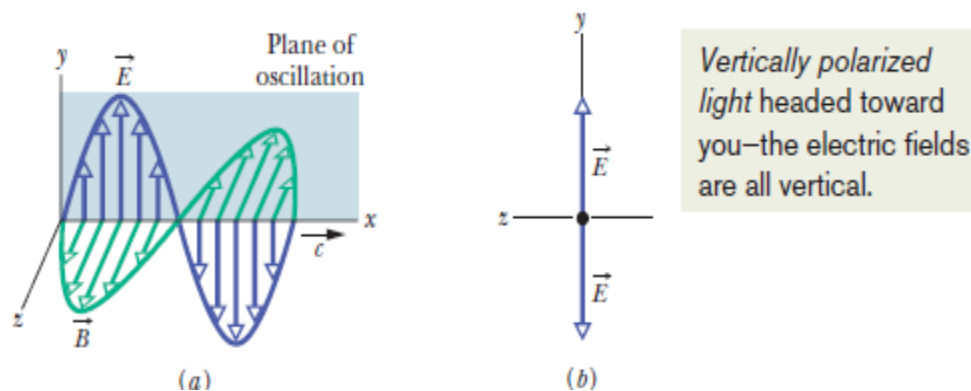


Polarization

Electromagnetic waves are polarized if their electric field vectors are all in a single plane, called the plane of oscillation. Light waves from common sources are not polarized; that is, they are unpolarized, or polarized randomly.

Figure *a* shows an electromagnetic wave with its electric field oscillating parallel to the vertical y axis. The plane containing the \vec{E} vectors is called the **plane of oscillation** of the wave (hence, the wave is said to be *plane-polarized* in the y direction). We can represent the wave's *polarization* (state of being polarized) by showing the directions of the electric field oscillations in a head-on view of the plane of oscillation, as in Fig. *b*. The vertical double arrow in that figure indicates that as the wave travels past us, its electric field oscillates vertically—it continuously changes between being directed up and down the y axis.



Polarized Light

The electromagnetic waves emitted by a television station all have the same polarization, but the electromagnetic waves emitted by any common source of light (such as the Sun or a bulb) are **polarized randomly**, or **unpolarized** (the two terms mean the same thing). That is, the electric field at any given point is always perpendicular to the direction of travel of the waves but changes directions randomly. Thus, if we try to represent a head-on view of the oscillations over some time period, we do not have a simple drawing with a single double arrow like that of above Fig. *b*; instead we have a mess of double arrows like that in below Fig. *a*.

In principle, we can simplify the mess by resolving each electric field of Fig. *a* into y and z components. Then as the wave travels past us, the net y component oscillates parallel to the y axis and the net z component oscillates parallel to the z axis. We can then represent the unpolarized light with a pair of double arrows as shown in Fig. *b*. The double arrow along the y axis represents the oscillations of the net y component of the electric field. The double arrow along the z axis represents the oscillations of the net z component of the

electric field. In doing all this, we effectively change unpolarized light into the superposition of two polarized waves whose planes of oscillation are perpendicular to each other—one plane contains the y axis and the other contains the z axis. One reason to make this change is that drawing Fig. b is a lot easier than drawing Fig. a .

We can draw similar figures to represent light that is **partially polarized** (its field oscillations are not completely random as in Fig. a , nor are they parallel to a single axis as in above Fig. b). For this situation, we draw one of the double arrows in a perpendicular pair of double arrows longer than the other one.

Polarizing Direction. We can transform unpolarized visible light into polarized light by sending it through a *polarizing sheet*.

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

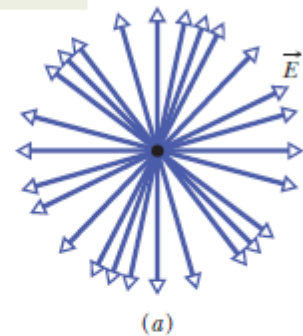
Thus, the electric field of the light emerging from the sheet consists of only the components that are parallel to the polarizing direction of the sheet; hence the light is polarized in that direction.

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

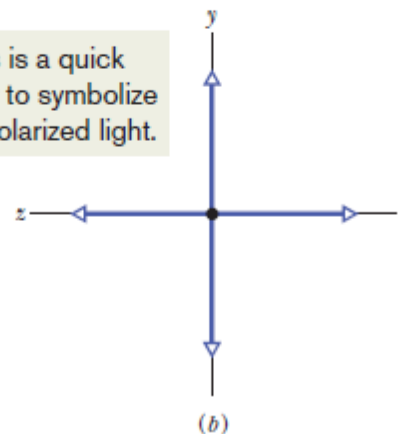
$$I = \frac{1}{2}I_0 \quad (\text{one-half rule}).$$

Let us call this the *one-half rule*; we can use it *only* when the light reaching a polarizing sheet is unpolarized. Recall that the intensity of an electromagnetic wave (such as our light wave) is proportional to the square of the electric field's magnitude. In our present case then, the intensity I of the emerging wave is proportional to and the intensity I_0 of the original wave is proportional to E_2 . Hence, we can write $I/I_0 = \cos^2\theta$, or

Unpolarized light headed toward you—the electric fields are in all directions in the plane.



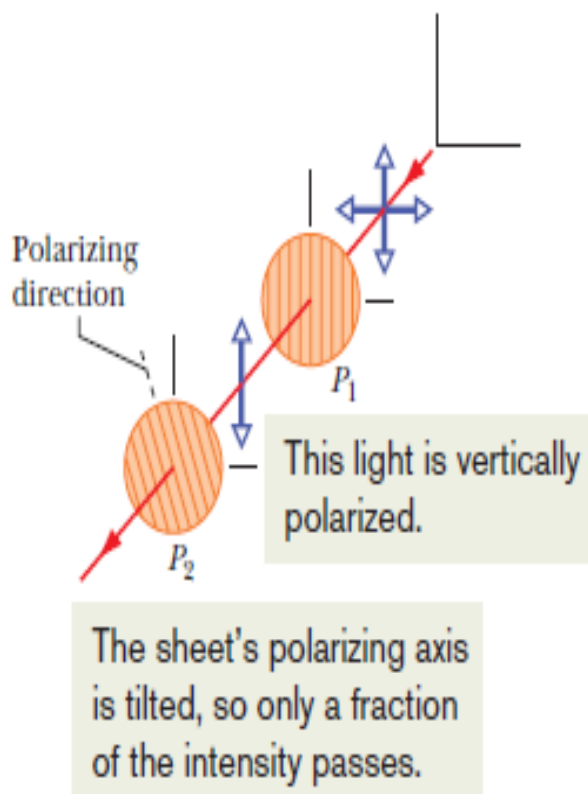
This is a quick way to symbolize unpolarized light.



$$I = I_0 \cos^2 \theta \quad (\text{cosine-squared rule}).$$

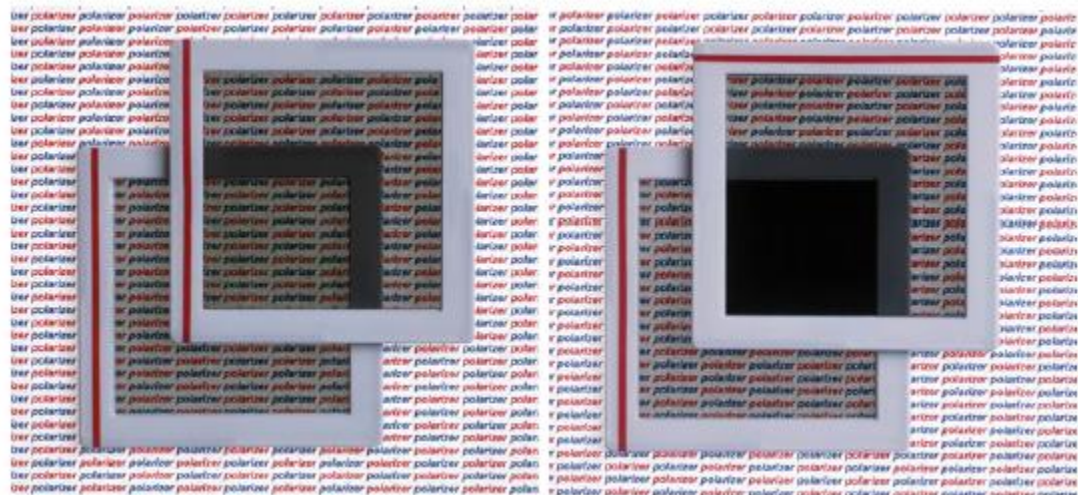
Let us call this the *cosine-squared rule*; we can use it *only* when the light reaching a polarizing sheet is already polarized. Then the transmitted intensity I is a maximum and is equal to the original intensity I_0 when the original wave is polarized parallel to the polarizing direction of the sheet (when θ in above equation 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°).

Two Polarizing Sheets. Figure 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. a). If those directions are perpendicular (the sheets are said to be *crossed*), no light is passed by the second sheet (Fig. b). Finally, if the two polarizing directions of Fig. above make an angle between 0° and 90° , some of the light

transmitted by P_1 will be transmitted by P_2 , as set by above equation.



(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.

Other Means. Light can be polarized by means other than polarizing sheets, such as by reflection 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.