normal eye focusing on an image at the near point. (*a*) What is its focal length? (*b*) What is its focal length if the 2.5× refers to a relaxed eye?

24. (II) Sherlock Holmes is using a 9.00-cm-focal-length lens as his magnifying glass. To obtain maximum magnification, where must the object be placed (assume a normal eye), and what will be the magnification?

25. (II) A 3.30-mm-wide beetle is viewed with a 9.50-cm-focal-length lens. A normal eye views the image at its near point. Calculate (*a*) the angular magnification, (*b*) the width of the image, and (*c*) the object distance from the lens.

26. (II) A small insect is placed 5.55 cm from a +6.00-cm-focal-length lens. Calculate (*a*) the position of the image, and (*b*) the angular magnification.

27. (II) A magnifying glass with a focal length of 8.5 cm is used to read print placed at a distance of 7.5 cm. Calculate (*a*) the position of the image; (*b*) the angular magnification.

28. (III) A magnifying glass is rated at 3.0× for a normal eye that is relaxed. What would be the magnification of this lens for a relaxed eye whose near point is (*a*) 55 cm, and (*b*) 16 cm? Explain the differences.

25–4 Telescopes

29. (I) What is the magnification of an astronomical telescope whose objective lens has a focal length of 76 cm and whose eyepiece has a focal length of 2.8 cm? What is the overall length of the telescope when adjusted for a relaxed eye?

30. (I) The overall magnification of an astronomical telescope is desired to be 25×. If an objective of 78-cm focal length is used, what must be the focal length of the eyepiece? What is the overall length of the telescope when adjusted for use by the relaxed eye?

31. (I) An 8.0× binocular has 2.8-cm-focal-length eyepieces. What is the focal length of the objective lenses?

32. (II) An astronomical telescope has an objective with focal length 85 cm and a +35-D eyepiece. What is the total magnification?

33. (II) An astronomical telescope has its two lenses spaced 75.2 cm apart. If the objective lens has a focal length of 74.5 cm, what is the magnification of this telescope? Assume a relaxed eye.

34. (II) A Galilean telescope adjusted for a relaxed eye is 32.8 cm long. If the objective lens has a focal length of 36.0 cm, what is the magnification?

35. (II) What is the magnifying power of an astronomical telescope using a reflecting mirror whose radius of curvature is 6.0 m and an eyepiece whose focal length is 3.2 cm?

36. (II) The Moon's image appears to be magnified 120× by a reflecting astronomical telescope with an eyepiece having a focal length of 3.2 cm. What are the focal length and radius of curvature of the main (objective) mirror?

37. (II) A 170× astronomical telescope is adjusted for a relaxed eye when the two lenses are 1.25 m apart. What is the focal length of each lens?

38. (III) A reflecting telescope (Fig. 25–21b) has a radius of curvature of 3.0 m for its objective mirror and a radius of curvature of −1.50 m for its eyepiece mirror. If the distance between the two mirrors is 0.90 m, how far in front of the eyepiece should you place the photographic film to record the image of a star?

* 25–5 Microscope

* 39. (I) A microscope uses an eyepiece with a focal length of 1.40 cm. Using a normal eye with a final image at infinity, the tube length is 17.5 cm and the focal length of the objective lens is 0.65 cm. What is the magnification of the microscope?

* **40.** (I) A 620× microscope uses a 0.40-cm-focal-length objective lens. If the tube length is 17.5 cm, what is the focal length of the eyepiece? Assume a normal eye and that the final image is at infinity.

* **41.** (I) A 17-cm-long microscope has an eyepiece with a focal length of 2.5 cm and an objective with a focal length of 0.28 cm. What is the approximate magnification?

* **42.** (II) A microscope has a 12.0× eyepiece and a 59.0× objective lens 20.0 cm apart. Calculate (*a*) the total magnification, (*b*) the focal length of each lens, and (*c*) where the object must be for a normal relaxed eye to see it in focus.

* **43.** (II) A microscope has a 1.8-cm-focal-length eyepiece and a 0.80-cm objective lens. Assuming a relaxed normal eye, calculate (*a*) the position of the object if the distance between the lenses is 16.0 cm, and (*b*) the total magnification.

* **44.** (II) Repeat Problem 43 assuming that the final image is located 25 cm from the eyepiece (near point of a normal eye).

* **45.** (III) The eyepiece of a compound microscope has a focal length of 2.70 cm, and the objective lens has $f = 0.740$ cm. If an object is placed 0.790 cm from the objective lens, calculate (*a*) the distance between the lenses when the microscope is adjusted for a relaxed eye, and (*b*) the total magnification.

* 25–6 Aberrations

* **46.** (II) An achromatic lens is made of two very thin lenses, placed in contact, that have focal lengths of $f_1 = -28$ cm and $f_2 = +23$ cm. (*a*) Is the combination converging or diverging? (*b*) What is the net focal length?

* **47.** (III) Let's examine spherical aberration in a particular situation. A planoconvex lens of index of refraction 1.50 and radius of curvature $R = 12.0$ cm is shown in Fig. 25–48. Consider an incoming ray parallel to the principal axis and a height h above it as shown. Determine the distance d, from the flat face of the lens, to where this ray crosses the principal axis if (*a*) $h = 1.0$ cm, and (*b*) $h = 6.0$ cm. (*c*) How far apart are these "focal points"? (*d*) What is the radius of the "circle of least confusion" produced by the $h = 6.0$-cm ray at the "focal point" for $h = 1.0$ cm?

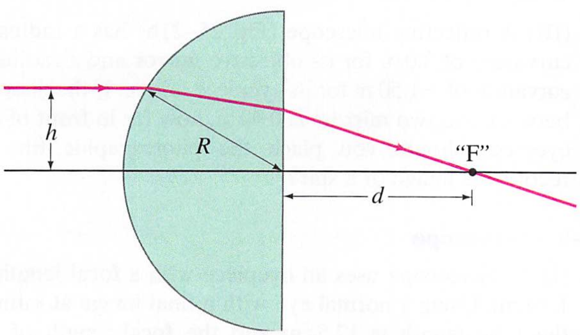

FIGURE 25–48 Problem 47.

25–7 to 25–9 Resolution

48. (I) What is the angular resolution limit (degrees) set by diffraction for the 100-in. (254-cm mirror diameter) Mt. Wilson telescope ($\lambda = 550$ nm)?

49. (II) Suppose that you wish to construct a telescope that can resolve features 7.0 km across on the Moon, 384,000 km away. You have a 2.0-m-focal-length objective lens whose diameter is 11.0 cm. What focal-length eyepiece is needed if your eye can resolve objects 0.10 mm apart at a distance of 25 cm? What is the resolution limit (radians) set by the size of the objective lens (that is, by diffraction)? Use $\lambda = 550$ nm.

50. (II) The normal lens on a 35-mm camera has a focal length of 50.0 mm. Its aperture diameter varies from a maximum of 25 mm ($f/2$) to a minimum of 3.0 mm ($f/16$). Determine the resolution limit set by diffraction for $f/2$ and $f/16$. Specify as the number of lines per millimeter resolved on the film. Take $\lambda = 550$ nm.

51. (II) Two stars 15 light-years away are barely resolved by a 55-cm (mirror diameter) telescope. How far apart are the stars? Assume $\lambda = 550$ nm and that the resolution is limited by diffraction.

52. (II) (*a*) How far away can a human eye distinguish two car headlights 2.0 m apart? Consider only diffraction effects and assume an eye pupil diameter of 5.0 mm and a wavelength of 550 nm. (*b*) What is the minimum angular separation an eye could resolve when viewing two stars, considering only diffraction effects? In reality, it is about 1′ of arc. Why is it not equal to your answer in (*b*)?

53. (II) The Earth and Moon are separated by about 400×10^6 m. When Mars is 8×10^{10} m from Earth, could a person standing on Mars resolve the Earth and its Moon as two separate objects without a telescope? Assume a pupil diameter of 5 mm and $\lambda = 550$ nm.

* 25–11 X-rays

* **54.** (II) X-rays of wavelength 0.133 nm fall on a crystal whose atoms, lying in planes, are spaced 0.280 nm apart. At what angle ϕ (relative to the surface, Fig. 25–37) must the X-rays be directed if the first diffraction maximum is to be observed?

* **55.** (II) X-rays of wavelength 0.0973 nm are directed at an unknown crystal. The second diffraction maximum is recorded when the X-rays are directed at an angle of 23.4° relative to the crystal surface. What is the spacing between crystal planes?

* **56.** (II) First-order Bragg diffraction is observed at 25.2° related to the crystal surface, with spacing between atoms of 0.24 nm. (*a*) At what angle will second order be observed? (*b*) What is the wavelength of the X-rays?

* 25–12 Computed Tomography

* **57.** (II) (*a*) Suppose for a conventional X-ray image that the X-ray beam consists of parallel rays. What would be the magnification of the image? (*b*) Suppose, instead, the X-rays come from a point source (as in Fig. 25–41) that is 15 cm in front of a human body 25 cm thick, and the film is pressed against the person's back. Determine and discuss the range of magnifications that results.

General Problems

58. Sam purchases +3.50-diopter eyeglasses which correct his faulty vision to put his near point at 25 cm. (Assume he wears the lenses 2.0 cm from his eyes.) (*a*) Calculate the focal length of Sam's glasses. (*b*) Calculate Sam's near point without glasses. (*c*) Pam, who has normal eyes with near point at 25 cm, puts on Sam's glasses. Calculate Pam's near point with Sam's glasses on.

59. As early morning passed toward midday, and the sunlight got more intense, a photographer noted that, if she kept her shutter speed constant, she had to change the f-number from $f/5.6$ to $f/22$. By what factor had the sunlight intensity increased during that time?

60. Show that for objects very far away (assume infinity), the magnification of a camera lens is proportional to its focal length.

61. For a camera equipped with a 50-mm-focal-length lens, what is the object distance if the image height equals the object height? How far is the object from the film?

62. A woman can see clearly with her right eye only when objects are between 45 cm and 155 cm away. Prescription bifocals should have what powers so that she can see distant objects clearly (upper part) and be able to read a book 25 cm away (lower part) with her right eye? Assume that the glasses will be 2.0 cm from the eye.

63. A child has a near point of 15 cm. What is the maximum magnification the child can obtain using an 8.0-cm-focal-length magnifier? What magnification can a normal eye obtain with the same lens? Which person sees more detail?

64. What is the magnifying power of a +4.0-D lens used as a magnifier? Assume a relaxed normal eye.

65. A physicist lost in the mountains tries to make a telescope using the lenses from his reading glasses. They have powers of +2.0 D and +4.5 D, respectively. (*a*) What maximum magnification telescope is possible? (*b*) Which lens should be used as the eyepiece?

66. A 50-year-old man uses +2.5-diopter lenses to read a newspaper 25 cm away. Ten years later, he must hold the paper 35 cm away to see clearly with the same lenses. What power lenses does he need now in order to hold the paper 25 cm away? (Distances are measured from the lens.)

67. Spy planes fly at extremely high altitudes (25 km) to avoid interception. Their cameras are reportedly able to discern features as small as 5 cm. What must be the minimum aperture of the camera lens to afford this resolution? (Use $\lambda = 550$ nm.)

68. When shooting pictures at very short distances, exposure times must be increased because of the increased distance of the lens from the film for a focused image. (*a*) Show that when the object is so close to the camera that the image height equals the object height, the exposure time must be four times longer (or 2 f-stops) than when the object is a long distance away (say, ∞), given the same illumination and f-stop. (*b*) Show that if d_o is at least four or five times the focal length f of the lens, the exposure time is increased by less than half an f-stop relative to the same object being a great distance away.

69. The objective lens and the eyepiece of a telescope are spaced 85 cm apart. If the eyepiece is +23 diopters, what is the total magnification of the telescope?

70. The Hubble Space Telescope, with an objective diameter of 2.4 m, is viewing the Moon. Estimate the minimum distance between two objects on the Moon that the Hubble can distinguish. Consider diffraction of light of wavelength 550 nm. Assume the Hubble is near the Earth.

71. Two converging lenses, one with $f = 4.0$ cm and the other with $f = 44$ cm, are made into a telescope. (*a*) What are the length and magnification? Which lens should be the eyepiece? (*b*) Assume these lenses are now combined to make a microscope; if the magnification needs to be 25×, how long would the microscope be?

72. An astronomical telescope has a magnification of 8.0. If the two lenses are 28 cm apart, determine the focal length of each lens.

73. You want to design a spy satellite to photograph license plate numbers. Assuming it is necessary to resolve points separated by 5 cm with 550-nm light, and that the satellite orbits at a height of 130 km, what minimum lens aperture (diameter) is required?

* 74. A Lucite planoconvex lens (Fig. 23–29a) has one flat surface and the other has $R = 18.4$ cm. This lens is used to view an object, located 66.0 cm away from the lens, which is a mixture of red and yellow. The index of refraction of the glass is 1.5106 for red light and 1.5226 for yellow light. What are the locations of the red and yellow images formed by the lens?

Answers to Exercises

A: 6.3 m.
B: $P = -4.0$ D.
C: 48 cm.
D: 2 m.