10.1 Polarization of Light

Figure 1
This calcite crystal (shown in pink light) creates a double image.

Interference in Young's experiment was a crucial test for the wave theory of light, but it gave no clue to whether light waves are transverse or longitudinal. Recall that it is possible to produce a two-source interference pattern with longitudinal sound waves in air as well as transverse water waves in a ripple tank.

In 1669, the Danish scientist Erasmus Bartholinus found that when he directed a beam of light into a crystal of Iceland spar (calcite), the ray was split into two beams. This effect can be observed if a calcite crystal is placed over a written word. **Figure 1** shows that the two rays create a double image. What causes the light to split into two rays travelling along different paths?

Let us hypothesize that the vibrations in a light wave are transverse and that they go in all directions, perpendicular to the direction in which the light is travelling. If such a transverse wave were to pass through a filter that allowed the vibrations to occur only in one plane, then the wave would be **plane-polarized**. We can illustrate this with a mechanical model. Transverse waves generated in a rope that is moved, in rapid succession, first up and down, then horizontally sideways, are **unpolarized** transverse waves. If the rope passes through a vertical slit, the transmitted waves vibrate only up and down, in the vertical plane. If these vertically polarized waves encounter a second slit, this time horizontal, the energy is absorbed or reflected, and the wave transmission will be almost completely stopped (**Figure 2**). This behaviour is also true for light.

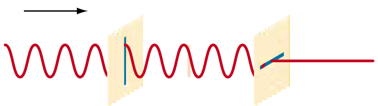

Figure 2
Vertically polarized waves in a rope are stopped almost completely by a horizontal polarizing slit.

Now that you have a basic understanding of **polarization**, we can study the effect of **polarizers**—natural and artificial—on light. How can the intensity of light be diminished or even appear to be cancelled? What type of wave is light, and how is light polarized by reflection and scattering? These are some of the questions we will be discussing.

plane-polarized a wave that can vibrate in one plane only

unpolarized a wave that vibrates in all directions perpendicular to the direction of travel

polarization confining the vibrations of a wave to one direction

polarizer a natural (e.g., clouds) or artificial (e.g., filters) means to achieve polarization

TRY THIS activity — Polaroid Sheets

1. Hold a Polaroid sheet up to a light and rotate it 180°.
2. Hold two sheets of Polaroid up together, so light passes through both. Keeping one fixed, rotate the other 180°.
3. Using a bright light, create some glare on a flat surface such as a lab desk. Look at the glare through a single Polaroid sheet. Rotate the sheet.
4. Hold the Polaroid sheet against various regions of a clear blue sky. Rotate the sheet each time.

Never look directly at the Sun, even with polarizing filters; they do not protect your eyes from the damaging ultraviolet and infrared radiation.

When light passes through a polarizing filter, the light waves are polarized in one plane. If the filter is oriented in such a way that the vibrations are horizontal, then we call the light horizontally polarized. If this horizontally polarized light falls on a second polarizing filter (the "analyzer") that polarizes light in the vertical plane, the light energy is almost completely absorbed (**Figure 3**). Such absorption occurs not just for vertical and horizontal orientations, but whenever the axes of the polarizing filters are at right angles to each other. When the axes of the two filters are parallel, the light polarized by the first filter passes through the second without further absorption (**Figure 4**).

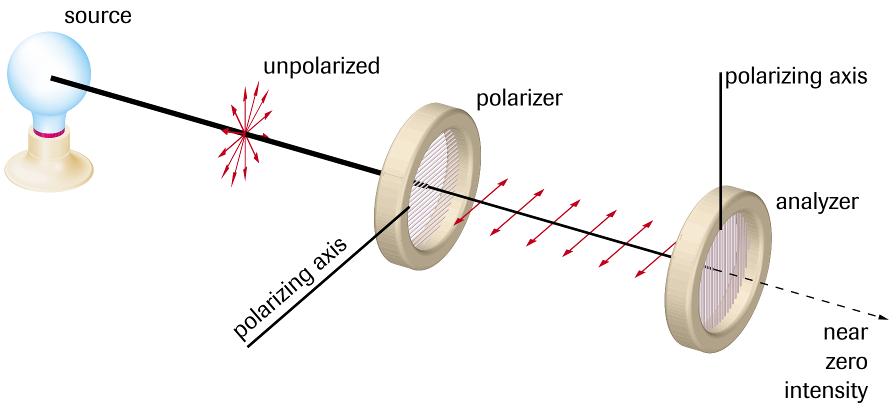

Figure 3
After horizontally polarized light passes through the analyzer, the light energy is reduced significantly

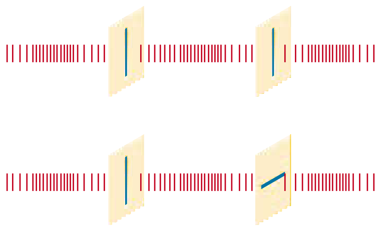

Figure 5
Longitudinal waves pass through polarizing filters unaffected.

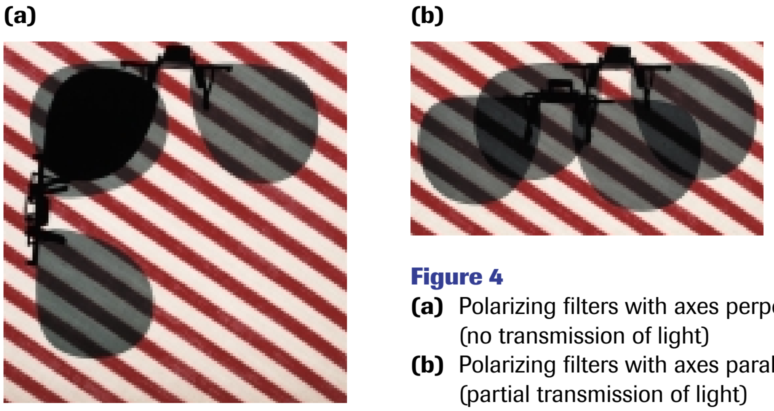

Figure 4
(a) Polarizing filters with axes perpendicular (no transmission of light)
(b) Polarizing filters with axes parallel (partial transmission of light)

Could these results be explained with longitudinal waves? If light travelled as a longitudinal wave, the vibrations could only be in only one direction, the direction in which the wave was travelling. Such a wave would pass through a pair of polarizing filters without being polarized (**Figure 5**). In other words, a longitudinal wave cannot be polarized. Light, which we have already decided behaves like a wave, must then behave like a transverse wave, not as a longitudinal wave.

Returning to the calcite crystal, why does it produce two beams? When a beam of unpolarized light strikes the calcite, it is separated by the crystal structure into two beams polarized at right angles, as in **Figure 6**, in a phenomenon called **double refraction**. Experimentally, it is found that one of the beams does not obey Snell's law in its simple form. For example, if **monochromatic** (i.e., light with only one wavelength) light with a wavelength of 590 nm strikes a calcite crystal, one beam behaves as though the crystal had a straightforward refractive index of 1.66, whereas the other beam behaves as though the crystal had a different index of refraction, varying from 1.49 to 1.66, depending on the angle of incidence. This difference suggests that the light beams travel through the crystal at different speeds, determined by the orientation of the planes within the crystal structure. The full explanation of the phenomenon, however, is too complex for us to consider in this text.

Polarization can be achieved four ways. The first is by double refraction, which we have just examined. The second is by reflection, when some absorption takes place at the point at which light is reflected off a smooth surface. Light waves reflected from a flat surface are partially polarized in the horizontal plane (**Figure 7**). Most glare comes from horizontal surfaces, such as a body of water, the hood of a car, or a paved road. The polarizing filters in Polaroid sunglasses are for this reason arranged in the vertical plane, reducing glare by absorbing the horizontally polarized light reflected from horizontal surfaces.

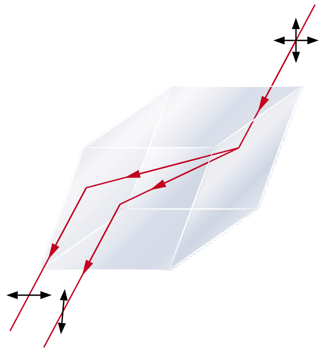

Figure 6
Polarization in a calcite crystal

double refraction the property of certain crystals (e.g., calcite) to split an incident beam of light into two

monochromatic of one colour, or one wavelength

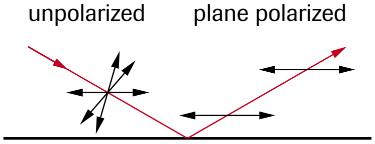

Figure 7
Light reflected by a nonmetallic surface is partially polarized in the horizontal plane.

DID YOU KNOW?

Rain, Radar, and Airplanes

Airplanes are the frequent targets of radar, but during the rain it can be difficult to separate the pulses from the reflected rain and the pulses from the reflected target. Because the reflected radar pulses from the target are polarized in a different way than those from the rain, polarizing filters at the radar station can be used to separate the "clutter" of the echoes of the rain from the real target, the airplane.

TRY THIS activity — Polaroid Sunglasses

Take a pair of Polaroid sunglasses and look at a shiny car in sunlight. Now rotate the lenses 90°. What do you see?

Never look directly at the Sun, even with polarizing filters; they do not protect your eyes from the damaging ultraviolet and infrared radiation.

The third way is through **scattering**. Light from the Sun passes through our atmosphere and encounters small particles that scatter the light. Scattering causes the sky to appear blue, since the shorter wavelengths (shades of violet and blue) are scattered more than the longer wavelengths (shades of orange and red). This scattering also causes the light to be polarized. You can demonstrate polarization by looking at the sky through a rotating Polaroid sheet or through polarized sunglasses. The amount of polarization depends on the direction in which you look, being greatest at right angles to the direction of light from the Sun (**Figure 8**). Photographers use Polaroid filters to enhance photographs of the sky and clouds. Since large stretches of the sky are significantly polarized, the polarizing filter makes the clouds more prominent by reducing the glare (**Figure 9**).

scattering the change in direction of particles or waves as a result of collisions with particles

The fourth method of polarizing is to use a polarizing filter. Calcite, tourmaline, and other naturally occurring polarizing crystals are scarce and fragile, keeping polarization a laboratory curiosity until 1928. In that year, Edwin Land developed the polarizing plastic he called **Polaroid**. Polaroid consists of long chains of polyvinyl alcohol impregnated with iodine, stretched so as to lie parallel to one another. (The original polarizer was made of microscopic, needle-like crystals of iodine.) Because Polaroid made it easy to produce polarized light, many everyday applications became feasible. Just as important, sheets of the new plastic could be used as convenient analyzers, making it easy to detect polarized light in nature and determine its plane of polarization.

Polaroid a plastic, light-polarizing material

Materials such as glass and Lucite (a transparent or translucent plastic), which become doubly refractive when subjected to mechanical stress, are said to have **photoelasticity**. When a photoelastic material is placed between polarizing and analyzing disks, the strain patterns (and thus the stress distributions) are revealed, as shown in **Figure 10**. Engineers analyzing stresses in objects such as trusses and gears build models in Lucite. When the models are placed under mechanical stress, areas of stress concentration are easily observable, allowing design changes to be made before the objects are constructed.

photoelasticity the property of a material that, when analyzed, reveals the material's stress distributions

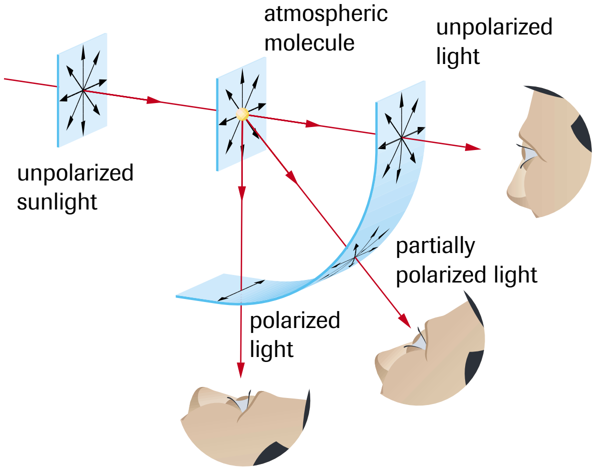

Figure 8
In being scattered from atmospheric particles, unpolarized light from the Sun becomes partially polarized.

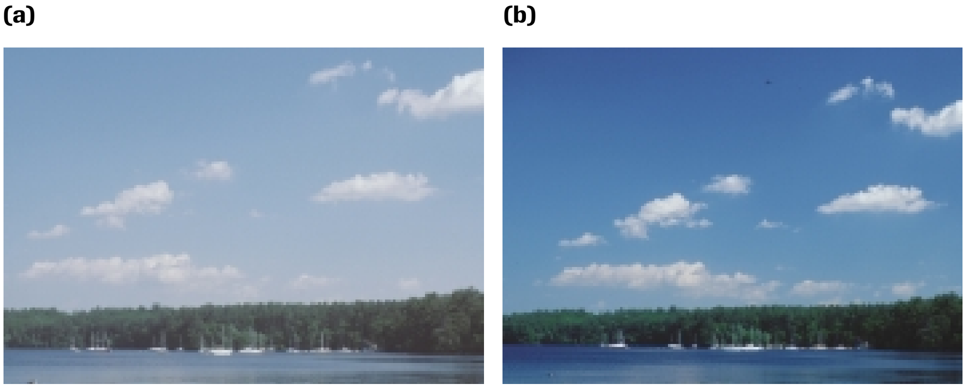

Figure 9
Cloud effects are enhanced when we add a polarizing filter to the camera.
(a) Without a filter
(b) With a polarizing filter

Polarization has been used to produce the illusion of three dimensions at the movies. Two overlapping pictures, shot by cinema cameras a few centimetres apart, in the manner of a pair of human eyes, are projected onto the theatre screen by a pair of projectors, each equipped with a Polaroid filter. The directions of polarization are chosen to be mutually perpendicular. The audience is provided cardboard-and-Polaroid spectacles, containing filters oriented to match the polarizing filters at the projector. The patron's left eye thus sees only the images taken in the film studio with the left-hand camera, the right eye only the images from the right-hand camera. Since the brain receives different left- and right-eye inputs, the screen looks like a window into a three-dimensional panorama.

To be able to detect polarized light, our eyes require an external polarizing filter. However, the eyes of certain creatures, for example, ants, horseshoe crabs, and spiders, are sensitive to polarized light; they use the polarized light from the sky, caused by scattering, as a navigational aid.

Many of the practical applications of polarization make use of the phenomenon of **optical activity**, the ability of some substances, such as sugar, turpentine, and insulin, to rotate the plane of polarization of a beam of light (**Figure 11**). Solutions of such substances rotate the plane of polarization in proportion to the concentration of the solution and to the length of the optical path through the substance. By placing a glass vessel between linear polarizers, we can measure the angle through which the plane of polarization has shifted, thereby obtaining a clue to the identity of the dissolved substance and the quantity present. The device used to measure the extent of polarization is called a *polarimeter*.

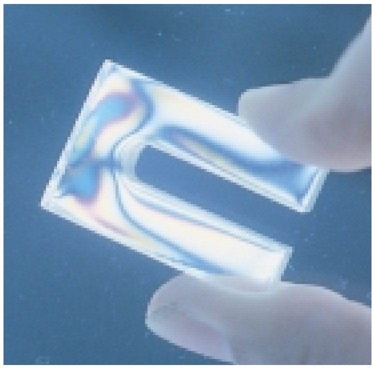

Figure 10
When placed between two polarizers, stresses on the Lucite are visible.

optical activity property of a substance whereby a transparent material rotates the plane of polarization of transmitted light

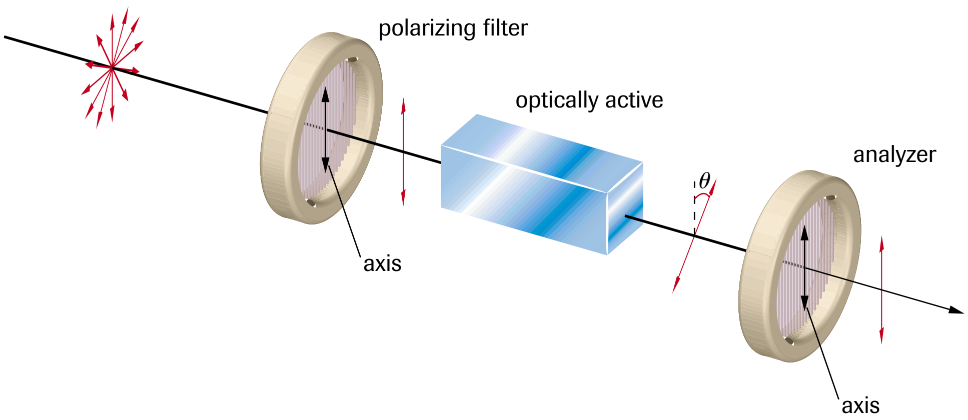

Figure 11
An analyzer reveals the ability of an optically active substance to rotate the plane of polarization.

DID YOU KNOW?

Edwin Land

Edwin Land (1909–1991) was an American physicist and inventor. Land became interested in polarized light while a freshman at Harvard University, in 1926. In his senior year, at the age of 19, he terminated his studies to found a laboratory near the university. With other young scientists, he applied the principles of polarization to various areas of optics, including filtering and cinematography. In 1948, the company he founded, the Polaroid Corporation, introduced the first model of its most successful product, the Polaroid Land camera for instant photography.

SUMMARY Polarization of Light

- Polarization of light can be achieved in the following ways: double refraction, reflection, scattering, and a polarizing filter.
- Polarization provided the proof that light is a transverse wave.
- Polaroid can be used to detect the presence of polarized light and the orientation of the plane of polarization.
- Scattering occurs when light from the Sun passes through our atmosphere and encounters small particles that scatter the light.
- Polarizing filters have many uses, including glare reduction, stress analysis, and photography.
- The optical activity of certain materials can be used to help identify some substances.

Section 10.1 Questions

Understanding Concepts

1. Briefly describe how each method of polarization polarizes light.
2. Explain how a pair of Polaroid sheets can be used to change the intensity of a beam of light.
3. Just before the Sun sets, a driver encounters sunlight reflecting off the side of a building. Will Polaroid sunglasses stop this glare?

Applying Inquiry Skills

4. Many sunglasses, advertised as polarizing, are not. Describe two different ways to test sunglasses for polarizing capabilities.
5. You have placed a calcite crystal over the letter A on an otherwise blank piece of paper and have rotated the crystal so that two images are produced. If you were to view the images through a Polaroid filter, rotating the filter slowly through 180°, what would you see? Explain your answer.

Making Connections

6. Using the Internet or other resources, research the liquid crystal displays (LCDs) common in electronic screens, such as calculator and digital wristwatch readouts. Write a short report explaining how LCDs use polarization.

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7. Using the Internet and print sources, research optical activity and polarimeters and answer the following questions:
   (a) The first general use of the polarimeter was in the sugar-beet industry, in the early 1900s. What was the polarimeter called at the time? Why was it such an important innovation for farmers?
   (b) In what industries is the polarimeter in common use today and for what purposes?

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