Ch. 24 Diffraction and thin-Film

AP Physics 1~2

- Refraction proof
- n = c/v = λ_0/λ_{new}
- Dispersion?

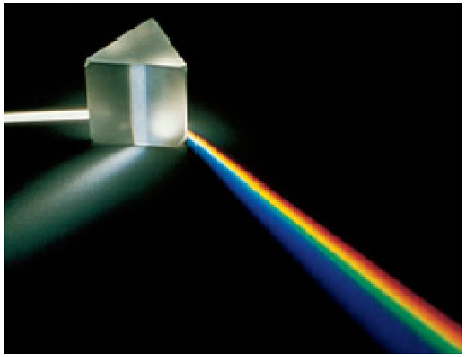
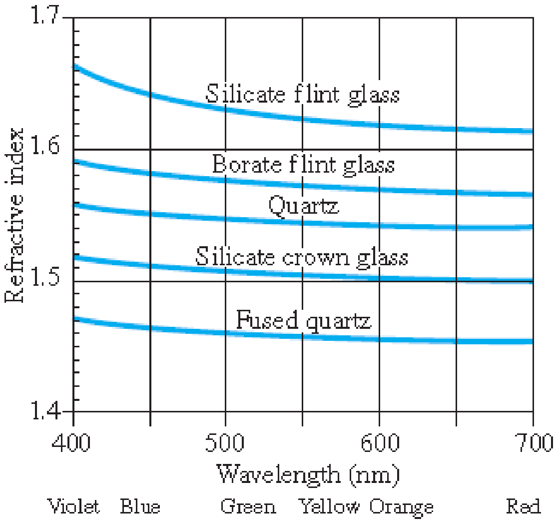


FIGURE 24–13 White light passing through a prism is spread out into its constituent colors.



Red vs. violet. Which is faster?

How do rainbows happen?

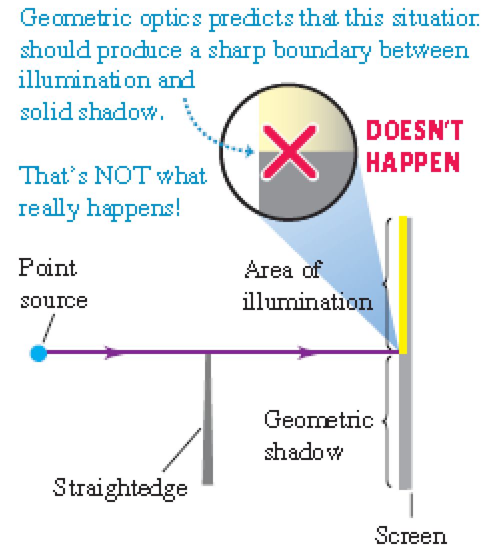
- Acoustic dispersion?
- https://www.youtube.com/watch?v=OC7_zpyqCrU

Huygens's Wave Principle?

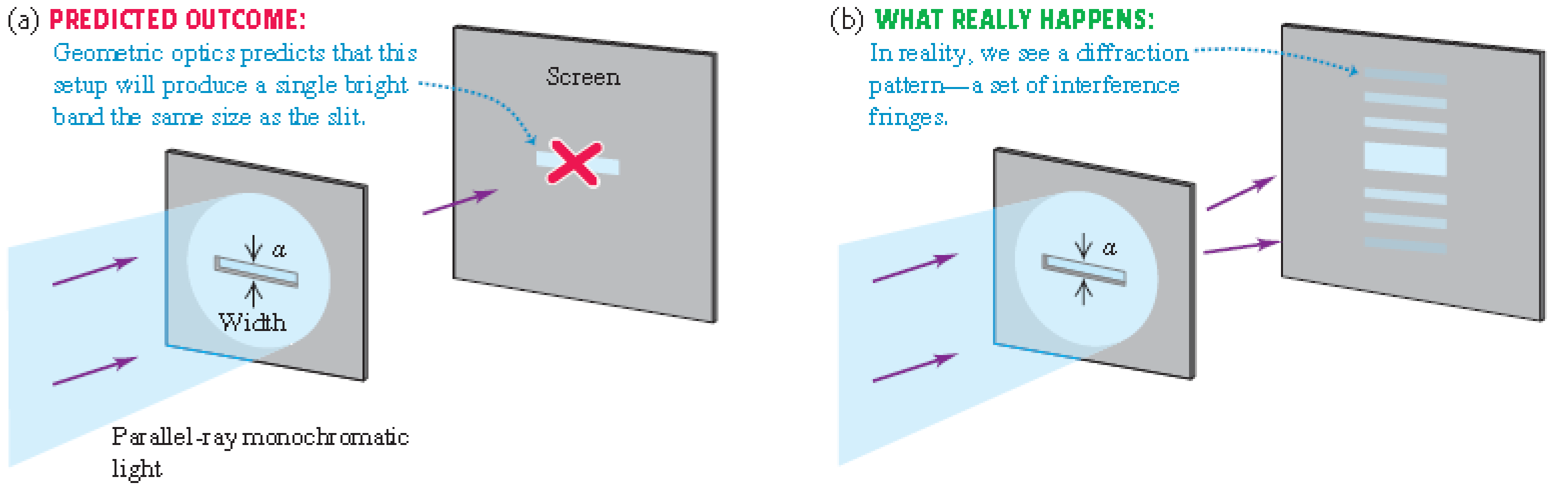
- What is the difference between diffraction and refraction?
- When is diffraction obvious?
- Huygens's Wave Principle? How does it explain diffraction?

DIFFRACTION

36.1 A point source of light illuminate a straightedge.



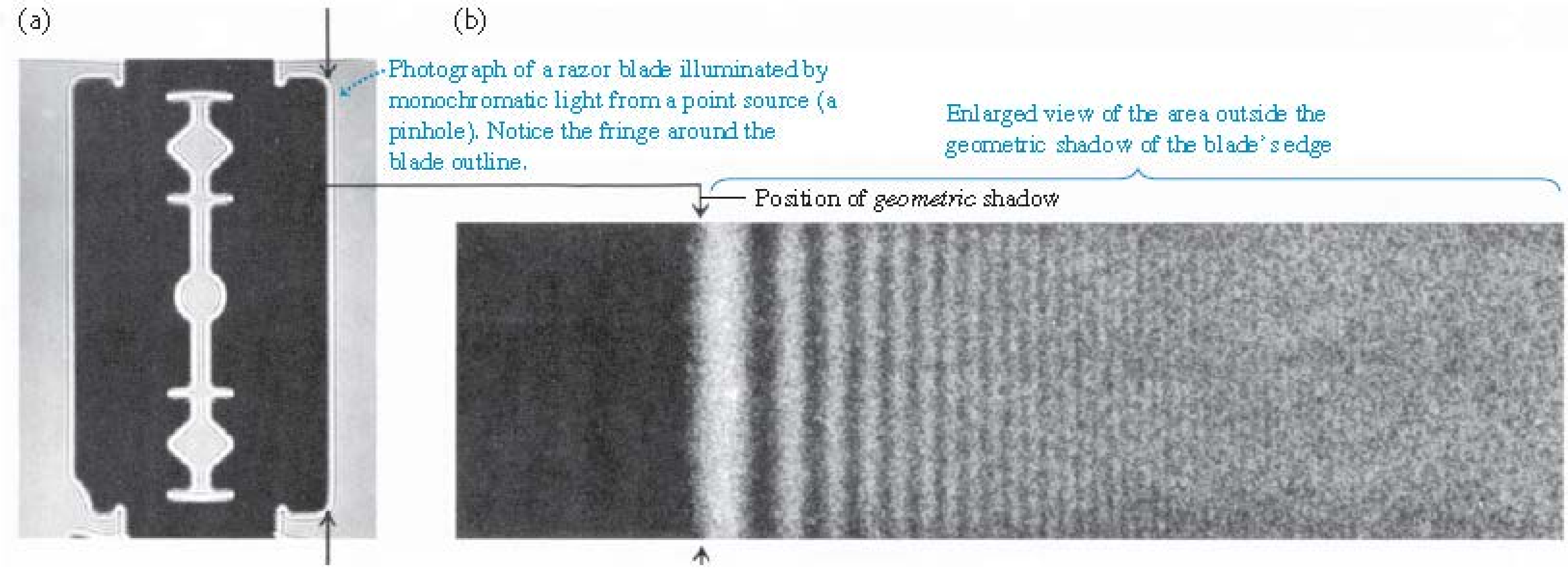
36.3 (a) The "shadow" of a horizontal slit as incorrectly predicted by geometric optics. (b) A horizontal slit actually produces a diffraction pattern. The slit width has been greatly exaggerated.



DIFFRACTION

- Point Source, one color → diffraction pattern
- Light bulb, many point sources → overlapping pattern not clear

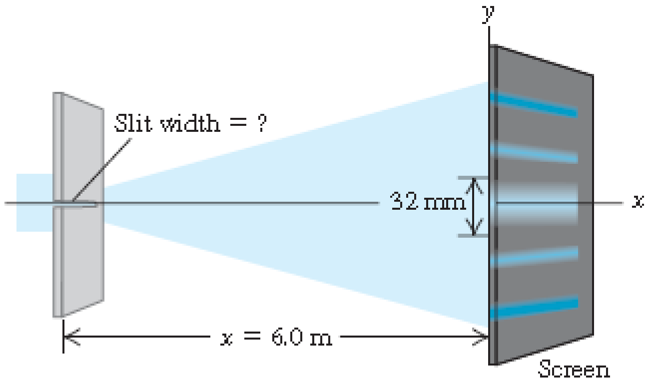
36.2 An example of diffraction.



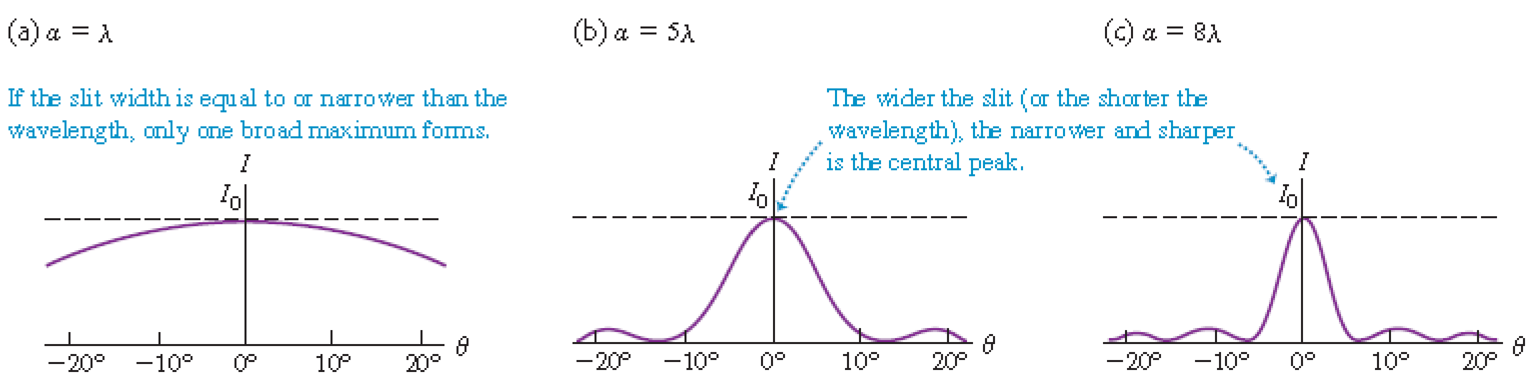
SINGLE SLIT

- 85% of the energy is in the central bright band
- The band is inversely proportional the slit width
- For small angle approximation, the central bright fringe = 2x width of other bands
- No diffraction along other length of slit because it's too big

36.7 A single-slit diffraction experiment.

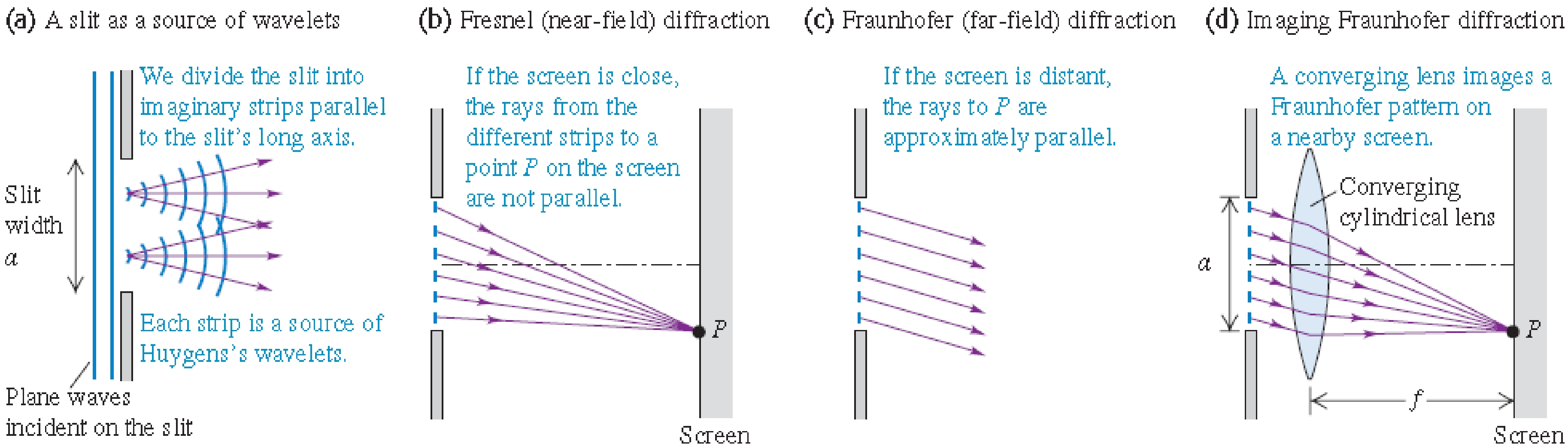


36.10 The single-slit diffraction pattern depends on the ratio of the slit width a to the wavelength λ.

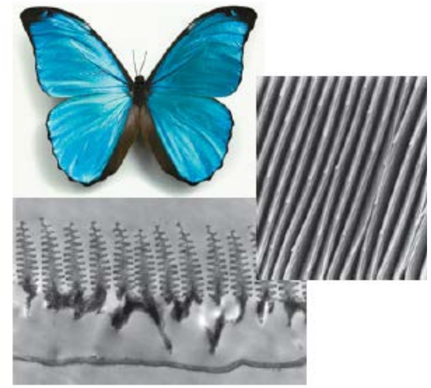


FRESNEL IS DIFFICULT. WE USE FRAUNHOFER

36.4 Diffraction by a single rectangular slit. The long sides of the slit are perpendicular to the figure.

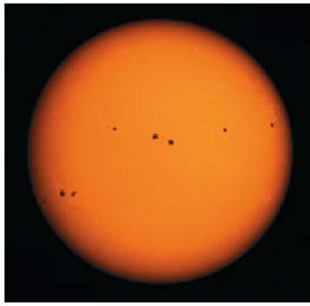


Review

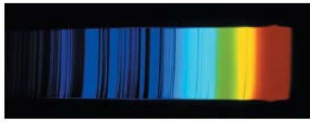


- Sketch the rays, wave-fronts, squiggly
- 3 cases
  - A) Picture
  - B) Equation for bright? Dark?
  - C) What affects? (color, size)
  - D) Example:

- Double Slit
- Single Slit
- Multiple Slit



(b)



- What kind of light? What if white light? (where’s red? violet)
- Hair lab? Use green vs. use red? Thin vs. thick hair?
- Radio waves. Do you want it to diffract?
- Telescope and stars. Big or small aperture?

Review: 3 Examples

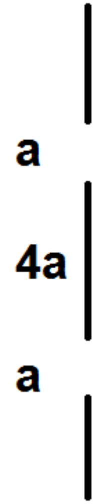
EXAMPLE 24–1 **Line spacing for double-slit interference.** A screen containing two slits 0.100 mm apart is 1.20 m from the viewing screen. Light of wavelength $\lambda = 500$ nm falls on the slits from a distant source. Approximately how far apart will adjacent bright interference fringes be on the screen?

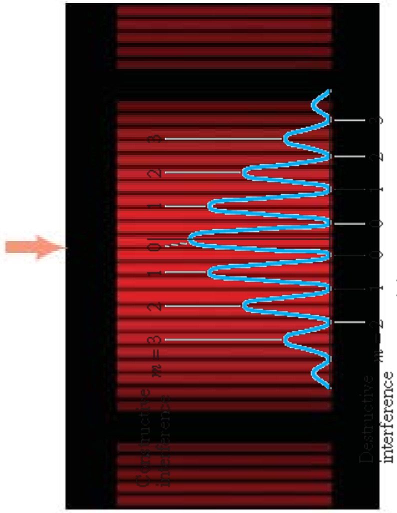
- When theta<15^0, $\sin\theta \approx \theta \approx \tan\theta$ → often seen formula

EXAMPLE 24–5 **Single-slit diffraction maximum.** Light of wavelength 750 nm passes through a slit 1.0×10^{-3} mm wide. How wide is the central maximum (*a*) in degrees, and (*b*) in centimeters, on a screen 20 cm away?

- Can you use the small-angle approximation here?

- Single and double-slit effect together

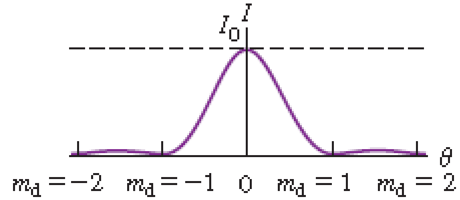




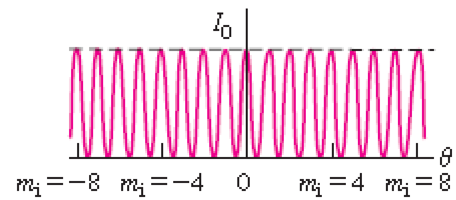
SINGLE AND MULTIPLE SLIT EFFECT TOGETHER

36.12 Finding the intensity pattern for two slits of finite width.

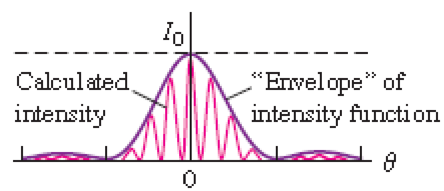
(a) Single-slit diffraction pattern for a slit width a



(b) Two-slit interference pattern for narrow slits whose separation d is four times the width of the slit in (a)



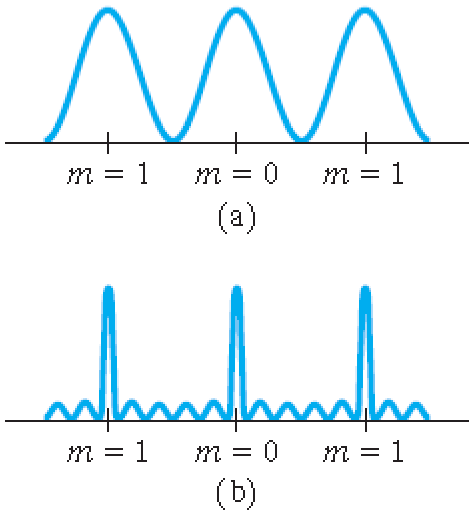
(c) Calculated intensity pattern for two slits of width a and separation $d = 4a$, including both interference and diffraction effects



Diffraction Grating

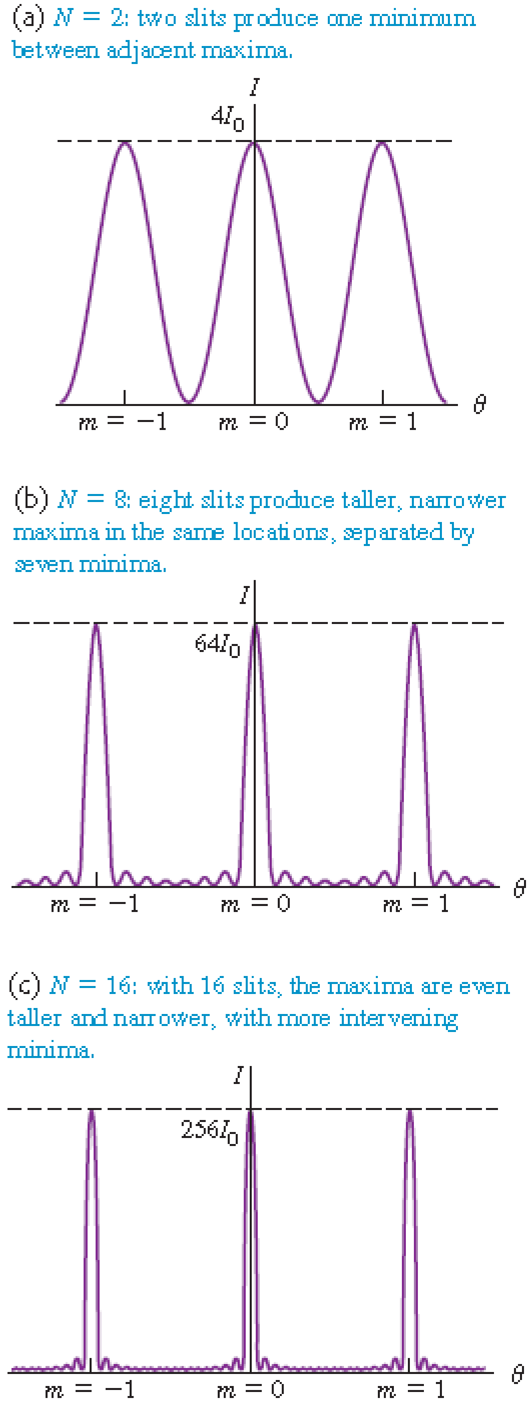
- Why higher? Why narrower?

FIGURE 24–25 Intensity as a function of viewing angle θ (or position on the screen) for (a) two slits, (b) six slits. For a diffraction grating, the number of slits is very large ($\approx 10^4$) and the peaks are narrower still.



There is an important difference between a double-slit and a multiple-slit pattern. The bright maxima are much *sharper* and *narrower* for a grating. Why? Suppose the angle θ in Fig. 24–24 is increased just slightly beyond θ required for a maximum. For only two slits, the two waves will be only slightly out of phase, so nearly full constructive interference occurs. This means the maxima are wide (see Fig. 24–9). For a grating, the waves from two adjacent slits will also not be significantly out of phase. But waves from one slit and those from a second one a few hundred slits away may be exactly out of phase; all or nearly all the light can cancel in pairs in this way. For example, suppose the angle θ is very slightly different from its first-order maximum, so that the extra path length for a pair of adjacent slits is not exactly λ but rather 1.0010λ. The wave through one slit and another one 500 slits below will have a path difference of $1\lambda + (500)(0.0010\lambda) = 1.5000\lambda$, or $1\frac{1}{2}$ wavelengths, so the two will be out of phase and cancel. A pair of slits, one below each of these, will also cancel. That is, the light from slit 1 cancels with light from slit 501; light from slit 2 cancels with light from slit 502, and so on. Thus even for a tiny angle† corresponding to an extra path length of $\frac{1}{1000}\lambda$, there is much destructive interference, and so the maxima of a diffraction grating are very narrow. The more slits there are in a grating, the sharper will be the peaks (see Fig. 24–25). Because a grating produces much sharper maxima than two slits alone, and also much brighter maxima because there are many more slits, a grating is a far more precise device for measuring wavelengths.

DIFFRACTION GRATING



36.15 Interference patterns for N equally spaced, very narrow slits. (a) Two slits. (b) Eight slits. (c) Sixteen slits. The vertical scales are different for each graph; I_0 is the maximum intensity for a single slit, and the maximum intensity for N slits is N^2I_0. The width of each peak is proportional to $1/N$.

DIFFRACTION GRATING

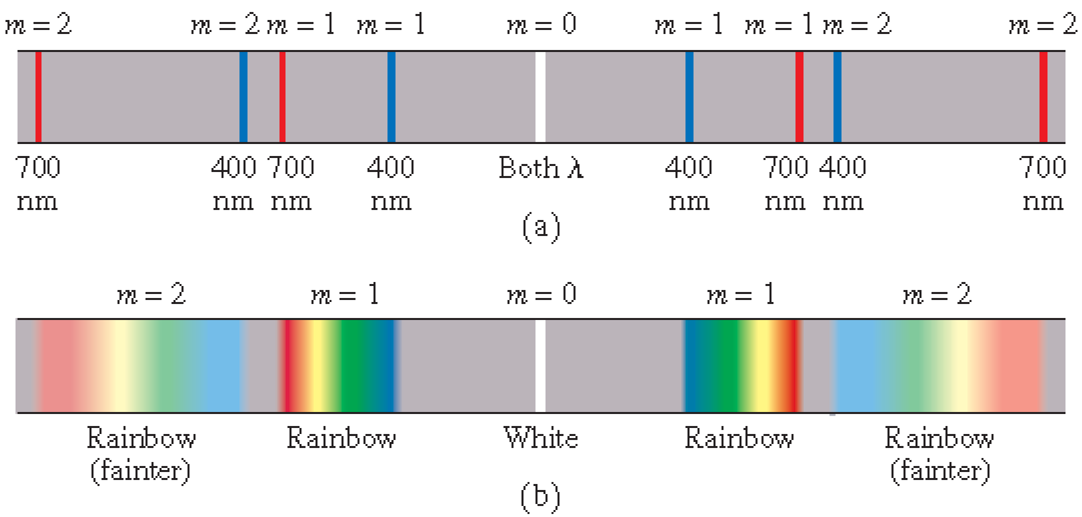


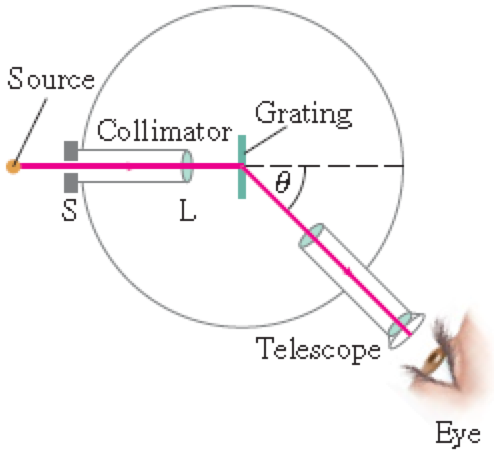
FIGURE 24–26 Spectra produced by a grating: (a) two wavelengths, 400 nm and 700 nm; (b) white light. The second order will normally be dimmer than the first order. (Higher orders are not shown.) If the grating spacing is small enough, the second and higher orders will be missing.

If white light strikes a grating, the central ($m = 0$) maximum will be a sharp white line. But for all other orders, there will be a distinct spectrum of colors spread out over a certain angular width, Fig. 24–26b. Because a diffraction grating spreads out light into its component wavelengths, the resulting pattern is called a **spectrum**.

EXAMPLE 24–7 Diffraction grating: line positions. Determine the angular positions of the first- and second-order lines (maxima) for light of wavelength 400 nm and 700 nm incident on a grating containing 10,000 slits per centimeter.

- See idea. Just do next question.

24–7 The Spectrometer and Spectroscopy



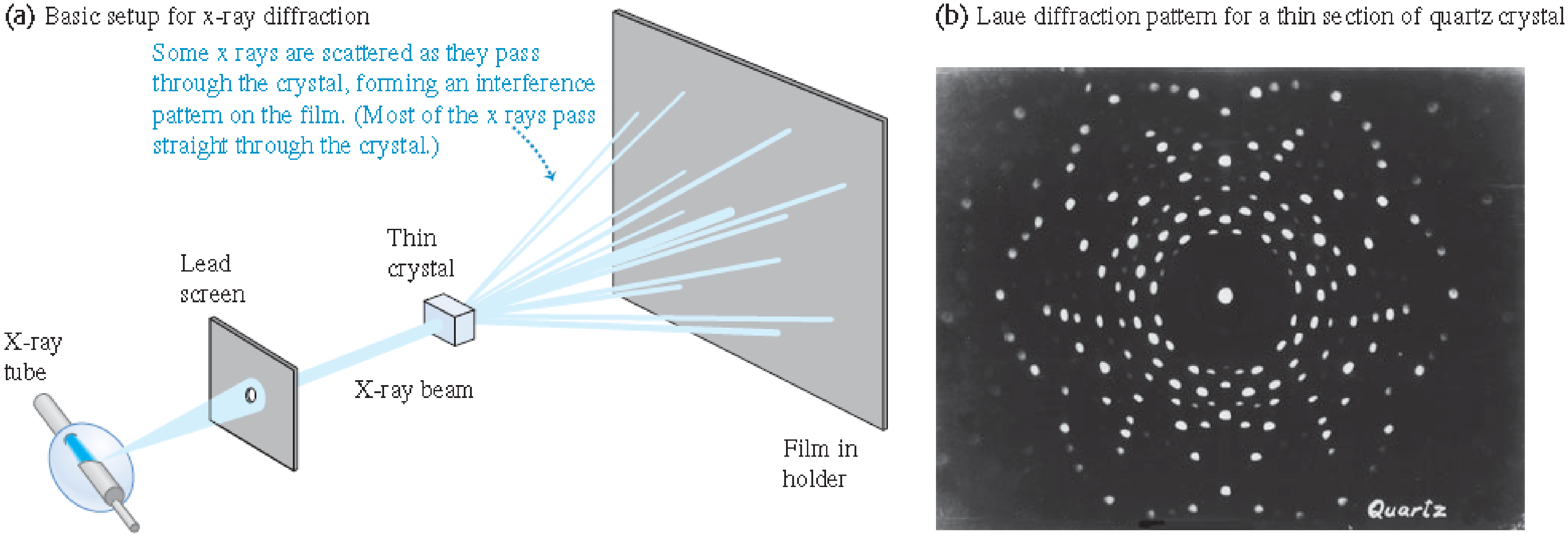
A **spectrometer** or **spectroscope**, Fig. 24–27, is a device to measure wavelengths accurately using a diffraction grating (or a prism) to separate different wavelengths of light. Light from a source passes through a narrow slit S in the "collimator." The slit is at the focal point of the lens L, so parallel light falls on the grating. The movable telescope can bring the rays to a focus. Nothing will be seen in the viewing telescope unless it is positioned at an angle θ that corresponds to a diffraction peak (first order is usually used) of a wavelength emitted by the source. The angle θ can be measured to very high accuracy, so the wavelength can be determined to high accuracy using Eq. 24–4:

$$\lambda = \frac{d}{m}\sin\theta,$$

EXAMPLE 24–9 **Hydrogen spectrum.** Light emitted by hot hydrogen gas is observed with a spectroscope using a diffraction grating having 1.00×10^4 slits/cm. The spectral lines nearest to the center (0°) are a violet line at 24.2°, a blue line at 25.7°, a blue-green line at 29.1°, and a red line at 41.0° from the center. What are the wavelengths of these spectral lines of hydrogen?

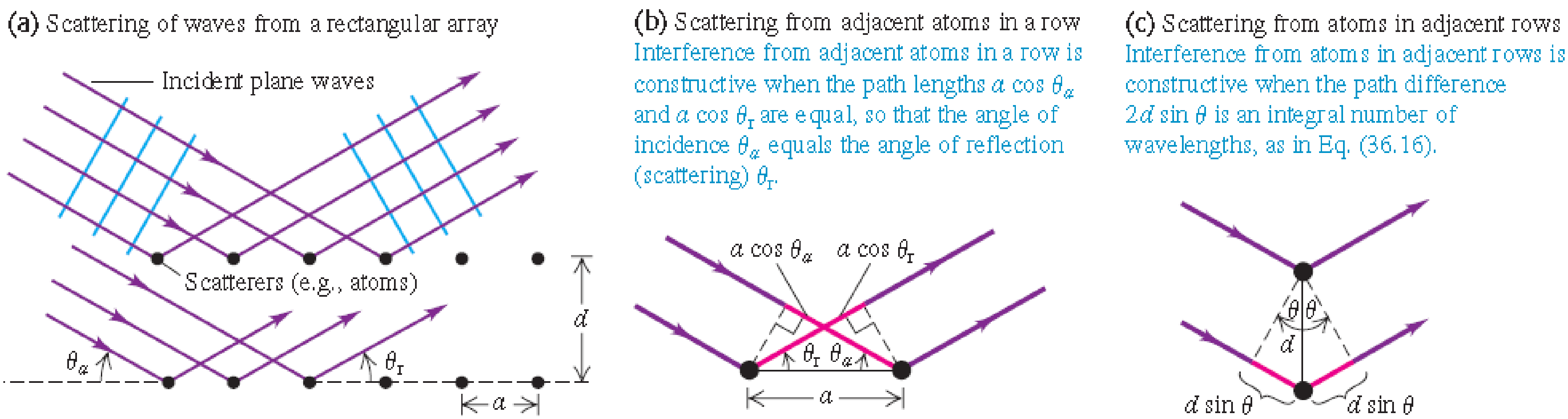
X-Ray diffraction
Bragg 'Diffraction' (Really Interference from reflections)

36.20 (a) An x-ray diffraction experiment. (b) Diffraction pattern (or *Laue pattern*) formed by directing a beam of x rays at a thin section of quartz crystal.



X-Ray diffraction
Bragg 'Diffraction' (Really Interference from reflections)

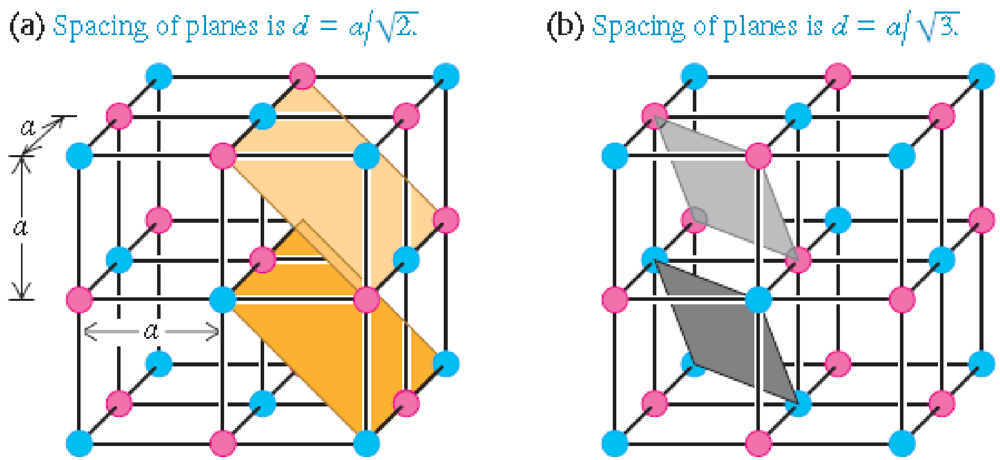
36.22 A two-dimensional model of scattering from a rectangular array. Note that the angles in (b) are measured from the *surface* of the array, not from its normal.



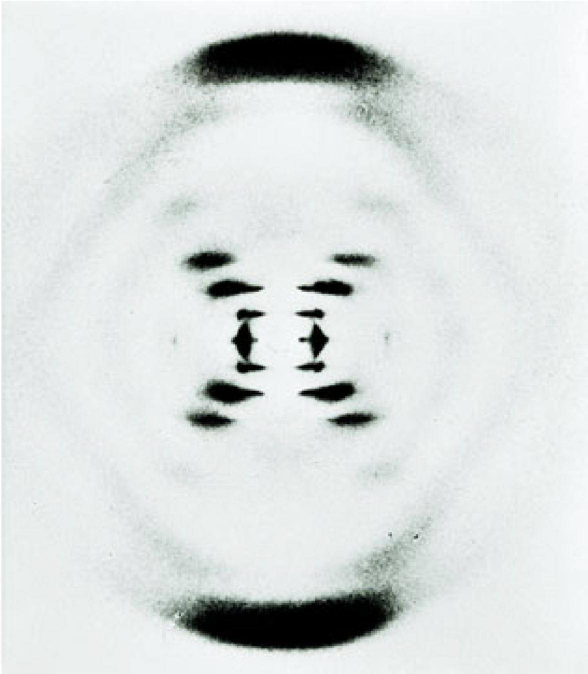
$$2d\sin\theta = m\lambda \qquad (m = 1, 2, 3, \ldots) \qquad \text{(Bragg condition for constructive interference from an array)} \qquad (36.16)$$

X-Ray Diffraction (Bragg Interference)

36.23 A cubic crystal and two different families of crystal planes. There are also three sets of planes parallel to the cube faces, with spacing a.

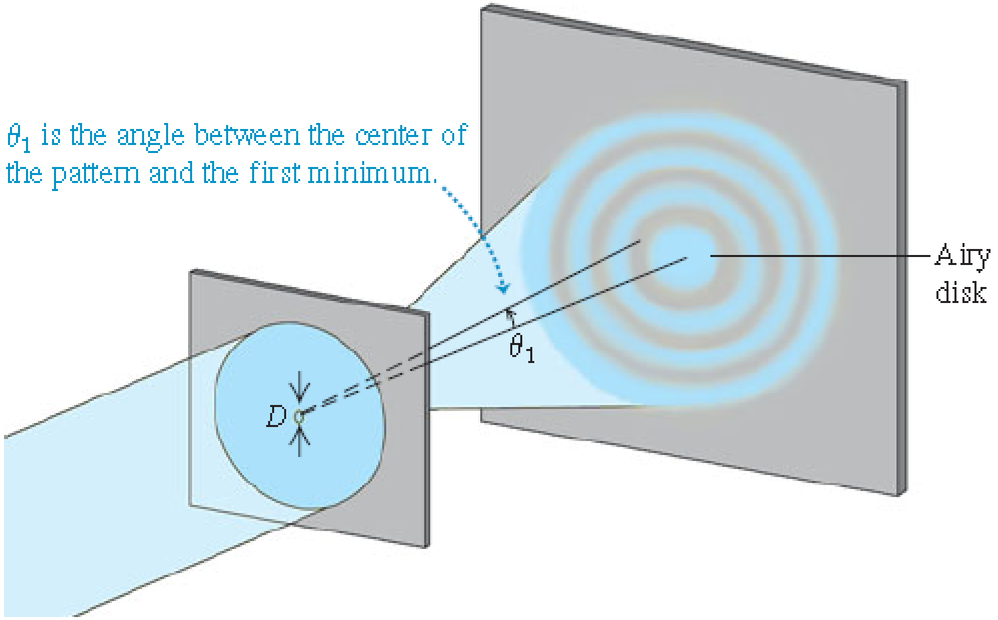


36.24 The British scientist Rosalind Franklin made this groundbreaking x-ray diffraction image of DNA in 1953. The dark bands arranged in a cross provided the first evidence of the helical structure of the DNA molecule.



Circular Apertures and Resolving Power

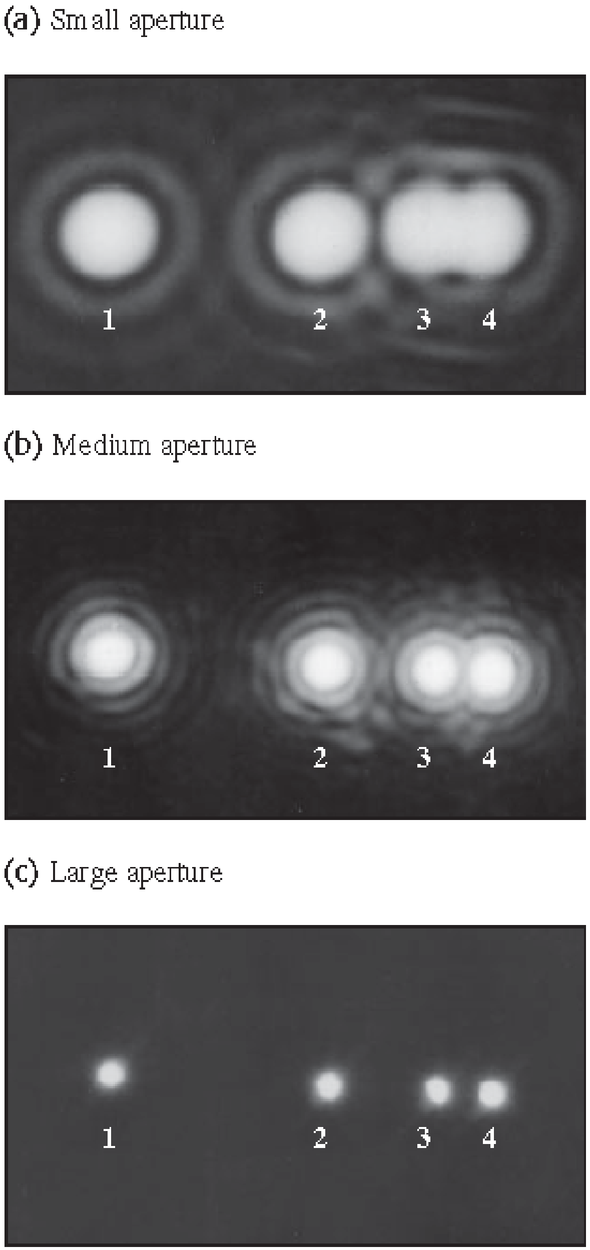
36.25 Diffraction pattern formed by a circular aperture of diameter D. The pattern consists of a central bright spot and alternating dark and bright rings. The angular radius θ_1 of the first dark ring is shown. (This diagram is not drawn to scale.)



$$\sin\theta_1 = 1.22\frac{\lambda}{D}$$

CIRCULAR APERTURES AND RESOLVING POWER

36.27 Diffraction patterns of four very small ("point") sources of light. The photographs were made with a circular aperture in front of the lens. (a) The aperture is so small that the patterns of sources 3 and 4 overlap and are barely resolved by Rayleigh's criterion. Increasing the size of the aperture decreases the size of the diffraction patterns, as shown in (b) and (c).

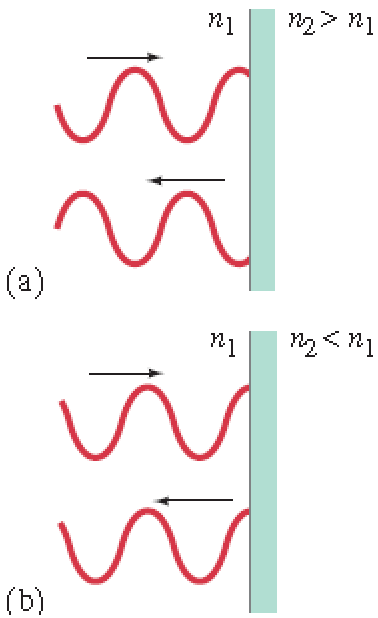


Circular Apertures and Resolving Power

Application Bigger Telescope, Better Resolution

One reason for building very large telescopes is to increase the aperture diameter and thus minimize diffraction effects. The effective diameter of a telescope can be increased by using arrays of smaller telescopes. The Very Large Array (VLA) in New Mexico is a collection of 27 radio telescopes, each 25 m in diameter, that can be spread out in a Y-shaped arrangement 36 km across. Hence the effective aperture diameter is 36 km, giving the VLA a limit of resolution of 5×10^{-8} rad at a radio wavelength of 1.5 cm. If your eye had this angular resolution, you could read the "20/20" line on an eye chart more than 30 km away!

Thin film Interference



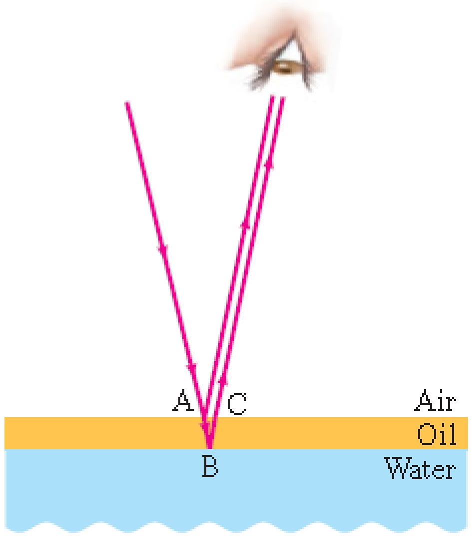
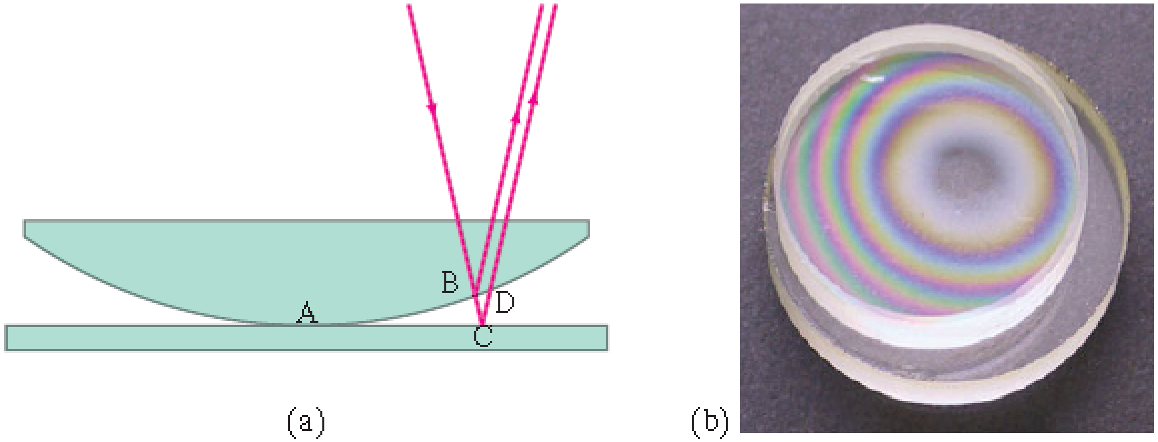


FIGURE 24–30 Light reflected from the upper and lower surfaces of a thin film of oil lying on water.

FIGURE 24–35 A coated lens. Note color of light reflected from the front lens surface.

Thin film Interference

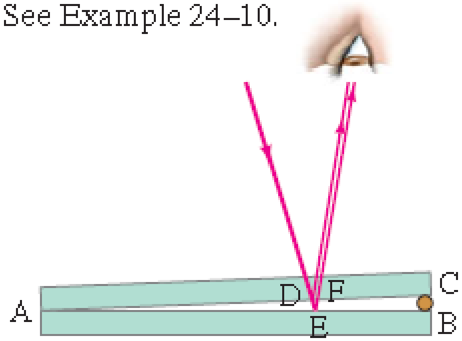
FIGURE 24–31 Newton's rings. (a) Light rays reflected from upper and lower surfaces of the thin air gap can interfere. (b) Photograph of interference patterns using white light.



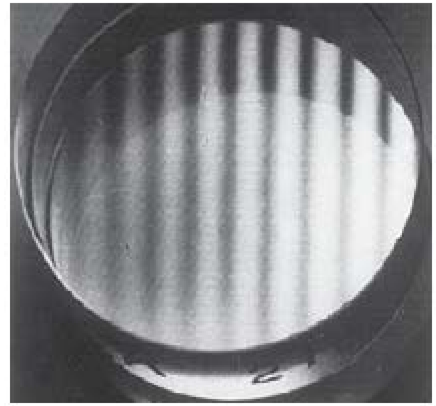
- Why red later?

THIN FILM INTERFERENCE

FIGURE 24–33 (a) Light rays reflected from the upper and lower surfaces of a thin wedge of air (between two glass plates) interfere to produce bright and dark bands. (b) Pattern observed when glass plates are optically flat; (c) pattern when plates are not so flat. See Example 24–10.



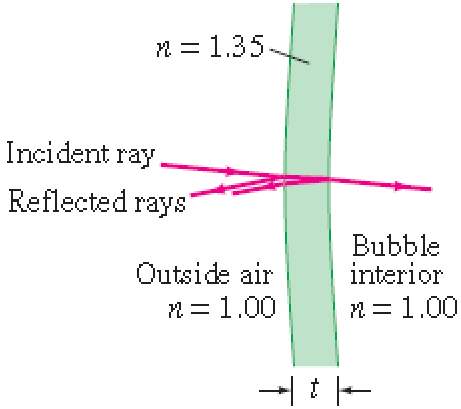
(a)


(b)

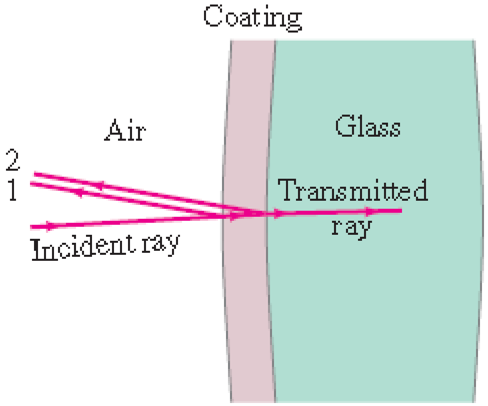

(c)

EXAMPLE 24–10 **Thin film of air, wedge-shaped.** A very fine wire 7.35×10^{-3} mm in diameter is placed between two flat glass plates as in Fig. 24–33a. Light whose wavelength in air is 600 nm falls (and is viewed) perpendicular to the plates and a series of bright and dark bands is seen, Fig. 24–33b. How many light and dark bands will there be in this case? Will the area next to the wire be bright or dark?

Thin film Interference



EXAMPLE 24–11 **Thickness of soap bubble skin.** A soap bubble appears green ($\lambda = 540$ nm) at the point on its front surface nearest the viewer. What is the smallest thickness the soap bubble film could have? Assume $n = 1.35$.



EXAMPLE 24–12 **Nonreflective coating.** What is the thickness of an optical coating of MgF_2 whose index of refraction is $n = 1.38$ and which is designed to eliminate reflected light at wavelengths (in air) around 550 nm when incident normally on glass for which $n = 1.50$?

*Colors in a Thin Soap Film

FIGURE 24–29b (Repeated.)

The thin film of soapy water (in a plastic loop) shown in Fig. 24–29b (repeated here) has stood vertically for a long time. Gravity has pulled the soapy water downward, so the film increases in thickness going toward the bottom. The top section is so thin (perhaps 30 nm thick $\ll \lambda$) that light reflected from the front and back surfaces have almost zero path difference. Thus the 180° phase change at the front surface assures that the two reflected waves are 180° out of phase for all wavelengths of visible light. The white light incident on this thin film does not reflect at the top part of the film, so the top is transparent and we see the background which is black.

Below the black area at the top, there is a thin blue line, and then a white band. The film has thickened to perhaps 75 to 100 nm, so the shortest wavelength (blue) light begins to partially interfere constructively. But just below, where the thickness is slightly greater (100 nm), the path difference is reasonably close to $\lambda/2$ for much of the spectrum and we see white or silver.[†]

Immediately below the white band in this Figure we see a brown band, where $t \approx 200$ nm, and many wavelengths (not all) are close to λ—and those colors destructively interfere, leaving only a few colors to partially interfere constructively, giving us murky brown.

[†]Why? Recall that red starts at 600 nm in air, so most colors in the spectrum lie between 450 nm and 600 nm in air; but in water the wavelengths are $n = 1.33$ times smaller, 340 nm to 450 nm, so a 100-nm thickness is a 200-nm path difference, not far from $\lambda/2$ for most colors.

Farther down in Fig. 24–29b, with increasing thickness t, a path difference $2t = 510$ nm corresponds nicely to $\frac{3}{2}\lambda$ for blue, but not for other colors, so we see blue ($\frac{3}{2}\lambda$ path difference plus $\frac{1}{2}\lambda$ phase change = constructive interference). Other colors experience constructive interference (at $\frac{3}{2}\lambda$ and then at $\frac{5}{2}\lambda$) at still greater thicknesses, so going down we see a series of separated colors something like a rainbow.

In the soap bubble of our Chapter-Opening Photo (page 679), similar things happen: at the top (where the film is thinnest) we see black and then silver-white, just as in the soap film shown in Fig. 24–29b.

Also examine the oil film on wet pavement shown in Fig. 24–29c (repeated here). The oil film is thickest at the center and thins out toward the edges. Notice the whitish outer ring where most colors constructively interfere, which would suggest a thickness on the order of 100 nm as discussed above for the white band in the soap film. Beyond the outer white band of the oil film, Fig. 24–29c, there is still some oil, but the film is so thin that reflected light from upper and lower surfaces destructively interfere and you can see right through this very thin oil film.

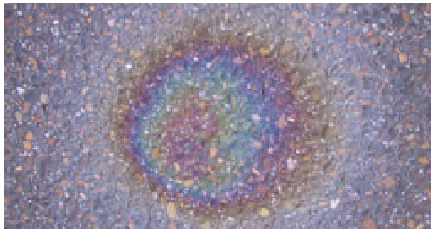


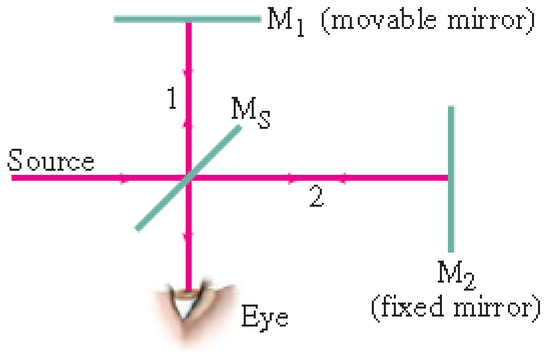
FIGURE 24–29c (Repeated.)

Classwork

- FRQ 2011B.3 (Single and Double slit)
- Misconceptual 6, 8, 9, 10, 11, 15, 17, 18, 19

Michelson Interferometer

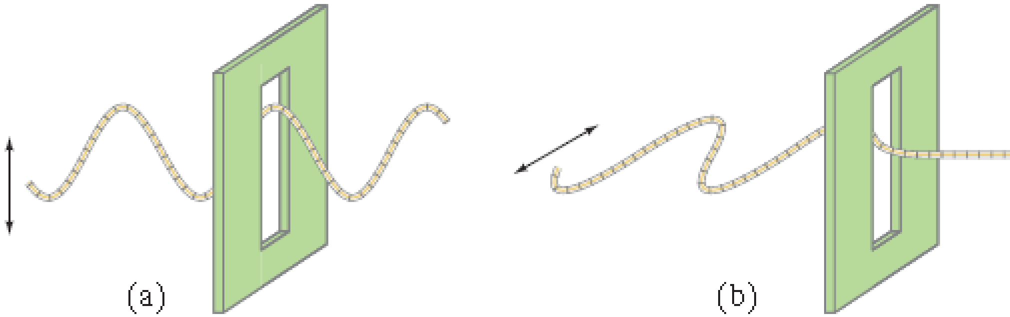
FIGURE 24–37 Michelson interferometer.



Very precise length measurements can be made with an interferometer. The motion of mirror M_1 by only $\frac{1}{4}\lambda$ produces a clear difference between brightness and darkness. For $\lambda = 400$ nm, this means a precision of 100 nm, or 10^{-4} mm! If mirror M_1 is tilted very slightly, the bright or dark spots are seen instead as a series of bright and dark lines or "fringes" that move as M_1 moves. By counting the number of fringes (or fractions thereof) that pass a reference line, extremely precise length measurements can be made.

- https://www.youtube.com/watch?v=QgA6L2n476Y&feature=related

Polarization



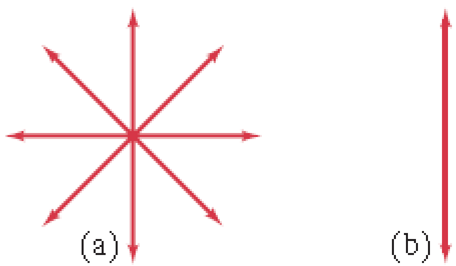
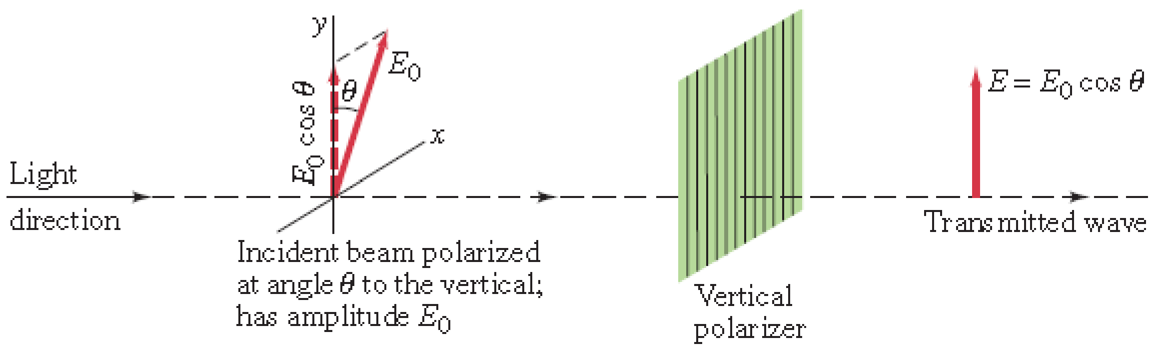
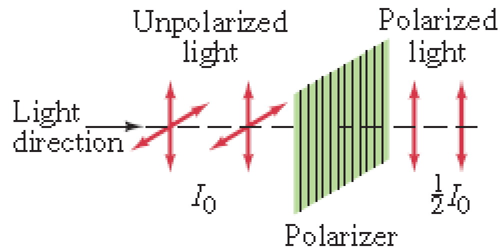
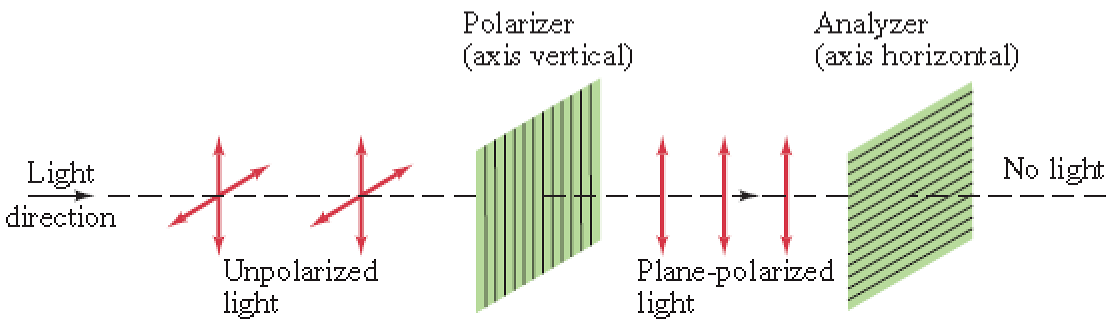


FIGURE 24–40 (a) Oscillation of the electric field vectors in unpolarized light. The light is traveling into or out of the page. (b) Electric field in linear polarized light.



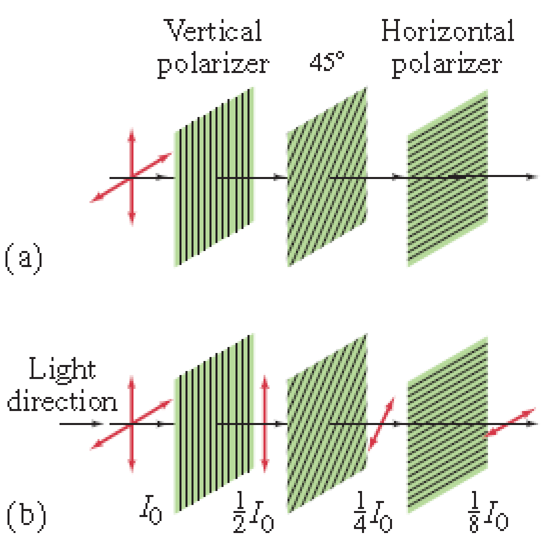
POLARIZATION





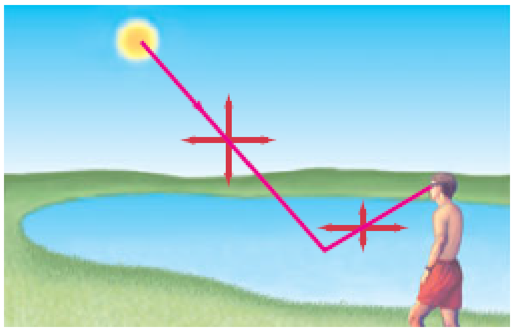
- Why's the intensity like this?

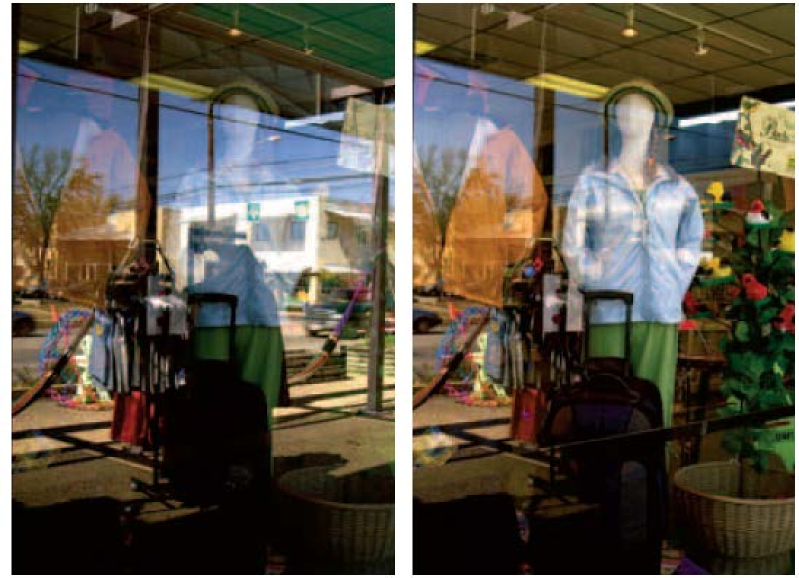
FIGURE 24–45 Example 24–14.



POLARIZATION: WATER, GLASS, SKY

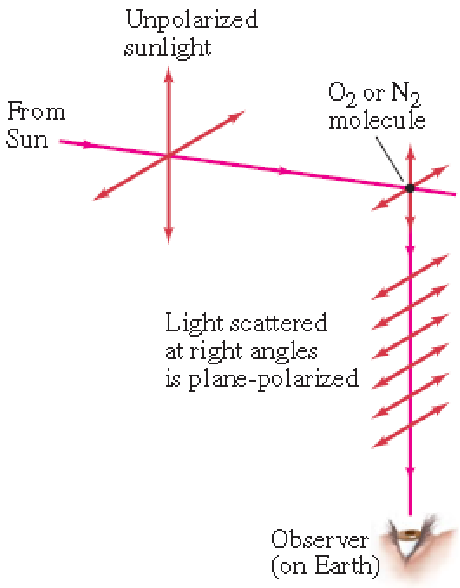
FIGURE 24–46 Light reflected from a nonmetallic surface, such as the smooth surface of water in a lake, is partially polarized parallel to the surface.



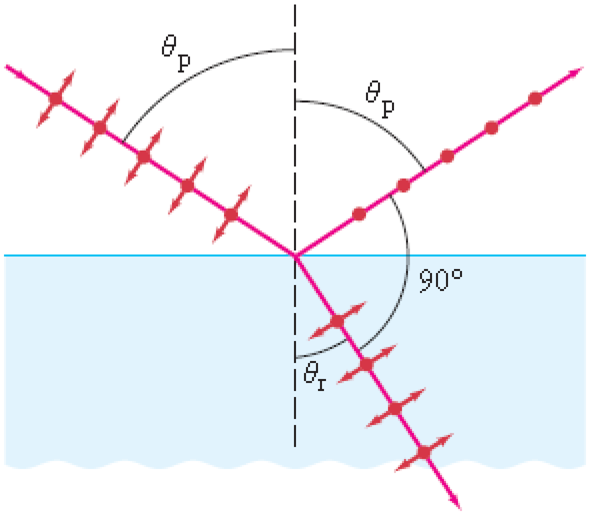


)
(b)

- What is scattering? Why is the sky blue?



Brewster's Angle

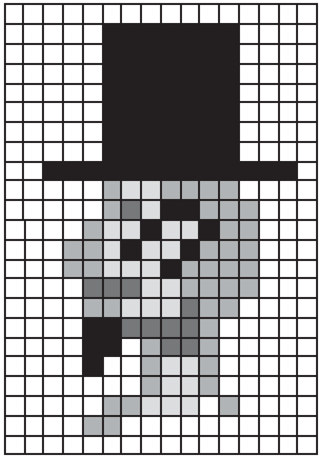


- Experimentally found (and theoretically from Maxwell's Equations)

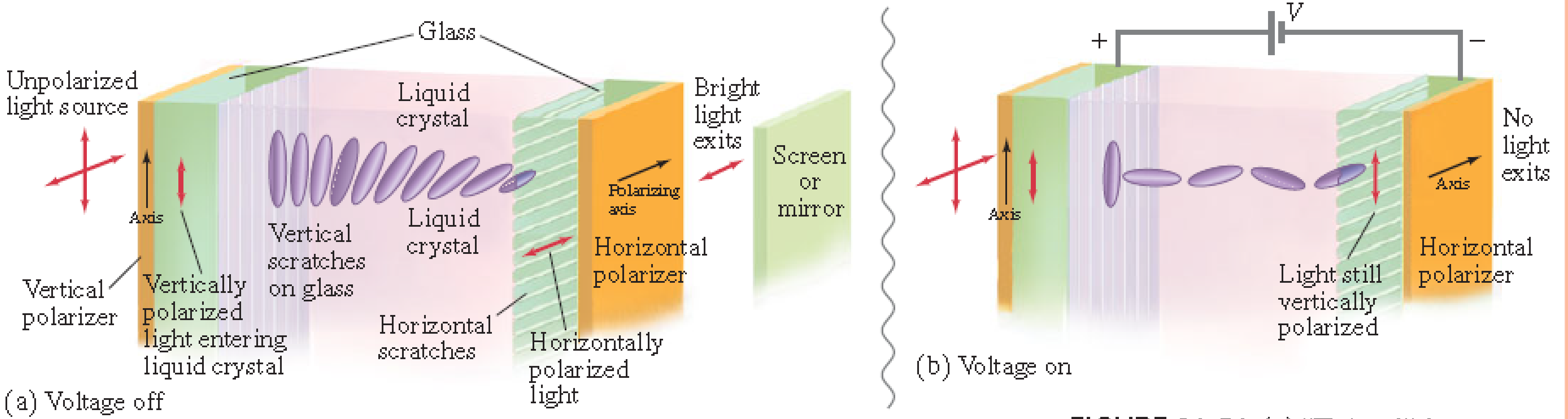
Happens when reflected and refracted rays are 90 degrees apart →

$$\tan \theta_p = \frac{n_2}{n_1},$$

LCD (Liquid Crystal Display)

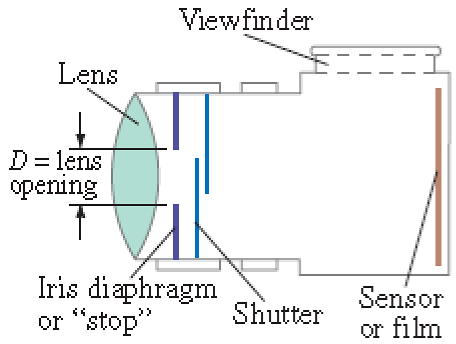


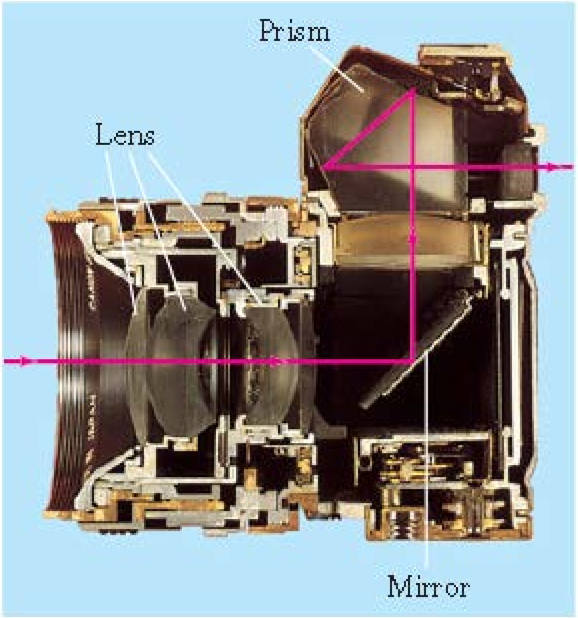
tps://www.youtube.com/watch?v=k7xGQKpQAWw



Ch. 25 Optics Applications

FIGURE 25–1 A simple camera.





- Cornea n = 1.376
- Lens n = 1.386~1.406
- Vitreous n = 1.336
- Fovea 0.25 mm (packed with rods/cones
- Most of the refraction by cornea.
- Lens does fine adjustments
  - Far-sighted (presbyopia). Ciliary muscles weaken with time
  - Near-sighted (myopia). Eyeball is too long.
  - Astigmatism: cornea is not smooth

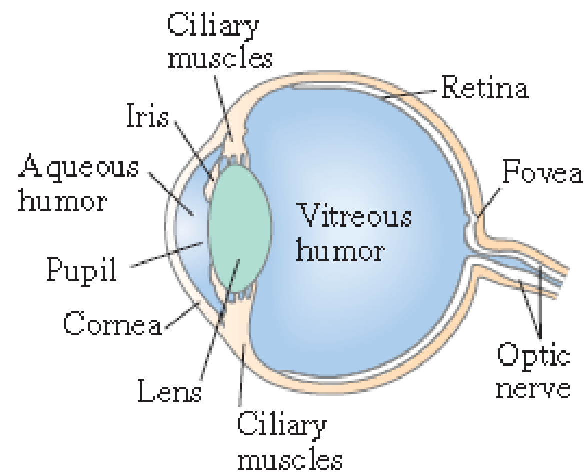
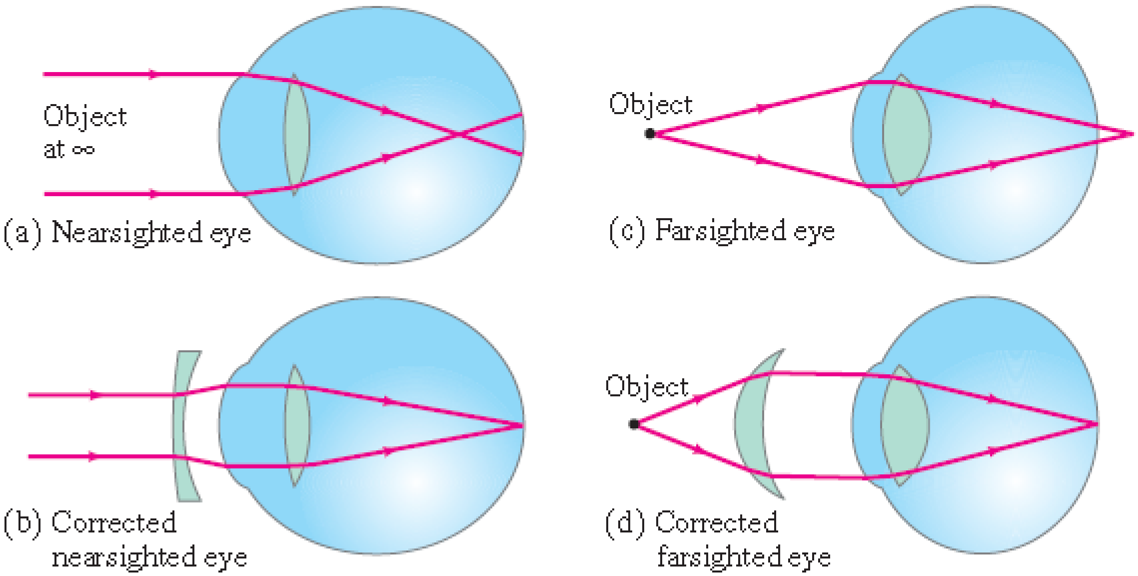


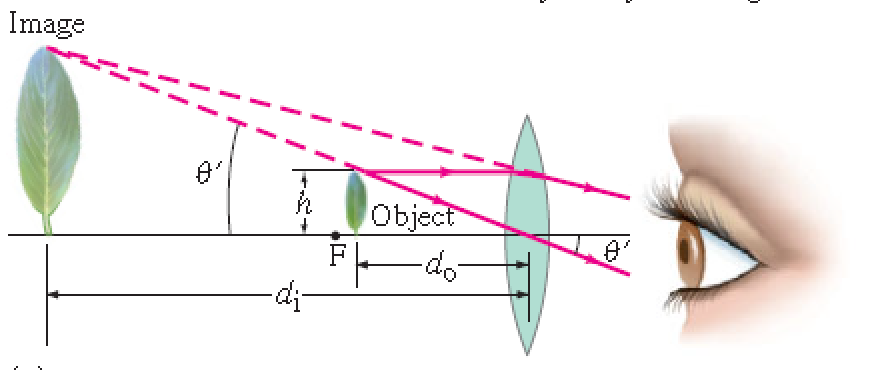
FIGURE 25–9 Diagram of a human eye.

FIGURE 25–11 Correcting eye defects with lenses. (a) A nearsighted eye, which cannot focus clearly on distant objects (focal point is in front of retina), can be corrected (b) by use of a diverging lens. (c) A farsighted eye, which cannot focus clearly on nearby objects (focus point behind retina), can be corrected (d) by use of a converging lens.



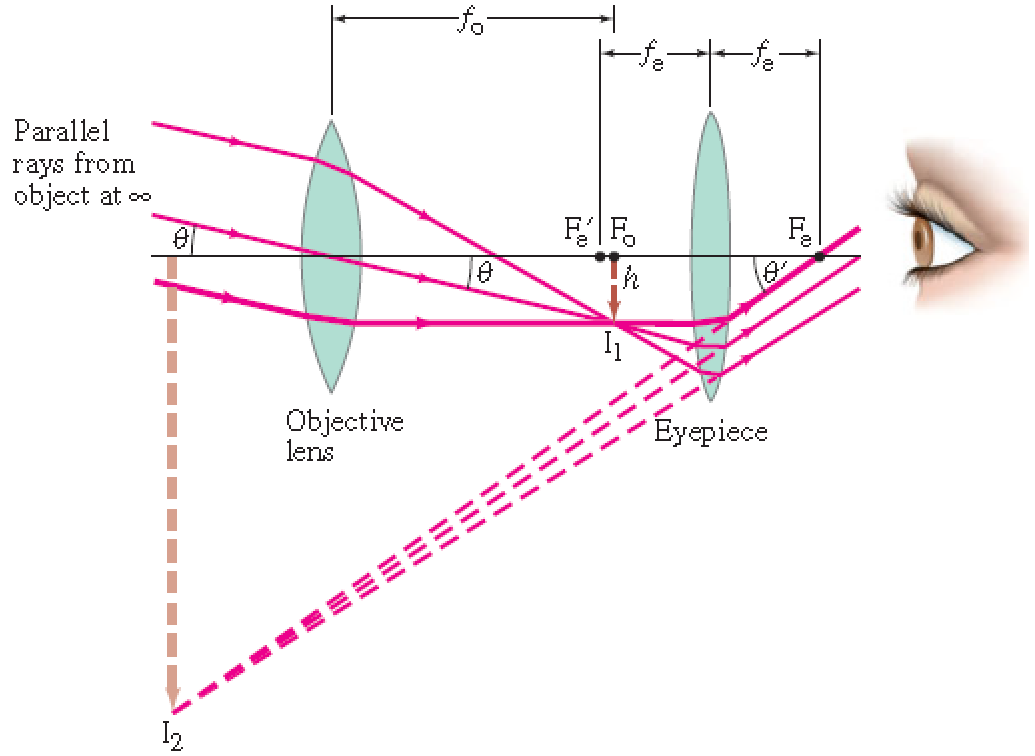
- Do near-sighted people see better or worse underwater?
- Why goggles when seeing underwater?

MAGNIFYING GLASS



TELESCOPE

FIGURE 25–20 Astronomical telescope (refracting). Parallel light from one point on a distant object ($d_o = \infty$) is brought to a focus by the objective lens in its focal plane. This image (I_1) is magnified by the eyepiece to form the final image I_2. Only two of the rays shown entering the objective are standard rays (2 and 3) as described in Fig. 23–37.



TELESCOPE

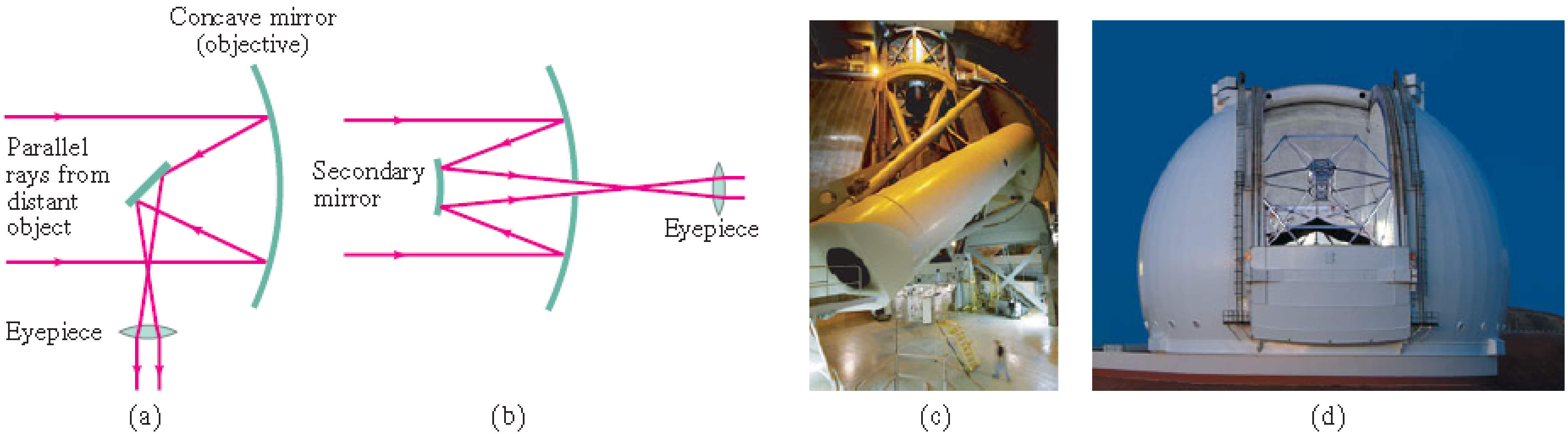
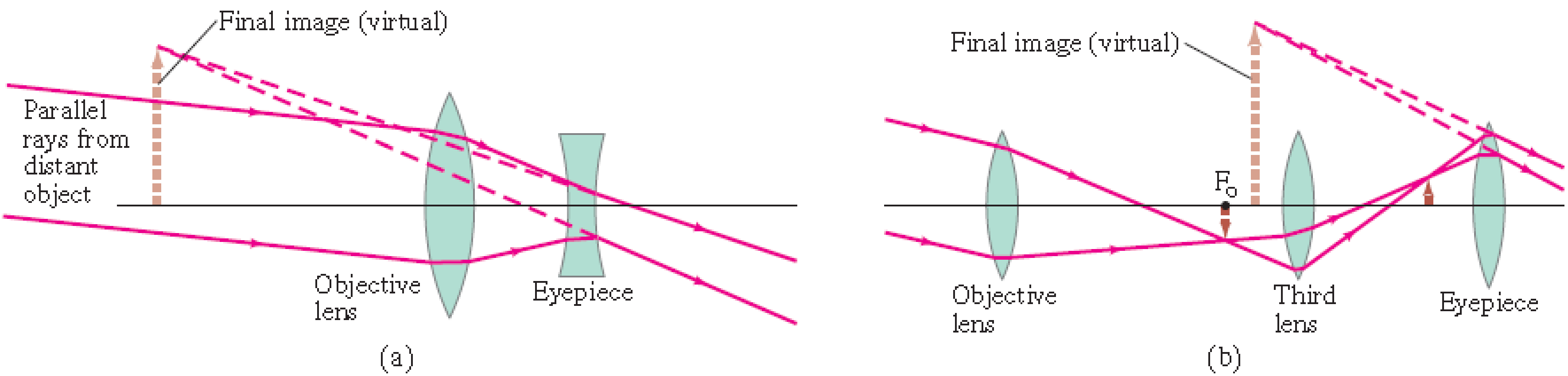


FIGURE 25–22 A concave mirror can be used as the objective of an astronomical telescope. Arrangement (a) is called the Newtonian focus, and (b) the Cassegrainian focus. Other arrangements are also possible. (c) The 200-inch (mirror diameter) Hale telescope on Palomar Mountain in California. (d) The 10-meter Keck telescope on Mauna Kea, Hawaii. The Keck combines thirty-six 1.8-meter six-sided mirrors into the equivalent of a very large single reflector, 10 m in diameter.

†Another advantage of mirrors is that they exhibit no chromatic aberration because the light doesn't pass through them; and they can be ground into a parabolic shape to correct for spherical aberration (Section 25–6). The reflecting telescope was first proposed by Newton.

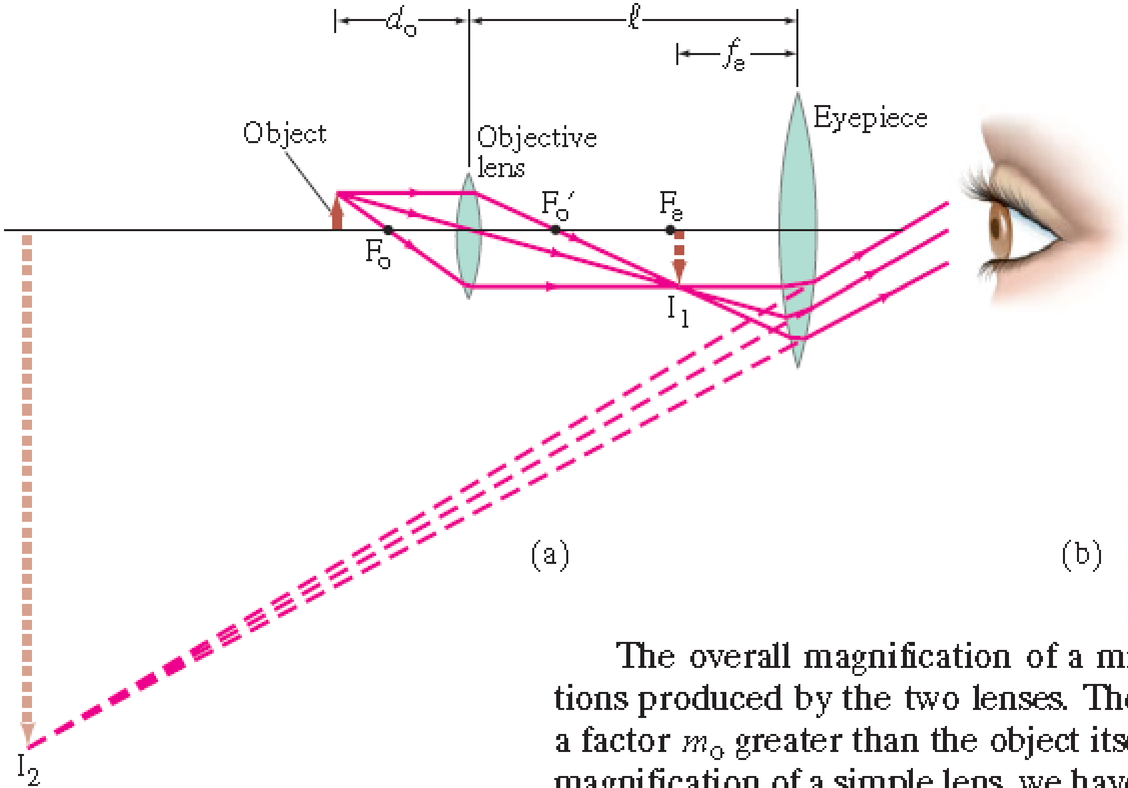
FIGURE 25–25 Terrestrial telescopes that produce an upright image: (a) Galilean; (b) spyglass, or erector type.

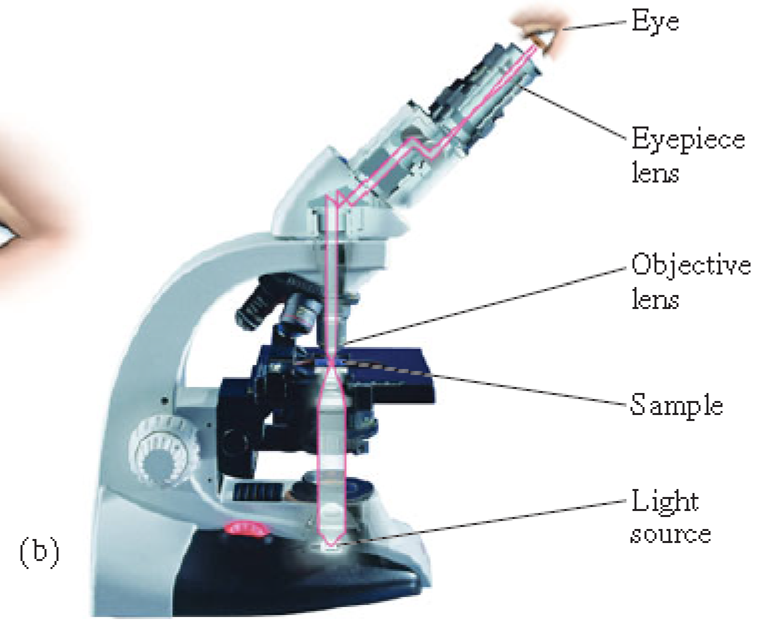


Microscope

FIGURE 25–24 Compound microscope: (a) ray diagram, (b) photograph (illumination comes from below, outlined in red, then up through the slide holding the sample or object).

far from the objective lens, and much enlarged. The eyepiece is positioned so that this image is near the eyepiece focal point F_e. The image I_1 is magnified by the eyepiece into a very large virtual image, I_2, which is seen by the eye and is inverted. Modern microscopes use a third "tube" lens behind the objective, but we will analyze the simpler arrangement shown in Fig. 25–24a.





The overall magnification of a microscope is the product of the magnifications produced by the two lenses. The image I_1 formed by the objective lens is a factor m_o greater than the object itself. From Fig. 25–24a and Eq. 23–9 for the magnification of a simple lens, we have