

The sheet's polarizing axis is vertical, so only vertically polarized light emerges.

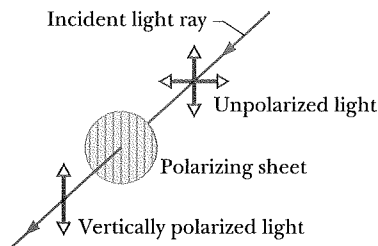



Fig. 33-11 Unpolarized light becomes polarized when it is sent through a polarizing sheet. Its direction of polarization is then parallel to the polarizing direction of the sheet, which is represented here by the vertical lines drawn in the sheet.

We can transform unpolarized visible light into polarized light by sending it through a *polarizing sheet*, as is shown in Fig. 33-11. Such sheets, commercially known as Polaroids or Polaroid filters, were invented in 1932 by Edwin Land while he was an undergraduate student. A polarizing sheet consists of certain long molecules embedded in plastic. When the sheet is manufactured, it is stretched to align the molecules in parallel rows, like rows in a plowed field. When light is then sent through the sheet, electric field components along one direction pass through the sheet, while components perpendicular to that direction are absorbed by the molecules and disappear.

We shall not dwell on the molecules but, instead, shall assign to the sheet a *polarizing direction*, along which electric field components are passed:

 An electric field component parallel to the polarizing direction is passed (*transmitted*) by a polarizing sheet; a component perpendicular to it is absorbed.

Thus, the electric field of the light emerging from the sheet consists of only the components that are parallel to the polarizing direction of the sheet; hence the light is polarized in that direction. In Fig. 33-11, the vertical electric field components are transmitted by the sheet; the horizontal components are absorbed. The transmitted waves are then vertically polarized.

Intensity of Transmitted Polarized Light

We now consider the intensity of light transmitted by a polarizing sheet. We start with unpolarized light, whose electric field oscillations we can resolve into *y* and *z* components as represented in Fig. 33-10*b*. Further, we can arrange for the *y* axis to be parallel to the polarizing direction of the sheet. Then only the *y* components of the light's electric field are passed by the sheet; the *z* components are absorbed. As suggested by Fig. 33-10*b*, if the original waves are randomly oriented, the sum of the *y* components and the sum of the *z* components are equal. When the *z* components are absorbed, half the intensity I_0 of the original light is lost. The intensity I of the emerging polarized light is then

$$I = \frac{1}{2}I_0 \tag{33-36}$$

Let us call this the *one-half rule*; we can use it *only* when the light reaching a polarizing sheet is unpolarized.

Suppose now that the light reaching a polarizing sheet is already polarized. Figure 33-12 shows a polarizing sheet in the plane of the page and the electric field \vec{E} of such a polarized light wave traveling toward the sheet (and thus prior to any absorption). We can resolve \vec{E} into two components relative to the polarizing direction of the sheet: parallel component E_y is transmitted by the sheet, and perpendicular component E_z is absorbed. Since θ is the angle between \vec{E} and the polarizing direction of the sheet, the transmitted parallel component is

$$E_y = E \cos \theta \tag{33-37}$$

Recall that the intensity of an electromagnetic wave (such as our light wave) is proportional to the square of the electric field's magnitude (Eq. 33-26, $I = E_{\text{rms}}^2/c\mu_0$). In our present case then, the intensity I of the emerging wave is proportional to E_y^2 and the intensity I_0 of the original wave is proportional to E^2 . Hence, from Eq. 33-37 we can write $I/I_0 = \cos^2 \theta$, or

$$I = I_0 \cos^2 \theta \tag{33-38}$$

Let us call this the *cosine-squared rule*; we can use it *only* when the light reaching

The sheet's polarizing axis is vertical, so only vertical components of the electric fields pass.

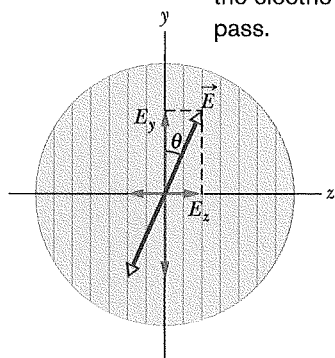


Fig. 33-12 Polarized light approaching a polarizing sheet. The electric field \vec{E} of the light can be resolved into components E_y (parallel to the polarizing direction of the sheet) and E_z (perpendicular to that direction). Component E_y will be transmitted by the sheet; component E_z will be absorbed.

a polarizing sheet is already polarized. Then the transmitted intensity I is a maximum and is equal to the original intensity I_0 when the original wave is polarized parallel to the polarizing direction of the sheet (when θ in Eq. 33-38 is 0° or 180°). The transmitted intensity is zero when the original wave is polarized perpendicular to the polarizing direction of the sheet (when θ is 90°).

Figure 33-13 shows an arrangement in which initially unpolarized light is sent through two polarizing sheets P_1 and P_2 . (Often, the first sheet is called the *polarizer*, and the second the *analyzer*.) Because the polarizing direction of P_1 is vertical, the light transmitted by P_1 to P_2 is polarized vertically. If the polarizing direction of P_2 is also vertical, then all the light transmitted by P_1 is transmitted by P_2 . If the polarizing direction of P_2 is horizontal, none of the light transmitted by P_1 is transmitted by P_2 . We reach the same conclusions by considering only the *relative* orientations of the two sheets: If their polarizing directions are parallel, all the light passed by the first sheet is passed by the second sheet (Fig. 33-14a). If those directions are perpendicular (the sheets are said to be *crossed*), no light is passed by the second sheet (Fig. 33-14b). Finally, if the two polarizing directions of Fig. 33-13 make an angle between 0° and 90° , some of the light transmitted by P_1 will be transmitted by P_2 , as set by Eq. 33-38.

Light can be polarized by means other than polarizing sheets, such as by reflection (discussed in Section 33-10) and by scattering from atoms or molecules. In *scattering*, light that is intercepted by an object, such as a molecule, is sent off in many, perhaps random, directions. An example is the scattering of sunlight by molecules in the atmosphere, which gives the sky its general glow.

Although direct sunlight is unpolarized, light from much of the sky is at least partially polarized by such scattering. Bees use the polarization of sky light in navigating to and from their hives. Similarly, the Vikings used it to navigate across the North Sea when the daytime Sun was below the horizon (because of the high latitude of the North Sea). These early seafarers had discovered certain crystals (now called cordierite) that changed color when rotated in polarized light. By looking at the sky through such a crystal while rotating it about their line of sight, they could locate the hidden Sun and thus determine which way was south.

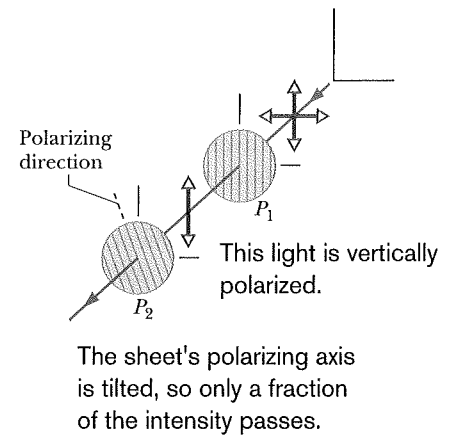
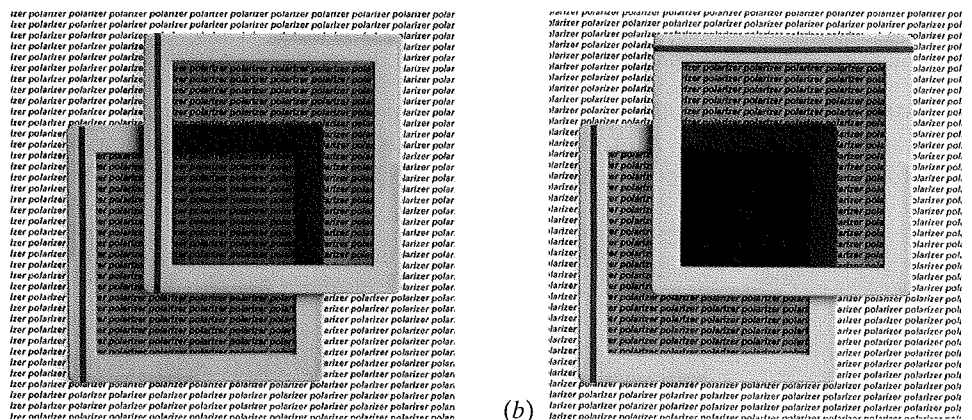


Fig. 33-13 The light transmitted by polarizing sheet P_1 is vertically polarized, as represented by the vertical double arrow. The amount of that light that is then transmitted by polarizing sheet P_2 depends on the angle between the polarization direction of that light and the polarizing direction of P_2 (indicated by the lines drawn in the sheet and by the dashed line).

Fig. 33-14 (a) Overlapping polarizing sheets transmit light fairly well when their polarizing directions have the same orientation, but (b) they block most of the light when they are crossed. (Richard Megna/Fundamental Photographs.)



CHECKPOINT 4

The figure shows four pairs of polarizing sheets, seen face-on. Each pair is mounted in the path of initially unpolarized light. The polarizing direction of each sheet (indicated by the dashed line) is referenced to either a horizontal x axis or a vertical y axis. Rank the pairs according to the fraction of the initial intensity that they pass, greatest first.

