19. Certain anisotropic materials, such as calcite, show double refraction, splitting a beam of light into two rays; this shows that light waves are transverse.
    a. Explain polarization of light and its importance in wave optics.
    b. State and explain Brewster's law.
    c. Describe a simple experiment that shows the transverse nature of light.
    d. What are Polaroids, and how are they used to make polarized light?
    e. Unpolarized light falls on a transparent surface at the polarizing angle. If the refractive index of the material is 1.5, calculate the polarizing angle.

A companion to your textbook, not a replacement for it: study from the book your school uses, and where the two differ, follow your teacher. Found a mistake? Please tell us.

Unit 13

Polarization

This unit online, with its interactives:
science-playground.com/s/12f13

Put on a pair of polarized sunglasses and look at a lake, a wet road or a phone screen, then tilt your head. The glare on the water fades and comes back; the phone's screen goes dark at one tilt and bright at another. Nothing about the light's color or brightness tells you why. The answer is a property of light you can't see with the naked eye: the **direction in which it vibrates**.

Interference and diffraction showed that light is a wave. They can't say what kind of wave: sound, a longitudinal wave, interferes and diffracts too. This unit shows that light's vibrations are **across** its direction of travel, so light is a **transverse** wave, and that they can be sorted, by a filter or by reflection, into a single direction. That sorting is **polarization**.

A STORY FROM SCIENCE

A palace window seen through a crystal

One evening in 1808, the French army engineer **Étienne-Louis Malus** (1775–1812) stood at his window in Paris, looking at the setting sun reflected in the windows of the Luxembourg Palace across the street. He was holding a crystal of **Iceland spar** (calcite), which shows two images of anything seen through it. As he turned the crystal, one of the two images of the reflected sun grew faint and the other bright, and a quarter of a turn later they swapped.

Sunlight seen directly through the crystal doesn't do that. So the reflection had changed the light: it now had a direction of its own across the ray, which the crystal could "feel". Malus called it **polarization**, as if light's particles had poles like little magnets. The name stuck long after the idea of poles was dropped. A year later he found how much light gets through when the direction is turned, the rule now called **Malus's law**. He died of tuberculosis at 36, but in four years he had opened a new field of optics.



Figure 13.1 *Étienne-Louis Malus (1775–1812), who discovered polarization by reflection.*
Photo: Ambroise Tardieu, Public domain

13.1 Introduction

Interference and diffraction show that light behaves as a wave: two beams can overlap and cancel or add, and light bends round edges into patterns of bright and dark bands. But every wave does that, longitudinal or

transverse.

Polarization is different. It is something only **transverse** waves can do, so it is strong evidence that light is a transverse wave. In ordinary light the vibrations are across the ray in **all** directions; in **polarized** light they are in **one** direction only. A longitudinal wave, such as sound, vibrates along its direction of travel, so there is nothing across the ray to sort, and sound can't be polarized.

You have probably met polarization already, without the name:

1. **Polarized sunglasses** cut the glare from water and roads, but not the light from the rest of the scene.
2. **3D glasses** at the cinema send a different picture to each eye, though both pictures are on the same screen at once.
3. Two polarizing filters, one turned against the other, let through less and less light as one of them is turned, until almost none gets through.

All three use the same idea: light vibrates across its path, and we can choose which direction of vibration gets through.

Figure 13.2 shows the activity.

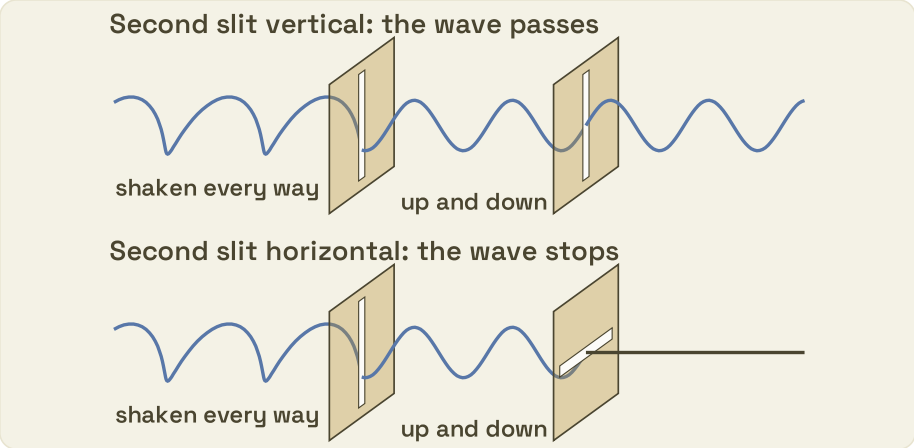


Figure 13.2 *A rope shaken in many directions passes through a vertical slit. Beyond it, the wave vibrates only up and down: it is polarized. A second vertical slit lets it through; a horizontal slit stops it.*

13.2 Polarized and unpolarized light

Light is an electromagnetic wave: an electric field and a magnetic field, at right angles to each other, both vibrating across the direction of travel. The **electric field** is the part that acts on the electrons in matter, in our eyes, in film, in filters, so the direction of light's vibration means the direction of its electric field, $\vec{E}$.

Unpolarized light has vibrations in **all directions** across the ray, changing at random many millions of times a second. Light from the sun, flames, bulbs and most LEDs is unpolarized: each atom sends out its light with its own direction, and the mixture has no favorite. Sunlight, a candle flame and a tube light all give unpolarized light.

Polarized light (in full, **plane-polarized** or **linearly polarized** light) vibrates in **one direction** only across the ray. It is made by passing unpolarized light through a polarizing filter, or by reflection from a surface such

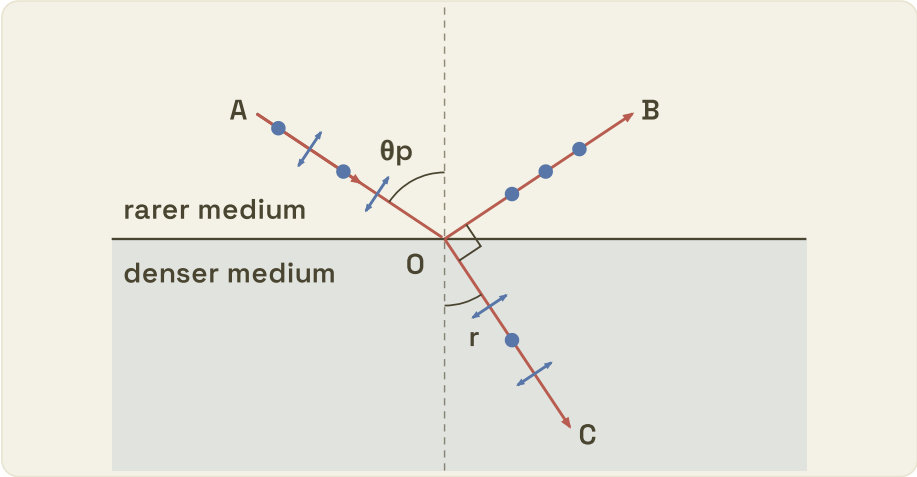


Figure 13.11 *Light reflected and refracted at the boundary between air (above) and a denser medium (below), at Brewster's angle. The reflected and refracted rays are at 90°.*

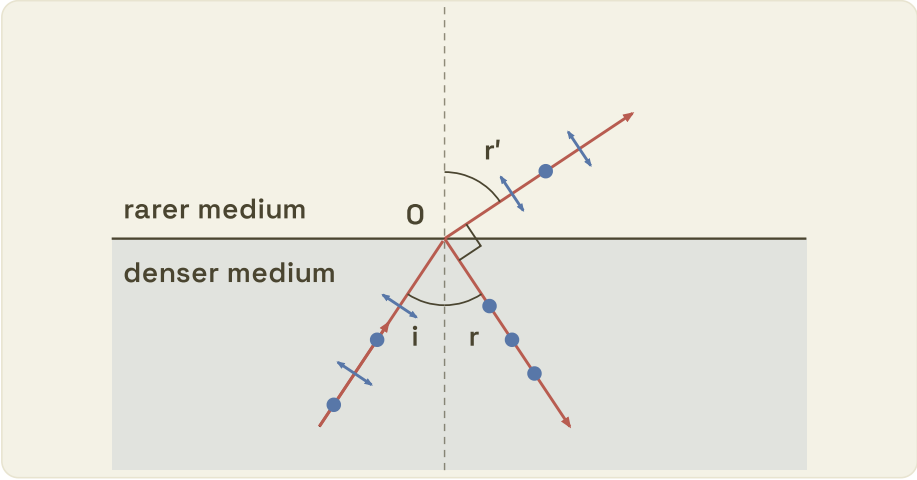


Figure 13.12 *Light going from a denser medium (below) into a rarer one (above), at the angle i at which the reflected and refracted rays are at 90°.*

13. Polarization is an important property of light waves: it shows that they are transverse, and has practical uses in optics.
    a. Define polarization of light.
    b. Differentiate between polarized and unpolarized light, with one example of each.
    c. A light ray falls on a glass surface at Brewster's angle, so the reflected ray is completely polarized and the reflected and refracted rays are at 90°. If the angle of refraction is 33.7°, calculate the refractive index of the glass and the angle of incidence.

14. Polarization of light shows that the direction of light's vibrations can be controlled, especially by reflection at particular angles.
    a. What is plane-polarized light?
    b. Explain polarization by reflection, with a suitable diagram.
    c. Light falls on a surface so that the angle between the reflected and refracted rays is 90°. If the angle of incidence is 56°, calculate:
    i. the refractive index of the medium,
    ii. the speed of light in that medium (take $c = 3 \times 10^8$ m/s).

15. Polaroids are optical devices that analyze and control the polarization of light, with important uses in reducing glare and improving contrast.
    a. What are Polaroids?
    b. Mention two practical applications of Polaroids in optics.
    c. Unpolarized light passes through two Polaroid sheets, one after the other.
    i. What happens to the intensity after the first Polaroid? Explain.
    ii. What happens if the second Polaroid's axis is perpendicular to the first? Why?
    iii. Describe what happens as the second Polaroid is slowly turned from perpendicular to parallel to the first. How does this show polarization?

16. When light is reflected at a particular angle, known as Brewster's angle, the reflected beam is completely polarized. This has important uses in optics.
    a. State Brewster's law and derive it.
    b. Using a diagram, explain why light reflected at Brewster's angle is completely polarized.
    c. State two practical uses of polarization in everyday life or technology.

17. Figure 13.11 shows light reflected and refracted at the boundary between a denser and a rarer medium.
    a. Define Brewster's angle and state its significance.
    b. Using the figure, explain why reflected light is completely polarized at Brewster's angle.
    c. If the refractive index of the denser medium is 1.5, calculate Brewster's angle.
    d. Unpolarized light falls on a glass slab so that the reflected light is completely polarized. If the refractive index of the glass is 1.66, calculate:
    i. Brewster's angle,
    ii. the angle between the reflected and refracted rays,
    iii. the speed of light in the glass.

as glass or water at a particular angle. Light from an LCD screen, and the glare reflected from a lake, are polarized (the glare partly, the screen almost wholly).

Between the two is **partially polarized** light, with more vibration in one direction than in the one at right angles to it. Light from the blue sky and light reflected from shiny non-metal surfaces is usually partially polarized.

Since we can't draw a wave vibrating in all directions at once, there is a shorthand (Figure 13.3). Looking along the ray, unpolarized light is a star of arrows, all equal. From the side, it is drawn as arrows across the ray (vibration in the page) and dots (vibration in and out of the page), in equal numbers. Polarized light is drawn as arrows only, or dots only.

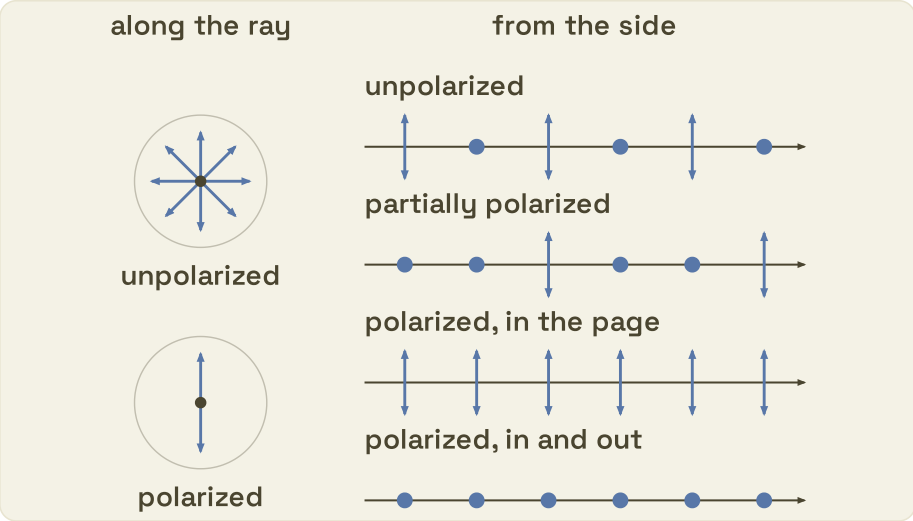


Figure 13.3 *How light is drawn. Left, looking along the ray: unpolarized light vibrates equally in all directions across the ray; polarized light in one. Right, from the side: arrows mean vibration in the plane of the page, dots vibration in and out of it. Unpolarized light has both, equally; partially polarized light more of one; polarized light only one.*

Polarized light is useful in many ways: polarizing sunglasses and camera filters cut glare; 3D films use it to show each eye its own picture; and scientists use it to study crystals, molecules and strains in materials.

Check 1
Which of these can't be polarized?

a light from a torch
b radio waves
c sound waves in air
d X-rays

13.3 Polarization of light waves

Polarization is the restricting of the vibrations of light to **a single direction** across the ray (a single plane through the ray). It can be done with a polarizing filter, by reflection, by scattering, and by some crystals.

The classic way, used since the early 1800s, is a pair of **tourmaline** crystals (Figure 13.4). Tourmaline is a semi-precious stone, a crystal that lets through light vibrating parallel to one direction in it (its **optic axis**) and absorbs nearly all the light vibrating at right angles to it.

1. Unpolarized light falls on the first crystal, called the **polarizer**. Only the vibrations parallel to its axis get through, so the light leaving it is **plane-polarized**. To the eye it looks the same, only dimmer (about half as bright, plus the crystal's own tint).
2. A second crystal, the **analyzer**, is placed after the first, with its axis **parallel** to the first one's. The polarized light vibrates along its axis, so it passes.
3. Now turn the analyzer slowly about the ray. Less and less light gets through, until, with its axis at **90°** to the polarizer's (**crossed**), **no light** comes through at all.
4. Keep turning: the light returns, and is brightest again at 180°.

The light leaving the polarizer looks just like ordinary light. Only the analyzer, turned, shows that it is different. This is why the second filter is called the **analyzer**: it tells whether light is polarized, and in which direction. Unpolarized light through one turning crystal gets through equally at every angle.

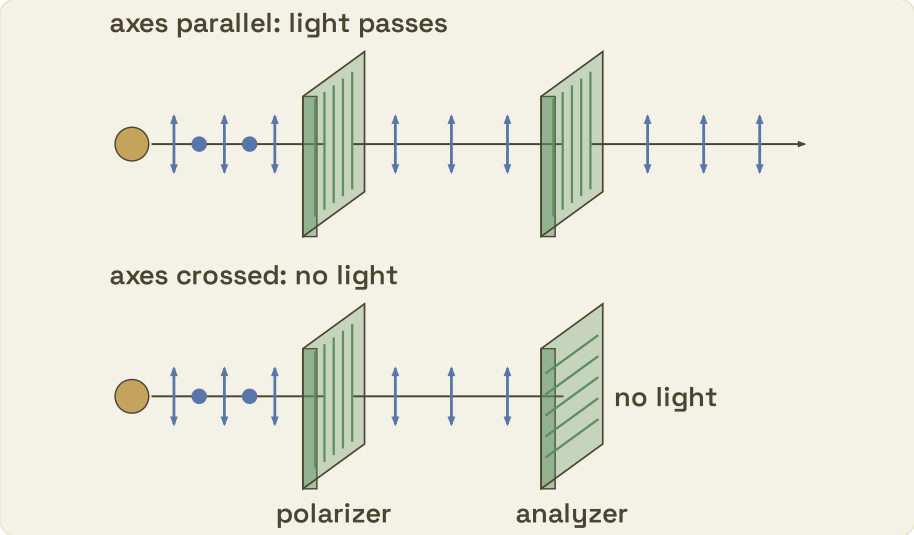


Figure 13.4 *Two tourmaline crystals. Top: axes parallel, the polarized light from the first passes the second. Bottom: axes crossed at 90°, the second crystal stops it.*

Malus's law

How much light gets through the analyzer at an angle in between? Malus found the rule in 1809. If polarized light of intensity I_0 falls on an analyzer whose axis is at an angle θ to the light's direction of vibration, only the part of the electric field along the axis, $E_0 \cos\theta$, gets through. Intensity goes as the square of the amplitude, so the light let through is

$$I = I_0 \cos^2\theta$$

This is **Malus's law**. At $\theta = 0$ all the light passes; at 90°, none; at 45°, half ($\cos^2 45^\circ = \frac{1}{2}$).

For **unpolarized** light falling on a single polarizer, the direction of vibration takes every angle equally, and the average of $\cos^2\theta$ over all angles is $\frac{1}{2}$. So an ideal polarizer lets through **exactly half** of unpolarized light, whichever way it is turned, and stops the other half.

Check 7

5. What happens at Brewster's angle?

a The angles of incidence and refraction are equal. b The reflected light is completely polarized.
c The light is completely absorbed. d There is no polarization.

Check 8

6. What is the angle of incidence for which reflected light is completely polarized at an air–glass surface, if the glass has a refractive index of 1.49?

a 55° b 56°
c 57° d 54°

Check 9

7. When reflected light is completely polarized at an air–glass surface, what is the angle between the reflected light and the refracted light?

a 45° b 180°
c 90° d 60°

Check 10

8. What is one application of polarization?

a sunglasses b optical fibers
c lasers d all of the above

Check 11

9. Which wave can't be polarized?

a sound wave b X-rays
c heat (infrared) waves d light waves

Check 12

10. What is the property of turning the plane of polarization called?

a dichroism b optical activity
c specific rotation d double refraction

Check 13

11. What is the polarizing angle of a crystal whose critical angle is 45°?

a $\tan^{-1}\sqrt{2}$ b $\tan^{-1}\dfrac{1}{\sqrt{2}}$
c $\sin^{-1}\sqrt{2}$ d $\sin^{-1}\dfrac{1}{\sqrt{2}}$

Check 14

12. What percentage of the intensity of unpolarized light is **not** transmitted by an ideal polarizing sheet?

a 25 % b 50 %
c 75 % d 90 %

Answer these questions

IN SHORT

In short

- **Polarization**, the restricting of light's vibrations to one direction across the ray, can happen only to **transverse** waves: it proves that light is transverse. Sound can't be polarized.
- **Unpolarized** light vibrates in all directions across the ray; **plane-polarized** light in one; partially polarized light more in one than the other.
- A **polarizer** makes polarized light; an **analyzer**, turned, tests it. Crossed (at 90°), they let no light through. **Malus's law:** $I = I_0 \cos^2\theta$; an ideal polarizer passes half of unpolarized light.
- The **plane of vibration** contains the vibration and the ray; the **plane of polarization** contains the ray and is at right angles to the plane of vibration.
- **Brewster's law:** at the polarizing angle, reflected light is completely polarized, the reflected and refracted rays are at 90° ($\theta_p + r = 90^\circ$), and $\mu = \tan\theta_p$.
- A **polaroid** is a stretched film of aligned chain molecules; it absorbs vibrations along the chains and passes those across them. Uses: sunglasses, cameras, 3D films, LCD screens, stress analysis.
- **Double refraction** (calcite) splits light into two rays polarized at right angles; **optically active** substances (sugar solutions, quartz) turn the plane of vibration.

Exercise

Choose the correct option

Check 3

1. What is polarization of light?

a bending of light
b change in frequency
c restricting light's vibrations to one plane
d reflection of light

Check 4

2. Which material is used as a polarizing filter?

a glass
b water
c Polaroid
d diamond

Check 5

3. In how many directions does plane-polarized light vibrate?

a all directions
b one direction
c two perpendicular directions
d no directions

Check 6

4. What happens to the transmitted light when the angle between the axes of two polarizers is 90°?

a The intensity becomes zero.
b The intensity is halved.
c The intensity remains the same.
d The intensity is doubled.

WORKED EXAMPLE

Example: two polarizers

Unpolarized light of intensity 40 W/m² passes through a polarizer, then an analyzer whose axis is at 60° to the polarizer's. Find the intensity of the light leaving each.

Answer

After the polarizer, half the unpolarized light gets through: $I_1 = \frac{1}{2} \times 40 = \mathbf{20\ W/m^2}$, now polarized along the polarizer's axis.
After the analyzer, by Malus's law: $I_2 = I_1 \cos^2 60^\circ = 20 \times (0.5)^2 = \mathbf{5\ W/m^2}$.

YOUR TURN

Three filters

Two polarizing filters are crossed, so no light gets through. A third filter is slipped **between** them, with its axis at 45° to both. Does any light now get through? If the light reaching the first filter is unpolarized, with intensity I_0, how much?

Hint

Work filter by filter: each one lets through $\cos^2$ of the angle between the light's vibration and its own axis, and the light leaving it vibrates along its axis.

Answer

Yes. After the first: $I_0/2$. After the middle one (45° from the first): $\frac{I_0}{2}\cos^2 45^\circ = I_0/4$, now vibrating at 45°. After the last (45° from the middle one): $\frac{I_0}{4}\cos^2 45^\circ = I_0/8$.
Adding a filter lets light through where there was none. The middle filter doesn't just remove light: it **turns the direction** of the light's vibration (by keeping only the part along its own axis), so the last filter is no longer at 90° to it.

13.4 Plane of vibration and plane of polarization

Polarized light vibrates in one direction across the ray. Two planes through the ray are named from it (Figure 13.5):

- The **plane of vibration** is the plane that contains the **direction of vibration** (the electric field $\vec{E}$) and the **direction of travel** of the light. The light vibrates in this plane.
- The **plane of polarization** is the plane that contains the direction of travel and is **perpendicular to the plane of vibration**. There is no vibration in it.

So the two planes both contain the ray, and they are at **right angles** to each other.

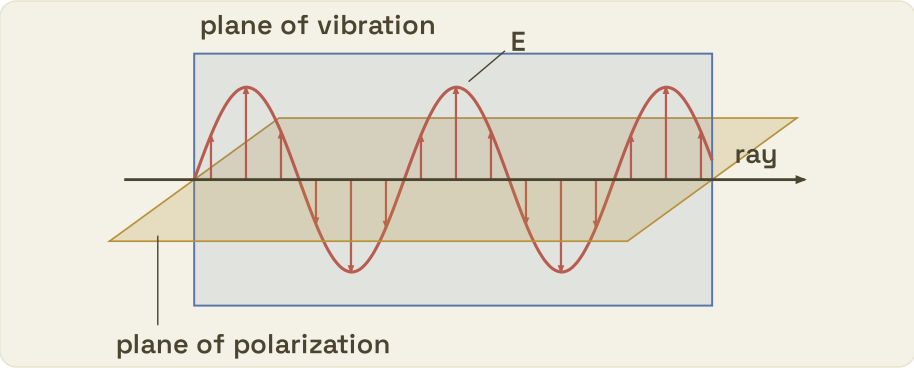


Figure 13.5 *Plane-polarized light travels along the ray, its electric field vibrating up and down. The plane of vibration contains the vibration and the ray; the plane of polarization contains the ray and is at right angles to the plane of vibration.*

CAREFUL

Which plane is which?

These names come from Malus's time, before anyone knew that light is an electric and magnetic field. His "plane of polarization" was the plane of reflection that made the light polarized, which turned out to be the plane **without** the electric field's vibration. Many modern books and the physics of lasers now use "the plane of polarization" for the plane that **contains** $\vec{E}$ and the ray, which is this section's plane of vibration. Both are in use. In an exam answer, use the classic pair given here, and draw it: the plane of vibration contains the vibration and the ray, and the plane of polarization is at right angles to it. Elsewhere, check how a writer uses the words.

13.5 Polarization by reflection: Brewster's law

In 1808, Malus discovered that light reflected from a transparent surface such as glass or water is **partially polarized**, and that how strongly depends on the angle of incidence. In 1815 the Scottish physicist **David Brewster** (1781–1868) found, by measuring many materials, that at **one particular angle** the reflected light is **completely** plane-polarized, and that at this angle the reflected and refracted rays are **at right angles** to each other. The angle is the **polarizing angle**, or **Brewster's angle**, θ_p.

Why does reflection polarize light? Unpolarized light falling on the surface can be thought of as two equal parts (Figure 13.6): one vibrating **perpendicular to the plane of incidence**, along the surface (drawn as dots), and one vibrating **in the plane of incidence** (drawn as arrows). The reflected ray is sent out by the electrons in the glass, set vibrating by the refracted light. An electron can't send light out along its own direction of vibration. At Brewster's angle the reflected ray is at 90° to the refracted ray, so it lies exactly along the direction in which the "arrow" vibrations in the glass move the electrons: that part can't be reflected at all. Only the "dot" part, vibrating along the surface, is reflected. The reflected light is completely polarized, vibrating parallel to the surface. The refracted light keeps all of the arrow part and most of the dot part: it is **partially** polarized.

Double refraction and optical activity

Two more effects of polarized light are worth knowing: calcite's double refraction (question 19) and optical activity (question 10) come up in the exercise, and both in any further study of light.

Double refraction

Some crystals, such as **calcite** (Iceland spar, Malus's crystal) and quartz, split a ray of light into **two** rays, refracted by different amounts. Look through a clear calcite crystal at a line of print and you see it **twice**. This is **double refraction**, or **birefringence**.

- One ray obeys Snell's law with a fixed refractive index (1.66 in calcite): the **ordinary ray**, or **o-ray**.
- The other has a refractive index that depends on its direction in the crystal (1.49 to 1.66 in calcite), and doesn't obey Snell's law in general: the **extraordinary ray**, or **e-ray**.

Both rays are **plane-polarized**, with their vibrations **at right angles** to each other. Turn an analyzer in front of the crystal and one image fades as the other brightens, just as Malus saw. A **Nicol prism**, two pieces of calcite cemented so that one ray is reflected out of the way, was the standard way to polarize light for a century before polaroids.

Optical activity

Some substances **turn the plane of vibration** of polarized light passing through them. They are called **optically active**, and the property **optical activity**. Quartz does it, and so do solutions of many substances whose molecules come in left- and right-handed forms, such as **sugar**: cane sugar turns the plane to the right (clockwise, looking towards the source), fructose to the left.



Figure 13.10 *A calcite crystal on lined paper: the red line under it is seen twice, once by the ordinary ray and once by the extraordinary ray.*
Photo: The High Fin Sperm Whale, CC BY-SA 3.0

The angle turned is proportional to the length of the solution the light passes through and to its concentration, so measuring it (with a **polarimeter**: polarized light, the tube of solution, and an analyzer turned until the light is darkest) gives the **concentration** of sugar in a solution. Sugar factories and laboratories testing medicines use it. The angle for a 1 dm tube and a concentration of 1 g/mL is the substance's **specific rotation**.

DID YOU KNOW?

Why polarization proves light is transverse

A filter, a crystal or a reflection that behaves differently when **turned about the ray** must be acting on something across the ray. A longitudinal wave is the same from every side, so turning a filter about it can't change anything. Thomas Young saw this in 1817, and with Fresnel concluded that light's vibrations are purely transverse, a claim that waited fifty years for Maxwell's electromagnetic theory to explain.

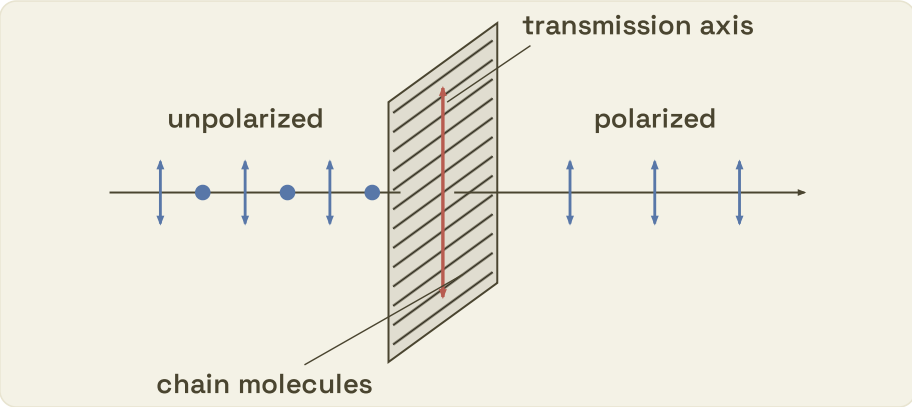


Figure 13.8 *A polaroid's long, stretched chain molecules (horizontal here) absorb the part of the light vibrating along them. The light that comes out vibrates at right angles to the chains, along the transmission axis.*

CAREFUL

The chains are not the slits

The rope in Activity 13.1 passes a slit **along** its length, so it is easy to think a polaroid lets through light vibrating **along** its chains. It does the opposite: the chains absorb the vibrations along them. The transmission axis is **across** the chains. (A grid of wires does the same to radio waves and microwaves: it reflects or absorbs the part along the wires and passes the part across them.)

3. **3D films.** The two pictures, for the left and right eye, are projected through polarizing filters of different kinds onto a screen that keeps polarization; each lens of the glasses lets through one picture only.
4. **LCD screens** (phones, calculators, watches): the liquid crystal sits between two polaroids and turns the light's plane of vibration, or doesn't, pixel by pixel; the second polaroid turns that into light and dark.
5. **Optical instruments**: polarizing microscopes show the structure of rocks, crystals and fibers in bright colors.
6. **Stress analysis** (photoelasticity): a clear plastic model of a part, between crossed polaroids, shows colored fringes where it is strained, so engineers can see where it would break.
7. **Window glass** that controls how much light comes in (two polaroids, one turned).

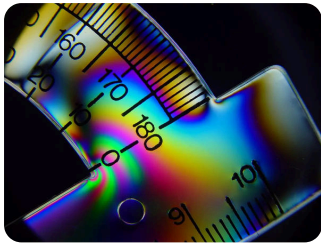


Figure 13.9 *A plastic protractor between crossed polaroids. The colors show where the plastic was left strained when it was molded.*

Photo: Nevit Dilmen, CC BY-SA 3.0

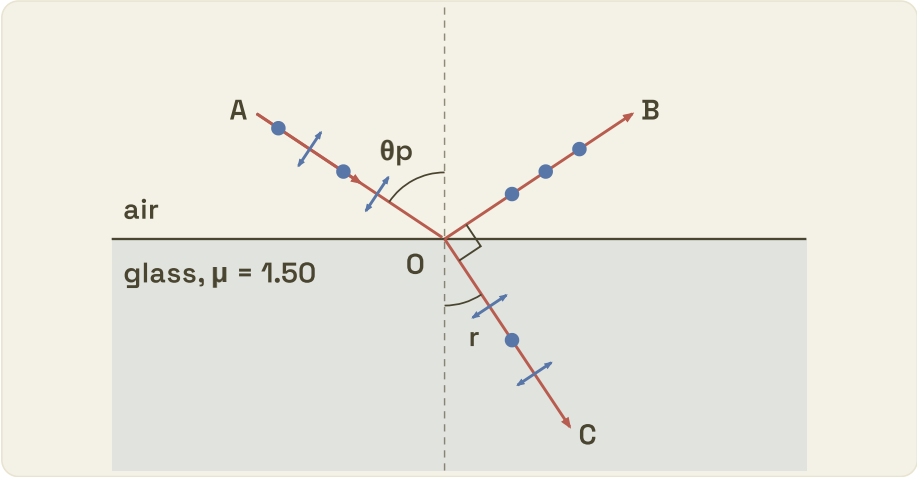


Figure 13.6 *Polarization by reflection at Brewster's angle, for glass of refractive index 1.50. Unpolarized light AO falls at θp = 56.3°. The reflected ray OB is completely polarized, vibrating at right angles to the plane of incidence (dots only). The refracted ray OC, at r = 33.7°, is partially polarized. OB and OC are at 90°.*

Brewster's law

Let unpolarized light AO fall at O on the surface of a transparent medium of refractive index μ, at the polarizing angle θ_p (Figure 13.6). It is refracted along OC at the angle r, and reflected along OB, completely polarized.

1. By Snell's law,
$$\mu = \frac{\sin\theta_p}{\sin r} \qquad (13.1)$$
2. At the polarizing angle, the reflected and refracted rays are at right angles. The angle of reflection is θ_p, so along the surface $\theta_p + 90^\circ + r = 180^\circ$, that is,
$$\theta_p + r = 90^\circ, \qquad r = 90^\circ - \theta_p$$
3. Put this in (13.1): $\sin r = \sin(90^\circ - \theta_p) = \cos\theta_p$, so
$$\mu = \frac{\sin\theta_p}{\cos\theta_p}$$
$$\mu = \tan\theta_p \qquad (13.2)$$

The refractive index of a medium equals the tangent of its polarizing angle. This is **Brewster's law**. For glass ($\mu = 1.50$), $\theta_p = \tan^{-1} 1.50 = 56.3^\circ$; for water ($\mu = 1.33$), 53.1°.

If the light goes from a medium of refractive index μ_1 into one of μ_2, the same steps give $\tan\theta_p = \mu_2/\mu_1$ (the refractive index of the second medium relative to the first, ${}_1\mu_2$).

CAREFUL

Only at one angle, and only the reflected light

Reflected light is **completely** polarized only at Brewster's angle; at other angles it is partially polarized (at 0° and near 90° hardly at all). And at Brewster's angle only about 15 % of the light vibrating along the surface is reflected from glass; most of the light goes into the glass. So the refracted light is only **partially** polarized, even at Brewster's angle. A **pile of plates**, ten or so glass sheets one behind the other at Brewster's angle, reflects away a little more of the "dot" part at each surface, so the light coming through the pile is nearly completely polarized.

Uses of Brewster's law

1. **Polarizing sunglasses and filters.** Glare from water, roads and windows is reflected light, strongly polarized along the surface (horizontally, for a lake or a road). Polarized sunglasses have their transmission axis **vertical**, so they block the glare but let through the rest of the scene.
2. **Photography.** A polarizing filter on a camera, turned to the right angle, removes reflections from water and shop windows, and darkens a blue sky.
3. **Lasers.** The windows at the ends of a gas laser's tube are set at Brewster's angle: light vibrating in the plane of incidence passes them with no loss by reflection at all, so the laser builds up that light, and its beam comes out polarized.
4. **Measuring refractive index.** Finding the angle at which reflected light is completely polarized gives $\mu = \tan\theta_p$, even for an opaque material that light can't be sent through.
5. **Studying surfaces.** How light reflected from a surface is polarized shows the thickness of thin films on it, such as an oxide layer on a silicon chip.



Figure 13.7 *A harbor photographed with a polarizing filter turned to block the most light (left) and turned to block the least (right). The filter cuts the polarized light scattered by the hazy blue sky and the glare on the roofs, so the sky is deeper and the clouds stand out.*

Photo: Angus MacRae from Nottingham, England, CC BY 2.0

WORKED EXAMPLE

Example 13.1: the angle of refraction

A beam of light falls at the polarizing angle on a piece of transparent material of refractive index 1.62. What is the angle of refraction of the transmitted beam?

Answer

$\mu = 1.62$. By Brewster's law, $\tan\theta_p = \mu$, so $\theta_p = \tan^{-1} 1.62 = \mathbf{58.3°}$.
At the polarizing angle, $\theta_p + r = 90^\circ$, so $r = 90^\circ - 58.3^\circ = \mathbf{31.7°}$.

WORKED EXAMPLE

Example 13.2: from water into glass

Calculate the polarizing angle for light going from water (refractive index 1.33) into glass (refractive index 1.53).

Answer

$\mu_w = 1.33$, $\mu_g = 1.53$. The refractive index of glass relative to water is ${}_w\mu_g = \mu_g/\mu_w$, so

$$\tan\theta_p = \frac{\mu_g}{\mu_w} = \frac{1.53}{1.33} = 1.150$$

$$\theta_p = \tan^{-1} 1.150 = \mathbf{49.0°}$$

Less than in air (56.8° for this glass), because water and glass are more alike than air and glass.

YOUR TURN

Test yourself 13.1

The refractive index of a certain glass is 1.66. At what angle of incidence is light reflected from its surface completely polarized, if the glass is in (a) air, (b) water of refractive index 1.33?

Answer

a. $\theta_p = \tan^{-1} 1.66 = \mathbf{58.9°}$.

b. $\tan\theta_p = \dfrac{1.66}{1.33} = 1.248$, so $\theta_p = \mathbf{51.3°}$.

Check 2

Light reflected from a lake at Brewster's angle is completely polarized. In which direction does it vibrate?

a horizontally, parallel to the water's surface
b vertically, in the plane of incidence
c along the reflected ray
d in all directions equally

13.6 Polaroids

A **Polaroid** is a thin plastic sheet that polarizes light, invented by the American **Edwin Land** in 1929 (as a student, aged 19) and improved by him in 1938 into the **H-sheet** still used today. Unlike a tourmaline crystal, it can be made cheaply in large sheets of any size.

An H-sheet is made from a film of **polyvinyl alcohol** (PVA), a plastic whose molecules are long chains. The film is warmed and **stretched**, which lines up its long chains in one direction, and then dipped in iodine. The iodine sticks along the chains, making them conduct electricity along their length, like millions of tiny parallel wires (Figure 13.8).

When light falls on the sheet:

- The part of the electric field **parallel to the chains** drives electrons along them. It loses its energy to them and is **absorbed**.
- The part **perpendicular to the chains** can't move the electrons far across a chain, so it passes through.

So the light that comes out is **plane-polarized**, vibrating **at right angles to the chains**. That direction is the sheet's **transmission axis** (its pass axis). A polaroid lets through about 40 % of unpolarized light: less than the ideal 50 %, because it absorbs a little of the light it is meant to pass. Its slight gray tint comes from that.

Uses of polaroids

1. **Sunglasses** with vertical transmission axes, to cut horizontally polarized glare from water, snow and roads.
2. **Camera filters**, to remove reflections and darken the sky.