28 Reflection and Refraction

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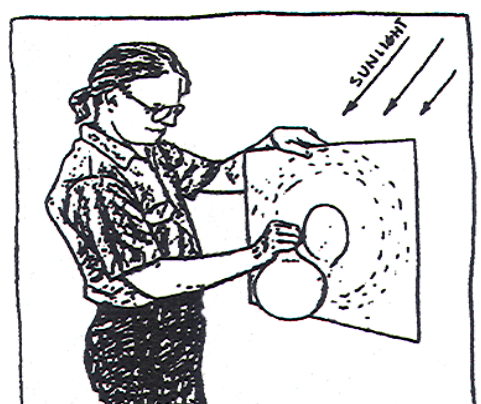
The first of the chapter opening photos shows Peter Hopkinson of Vancouver Community College in Canada performing one of his many classroom antics. The duck on the rock, second photo, shows that the reflected view is not identical to the right-side-up view, because the viewing angles differ. The duck's feet do not show in the reflection. Photo three is Fred Myers and his daughter McKenzie posing between a pair of parallel mirrors. Karen Jo Matsler goes further with three mirrors in the fourth photo, all of which show interesting reflections.

The personal profile for this chapter is Pierre de Fermat.

Reflection and refraction are introduced via Fermat's Principle of Least Time, a la Feynman. The treatment of reflection is brief, with only scant application to convex and concave mirrors. The treatment of refraction is supported by many examples. You may wish to further support the cases of atmospheric refraction by discussing the analogous case of sound refraction in a region where the temperature of air at the ground is appreciably higher or lower than the air temperature above as was treated in Chapter 20.

For a very brief treatment on light, this chapter may be covered in place of the regular sequence of Part 6. In this case, the behavior rather than the nature of light would be emphasized (which most introductory texts stress anyway).

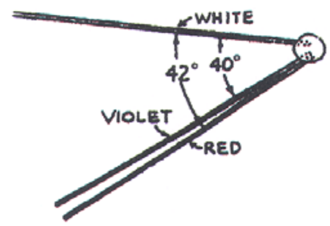
Paul Doherty makes rainbows that his students can study first hand at the Exploratorium. You can too. Your giant water drop is a glass sphere filled with water. Cut a hole that's slightly larger than your sphere in a piece of white cardboard. Shine a bright beam of light from a slide projector or the Sun through the hole so that the beam illuminates the entire water drop. The drop will project a colored circle of light onto the cardboard screen around the hole you have cut. If at first you don't see a circle of light, move the screen closer to the drop, as Paul shows to the right! (See his article on rainbows back in the Exploratorium quarterly, *Exploring* (Summer 1992). Thanx Paul!



Courtesy Exploratorium

I owe the conical treatment of the rainbow in the text to one of Cecil Adams's syndicated newspaper columns, *The Straight Dope*.

An explanation of why a rainbow is bow-shaped is aided with this simple easy-to-construct apparatus: Stick three colored dowels into a sphere of clay, Styrofoam, wood, or whatever that represents a raindrop. One dowel is white, one violet, and the other red, to represent incident white light and refracted red and violet. The angles between dowels are shown in the sketch. A student volunteer crouching in front of your chalkboard shows the class how the only drops that cast light to him or her originate in drops along a bow-shaped region. (More on this in a lecture video and in the lecture below.)



A plastic viewing tank designed by Dean Baird is available from Arbor Scientific. Laser beam refraction and reflection and diffraction are nicely seen in a tank that is lightweight and easy to store. It's 18 inches × 6 inches × 1 inch, skinny, so it weighs only about 3 pounds with water (P2-7690). A photo of Dean with his tank is on page 513 of the previous chapter.

Nanoparticles of zinc oxide or titanium in sunscreen are totally transparent to ordinary visible light, because of their size, but are highly reflecting to UV.

Black fabrics normally absorb about 90 percent of the Sun's heat. An exception is black fabrics that have been chemically treated to reflect about 80 percent of Sun's rays, nearly as much as white fabrics. Watch for them in winter wear.

The first telescope is credited to a Dutch spectacle maker, Hans Lippershey, in 1608. Galileo was the first to be reported as using it to observe the nighttime sky.

The half-size mirror problem, as well as Think and Rank 43 and Think and Explains 47 - 50, nicely illustrate one of the valuable things about your course—that the richness in life is not only seeing the world with wide open eyes, but in knowing what to look for. Concepts in this chapter provide a lot of guidance in this respect.

Not covered in the text or ancillaries is the green flash, the momentary flash of green light that is sometimes seen when the Sun sets. A simple explanation is that the atmosphere acts as a prism, but upside down, so that white light of the Sun is dispersed with blue on top, green near the top, and red on the bottom. At the moment the Sun sets, the red is cut off by the Earth, the blue is removed by scattering, and green survives to give the famous green flash.

Animals with 360° vision without turning their heads include rabbits and hares because of their big protruding eyes on the sides of their heads. But they have depth perception only where the view from each eye overlaps a bit in front of their heads and behind them.

Practicing Physics Book:
- Pool Room Optics
- Reflection
- Reflected Views
- More Reflection
- Refraction
- More Refraction
- Lenses

Problem Solving Book:
Problems on reflection and refraction

Laboratory Manual:
- Mirror rorriiM *The Geometry of Plane Mirror Images* (Activity)
- Mirror Experiences *Images in Spherical Mirrors* (Activity)
- Diversion into Refraction *The Nature of Refraction* (Activity)
- Coin Under the Cup *The Magic of Reflection* (Activity)
- Diversion into Dispersion *Turning White Light into a Full Spectrum* (Activity)

• Trapping the Light Fantastic *Total Internal Reflection* (Activity)
• A Sweet Mirage *Gradual Refraction* (Activity)
• Lenses Positive and Negative *The Geometry of the Focal Point* (Activity)
• Lens Experience *Images in a Fresnel Lens* (Activity)

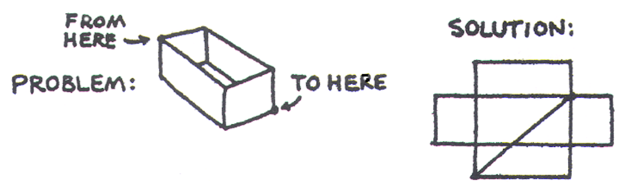
Next-Time Questions:
• Shortest Distance
• Refraction
• View in Full-Length Mirror
• View in Pocket Mirror
• View in Hand-held Mirror
• Bridge Reflection
• Light Column on Water
• Red Sunset
• Photographing a Rainbow
• Spearing a Fish
• Submerged Coin
• Laser Beam
• Underwater Viewing
• Red Lunar Eclipse
• Corner Refractor

Hewitt-Drew-It! Screencasts: •*Reflection* •*Refraction* •*The Rainbow* •*Pinhole Images* •*Lenses*

The following suggested lecture will probably take at least two class periods.

SUGGESTION LECTURE PRESENTATION

Principle of Least Time
You can lead into Fermat's principle of least time for reflection by posing to your class the following: Consider a rectangular box, like a shoe box, with an ant inside at one of its corners, say an upper corner. Question: What would be the path of least distance along the inside surface of the box to the diagonally opposite corner? (Most will likely answer "straight down to the lower corner, then diagonally across the floor.") Then after a "talk to your neighbor" routine, provide this hint: Flatten the box out and consider the shortest distance.



Law of Reflection
Now you're ready to discuss Figures 28.2 through 28.5, and cap it off with Figure 28.6, the law of reflection.

Plane Mirror
Sketch Figure 28.7 on the board and carefully show how image and object distance are the same. Call attention to the curved mirrors of Figure 28.9 and stress that the law reigns in whatever small region a light ray strikes. Likewise with diffuse reflection. Discuss Think and Discuss 93, about the diffuse dry road becoming a "plane mirror" when wet, and hence the difficulty of seeing the road in a car on a rainy night.

> CHECK QUESTION: If a camera shot on TV or in the movies shows a person and a mirror in which we see the person's reflection, what does the person see when looking at the mirror? [The camera!] (This is the crux of Think and Discuss 96.)

There is common confusion about just what a mirror reverses. Left and right aren't reversed. What *is* reversed is front and back. I hope the diagram next to the photo of my sister in Figure 28.8 helps clear this.

Half-Size Mirror
Answers to the question about the minimum size mirror needed to view a full-size image will elicit much class interest. My screencast on *Reflection* featuring "Blinky Bill" treats this. You can expect spirited discussions of Think and Rank 43, Think and Explains 60 – 64. I regret to report, that seldom do I find half of my class answering these questions correctly—particularly when I first emphasize that the results will be

surprising, and that if they are careful they will learn something about their image in a mirror that has likely escaped them all their lives (that the size of the mirror is independent of their distance from it). Most correctly get the first part, the half-size answer, but miss the part about distance from the mirror being irrelevant. That's where I ask them to mark the mirror where they see the top of their head and bottom of their chin, and then to step back and look carefully for the effect of distance. Perhaps like the visual illusion of Think and Do 31 on page 177 at the end of Chapter 9 (judging hand sizes), their belief in their uninvestigated answer is so strong that they will not see what is there unless it is explicitly pointed out to them. Are your students more perceptive than mine? In any event, when you discuss the answers to the minimim-size mirror questions, bring into class a full-length mirror or pass a few small mirrors among your students. It's worth the extra effort.

Refraction
Discuss Fermat's principle for refraction, via the lifeguard analogy presented in the text. Contrast the path the lifeguard would take compared to the path a seal would take. Point out that the bend you draw on the board when illustrating these "refractions" depends on the relative speeds on the sand and in the water. Continue with the examples in the text, that light takes a longer path but shorter distance, time wise when incident obliquely on glass; likewise through a prism, and through a lens, above the atmosphere during sunsets, and close to the ground when a mirage is produced. Consider relating the refraction of light during a mirage to the reaction of sound as treated in Chapter 20. Then to the mechanics of how light follows these incredible paths.

Cause of Refraction
Refraction hinges on the slowing of light in a transparent medium. This was established in Chapter 26. The analogy of the wheels rolling onto the grass lawn (Figure 28.23) shows that bending of path is the result of this change of speed. This is reinforced in the *Practicing Physics Book*. So we see that the bending is the result of light changing speed, rather than the result of light "waning" to reach a place in the least time. It is important to underscore this distinction. Here a straightforward physics explanation is much simpler than the mystical explanation. How many other mystical explanations fall in this category?

Index of Refraction
New to the 12th edition is Snell's Law, not in a footnote as in previous editions, but as a text section, *Index of Refraction*. The math is light and involves, a bit of trigonometry, which can either be amplified or glossed over, depending on the class time you want to allot to quantitative coverage.

When the speed of light in a transparent object is the same as the speed of light in a fluid in which it is immersed (or in physics lingo, when the index of refraction is the same for each), then the object won't be seen. Putting glass items in some vegetable oils will demonstrate this, as shown by my niece Stephanie in Think and Explain 91.

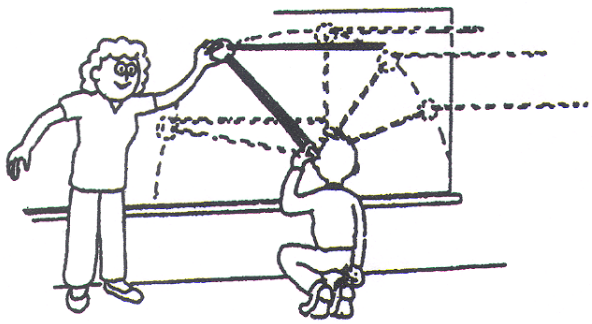
Dispersion
Now that you've established refraction as a result of changes in light speed, it follows that different speeds of different frequencies of light in transparent materials refract at different angles. This is dispersion, nicely illustrated with a prism.

Rainbows
Amplify the section on rainbows, and liken them to viewing a cone held with its apex to the eye. The deeper the misty region, the more intense the rainbow appears. The cone bit explains why the rainbow is round. Another is via the ball-and-sticks demonstration.

> DEMONSTRATION: Show the rainbow-sticks apparatus described and compare it to the rainbow schematic drawing of Figures 28.30 and 28.31. The white stick represents incoming white light, and the red and violet sticks represent the refracted rays. Have a student volunteer crouch in front of the board as shown in the sketch. Place the ball near the chalkboard so the white dowel is perpendicular to the board (from the Sun at the horizon for simplicity). Position the free end of the violet dowel so that it nearly meets the volunteer's eye. State that a drop at this location refracts violet light to the eye. The question follows: Are there other locations that will also refract violet

light to the eye? Move the "drop" to other locations along the board while keeping the white dowel perpendicular to the board. It is easy to see that refracted violet coming from drops farther away miss the eye altogether. The only locations that send violet light to the eye are along a bow—which you trace with violet or blue chalk. This is easy to do if the student holds the end of the violet dowel near the eye while you scribe the arc in compass fashion.

Enlist a second volunteer to crouch in front of the board at a different position. Show how this volunteer must look to different drops in the sky to see a rainbow. Ask the class if the two volunteers see the same rainbow. [No, each sees his or her own personal rainbow!]



CHECK QUESTION: With the ball and dowels positioned at the top of the bow, ask where the volunteer must look to see red—above the violet, or below? [Above (2° to be exact).] Show this by moving the "drop" up, whereupon the red dowel lines up with the eye. Complete your demo by sweeping this wider bow with red chalk.

Rainbows cannot be seen when the Sun is more than 42 degrees in the sky because the bow is below the horizon where no water drops are to be seen. Hence rainbows are normally seen early and late in the day. So we don't see rainbows in midday in summer in most parts of the world (except from an airplane, where they are seen in full circles).

Point out a significant yet commonly unnoticed feature about the rainbow—that the disk segment bounded by the bow is appreciably brighter than the rest of the sky. Refracted light overlaps in this region. Only at the edges, the rainbow, does it not overlap. The rainbow is similar to the chromatic aberration around a bright spot of projected white light. Notice this in Figure 28.34 (taken from my former bedroom window in Hilo, HI).

Show Paul Doherty's rainbow from a sphere of water (described on page 291, four pages back).

Extend rainbows to the similar phenomenon of the halo around the Moon. Explain how the halo is produced by refraction of moonlight through ice crystals in the atmosphere. Note the important difference: Whereas both refraction and internal reflection produce rainbows, only refraction produces halos. And whereas the observer is between the Sun and the drops for seeing a rainbow, the ice crystals that produce halos are between the observer and the Moon. Moonlight is refracted through ice crystals high in the atmosphere—evidence of the coldness up there even on a hot summer night.

Total Internal Reflection

DEMONSTRATION: Show examples of reflection, refraction and total internal reflection with the usual apparatus—light source (laser), prisms, and a tank of water with the addition of a bit of fluorescence dye.

(You may notice that at the critical angle, some light skims the surface of the water. This is because your beam is slightly divergent, so where the central axis of the beam may be at the critical angle and reflect back into the medium, part of the beam is slightly beyond the critical angle and refracts.)

Ask your class to imagine how the sky would look from a lake bottom. For humor, whereas above water we must turn our heads through 180 degrees to see from horizon to horizon, a fish needs only scan twice the 48 degree critical angle to see from horizon to horizon—which is why fish have no necks!

Fiber Optics

Show some examples of light pipes. Discuss some of the many applications of these fibers, or "light pipes," particularly in telephone communications. The principle underlying fiber optics is similar to a boy scout signaling Morse code by flashlight to a distant friend. In fiber optics, computers fire lasers that turn on and off rapidly in digital code. Current lasers send about 1.7 billion pulses per second to optical detects that receive and interpret the information.

Today glass fibers as thin as a human hair carry thousands of simultaneous telephone conversations, compared to the only 24 that can be carried per conventional copper cable. Signals in copper cables must be boosted every 4 to 6 kilometers, whereas re-amplification in light-wave systems occurs every 10 to 50 kilometers. For infrared optical fibers, the distance between regenerators may be hundreds or perhaps thousands of kilometers. Fibers are indeed very transparent!

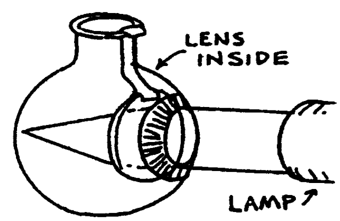
Lenses

The explanation of lenses follows from your demo of light deviating through a prism. Whereas a study of lenses is properly a laboratory activity, all the ray diagrams, in the world are of little value unless paired with a hands-on experience with lenses. So if a laboratory experience is not part of your course, I would recommend lenses be treated very briefly if at all in lecture.

State the difference between a virtual and a real image: A virtual image is formed by light rays that only appear to intersect. A real image is formed where light rays do intersect at a single point.

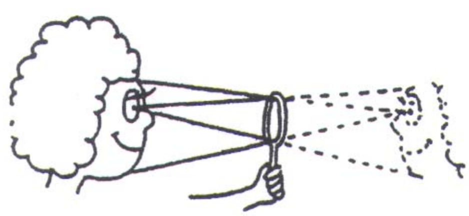
DEMONSTRATION: Show examples of converging a diverging lenses. A white light source will do, but a neat source of light is a laser beam that is widened by lenses and then directed through a mask of parallel slits. Then parallel rays of light are incident upon your lenses.

DEMONSTRATION: Simulate the human eye with a spherical flask filled with a bit of fluorescence dye. Paint an "iris" on the flask and position appropriate lenses in back of the iris for normal, farsighted and nearsighted vision. Then show how corrective lenses placed in front of the eye put the light in focus on the retina.



Think and Discuss 107 about sheets of lenses that supposedly direct more solar energy into a swimming pool makes a good discussion topic.

NEXT-TIME QUESTION: Refer to the minimum size mirror and respective distances questions, and tie them to Think and Rank 43. This activity is also a Next-Time Question, and a concluding question in my screencast on *Reflection*.



Answers and Solutions for Chapter 28

Reading Check Questions

1. Incident light sets electrons into vibration.
2. Vibrating electrons emit electromagnetic waves.
3. Fermat's principle of least time states that light will take the path of least time when going from one point to another.
4. The angle of incidence equals the angle of reflection.
5. Image distance and object distance are the same.
6. About 4% of incident light is reflected from the first surface.
7. Yes, a surface may be polished for short-wavelength waves and not for longer ones. The mesh on a parabolic dish is rough for short waves, but not for long waves.
8. Both angles are the same for window glass.
9. When the faces of the glass are not parallel, as with a prism.
10. Light travels faster in thin air. This produces atmospheric refraction, which lengthens the daylight hours.
11. Yes, the law of reflection holds locally at each tiny part of the curved surface, but not for the curved mirror as a whole.
12. A mirage is a result of atmospheric refraction.
13. Interaction of light with transparent material lowers the speed of light in the material.
14. The angle is always 90°.
15. Light speed slows when refracted in a medium.
16. High index glass means more bending and thinner lenses.
17. Refraction makes the pool bottom appear shallower.
18. Violet light travels more slowly in glass than red light.
19. Each drop disperses a spectrum of colors.
20. A viewer only sees a small segment of colors, a single color, dispersed from a far-away drop
21. A secondary bow is dimmer due to an additional internal reflection.
22. Critical angle is the minimum angle of incidence inside a medium at which a light ray is totally reflected.
23. Inside glass light is totally reflected at about 43°, depending on the type of glass; in a diamond, 24.5°.
24. It bends by a succession of internal reflections, following the contour of the fiber.
25. A converging lens is thickest in the middle, causing parallel rays to come together at a point. A diverging lens is thickest at the edges.
26. The focal length of a lens is the distance between the center of the lens and the point where parallel light rays intersect.
27. A real image can be cast on a screen; a virtual image cannot.
28. Only a converging lens can produce a real image; both converging and diverging lenses can produce a virtual image.
29. Small pupils mean small opening, which means less overlapping of out-of-focus rays.
30. Astigmatism is a defect in which there is more curvature of the lens in one direction than the other. The remedy is eyeglasses with cylindrical lenses that curve more in one direction than in another.

Think and Do

31. Many Grandmas do not realize that only a half-size mirror gives a full view of oneself.
32. This is an intriguing activity.
33. This is an intriguing activity.
34. This is an intriguing activity.
35. This is an intriguing activity.
36. Experiment will show that about 100 coins will fit between the coin-sized image of the Sun and the hole in the paper. And incredibly, that's the same number of Suns that would fit between Earth and the position of the Sun!

Think and Solve

37. 4 m/s. You and your image are both walking at 2 m/s.

38. When a mirror is rotated, its normal rotates also. Since the angle that the incident ray makes with the normal is the same angle that the reflected ray makes, the total deviation is twice. In the sample diagram, if the mirror is rotated by 10°, then the normal is rotated by 10° also, which results in a 20° total deviation of the reflected ray. This is one reason that mirrors are used to detect delicate movements in instruments such as galvanometers. The more important reason is the amplification of displacement by having the beam arrive at a scale some distance away.

39. The butterfly's image is 20 cm in back of the mirror, so the distance from the image to your eye is 70 cm.

40. If 96% is transmitted through the first face, and 96% of 96% is transmitted through the second face, 92% is transmitted through both faces of the glass.

41. The amount of light transmitted through two sheets of glass is about 85%. To see this, consider an incident intensity of 100 units. Then 92 units are transmitted through the first pane. 92% of this amount is transmitted through the second pane (0.92 of 92 = 84.6).

42. Use ratios: (1440 min)/(360 deg) = (unknown time)/(0.53 deg). So the unknown time is 0.53 x 1440/360 = 2.1 minutes. So the Sun moves a solar diameter across the sky every 2.1 minutes. At sunset, time is somewhat extended, depending on the extent of refraction. Then the disk of the setting Sun disappears over the horizon in a little longer than 2.1 minutes (the Sun's path also varies with latitude and day of the year).

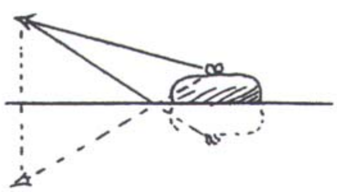
Think and Rank

43. A=B=C (all same)
44. B, C, A
45. B, C, A
46. C, B, A

Think and Explain

47. Peter's left foot is firmly planted on the table, behind the mirror between his legs.

48. First of all, the reflected view of a scene is different than an inverted view of the scene because the reflected view is seen from lower down. Just as a view of a bridge may not show its underside where the reflection does, so it is with the bird. The view reflected in water is the inverted view you would see if your eye were positioned as far beneath the water level as your eye is above it (and there were no refraction). Then your line of sight would intersect the water surface where reflection occurs. Put a mirror on the floor between you and a distant table. If you are standing, your view of the table is of the top. But the reflected view shows the table's bottom. Clearly, the two views are not simply inversions of each other. Take notice of this whenever you look at reflections (and of paintings of reflections—it's surprising how many artists are not aware of this).



49. e are between two parallel mirrors. The reflection from one mirror is incident on the other, and

50. Only three plane mirrors produce the multiple images of Karen Jo, who shows a large kaleidoscope.

51. Fermat's principle for refraction is of least time, but for reflection it could be of least distance as well. This is because light does not change mediums for reflection so no change in speed occurs and least-time paths and least-distance paths are equivalent. But for refraction, light goes from a medium where it has a certain speed to another medium where its speed is different. When this happens the least-distance straight-line paths take a longer time to travel than the nonstraight-line least-time paths. See, for example, the difference in the least-distance and least-time paths in Figure 28.13.

52. Only light from card number 2 reaches her eye.

53. Cowboy Joe should simply aim at the mirrored image of his assailant, for the ricocheting bullet will follow the same changes in direction when its momentum changes (angle of incidence = angle of rebound) that light follows when reflecting from a plane surface.

54. Such lettering is seen in proper form in the rearview mirrors of cars ahead.

55. Light that takes a path from point A to point B will take the same reverse path in going from point B to point A, even if reflection or refraction is involved. So if you can't see the driver, the driver can't see you. (This independence of direction along light's path is the "principle of reciprocity.")

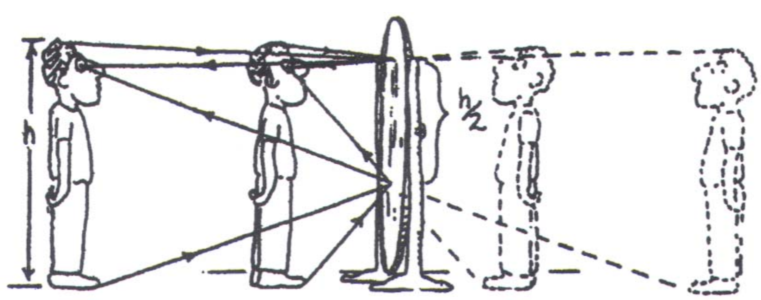
56. When you wave your right hand, image of the waving hand is still on your right, just as your head is still up and your feet still down. Neither left and right nor up and down are inverted by the mirror—but *front and back* are, as the author's sister Marjorie illustrates in Figure 28.8. (Consider three axes at right angles to each other, the standard coordinate system; horizontal x, vertical y, and perpendicular-to-the-mirror z. The only axis to be inverted is z, where the image is $-z$.)

57. Two surfaces of the mirror reflect light. The front surface reflects about 4% of incident light, and the silvered surface reflects most of the rest. When the mirror is tilted in the "daytime" position, the driver sees light reflecting from the silvered surface. In the "nighttime" position, with the mirror tilted upward, light reflecting from the silvered surface is directed above the driver's view and the driver sees light reflected from the front surface of the mirror. That 4% of rearview light is adequate for night driving.

58. A window both transmits and reflects light. Window glass typically transmits about 92% of incident light, and the two surfaces reflect about 8%. Percentage is one thing, total amount is another. The person outside in the daylight who looks at the window of a room that is dark inside sees 8% of the outside light reflected back and 92% of the inside light transmitted out. But 8% of the bright outside light might be more intense than 92% of the dim inside light, making it difficult or impossible for the outside person to see in. The person inside the dark room, on the other hand, receiving 92% of the bright outside light and 8% of the dim inside light, reflected, easily sees out. (You can see how the reverse argument would be applied to a lighted room at night. Then the person inside may not be able to see out while the person outside easily sees in.)

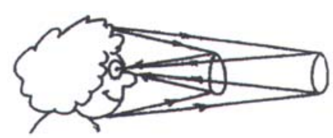
59. Rough pages provide diffuse reflection, which can be viewed from any angle. If the page were smooth it could only be viewed well at certain angles.

60. The minimum length of a vertical mirror must be half your height in order for you to see a full-length view of yourself. The part of the mirror above and below your line of sight to your image isn't needed, as the sketch shows.



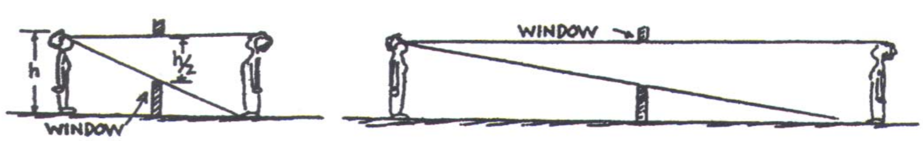
61. The half-height mirror works at any distance, as shown in the sketch above. This is because if you move closer, your image moves closer as well. If you move farther away, your image does the same. Many people must actually try this before they believe it. Distinguish this from looking at a tall building in a pocket mirror and looking at *yourself* in the pocket mirror!

62. Note in your pocket mirror that the amount of your face you can see is twice the size of the mirror—whether you hold it close or at arm's length. (You can win bets on this question!)



63. The wiped area will be half as tall as your face.

64. The smallest window will be half the height of the person or her twin. Note that this does not depend on distance, providing both subjects are the same distance from the wall. This illustrates the preceding questions on mirror height.



65. The person is farsighted.

66. A lens of higher index of refraction will allow thinner lenses.

67. Agree, as inspection of Figure 28.24 shows. Note wavefronts are closer together in water as compared with in air above.

68.

69. Red light travels faster through glass and will exit first.

70. During a lunar eclipse the Moon is not totally dark, even though it is in Earth's shadow. This is because the atmosphere of Earth acts as a converging lens that refracts light into Earth's shadow. It is the low frequencies that pass more easily through the long grazing path through Earth's atmosphere to be refracted finally onto the Moon. Hence its reddish color—the refraction of the whole world's sunrises and sunsets.

71. The "non-wetting" leg of the water strider depresses and curves the surface of the water, which effectively produces a lens that directs light away from its path to form the extended shadow region. (Close observation shows a bright ring around the darker region. Interestingly, the overall brightness of the shadow and the bright ring average the same brightness—"conservation of light.")

72. We cannot see a rainbow "off to the side," for a rainbow is not a tangible thing "out there." Colors are refracted in infinite directions and fill the sky. The only colors we see that aren't washed out by others are those that are along the conical angles between 40° and 42° to the Sun-anti-Sun axis. To understand this, consider a paper-cone cup with a hole cut at the bottom. You can view the circular rim of the cone as an ellipse when you look at it from a near side view. But if you view the rim only with your eye at the apex of the cone, through the hole, you can see it only as a circle. That's the way we view a rainbow. Our eye is at the apex of a cone, the axis of which is the Sun-anti-Sun axis, and the "rim" of which is the bow. From every vantage point, the bow forms part (or all) of a circle.

73. Normal sight depends on the amount of refraction that occurs for light traveling from air to the eye. The speed change ensures normal vision. But if the speed change is from water to eye, then light will be refracted less and an unclear image will result. A swimmer uses goggles to make sure that the light travels from air to eye, even if underwater.

74. What is true of the swimmer in the previous exercise is true for the fish above water. Normal vision for the fish is for light going from water to the eye. This condition is met if the fish wears goggles filled with water.

75. The diamond sparkles less because there are smaller angles of refraction between the water and the diamond. Light is already slowed when it meets the diamond so the amount of further slowing, and refraction, is reduced.

76. Cover half the lens and you cut out half the illumination of the light. But you don't cut out half the image, as is commonly and mistakenly thought. (This incorrect thinking, unfortunately, may be fostered by ray diagrams, which are useful for locating image positions, but not for defining image formation.)

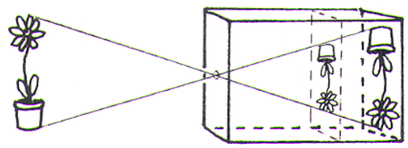
77. The image will be a bit dimmer with original colors, but otherwise unaffected.

78. A lens that refracts sound waves is a sphere of gas that transmits sound at a slower speed. Like a glass lens redirects waves of light, the sound lens redirects waves of sound.

79. If light had the same average speed in glass lenses that it has in air, no refraction of light would occur in lenses, and no magnification would occur. Magnification depends on refraction, which in turn depends on speed changes.

80. A magnifying glass will magnify less under water. Under water there is less difference in speeds between water and the lens, than in air.
81. A pinhole image is one of sharpness.

82. Rays do not converge as with a glass lens, so a pinhole image is sharp in all positions.



83. The image produced by a pinhole is sharp, but very dim—a serious liability for a spy camera. A spy camera needs all the light it can get because the image is highly enlarged, so the light is spread way out. Hence, a large aperture is advantageous.

84. The circular spots are images of the Sun cast through "pinholes" in the spaces between leaves above. (See other such images in the photo openers of Chapter 26.)

85. For very distant objects, effectively at "infinity," light comes to focus at the focal plane of the lens. So the photosensitive surface is one focal length in back of the lens for very distant shots. For shorter distances, it is farther from the lens.

86. Real images—those that can be projected on a screen—are always inverted. Therefore, your slides should be upside down so that the image will be right-side-up.

87. Yes, the images are indeed upside down! The brain re-inverts them.

88. Yes! The images are indeed upside down! You view them as you wish, right-side up or upside down.

89. Moon maps are upside-down views of the Moon to coincide with the upside-down image that Moon watchers see in an astronomical telescope.

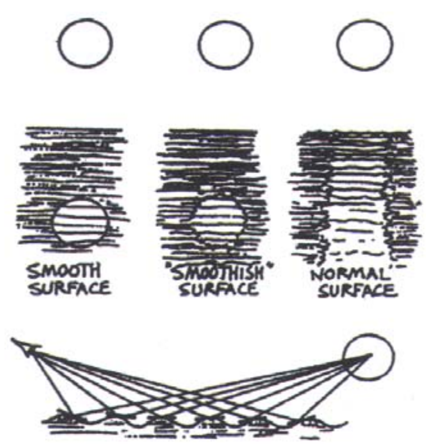
90. The near point of vision recedes with advancing age because the lenses in peoples eyes get less flexible with age. When you have to hold a book at arm's length to see it clearly, you're really ready for glasses (or other corrective options).

91. The speed of light in the glass rod and the oil is the same. Said another way, both have the same index of refraction. You'd only see the submerged transparent rod if light underwent a change in speed as it passes from oil to glass and back to oil again. No change in light speed means no visual evidence of its presence.

Think and Discuss

92. When the source of glare is somewhat above the horizon, a vertical window will reflect it to people in front of the window. By tipping the window inward at the bottom, glare is reflected downward rather than into the eyes of passersby.

93. The pebbly uneven surface is easier to see. Light reflected back from your headlights is what lets you see the road. The mirror-smooth surface might reflect more light, but it would reflect it forward, not backward, so it wouldn't help you see. Whereas diffuse reflection from a rough road allows a motorist to see the road illuminated by headlights on a dry night, on a rainy night the road is covered with water and acts like a plane mirror. Very little of the illumination from the headlights returns to the driver, and is instead reflected ahead (causing glare for oncoming motorists).

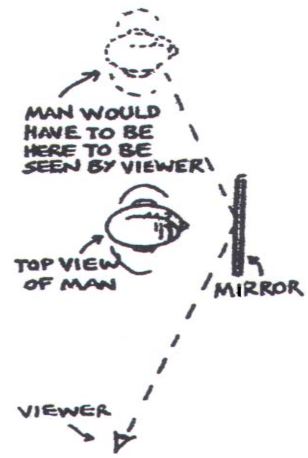


94. If the water were perfectly smooth, you would see a mirror image of the round Sun or Moon, an ellipse on the surface of the water. If the water were slightly rough, the image would be wavy. If the

water were a bit more rough, little glimmers of portions of the Sun or Moon would be seen above and below the main image. This is because the water waves act like tiny parallel mirrors. For small waves only light near the main image reaches you. But as the water becomes choppier, there is a greater variety of mirror facets that are oriented to reflect sunlight or moonlight into your eye. The facets do not radically depart from an average flatness with the otherwise smooth water surface, so the reflected Sun or Moon is smeared into a long vertical streak. For still rougher water there are facets off to the side of the vertical streak that are tilted enough for Sun or moonlight to be reflected to you, and the vertical streak is wider.

95. You are seeing skylight refracted upward near the road surface.

96. We would not see an image of the man in the mirror as shown. If he is viewing himself, then we wouldn't also be able to see his image unless we were in back (or in front) of him. If we are to stand to the side of the man and see him *and* an image of him in the mirror, then the mirror cannot be exactly in front of him. The mirror would have to be located to the man's right, as shown in the sketch. The man's view would miss the mirror completely. Such arrangements are made when staging an actor who is supposed to be viewing himself in a mirror. Actually, however, the actor pretends to be looking at himself. If he really were, his image in the mirror wouldn't be shared by the audience. That's Hollywood!

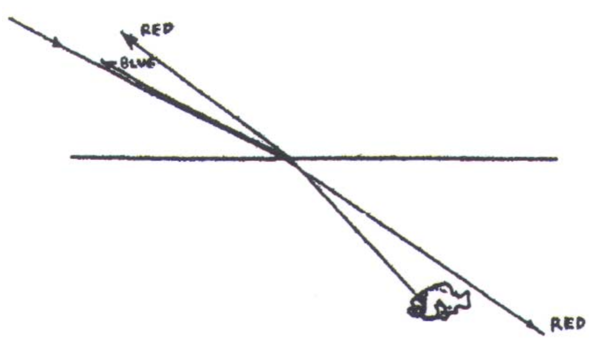


97. The two pictures do not contradict each other. In both cases light is bent away from the normal upon emerging from the water. That's why the corner of the immersed square appears to be shallower. Notice that it's easy to confuse the beam of the left-hand picture with the edge of the immersed square in the right-hand picture. Light travels *from* the edge, not *along* the edge of the square.

98. The speed of light increases in going from water into the air above.

99. Throw the spear below the apparent position of the fish because refraction makes the fish appear closer to the surface than it really is. But in zapping a fish with a laser, make no corrections and simply aim directly at the fish. This is because the light from the fish you see has been refracted in getting to you, and the laser light will refract along the same path in getting to the fish. A slight correction may be necessary, depending on the colors of the laser beam and the fish—see the next exercise.

100. The angle of refraction for blue light is greater than for red, so if you fired your red beam along the line of sight for blue, the beam would pass above the fish. So you should aim slightly below the sighted fish.



101. A fish sees the sky (as well as some reflection from the bottom) when it looks upward at 45°, for the critical angle is 48° for water. If it looks at and beyond 48° it sees only a reflection of the bottom.

102. Total internal reflection occurs only for light rays that would gain speed in crossing the boundary they encounter. For light in air encountering a water surface, there is no total reflection. You can see this by sketching rays that go from water to air, and noting that light can travel in the other direction along all of these rays.

103. In sending a laser beam to a space station, make no corrections and simply aim at the station you see. This is like zapping the fish while standing on the shore of question 99. The path of refraction is the same in either direction.

104. The fact that two observers standing apart from one another do not see the same rainbow can be understood by exaggerating the circumstance: Suppose the two observers are several kilometers apart. Obviously they are looking at different drops in the sky. Although they may both see a rainbow, they are looking at different rainbows. Likewise if they are closer together. Only if their eyes are at the very same location will they see exactly the same rainbow.

105. When the Sun is high in the sky and people on the airplane are looking down toward a cloud opposite to the direction of the Sun, they may see a rainbow that makes a complete circle. The shadow of the airplane will appear in the center of the circular bow. This is because the airplane is directly between the Sun and the drops or rain cloud producing the bow.

106. Moon halos and rainbows are similar in that both are produced by light refracting from water. Ice crystals can disperse moonlight into two halos, much as water droplets disperse light into two rainbows. For both, the outer bow is much fainter than the inner one. Halos and rainbows are different in that a halo and Moon are seen in the same part of the sky, with the Moon in the middle of the halo—whereas a rainbow is seen in the part of the sky opposite to the Sun (your shadow, if it can be seen, is in the middle of the rainbow). Another difference is that for rainbows reflection as well as refraction is important, whereas for halos only refraction is important. Yet another difference is that whereas a rainbow involves liquid water droplets, a halo involves frozen water crystals.

107. A magnifying lens used as a "burning glass" does nothing more than gather a certain amount of energy and concentrate it at some focal point. The important point is that the lens is considerably larger than the area over which the light is concentrated. But the solar heat sheet is not larger than the surface area of the swimming pool, and doesn't collect any more solar energy than the pool receives anyway. The sheet may help warm the pool by preventing evaporation, as would be the case with any cover, but in no way do the lenses direct additional solar energy to the water beneath. This fraudulent advertising plays on the ignorance of the public.

108. The average intensity of sunlight at the bottom is the same whether the water is moving or is still. Light that misses one part of the bottom of the pool reaches another part. Every dark region is balanced by a bright region—"conservation of light."

109. The bending is less because the light is already slowed down in water, and slows only slightly more in your cornea. That's why nearsighted eyes see clearer in water than in air. The index of refraction of your cornea is closer to that of water than of air.

110. The speed of light decreases as it passes from the water into your cornea, but not as much as from air to your cornea.

111. The two rays are a sample of many many rays needed to produce a sharp image. The pair of rays merely locate image distance from the lens. The two rays are hardly enough to produce an image.