Scattering and Polarization

CHAPTER 13

13.1 INTRODUCTION

So far we have considered what happens when light encounters material obstacles of a size much greater than the wavelength (geometrical optics) or of a size so small as to be comparable with the wavelength of light (wave optics). But you can also observe effects due to even smaller obstacles, much smaller than the wavelength of visible light. When light interacts with an isolated object that small, it shakes all the charges in the object, which then radiate in all directions. This phenomenon is called ***scattering.***

To scatter with appreciable *intensity,* light must encounter *many* isolated small objects: for example, the molecules that constitute the air. Indeed, it is only because light does scatter in air that you can see the beams of Figures 1.3, 1.4, and 8.19b. Without scattering, the light's path through the air would be invisible and the camera could not record it.

This simple explanation, offered when these figures were introduced, now bears closer scrutiny. It would seem that when propagating in any dense medium, such as glass, light should be scattered by the many molecules that are present. Instead, as we know, it continues to propagate in a sharp beam, as in vacuum, only with a different *speed.* This is because there are many molecules present in glass, and whenever there is one molecule to scatter light, there will be another one for which the light path to your eye is half a wavelength longer. The scattered light from these two molecules interferes destructively, as in Figure 12.4 (along the *x*-axis), and this is so for any sideways direction from which you look at the beam. Air, on the other hand, is a gas, so there is no guarantee that there will be another molecule half a wavelength beyond the first—sometimes there may be a few extra molecules around one point, sometimes a few less. You see the scattering from these points because of these fluctuations. (The TRY IT suggests ways to enhance the scattering in air.)

Scattering is *selective* in several ways: light of certain *wavelengths* is scattered more than light of other wavelengths, and light of one *polarization* (Sec. 1.3B) is scattered more than light of another polarization. Because our eyes are not very sensitive to the polarization of light, we have not yet discussed the phenomena associated with it. Scattering provides us with the opportunity to do so, even as it actually provides most of the polarized light around us. Much of this chapter will therefore deal with polarized light, produced by scattering as well as by other means.

TRY IT

FOR SECTION 13.1
Light beams

To see the path of light rays, you need tiny objects in the path that will scatter part of the light to your eye. To see the beam of your flashlight, put larger particles in the air, such as dust motes, smoke, or chalk dust. In their presence you should be able to trace the light's path, including reflections from mirrors and water surfaces, to test the law of reflection (Sec. 2.4) and Snell's law (Sec. 2.5).

13.2 RAYLEIGH SCATTERING

When white light scatters from some molecules, it scatters selectively because part of the light is absorbed at the resonant frequencies of the molecules—the scattered light is then colored. For many other molecules, however, the important resonant frequencies are significantly higher than visible frequencies. White light nevertheless becomes colored when it scatters from these molecules—the higher the frequency of the incident light, the more light will be scattered. This type of scattering is called ***Rayleigh scattering*** and occurs whenever the scattering particles are much smaller than the incident wavelength and have resonances at frequencies higher than those of visible light. Equivalently, we may write the rule for Rayleigh scattering:

The shorter the wavelength of the incident light, the more light is scattered.

This result was worked out in detail by the same Lord Rayleigh we met in Sections 10.5B and 12.5C. It says that blue light will be scattered more than red light. In fact, for incident broad-band white light, the intensity of scattered 400-nm light is almost ten times as great as that of 700-nm light.

One consequence of Rayleigh scattering is the sky's blue color. Light reaching your eyes from the sky is sunlight that has been scattered by the air molecules (Fig. 13.1) and is therefore predominately blue. Since the direct rays from the sun have some of the blue part of the spectrum scattered out of them they should look slightly yellowish. When the sun is overhead, and if the sky is very clear, this is a small effect. However, if there are lots of tiny dust and smoke particles in the air, the effect is larger. It becomes even larger as the sun sets; the direct rays from it to your eyes must pass through more and more atmosphere, so these rays are depleted of more and more of the shorter wavelengths, and the sun looks redder and redder. (See the TRY IT.)

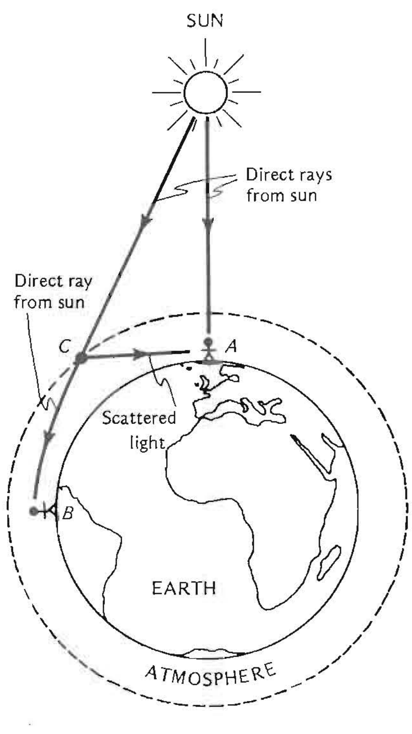


FIGURE 13.1

When *A* looks at point C in the sky, only scattered light from the sun reaches her eyes. As short-wavelength light is scattered most, the sky looks blue to her. Direct rays from the sun, from which the blue end of the spectrum has been removed by scattering, vary from white to yellow to red, depending on how much atmosphere they have traversed and how much dust is in the air—that is, on how much scattering the light has suffered. Thus to *B*, who sees the sun setting, the sun appears much redder than to *A*.

There are a number of other examples where blue coloring is due to Rayleigh scattering. We've already noted (Sec. 9.9E) that fine black pigment mixed into white paint gives it a bluish cast for just this reason. In fact, da Vinci noted this and attributed it to the same cause that makes the sky blue. The writer George MacDonald correctly identifies another blue with the blue of the sky when he writes, "Where did you get those eyes so blue?/Out of the sky as I came through." Your beautiful blue eyes are due to scattering from small, widely separated particles in your irises. Similarly, the moonstone owes its blue sheen to Rayleigh scattering.

You can see the same effect in fine smoke, say from a wood fire. The smoke looks bluish when illuminated from the side and viewed against a dark background, so only scattered light reaches your eyes. If instead the smoke is seen against a bright background, it looks red or brown (due to the *removal* of blue by scattering). If the smoke gets too thick, the particles become dense enough that *all* light is repeatedly scattered, and the light that emerges sideways is white or gray.

A similar effect can occur when the particles become larger. For example, the smoke rising from the end of a cigarette is bluish, but after you inhale and exhale it, the smoke looks gray or white. Here you have covered the smoke particles with moisture, making them much larger. They are then large enough to scatter light of all wavelengths equally—as in the reflections of geometrical optics—and thus they look white. This is also why clouds are white: The water droplets in clouds may be fifty times as large as the wavelength of visible light. With so many droplets, and thus so many surfaces to reflect the light, the clouds scatter almost all the light and look white even though the individual drops are nearly transparent. (Of course, very dense clouds will not transmit light—they either absorb it or reflect it upward—so they look black.) Small grains of salt or sugar, talcum powder, chalk, the white spots of moths and butterflies, white paper, fog, snow, beaten egg white, and beer foam all look white for the same reason. The white pattern in star rubies and sapphires, and in tiger's-eye quartz are similarly due to scattering from large inclusions. Likewise, the clear albumen becomes white as an egg is cooked because the protein molecules are freed of their surface water and are then able to coagulate into large clumps, which scatter nonselectively. When the watery whey from milk is made into cheese (such as ricotta), the cheese is white because of the same coagulation process.

Yellow lights are often used as fog lights or headlights on cars because yellow is as easily detected by your eyes as white but is scattered less in a fine mist, when the droplets are very small compared to the wavelength of visible light. Unfortunately, more often the droplets are larger, and the yellow is then scattered as well.

Particles may, of course, also produce colors by selective *absorption* and *reflection*. The smog we all know and love takes its brown color because of absorption by particles of nitrous oxide, which has resonances at visible frequencies. Not all particles in the sky produce ugly colors, however. For example, in 1883 the volcano Krakatoa erupted spectacularly, spewing micrometer-size particles into the atmosphere in such abundance that all over the world there were unusually colorful sunrises and sunsets for three years!

Scattering by the air or the particles in it is thus responsible for aerial perspective (Sec. 8.6E), which makes distant dark hills look blue and distant snow-clad peaks look yellow (see Plate 8.4). The purer and more transparent the air, the bluer those dark hills.

TRY IT

FOR SECTION 13.2
Blue skies

A good source of small scattering particles is milk, whose solid particles are much smaller than the wavelength of visible light. You can use these to make a blue "sky" and a red "sunset." In a dark room, shine a light beam, say from a flashlight, through a clear glass of water. Look at the beam from the side so you can see the scattered light. (It helps if there is a black background.) At the same time look at the direct, transmitted light, for example, by reflecting it from a piece of white paper. Now add a little milk, one or two drops at a time, and stir the water. The scattered light will become bluish as the transmitted light becomes yellowish and then reddish. As you add even more milk, the scattered light becomes white because of repeated scattering, and you have made a white "cloud."

You can see the blue of the air directly if you have enough air with a dark background, and something black with which to compare the color of the air. An otherwise dark room viewed from the outside through an open window makes a good dark background. To block all extraneous light, view the window through a long mailing tube. Since you'll want to be as far as possible from the window (30 or 40 m), cover the far end of the tube with some aluminum foil in which you've made a small (several millimeters) hole. To avoid light entering the hole at an angle, wrap a piece of black paper around the far end of the tube, so it extends 15 or 20 cm beyond the foil. Look toward the window when the sun is to one side or overhead. Then the only light entering the tube will be the sunlight that is scattered by the air between you and the window. This should look distinctly bluish compared to the dark surrounding of the aperture in the foil. What happens to the blue as you change your distance from the window?

Since Rayleigh scattering also occurs at night (except that there is less light to scatter), a moonlight photograph taken with a long enough exposure time should show the same colors as one taken by daylight. Try it on a clear night during a full moon. The moonlight is then almost a factor of 10^6 weaker than sunlight. Because of the failure of reciprocity of the film at long exposures (Sec. 4.6), you should make an exposure about 10^7 times as great as you would need by sunlight. For example, if a good exposure by sunlight was $\frac{1}{1000}$ sec, then, with the moon in the same position as the sun was, you might open your lens an additional three f-stops and make a 20-minute exposure. Most color film won't give accurate color with such a long exposure—Kodak recommends Kodacolor 400 if you want prints, or Kodachrome 25 (daylight) with a CC10M filter if you want slides.

13.3 POLARIZATION DUE TO SCATTERING

The same Rayleigh scattering that gives us the blue sky also polarizes the scattered light. In order to see how this comes about, let's return to some of the basic ideas of polarization, which were first introduced in Section 1.3B.

A. Polarized light

Light, recall, is a *transverse* wave—the electric field is always perpendicular to the direction of propagation of the wave (the direction of the ray). For example, if the wave is traveling in the z-direction (Fig. 13.2a), the electric field may be in the x-direction, in the y-direction, or in any other direction within the x-y plane. If the light wave's electric field is always parallel to the x-axis, we say the light is ***linearly polarized*** in the x-direction (Figs. 13.2b and c). Similarly, a wave whose electric field is always parallel to the y-axis is linearly polarized in the y-direction.

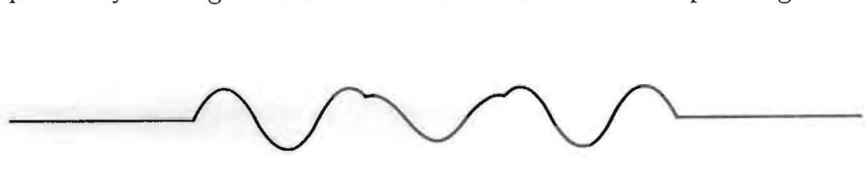
Suppose the wave is linearly polarized in some other direction, say at an angle of 45° between the x- and y-axes. We may nevertheless think of this wave as consisting of two *in-phase* waves (Fig. 13.2d), one linearly polarized in the x-direction (the ***x-component***) and one in the y-direction (the y-component). There are a number of gadgets that illustrate this concept. One, called "Etch-A-Sketch®," allows you to draw a picture by turning two dials. One dial causes a horizontal line to be drawn on a screen, the other makes a vertical line. If you simultaneously turn both dials in the same direction ("in phase"), you draw a 45° line. Another toy is a maze with two knobs that control its tilt in two perpendicular directions. Simultaneous control of both knobs allows you to roll a ball in any direction through the maze. Analogously, any direction of the electric field in the x-y plane can be thought of as consisting of two components that lie in two mutually perpendicular directions. Further, these directions can be any pair that we choose, not necessarily the x- and y-directions (Fig. 13.2e). While this seems like only a way to think about things now, we'll see that Nature thinks about them in just this way (Sec. 13.6).

What about ***unpolarized light***? Such light is polarized in all different directions (perpendicular to the direction of propagation); the direction of the electric field *varies rapidly and randomly*—it has no preferred direction. We can think of this as a wave with two components that have a rapid and random variation of their relative phase—the two components are incoherent. It is like the result of turning the two dials of the Etch-A-Sketch® back and forth with no particular relation between them—you then get a line that wiggles around in all directions, going no place special. Figure 13.2f shows how we'll indicate such unpolarized light.

With this information, let's see why Rayleigh scattering produces polarized light.

B. Polarization due to Rayleigh scattering

A simple model can illustrate how scattering produces polarization. Figure 13.3 shows two long jump ropes that are joined together at their centers by a ring and then stretched out tightly at right angles, so as to form a (horizontal) cross. The ring is like a scatterer in this sense: If one end of one rope is wig-



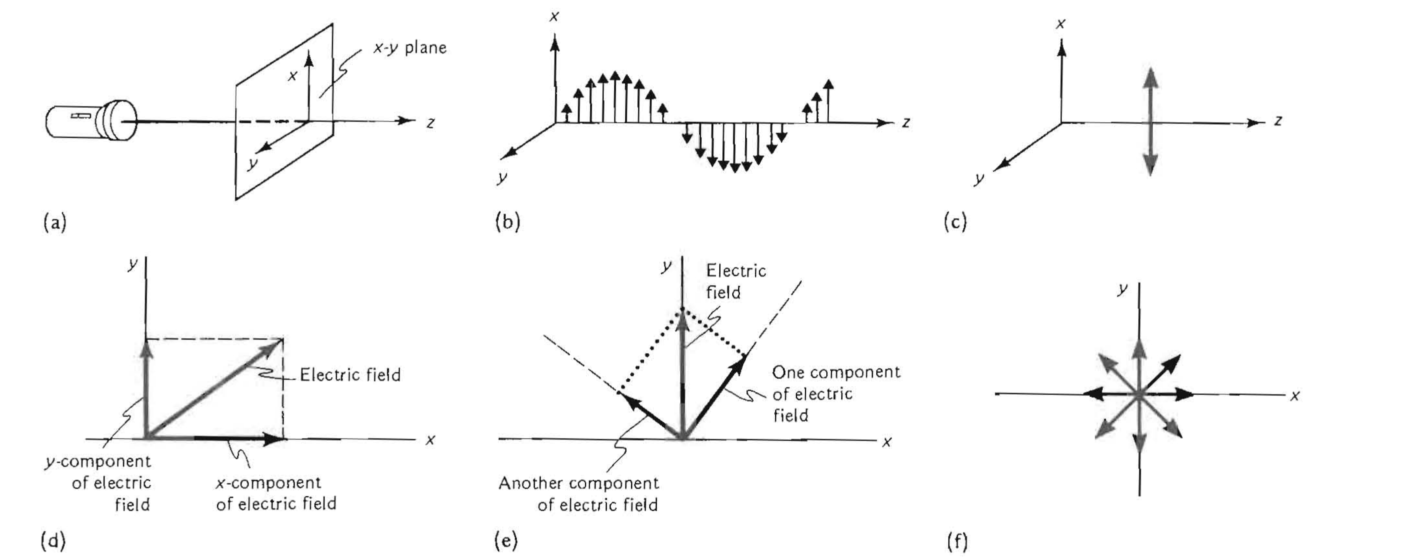


FIGURE 13.2

(a) A light wave traveling in the z-direction can have its electric field only in the x-y plane (or in any parallel plane). **(b)** The electric field of a light wave that is linearly polarized in the x-direction (also commonly, but less appropriately, called **plane polarized**). **(c)** A shorthand notation for the same wave as in **(b)**. **(d)** Any electric field in the x-y plane can be thought of as a combination of a field in the x-direction with one in the y-direction. **(e)** An electric field in one direction within a plane can be thought of as a combination of fields in *any* two mutually perpendicular directions within that plane. **(f)** Unpolarized light (traveling in the z-direction).

gled up and down (linearly polarized in the x-direction), a wave propagates down that string, wiggling the ring up and down (Fig. 13.3a). This causes a (scattered) wave oscillating up and down to develop on the cross rope. However, if the first rope is wiggled sideways (linearly polarized in the y-direction), it cannot set up a wave in the cross rope because the ring *slides along* that rope and doesn't move it—there is no motion transverse to the cross rope (Fig. 13.3b). Thus, if we wiggle the first rope in both x- and y-directions, making an *unpolarized* wave, the only wave resulting in the cross rope would be *linearly polarized* in the vertical, x-direction.

The same idea applies to scattering of electromagnetic waves. Imagine that an unpolarized wave traveling in the z-direction strikes a small scatterer at O (Fig. 13.4).

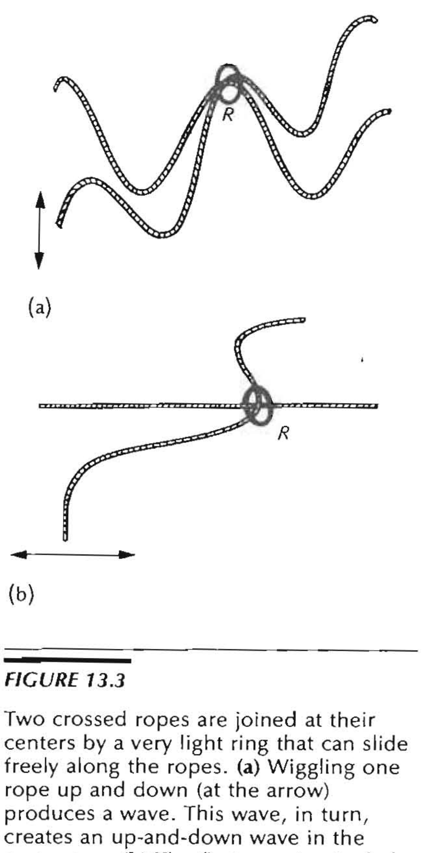


FIGURE 13.3

Two crossed ropes are joined at their centers by a very light ring that can slide freely along the ropes. **(a)** Wiggling one rope up and down (at the arrow) produces a wave. This wave, in turn, creates an up-and-down wave in the cross rope. **(b)** The first rope is wiggled sideways and simply slides over the cross rope, producing no wave in it.

Since the electric field of the unpolarized wave points in all directions *in the* x-y *plane*, the charges in the scatterer will oscillate in all those directions, but *not* in the z-direction. As usual, we may think of any such oscillations in the x-y plane as consisting of just an x- and a y-component. Only the x-component of oscillation radiates in the y-direction—the y-component cannot (because the scattered wave is transverse) and there is no z-component (because the incident wave is transverse). Hence, any light *radiated* in the y-direction (to E_1 or E_2) is *linearly polarized* in the x-direction. Similarly, the light reaching observers at E_3 and E_4 is linearly polarized in the y-direction. An observer at E_5, however, sees the incident wave as well as light scattered in the forward direction, both of which are unpolarized.

For the blue, Rayleigh scattered sky light this means that the blue light is linearly polarized for light coming from points in the sky 90° away from the sun (observers E_1 to E_4). However, the light coming from directions near the sun (observer E_5) or opposite the sun is unpolarized. For regions in between, the light is ***partially polarized***—a mixture of polarized and unpolarized light. If there are large particles in the air (as in smog), the forces *within* them may cause the charges

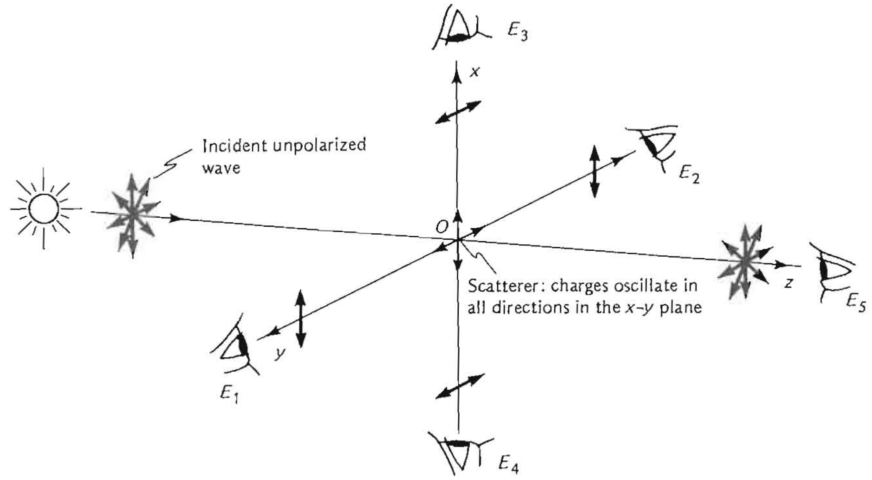


FIGURE 13.4

An unpolarized wave traveling in the z-direction strikes a scatterer at O. The wave that scatters along the y-axis is linearly polarized in the x-direction, while that which scatters along the x-axis is linearly polarized in the y-direction. That which scatters in the z-direction is unpolarized.

to oscillate in other directions than that of the electric field of the incident wave, so the scattered light is polarized less, if at all. Repeated scattering, as in clouds, causes the light to come out polarized in all directions—that is, unpolarized—so light from clouds is not polarized. (The TRY IT tells you how to verify some of these statements.)

It is possible to determine the location of the sun by measuring the polarization of the light from the blue sky. Many insects and arachnids seem to use this as a navigational device. For example, the wiggle dance of bees, by which they communicate the direction of food, depends on the direction of the light's polarization. The sensitivity of the bee's eye to polarization is different at different wavelengths, reaching a maximum at 355 nm. This suggests that a pattern of polarized light appears as a colored pattern to the bee. (Why?) These and other insects can locate the sun even when it is behind a cloud by detecting the polarization of the light from a patch of blue sky.

While *our* eyes are not sufficiently sensitive to the polarization of light for this navigational trick, we can still use it if we have the help of polarizing devices, which we'll describe below. With one such device (cordierite, a dichroic crystal—Sec. 13.5), which they called a "sun stone," Vikings are said to have used the polarization of the sky's light to navigate. Even today, the polarization of the sky in the twilight is of use to airplane navigators who fly over the poles.

A polarizing device that transmits light of one polarization, but not light of a perpendicular polarization, is called a ***polarizing filter.*** Because of the polarization of the light from the blue sky, a properly oriented polarizing filter in front of your camera can block out that light, increasing the contrast between the sky and the white clouds.

Light can also undergo Rayleigh scattering from small scatterers *under water.* The resulting polarized light may be, as for airborne insects, a useful clue to underwater denizens for navigation. It may also provide a stable reference to help the animal stay in one place (station keeping). It may help to improve the animal's visual contrast (as it helped the camera "see" the clouds). For these and possibly other reasons, numerous underwater animals show a sensitivity to polarized light: crustaceans, cephalopods, fishes, and amphibians. Octopuses, for example, have even been trained to respond to 90° changes in the direction of polarization—so if you can't get a polarizing filter for the TRY IT, you can use a trained octopus.

TRY IT

FOR SECTION 13.3B
Polarization of the sky

You will need a polarizing filter such as used in polarizing sun glasses, viewers for 3-D movies, or polarizing camera filters. Alternatively, Figure 13.6 shows how you can make one. You can detect the presence of polarized light by noting if the light becomes alternately dark and bright as you rotate the filter around your line of sight.

First use the filter to convince yourself that sunlight is unpolarized. In order to avoid looking directly at the sun, use a pinhole to project its image. Cover the pinhole with the filter and rotate the filter while you look at the image. Does the image of the sun become darker and lighter? Next look through the filter at some blue sky, 90° away from the sun. Again, rotate the filter. Is the light from that part of the sky polarized, as it's supposed to be? Try other parts of the sky. The more the polarization, the greater the difference between dark and light as you rotate the filter. Where is the polarization greatest and where least? How would you locate the sun by using the polarization of sky light? Also look at clouds and smog.

Check these ideas with the blue "sky" you made for the TRY IT for Section 13.2. From the side and from above, look through your polarizing filter at the blue scattered light. Also look end on into the transmitted beam. Additionally, place the filter between the flashlight and the milky water. Look from the side and notice what happens to the scattered light as you rotate the polarizer. Also notice what happens to the transmitted red "sunset." Explain what you see, using Figure 13.4. Repeat these experiments as you add more milk. In particular, when you've added more milk and you look through the filter at the beam from the side, you should notice that there is polarized light coming from the water close to the flashlight, but not from the water farther from the flashlight. Why does this happen?

13.4 POLARIZATION DUE TO REFLECTION

Polarized light may be made in other ways beside scattering. Probably the second most common source of polarized light also relies on the transverse nature of light—polarization by *reflection*.

When light in air strikes a smooth glass surface at an angle of incidence θ_i (Fig. 13.5), it wiggles the charges at the surface of the glass. There is a direction θ_r in which the radiation emitted from all these charges is in phase. This is the reflected beam, at $\theta_r = \theta_i$. In any other direction (in the air) the radiation from the different charges interferes destructively. Similarly, there is a direction θ_t of constructive interference between the incident radiation and that from the glass atoms. This is the transmitted beam, given by Snell's law. Again destructive interference eliminates rays in any other direction in the glass. We've drawn the figure for a special case we want to examine, where the *transmitted and reflected rays* just happen to be at *right angles to each other*. If the incident light is unpolarized, we can consider it as consisting of two components: one linearly polarized in the plane of the figure (the *x-y* plane), as drawn, and one polarized perpendicular to the plane of the figure (the z-direction).

Let's consider the first component. The direction of polarization of the incident beam must be, as shown, perpendicular to the incident ray. Similarly, the direction of polarization of the transmitted beam must be perpendicular to the transmitted ray. This means that the electric field in the glass, and thus the direction in which the *charges oscillate* there, is *perpendicular to the transmitted ray*. But it is the radiation from these oscillating charges that produces the *reflected ray*. Because light is transverse, these charges cannot radiate along their direction of oscillation. Hence there *cannot* be a reflected ray perpendicular to the transmitted ray. Thus, the intensity of the reflected ray is zero for this special angle of incidence, called ***Brewster's angle,*** for which the reflected beam is perpendicular to the transmitted beam. (This is named after Sir David Brewster, who also invented the kaleidoscope.) Since angles of refraction depend on the two media involved, so does Brewster's angle. (Appendix L gives a mathematical expression.) Brewster's angle is typically near 56°, the value for light in air incident on glass.

Now consider the other component of the incident light—linearly polarized in the z-direction (i.e., perpendicular to the plane of the figure). Here the charges in the glass oscillate in the z-direction and are perfectly free to radiate in the direction of the reflected beam. There is nothing unusual in this case, so there *is* a reflected beam of this polarization.

Thus, if an *unpolarized* beam arrives at Brewster's angle of incidence, only one component of polarization is reflected. The reflected beam is then linearly polarized in the z-direction. At nearby angles this is almost true—that is, of the light polarized in the *x-y* plane, very little is reflected. Hence, the reflected light is partially polarized, consisting of a large component of one polarization and a small component of the other. Since you often look at objects at angles near Brewster's angle, much of the reflected light that you see is polarized. (The TRY IT invites you to check this.)

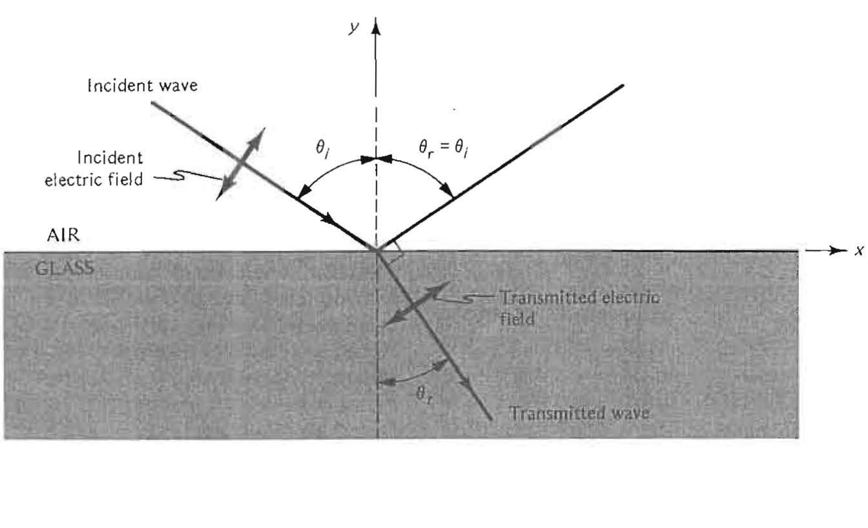
The situation is different for light reflected from *metals*. Visible light is not transmitted into metals because there are so many electrons free to move parallel to the surface, which cancel any internal electric fields (Sec. 2.3B). Electrons moving freely parallel to the surface can radiate in all directions away from the surface and can hence create reflected beams of *both* polarizations—the reflected light is not linearly polarized.

Because much of the specularly reflected light from nonmetallic surfaces is at least partially polarized, polarizing filters are often used as sunglasses. If they are oriented so as to remove the component of light that is polarized horizontally, such sunglasses eliminate *specular* reflections (glare) from roadways, lakes, and other horizontal surfaces. On the other hand, light reflected *diffusely* will have been reflected or scattered several times and will thus be unpolarized. Only half of such light is blocked by your sunglasses (the horizontal component), so you still see the road itself but with the glare reduced. For the same reason, airport control towers and the bridges of ocean liners often have sheets of polarizing filters over their windows.

The surface reflections shown in

FIGURE 13.5

Incident, transmitted, and reflected ray directions for the case when the angle of incidence is equal to Brewster's angle.



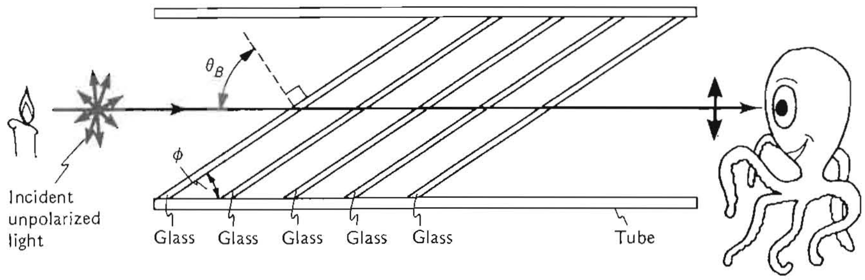


FIGURE 13.6

A polarizing filter made of Brewster windows. Each piece of glass is at Brewster's angle, θ_B, to the incident light direction. The light that reaches the observer consists predominantly of the component of polarization in the plane of the figure. The inside of the tube should be black, so the reflected light is absorbed. The angle ϕ is equal to $90° - \theta_B$. For a glass in air, $\theta_B = 56.3°$, so $\phi = 33.7°$.

Plate 9.7a were eliminated in Plate 9.7b by means of a polarizing filter in front of the camera lens, oriented so as to block them.

PONDER

What was the orientation of the polarizing filter?

Several other devices take advantage of the polarization at Brewster's angle. At normal incidence, each surface of a piece of glass reflects 4% of the incident intensity, so 92% is transmitted. But suppose you want to transmit light through 100 pieces of glass. Then 0.92 of the incident beam is transmitted by the first piece, 0.92 of *that* by the second, etc. After 100 pieces, only

$$(0.92)^{100} = 2.4 \times 10^{-4}$$

of the original intensity has been transmitted—that is, hardly anything. You can do much better if you slant the pieces of glass so that the light is incident on them at Brewster's angle. At this angle, about 15% of one polarization component is reflected at each of the 200 surfaces. However, *none* of the other polarization component is reflected. Since *all* of that polarization is transmitted, it can comfortably pass through all 100 pieces of glass. Hence, if unpolarized light is incident on this arrangement, half of the intensity is transmitted.

This idea is often used in gas lasers (Sec. 15.4). In such a laser, the light is reflected back and forth between two mirrors about 100 times. For precise adjustment, the mirrors are situated outside glass windows that contain the gas. To avoid losses by reflection, these windows are positioned so the beam strikes them at Brewster's angle. They are then called ***Brewster windows.*** After 100 passages back and forth through these windows, light of one polarization is completely lost, but the other polarization is not diminished by reflections—the laser light produced this way is therefore polarized.

The idea of the Brewster window can be used to make a polarizing filter of the type needed in many of the TRY IT's. About five pieces of glass (microscope slides work well) are positioned one behind the other, each at Brewster's angle to the incident beam (Fig. 13.6). While not as effective as 100 pieces of glass, this device considerably diminishes the component of light polarized perpendicular to the plane of the figure, but still passes the component polarized in that plane—it therefore acts as a polarizing filter. Like all other polarizing filters, you can use this to detect polarized light. Unlike other filters, however, you can use this to tell the *direction of polarization* of the light, since the easily visible slant of the glass tells you which component the Brewster window passes.

TRY IT

FOR SECTION 13.4
Polarization of reflected light

You will need a polarizing filter, as in the TRY IT for Section 13.3B. Look through this filter at light reflected from a shiny surface (not metal) such as a polished desk or floor, a shiny table top, a piece of smooth white paper, or a piece of glass with some black paper behind it. Position yourself and a light so you see a good specular reflection of the light. Rotate the filter to see if the light is polarized, as you did before. Compare the amount of polarization that you see when the light strikes the surface at near normal incidence, at intermediate angles, and at glancing incidence. At which angle do you expect to see the greatest polarization? Do you?

Repeat the experiment with a diffusely reflecting surface such as a piece of cloth or a piece of white paper with a matte finish. Why isn't the light polarized here? Also try a shiny metal surface, such as a polished cooking pan, a stainless steel knife blade, or the chrome surfaces of a car.

Light reflected from the road has both a diffuse part (by which you see the road) and a specular part (the glare). On a sunny day, look at a road through your polarizing filter, and notice what happens to the glare as you rotate the filter.

Light in the primary rainbow has been reflected once (Sec. 2.6B), so you can expect it to be polarized also. If you think of how a mirror located at some point on the rainbow would have to be oriented if it were to reflect sunlight to your eyes (as the droplets do), you should be able to convince yourself that the light from the rainbow must be polarized along the direction of the arc (rather than radially). That is, light from the (horizontal) top of the bow should be polarized horizontally, whereas light from the vertical arms of the bow (near the pot of gold) should be polarized vertically. Check this with a polarizing filter the next time you see a rainbow (or make a rainbow with your garden hose). What do you expect happens in the secondary rainbow? Does it?

13.5 POLARIZATION DUE TO ABSORPTION

One of the most commonly used visible-light linear polarizers *absorbs* one component of polarization, while transmitting the perpendicular components. ***Polaroid*** consists of a parallel array of long-chain molecules whose electrons cannot freely move *across* the narrow molecules. When incident light is polarized so its electric field pulls across the molecules, it can't make the electrons move. Hence they don't radiate, and the incident wave continues unaffected—that component of polarization is transmitted. However, when the electric field of the light drives electrons *along* the long molecules, the electrons do move and *absorb* the light's energy. Thus only light of one polarization (across the molecules) is transmitted.

This type of polarizing filter was invented by Edwin H. Land in 1928 when he was a 19-year-old undergraduate. (His interest had been stimulated by reading about some polarizing crystals that had been discovered in the 1850s when a physician's pupil, for some peculiar reason, put drops of iodine in the urine of a dog who had previously been fed quinine.) Sheets of Polaroid material, usually mounted between thin sheets of glass or plastic, form the polarizing filters you often find in sunglasses. Whereas they absorb most of the visible light of the appropriate polarization, they are not completely effective at the shorter wavelengths. For this reason very bright horizontally polarized light (e.g., bright sunlight polarized by reflection from water) may look deep blue or violet through your polarizing sunglasses, instead of black as it would for an ideal polarizing filter.

Various naturally occurring crystals absorb one component of polarization more than they do the perpendicular component. The semiprecious stone tourmaline is one example. However, tourmaline's absorption is more selective than Polaroid's—not all wavelengths are absorbed equally, so the transmitted light is colored. Such crystals are called ***dichroic*** because even unpolarized light passing through them in one direction becomes a different color than light that passes through them in another direction.* Because of the color produced, these dichroic crystals are not usually used as polarizing filters. The word dichroic has come to mean any material that produces polarized light by absorption, so Polaroid is considered dichroic.

The back of your eye contains a dichroic material: the yellow pigment (macula lutea) that absorbs light between 430 and 490 nm (blue) and covers your fovea (the place corresponding to the center of your field of view—see Sec. 5.2B). The dichroism in this case consists of stronger absorption when the direction of polarization of light is perpendicular to the pigment fibers than when it is parallel. The pigment in the macula is arranged radially, like the spokes of a wheel, as shown schematically in Figure 13.7a. Suppose that white light incident on your eye is polarized vertically (i.e., parallel to fibers *6* and *12* in Fig. 13.7a). As a consequence of the dichroism, the vertical fibers (*6* and *12*) absorb the blue part of this light least, and fibers perpendicular to this direction (fibers *3* and *9*) absorb it most strongly. Therefore, you see a horizontal dark yellow line (Fig. 13.7b) known as ***Haidinger's brush.*** As shown in the figure, the yellow brush is often accompanied by adjacent blue regions, presumably due to simultaneous color contrast (Sec. 10.6A). If, instead, the direction of polarization were horizontal, the yellow brush would be vertical—it always lies perpendicular to the direction of polarization. The TRY IT tells you how to look for Haidinger's brush.

*Greek *dis*, twice, plus *chros*, color. Crystals exhibiting three colors, for light passing through them in three different directions, are called trichroic (Greek *treis*, three). Generally, all such crystals are called pleochroic (Greek *pleion*, more).

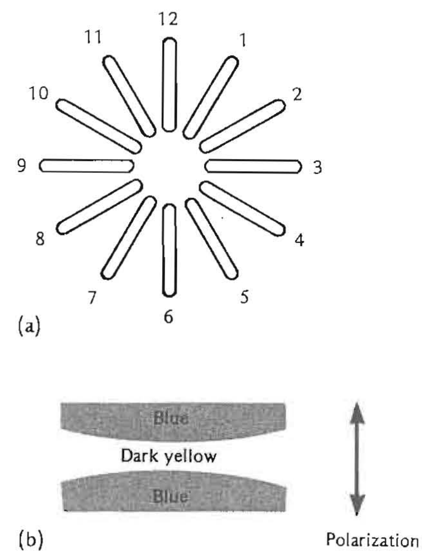


FIGURE 13.7

(a) The dichroic pigment in the macula lutea is arranged radially. **(b)** Haidinger's brush, when the light is polarized vertically (arrow).

TRY IT

FOR SECTION 13.5
Haidinger's brush

The best way to look for Haidinger's brush is to use a linear polarizing filter and a light blue, nonshiny background, such as a large piece of blue construction paper. Brightly illuminate the paper, and look through the filter at a point near the center of the paper. Because the image will fade as your eye adapts, it helps to rotate the filter occasionally about your line of sight. If you don't see the yellow-brown brush at first, don't be dismayed; it took Helmholtz twelve years to see it after he first learned of the phenomenon from Haidinger. You should be able to do much better—perhaps a few minutes. Once you see the brush, notice how it rotates as you slowly rotate the filter. This provides another technique for determining the direction of polarization of the filter, because the brush is always perpendicular to it.

Another good background is the blue sky. Use your polarizing filter to see the brush there. Because the light from the blue sky is already polarized (Sec. 13.3B), some people are able to see Haidinger's brush in the sky without the aid of a filter. In what direction should you look? Try it!

13.6 POLARIZING AND ANALYZING

A polarizing filter can be used in two different ways. It can be used as a ***polarizer***—because it transmits only one component of polarization, incident unpolarized light striking a polarizing filter results in polarized transmitted light. Alternatively, it can be used as an ***analyzer***—you can detect the *presence* of polarized light with it, as in the TRY IT for Section 13.3B, and even the *direction* of polarization once the filter is calibrated. (You can calibrate a polarizing filter—i.e., find the direction of polarization that it passes—by looking at the light reflected near Brewster's angle from a shiny floor, since that light must be horizontally polarized.)

Figure 13.8a shows a set-up using two polarizing filters, one as a polarizer and one as an analyzer. Let's start with the incident light unpolarized, and the polarizer oriented to pass only *vertically* polarized light. Suppose the analyzer is oriented to pass only *horizontally* polarized light (the polarizer and analyzer are ***crossed***—Fig. 13.8b). Since only vertically polarized light strikes the analyzer, no light passes through it—there is no transmitted beam reaching the observer. If instead the analyzer is oriented *vertically* (the polarizer and analyzer are ***parallel***—Fig. 13.8c), it passes all the light striking it—the observer then sees the full intermediate intensity (assuming ideal polarizing filters).

Thus you can use an analyzer to tell if the polarizer is doing its job. Makers of polarizing sunglasses often give you a little analyzer so you can convince yourself that the glasses do polarize (without breaking the pair in half).

PONDER

What transmitted light results if the polarizer is oriented horizontally in Figures 13.8b and c?

Suppose now that the analyzer is oriented at some other angle to the polarizer (Fig. 13.8d). Now we must think of the vertically polarized intermediate light as consisting of two components (as in Fig. 13.2e), one *along* the angle of the analyzer, and one oriented *perpendicular* to it. Only the former component (that parallel to the analyzer's orientation) passes through the analyzer. There *is* a transmitted beam in this case, but it has less intensity than in the case where the analyzer and polarizer are parallel. (Malus's law, the mathematical relation between the intensity of the transmitted light and the angle between the analyzer and polarizer, is given in Appendix M.)

Thus, by adjusting the angle of orientation between the polarizer and analyzer, you can control the intensity of the transmitted light. This is often a convenient way of controlling light intensity because it doesn't modify the size or shape of the beam (as a mechanical diaphragm would), and, at least for ideal polarizing filters, it doesn't affect the color temperature (as dimming an incandescent bulb would).

Since the analyzer tests the polar-

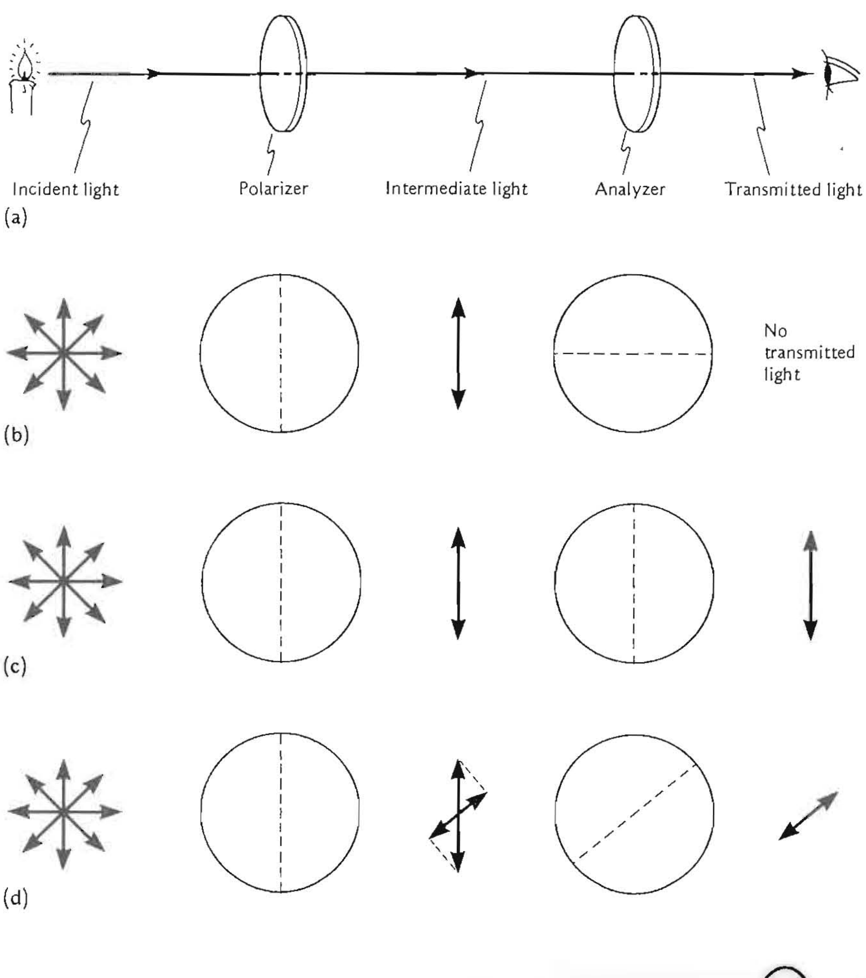


FIGURE 13.8

(a) Incident light strikes the first polarizing filter (the polarizer). The light that passes through the polarizer (the intermediate light) strikes the second polarizing filter (the analyzer). The amount of light that passes through the analyzer (the transmitted light) depends on the relative angle of the polarizer and analyzer. **(b)** Crossed polarizer and analyzer: incident unpolarized light striking a vertically oriented polarizer produces vertically polarized light, which is not passed by a horizontally oriented analyzer. **(c)** Parallel polarizer and analyzer: the same as in **(b)**, but now the vertically polarized light is passed by the vertically oriented analyzer. **(d)** Now the analyzer, oriented at an intermediate angle, passes only that component of the intermediate light polarized at that same angle. A weaker transmitted light results. Note that **(b)** to **(d)** represent head-on views of the light beam and of the filters.

ization of the intermediate light, we can use this set-up to examine the effect of various types of obstacles on polarized light. For example, in Section 13.3B we mentioned that polarized light that suffers repeated scatterings, as in clouds, becomes unpolarized—it is ***depolarized.*** The TRY IT shows how you can verify that statement using this set-up and depolarizers such as waxed paper or ground glass.

A remarkable phenomenon occurs when you introduce a *third* polarizing filter, inserted between the polarizer and the analyzer. Initially, with only two filters present, no light passed through the crossed polarizer and analyzer; when you looked through them they appeared dark. But now you insert the third polarizing filter between them, oriented at an angle of 45°, an orientation midway between those of the polarizer and the analyzer. When you look through this *three*-filter combination, you see light. This is quite remarkable when you think about it; the filter you insert does nothing but absorb some of the light, yet some light is now transmitted after you inserted an absorber!

We can understand this magic by simply repeating our previous analyses. At each polarizing filter we must think of the light as consisting of two components: one along the polarizing filter's orientation and one perpendicular to it. Thus you start with unpolarized light incident on the vertically oriented polarizer. As in Figure 13.8, only the vertical component passes. When only the crossed analyzer is present, the vertical component incident on it is blocked, so no light is transmitted (Fig. 13.8b). When the third polarizing filter is inserted at a 45° angle, however, some of the vertically polarized light incident on it is transmitted by it *as light polarized at 45°* (as in Fig. 13.8d). *This* light, now incident on the horizontally oriented analyzer, can be thought of as consisting of *both* a vertical and a horizontal component, as in Figure 13.2d. Since there is now a horizontal component present, *it* can pass through the analyzer—some of the light is therefore transmitted through the entire system. (If the filters are ideal, the transmitted intensity is one-fourth of the original intensity.)

This is a dramatic demonstration that not only is it *useful* to think of any electric field in terms of components, it is *necessary*—it is the way Nature works.

TRY IT

FOR SECTION 13.6
Depolarization by multiple scattering

You will need two polarizing filters: a polarizer and an analyzer, as in Figure 13.8. Place one behind the other with their polarization directions crossed, so no light passes through them. A good source of multiple scattering is a piece of waxed paper or ground glass (which are translucent rather than transparent because they repeatedly scatter the light). If the light is depolarized by this multiple scattering, the analyzer will pass some of it because one component of the then unpolarized *light will be parallel to the analyzer's orientation. Hold a piece of waxed paper between the crossed polarizer and analyzer and look through this arrangement at a light source. The waxed paper should intercept only a part of the intermediate beam, so you can still see the polarizer through the analyzer. Can you see any light passing through the waxed paper when the polarizer and analyzer are crossed? What happens as you rotate the analyzer? Does the polarized light that strikes the waxed paper remain polarized after passing through it?*

*13.7 CONTROLLING POLARIZATION WITH ELECTRIC FIELDS

We can carry the "magic" of the last section further and arrange that *all* of the intensity be transmitted.

Suppose the polarizer *(a)* is oriented vertically (Fig. 13.9). Light passing through it will then be polarized vertically. If the next polarizing filter *(b)* is oriented at a *slight* angle from the vertical, the light that passes through it will be polarized in this tipped direction, but the reduction of its intensity is negligible. If now we add another polarizing filter *(c)* that is tipped still further from the vertical, at a small angle from the previous one, it will pass light polarized in this new direction. If we continue this process, with enough filters we can rotate the angle of polarization to any direction we choose; and if the angle between successive polarizing filters is small enough, the intensity is not diminished.

Thus, with such a twisted stack of ideal polarizing filters, we could rotate the angle of polarization by 90° without loss of intensity. Such a device could then be used to pass light through a crossed polarizer and analyzer when inserted between them.

If we could make such a stack whose total angle of twist could be *changed* fast enough, we could have a *shutter*—a zero angle of twist would pass no light through the crossed polarizer and analyzer, while a 90° angle would pass all the light emerging from the polarizer (that is, half of the intensity of the original unpolarized light). It is possible to create the effect of such stacks out of layers of suitable *molecules* and to change the amount of twist with *electric fields*. There are several ways of doing this.

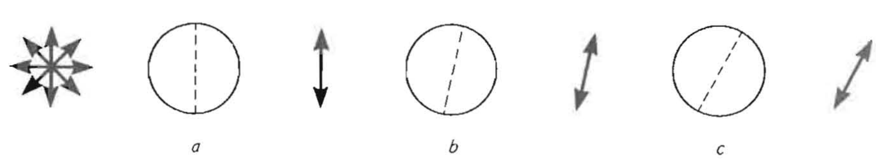


FIGURE 13.9

Successive polarizing filters oriented at slightly different angles rotate the direction of polarization. The intensity of light is unchanged after filter *a* if successive orientations change only slightly.

A. Liquid crystal displays

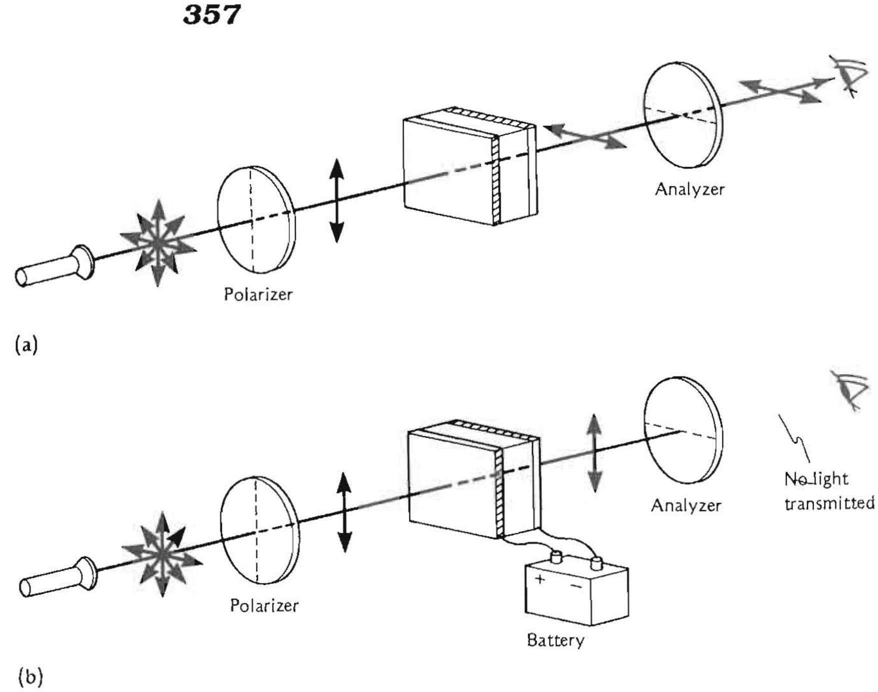


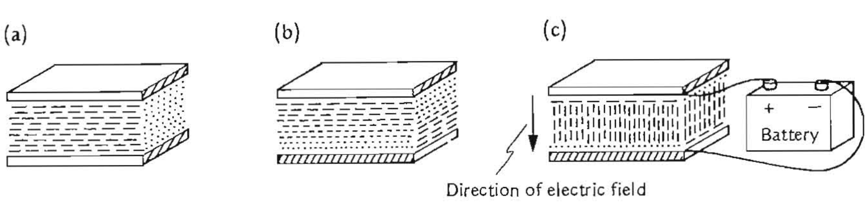
FIGURE 13.11

(a) A twisted nematic cell allows light to pass through a crossed polarizer and analyzer. **(b)** With an electric field applied between the plates of the cell, no light emerges from the analyzer.

Liquid crystals are liquid because their molecules move about within the liquid; they are crystals because their molecules orient themselves in an array. In one type of liquid crystal (called ***nematic***), all the molecules in a given layer are oriented parallel to each other and to the layer (Fig. 13.10a). The direction of orientation depends on the environment at the surface. For example, a piece of glass whose surface has been rubbed with a cloth or paper in a given direction will have microscopic grooves (a few atoms deep) in that direction. Nematic molecules adjacent to that surface of the glass will then orient themselves along these grooves. If the liquid crystal lies between *two* glass plates whose surfaces have been rubbed in a given direction, then all the molecules will lie oriented in that direction, as in the figure. If now one of the glass plates is rotated, the molecules closest to that plate will be rotated along with it, producing a twist in the layers of the molecules (Fig. 13.10b). If the thickness of this layer of liquid crystal is large compared with the wavelength of visible light, this ***twisted nematic cell*** is similar to a twisted stack of polarizing filters in the following sense—if light is polarized in the plane of the figure and incident on the top of the cell, it emerges from the bottom polarized perpendicular to the plane of the figure. However, if a battery of a few volts is connected to transparent conductors on the two plates, the molecules tend to line up parallel to the electric field—that is, perpendicular to the plates (Fig. 13.10c). Light incident on the top of the cell now will *not* have its polarization altered. If the battery is then disconnected, the molecules return to the alignment of Figure 13.10b.

FIGURE 13.10

(a) The elongated molecules of a nematic liquid crystal between two suitably prepared glass plates. **(b)** A twisted nematic cell: the same as **(a)**, but now the bottom plate has been rotated 90°, so the molecules of the liquid crystal closest to the bottom are now oriented perpendicular to the plane of the figure. **(c)** The same cell as in **(b)**, but with an electric field between the plates.



This cell thus provides a convenient switch for light. The cell is placed, suitably oriented, between a crossed polarizer and analyzer. When there is no electric field, light passes through the system (Fig. 13.11a). When the electric field is turned on, however, no light passes (Fig. 13.11b).

This arrangement is commonly used in display devices, such as the display in digital watches ***(liquid crystal displays, LCD's)***. In that case, the same set-up shown in the figure is used with a mirror after the analyzer. Thus, with no applied electric field, incident light is polarized vertically, say, by the polarizer, is rotated 90° by the cell, passes through the analyzer, is reflected by the mirror back through the analyzer (still polarized horizontally), is rotated 90° by the cell to become vertically polarized again, and passes back out through the polarizer. If you look at this display from the front, you see this reflected light, and the display looks bright. When the electric field is turned on, however, no light reaches the mirror and hence none is reflected—the display looks dark. If the electric field is applied only in certain regions that form the segments of a number, you see a dark number against a bright display. Figure 13.12 shows one way of controlling the location of the electric field to form numerals.

B. Pockels and Kerr cells

Certain solids, whose crystal structures are sufficiently asymmetric,