The goal of Chapter 19 has been to understand how common optical instruments work.

**IMPORTANT CONCEPTS**

**Color and dispersion**

The eye perceives light of different wavelengths as having different colors. Dispersion is the dependence of the index of refraction $n$ of a transparent medium on the wavelength of light: Long wavelengths have the lowest $n$, short wavelengths the highest $n$.

White light is composed of all wavelengths of light. A prism breaks white light into its constituent colors. Violet light, with its higher $n$ is refracted more than red.

**Lenses in combination**

When two lenses are used in combination, the image from the first lens serves as the object for the second. The refractive power $P$ of a lens is the inverse of its focal length: $P = 1/f$. Refractive power is measured in diopters:

$$1 \text{ D} = 1 \text{ m}^{-1}$$

**APPLICATIONS**

**The camera and the eye**

Both the camera and the eye work by focusing an image on a light-sensitive surface.

The camera focuses by changing the lens-film distance, while the eye focuses by changing the focal length of its lens.

**The telescope** magnifies distant objects. The objective lens creates a real image of the distant object. This real image is then magnified by the eyepiece lens, which acts as a simple magnifier. The angular magnification is $M = -f_o/f_e$.

**Resolution of optical instruments**

The resolution of a telescope or microscope is limited by imperfections, or aberrations, in the optical elements, and by the more fundamental limits imposed by diffraction.

For a microscope, the minimum resolvable distance between two objects is

$$d_{min} = \frac{0.61 \lambda}{\text{NA}}$$

For a telescope, the minimum resolvable angular separation between two objects is

$$\theta_{min} = \frac{1.22 \lambda}{D}$$

**Angular and apparent size**

Both objects have the same angular size and hence the same apparent size.

**The magnifier**

Without a lens, an object cannot be viewed closer than the eye’s near point of $\approx 25 \text{ cm}$. Its angular size $\theta_0$ is $h/25 \text{ cm}$.

If the object is now placed at the focal point of a converging lens, its angular size is increased to $\theta = h/f$.

The angular magnification is $M = \theta/\theta_0 = 25 \text{ cm}/f$.

**The microscope** magnifies a small, nearby object. The objective lens creates a real image of the object. This real image is then further magnified by the eyepiece lens, which acts as a simple magnifier. The angular magnification is

$$M = -\frac{L \times 25 \text{ cm}}{f_o f_e}$$
**Conceptual Questions**

1. On a sunny summer day, with the sun overhead, you can stand under a tree and look on the ground at the pattern of light that has passed through gaps between the leaves. You may see illuminated circles of varying brightness. Why are there circles when the gaps between the leaves have irregular shapes?

2. Suppose you have two pinhole cameras. The first has a small round hole in the front of the camera. The second is identical in every regard, except that it has a square hole of the same area as the round hole in the first camera. Would the pictures taken by these two cameras, under the same conditions, be different in any obvious way? Explain.

3. A photographer focuses his camera on his subject. The subject then moves closer to the camera. To refocus, should the lens be moved closer to or farther from the film? Explain.

4. Many cameras have a zoom lens. This is a lens whose focal length and distance from the film can be varied. If the camera’s exposure is correct when the lens has a focal length of 8.0 mm, will it be overexposed, underexposed, or still correct when the focal length is increased to 16.0 mm (assuming the lens diameter remains constant)? Explain.

5. A nature photographer taking a close-up shot of an insect replaces the standard lens on his camera with a lens that has a shorter focal length and is positioned farther from the film. Explain why he does this.

6. The CCD detector in a certain camera has a width of 8 mm. The photographer realizes that with the lens she is currently using, the 6.3 mm she is trying to photograph into her picture. Should she switch to a lens with a longer or shorter focal length? Explain.

7. All humans have what is known as a blind spot, where the optic nerve exits the eye and no light-sensitive cells exist. To locate your blind spot, look at the figure of the cross. Close your left eye and place your index finger on the cross. Slowly move your finger to the left while following it with your right eye. At a certain point the cross will disappear. Is your right eye’s blind spot on the right or left side of your retina? Explain.

8. Suppose you wanted special glasses designed to wear underwater, without a face mask. Should the glasses use a converging or diverging lens in order for you to be able to focus under water? Explain.

9. You have lenses with the following focal lengths: $f = 25$ mm, 50 mm, 100 mm, and 200 mm. Which lens or pair of lenses would you use, and in what arrangement, to get the highest-power magnifier, microscope, and telescope? Explain.

10. An 8-year-old child and a 75-year-old man both use the same magnifier to observe a bug. For whom does the magnifier more likely have the higher magnification? Explain.

11. A friend lends you the eyepiece of his microscope to use on your own microscope. He claims that since his eyepiece has the same diameter as yours but twice the focal length, the resolving power of your microscope will be doubled. Is his claim valid? Explain.

12. An astronomer is using a telescope to observe two distant stars. The stars are marginally resolved when she looks at them through a filter that passes green light near 550 nm. Which of the following actions would improve the resolution? Assume that the resolution is not limited by the atmosphere:
   a. Changing the filter to a different wavelength? If so, should she use a shorter or a longer wavelength?
   b. Using a telescope with an objective lens of the same diameter but a different focal length? If so, should she select a shorter or a longer focal length?
   c. Using a telescope with an objective lens of the same focal length but a different diameter? If so, should she select a larger or a smaller diameter?
   d. Using an eyepiece with a different magnification? If so, should she select an eyepiece with more or less magnification?

13. A pair of binoculars has a magnification of 7x. What would be their magnification if you were to look through them the wrong way, that is, through one of their objective lenses instead of the eyepieces?

14. Is the wearer of the glasses in Figure Q19.14 nearsighted or farsighted? How can you tell?

15. A red card is illuminated by red light. What color does it appear to be? What if it’s illuminated by blue light?

**Multiple-Choice Questions**

16. A photographer takes a perfectly exposed picture at an $f$-number of $\frac{f}{2.0}$ and a shutter speed of $1/125$ s. Now he wishes to use a shutter speed of $1/250$ s. What $f$-number should he choose to get a correctly exposed picture?
   A. $\frac{f}{2.0}$  B. $\frac{f}{2.8}$  C. $\frac{f}{5.6}$  D. $\frac{f}{8.0}$

17. A microscope has a tube length of 20 cm. What combination of objective and eyepiece focal lengths will give an overall magnification of 100?
   A. 1.5 cm, 3 cm  B. 2 cm, 2 cm
   C. 1 cm, 5 cm  D. 3 cm, 8 cm
18. The distance between the objective and eyepiece of a telescope is 55 cm. The focal length of the eyepiece is 5.0 cm. What is the angular magnification of this telescope?
   A. -10  B. -11  C. -50  D. -275

19. A nearsighted person has a near point of 20 cm and a far point of 40 cm. When he is wearing glasses to correct his distant vision, what is his near point?
   A. 10 cm  B. 20 cm  C. 40 cm  D. 1.0 m

20. A nearsighted person has a near point of 20 cm and a far point of 40 cm. What power lens is necessary to correct this person’s vision to allow her to see distant objects?
   A. -2.5 D  B. -1.5 D  C. +1.5 D  D. +2.5 D

21. A 60-year-old man has a near point of 100 cm, making it impossible to read. What power reading glasses would he need to focus on a newspaper held at a comfortable distance of 40 cm?
   A. -2.5 D  B. -1.5 D  C. +1.5 D  D. +2.5 D

22. A person looking through a -10 D lens sees an image that appears 8.0 cm from the lens. How far from the lens is the object?
   A. 10 cm  B. 20 cm  C. 25 cm  D. 40 cm

23. In a darkened room, red light shines on a red cup, a white card, and a blue toy. The cup, card, and toy will appear, respectively, A. Red, red, blue.  B. Red, white, blue.  C. Red, red, black.  D. Red, black, blue.

24. An amateur astronomer looks at the moon through a telescope with a 15-cm-diameter objective. What is the minimum separation between two objects on the moon that she can resolve with this telescope? Assume her eye is most sensitive to light with a wavelength of 550 nm.
   A. 120 m  B. 1.7 km  C. 26 km  D. 520 km

Section 19.1 The Camera

1. The human eye has a lot in common with a pinhole camera, being essentially a small box with a hole in the front (the pupil) and “film” at the back (the retina). The distance from the pupil to the retina is approximately 24 mm.
   a. Suppose you look at a 180-cm-tall friend who is standing 7.4 m in front of you. Assuming your eye functions like a pinhole camera, what will be the height, in mm, of your friend’s image on your retina?
   b. Suppose your friend’s image begins to get bigger. How does your brain interpret this information?

2. A student has built a 20-cm-long pinhole camera for a science fair project. She wants to photograph the Washington Monument, which is 167 m (550 ft) tall, and to have the image on the film be 5.0 cm high. How far should she stand from the Washington Monument?

3. A pinhole camera is made from an 80-cm-long box with a small hole in one end. If the hole is 5.0 m from a 1.8-m-tall person, how tall will the image of the person on the film be?

4. A photographer uses his camera, whose lens has a 50 mm focal length, to focus on an object 2.0 m away. He then wants to take a picture of an object that is 40 cm away. How far, and in which direction, must the lens move to focus on this second object?

5. A camera takes a perfectly exposed picture when the lens diaphragm is set to f/4 and the shutter speed is 1/250 s. If the diaphragm is changed to f/11, what should the new shutter speed be so that the exposure is still correct? (Standard camera shutter speeds include 1/250 s, 1/125 s, 1/60 s, 1/30 s, and 1/15 s.)

6. In Figure P19.6 the camera lens has a 50 mm focal length. How high is the man’s well-focused image on the film?

7. A telephoto lens with focal length of 135 mm has f-numbers ranging from f/2.8 to f/22. What is the diameter of the lens aperture at these two f-numbers?

Section 19.2 The Human Eye

8. a. Estimate the diameter of your eyeball.
   b. Bring this page up to the closest distance at which the text is sharp—not the closest at which you can still read it, but the closest at which the letters remain sharp. If you wear glasses or contact lenses, leave them on. This distance is called the near point of your (possibly corrected) eye. Record it.
   c. Estimate the effective focal length of your eye. The effective focal length includes the focusing due to the lens, the curvature of the cornea, and any corrections you wear. Ignore the effects of the fluid in your eye.

9. A farsighted person has a near point of 50 cm rather than the normal 25 cm. What strength lens, in dioptrons, should be prescribed to correct this vision problem?

10. A nearsighted woman has a far point of 300 cm. What kind of lens, converging or diverging, should be prescribed for her to see distant objects more clearly? What power should the lens have?

11. The relaxed human eye is about 2 cm from front to back. If the iris of the human eye can be opened to 7 mm at its widest, what is the f-number of the human eye?

12. The near point for your myopic uncle is 10 cm. Your own vision is normal; that is, your near point is 25 cm. Suppose you and your uncle hold dimes (which are 1.7 cm in diameter) at your respective near points.
   a. What is the dime’s angular size, in radians, according to you?
   b. What is the dime’s angular size, in radians, according to your uncle?
   c. Do these calculations suggest any benefit to near-sightedness?
Section 19.3 The Magnifier

15. The diameter of a penny is 19 mm. How far from your eye must it be held so that it has the same apparent size as the moon? (Use the astronomical data inside the back cover.)

16. What is the angular size of the moon? (Use the astronomical data inside the back cover.)

17. A magnifier has a magnification of 5X. How far from the lens should an object be placed so that its (virtual) image is at the near-point distance of 25 cm?

18. A farsighted man has a near point of 40 cm. What power lens should he use as a magnifier to see clearly at a distance of 10 cm without wearing his glasses?

Section 19.4 The Microscope

19. An inexpensive microscope has a tube length of 12.0 cm, and its objective lens is labeled with a magnification of 10X.
   a. Calculate the focal length of the objective lens.
   b. What focal length eye piece lens should the microscope have to give an overall magnification of 150X?

20. A standard biological microscope is required to have a magnification of 200X.
   a. When paired with a 10X eyepiece, what power objective is needed to get this magnification?
   b. What is the focal length of the objective?

21. A forensic scientist is using a standard biological microscope with a 15X objective and a 5X eyepiece to examine a hair from a crime scene. How far from the objective is the hair?

22. A microscope with an 8.0-mm-focal-length objective has a tube length of 16.0 cm. For the microscope to be in focus, how far should the objective lens be from the specimen?

23. The distance between the objective and eyepiece lenses in a microscope is 20 cm. The objective lens has a focal length of 5.0 mm. What eyepiece focal length will give the microscope an overall angular magnification of 350?

Section 19.5 The Telescope

24. For the combination of two identical lenses shown in Figure P19.24, find the position, size, and orientation of the final image of the 2.0-cm-tall object.

25. For the combination of two lenses shown in Figure P19.25, find the position, size, and orientation of the final image of the 1.0-cm-tall object.

Section 19.6 Color and Dispersion

30. A narrow beam of light with wavelengths from 450 nm to 700 nm is incident perpendicular to one face of a 40.0° prism made of crown glass, for which the index of refraction ranges from \( n = 1.533 \) to \( n = 1.517 \) for those wavelengths. What is the angular spread of the beam after passing through the prism?

31. A ray of white light strikes the surface of a 4.0-cm-thick slab of flint glass as shown in Figure P19.31. As the ray enters the glass, it is dispersed into its constituent colors. Estimate how far apart the rays of deepest red and deepest violet light are as they exit the bottom surface. Which exiting ray is closer to point \( P \)?

32. A ray of red light, for which \( n = 1.54 \), and a ray of violet light, for which \( n = 1.59 \), travel through a piece of glass. They meet right at the boundary between the glass and the air, and emerge into the air as one ray with an angle of refraction of 22.5°. What is the angle between the two rays in the glass?
Section 19.7 Resolution of Optical Instruments

33. Two light bulbs are 1.0 m apart. From what distance can these light bulbs be marginally resolved by a small telescope with a 4.0-cm-diameter objective lens? Assume that the lens is limited only by diffraction and $\lambda = 600 \text{ nm}$.

34. A 1.0-cm-diameter microscope objective has a focal length of 2.8 mm. It is used in visible light with a wavelength of 550 nm.
   a. What is the objective’s resolving power if used in air?
   b. What is the resolving power of the objective if it is used in an oil-immersion microscope with $n_{oil} = 1.45$?

35. A microscope with an objective of focal length 1.6 mm is used to inspect the tiny features of a computer chip. It is desired to resolve two objects only 400 nm apart. What diameter objective is needed if the microscope is used in air with light of wavelength 550 nm?

General Problems

36. Suppose you point a pinhole camera at a 15-m-tall tree that is 75 m away.
   a. If the film is 22 cm behind the pinhole, what will be the size of the tree’s image on the film?
   b. If you would like the image to be larger, should you get closer to the tree or farther from the tree? Explain.
   c. If you had time, you could make the image larger by rebuilding the camera, changing the length or the pinhole size. What one change would give a larger image?

37. “Jason uses a lens with focal length of 10.0 cm as a magnifier by holding it right up to his eye. He is observing an object that is 8.0 cm from the lens. What is the angular magnification of the lens used this way if Jason’s near-point distance is 25 cm?”

38. A magnifier is labeled “5X.” What would its magnification be if used by a person with a near-point distance of 50 cm?

39. A 20X microscope objective is designed for use in a microscope with a 16 cm tube length. The objective is marked $NA = 0.40$. What is the diameter of the objective lens?

40. Two converging lenses with focal lengths of 40 cm and 20 cm are 10 cm apart. A 2.0-cm-tall object is 15 cm in front of the 40-cm-focal-length lens.
   a. Use ray tracing to find the position and height of the image. To do this accurately use a ruler or paper with a grid. Determine the image distance and image height by making measurements on your diagram.
   b. Calculate the image height and image position relative to the second lens. Compare with your ray-tracing answers in part a.

41. A converging lens with a focal length of 40 cm and a diverging lens with a focal length of ~40 cm are 160 cm apart. A 2.0-cm-tall object is 60 cm in front of the converging lens.
   a. Use ray tracing to find the position and height of the image. To do this, accurately use a ruler or paper with a grid. Determine the image distance and image height by making measurements on your diagram.
   b. Calculate the image height and image position relative to the second lens. Compare with your ray-tracing answers in part a.

42. A lens with a focal length of 25 cm is placed 40 cm in front of a lens with a focal length of 5.0 cm. How far from the second lens is the final image of an object infinitely far from the first lens? Is this image in front of or behind the second lens?

43. A microscope with a 5x objective lens images a 1.0-mm-diameter specimen. What is the diameter of the real image of this specimen formed by the objective lens?

44. Your task in physics lab is to make a microscope from two lenses. One lens has a focal length of 10 cm, the other a focal length of 3.0 cm. You plan to use the more powerful lens as the objective, and you want its image to be 16 cm from the lens, as in a standard biological microscope.
   a. How far should the objective lens be from the object to produce a real image 16 cm from the objective?
   b. What will be the magnification of your microscope?

45. A 20X objective and 10X eyepiece give an angular magnification of 200X when used in a microscope with a 160 mm tube length. What magnification would this objective and eyepiece give if used in a microscope with a 200 mm tube length?

46. The objective lens and the eyepiece lens of a telescope are 1.0 m apart. The telescope has an angular magnification of 50. Find the focal lengths of the eyepiece and the objective.

47. Your telescope has an objective lens with a focal length of 1.0 m. You point the telescope at the moon, only to realize that the eyepiece is missing. Even so, you can still see the real image of the moon formed by the objective lens if you place your eye a little past the image so as to view the rays diverging from the image plane, just as rays would diverge from an object at that location. What is the angular magnification of the moon if you view its real image from 25 cm away, your near-point distance?

48. The 200-inch-diameter objective mirror of the reflecting telescope at the Mt. Palomar Observatory has a focal length of 17 m.
   a. The f-number of a mirror is defined exactly the same as the f-number of a lens. What is the f-number of this mirror?
   b. The f-number of the 200-inch telescope is well within the range of f-numbers of a cheap camera. So why not just use the camera to take pictures of distant galaxies, instead of constructing this very expensive telescope?

49. Marooned on a desert island and with a lot of time on your hands, you decide to disassemble your glasses to make a crude telescope with which you can scan the horizon for rescuers. Luckily you’re farsighted, and as for most people your two eyes have somewhat different lens prescriptions. Your left eye uses a lens of power $+4.5 \text{ D}$ and your right eye’s lens is $+3.0 \text{ D}$.
   a. Which lens should you use for the objective and which for the eyepiece? Explain.
   b. What will be the magnification of your telescope?
   c. Approximately how far apart should the two lenses be when you focus on distant objects?

50. A spy satellite uses a telescope with a 2.0-m-diameter mirror. It orbits the earth at a height of 220 km. What minimum spacing must there be between two objects on the earth’s surface if they are to be resolved as distinct objects by this telescope? Assume the telescope’s resolution is limited only by diffraction and that it is recording light with a wavelength of 500 nm.

51. Two stars have an angular separation of $3.3 \times 10^{-6} \text{ rad}$. What diameter telescope objective is necessary to just resolve these two stars, using light with a wavelength of 650 nm?
52. The planet Neptune is \(4.5 \times 10^{12}\) m from the earth. Its diameter is \(4.9 \times 10^7\) m. What diameter telescope objective would be necessary to just barely see Neptune as a disk rather than as a point of light? Assume a wavelength of 550 nm.

53. What is the angular resolution of the Hubble Space Telescope’s 2.4-m-diameter mirror when viewing light with a wavelength of 550 nm? The resolution of a reflecting telescope is calculated exactly the same as for a refracting telescope.

54. The Hubble Space Telescope has a mirror diameter of 2.4 m. Suppose the telescope is used to photograph stars near the center of our galaxy, 30,000 light years away, using red light with a wavelength of 650 nm.
   a. What is the distance (in km) between two stars that are marginally resolved? The resolution of a reflecting telescope is calculated exactly the same as for a refracting telescope.
   b. For comparison, what is this distance as a multiple of the distance of Jupiter from the sun?

55. Once dark adapted, the pupil of your eye is approximately 7 mm in diameter. The headlights of an oncoming car are 120 cm apart. If the lens of your eye is limited only by diffraction, at what distance are the two headlights marginally resolved? Assume the light’s wavelength in air is 600 nm and the index of refraction inside the eye is 1.33. (Your eye is not really good enough to resolve headlights at this distance, due both to aberrations in the lens and to the size of the receptors in your retina, but it comes reasonably close.)

56. The normal human eye has maximum visual acuity with a pupil size of about 3 mm. For larger pupils, acuity decreases due to increasing aberrations; for smaller pupils, acuity decreases due to increasing effects of diffraction. If your pupil diameter is 2.0 mm, as it would be in fairly bright light, what is the smallest diameter circle that you can barely see as a circle, rather than just a dot, if the circle is at your near point, 25 cm from your eye? Assume the light’s wavelength in air is 600 nm and the index of refraction inside the eye is 1.33.

57. Microtubules are filamentous structures in cells that maintain cell shape and facilitate the movement of molecules within the cell. They are long, hollow cylinders with a diameter of about 25 nm. It is possible to incorporate fluorescent molecules into microtubules; when illuminated by an ultraviolet light, the fluorescent molecules emit visible light that can be imaged by the optical system of a microscope. If the emitted light has a wavelength of 500 nm and the NA of the microscope objective is 1.4, can a biologist looking through the microscope tell whether she is looking at a single microtubule or at two microtubules lying side by side?

**Passage Problems**

**Surgical Vision Correction**

Light that enters your eyes is focused to form an image on your retina. The optics of your visual system have a total power of about +60 D—about +20 D from the lens in your eye and +40 D from the curved shape of your cornea. Surgical procedures to correct vision generally do not work on the lens; they work to reshape the cornea. In the most common procedure, a laser is used to remove tissue from the center of the cornea, reducing its curvature. This change in shape can correct certain kinds of vision problems.

58. Flattening the cornea would be a good solution for someone who was
   A. Nearsighted.  B. Farsighted.  C. Either nearsighted or farsighted.

59. Suppose a woman has a far point of 50 cm. How much should the focusing power of her cornea be changed to correct her vision? A. −2.0 D.B. −1.0 D. C. +1.0 D.D. +2.0 D.

60. A cataract is a clouding or opacity that develops in the eye’s lens, often in older people. In extreme cases, the lens of the eye may need to be removed. This would have the effect of leaving a person
   A. Nearsighted.  B. Farsighted.  C. Neither nearsighted nor farsighted.

61. The length of your eye decreases slightly as you age, making the lens a bit closer to the retina. Suppose a man had his vision surgically corrected at age 30. At age 70, once his eyes had decreased slightly in length, he would be
   A. Nearsighted.  B. Farsighted.  C. Neither nearsighted nor farsighted.

**Stop to Think 19.1:** B. The diameter \(d\) of the lens is constant, so increasing the focal length increases the \(f\)-number \(f/d\) of the lens. A lens with a higher \(f\)-number needs more light for a correct exposure, requiring a slower shutter speed.

**Stop to Think 19.2:** D. Because Maria can focus on an object 0.5 m away, but not on one 10 m away, her far point must lie between these two distances. Following Example 19.4, we see that the prescription for her lens must then lie between \(1/(−0.10) = −10\ D\) and \(1/(−0.50) = −2\ D\). Only the −1.5 D prescription falls in this range.

**Stop to Think 19.3:** A. Ray tracing shows why.

**Stop to Think 19.4:** B. The total magnification is the product of the objective magnification \(m_o\) and the eyepiece angular magnification \(M_p\). If \(m_o\) is halved, from \(20\times\) to \(10\times\), \(M_p\) must be doubled. Because \(M_p\) is inversely proportional to the eyepiece focal length, the focal length of the eyepiece must be halved.

**Stop to Think 19.5:** D. A green filter lets through only green light, so it blocks the red light from the apple. No light from the apple can pass through the filter, so it appears black.

**Stop to Think 19.6:** \(R_4 > R_3 > R_2 > R_1\). The resolving power is \(RP = 0.61\lambda/\sin \Phi_0\) for objectives used in air \((n = 1)\), so the resolving power is higher (worse resolution) when the angle \(\Phi_0\) is smaller. From Figure 19.29 you can see that \(\Phi_0\) is smaller when the ratio \(Df\) is smaller. These ratios are \((Df)_1 = 1/5, (Df)_2 = 2/5, (Df)_3 = 2/5,\) and \((Df)_4 = 1/3\).