Lectures: Physics 3306

Provides an introduction to a wide variety of topics in classical (pre-quantum) physics as a bridge to prepare students for subsequent upper-level courses in physics. The topics covered include thermodynamics, fluid mechanics, mechanical waves, optics, radiation, electromagnetic phenomena, atoms, and laboratory techniques. Prerequisites: C- or better in PHYS 1106; and in PHYS 1304 or PHYS 1308.

Saptaparna Bhattacharya

April 24th, 2026

Based on Simon Dalley's lectures taught in Spring 2025

Labs

Lectures

Schedule

No class

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
January	19	20	21 ✅	22	23 ✅	24	25
	26 ❄️🌨️❄❄❄	27	28 ❄️🌨️❄❄❄	29	30 ✅	31	1
February	2 ✅	3	4 ✅	5	6 ✅	7	8
	9 ✅	10	11 HWB due ✅	12	13 ✅	14	15
	16 ✅	17	18 ✅	19	20 HWC due ✅	21	22
	23 Hegi Center ✅	24	25 HWD due ✅	26	27 ✅	28	1
March	2 ✅	3	4 HWE due	5	6 ✅	7	8
	9 ✅	10	11	12	13 Midterm	14	15
	16	17	18	19	20	21	22
	23 ✅	24	25	26	27 ✅	28	29
April	30 Lecture 11 ✅	31	1 HWF due	2	3	4	5

Labs

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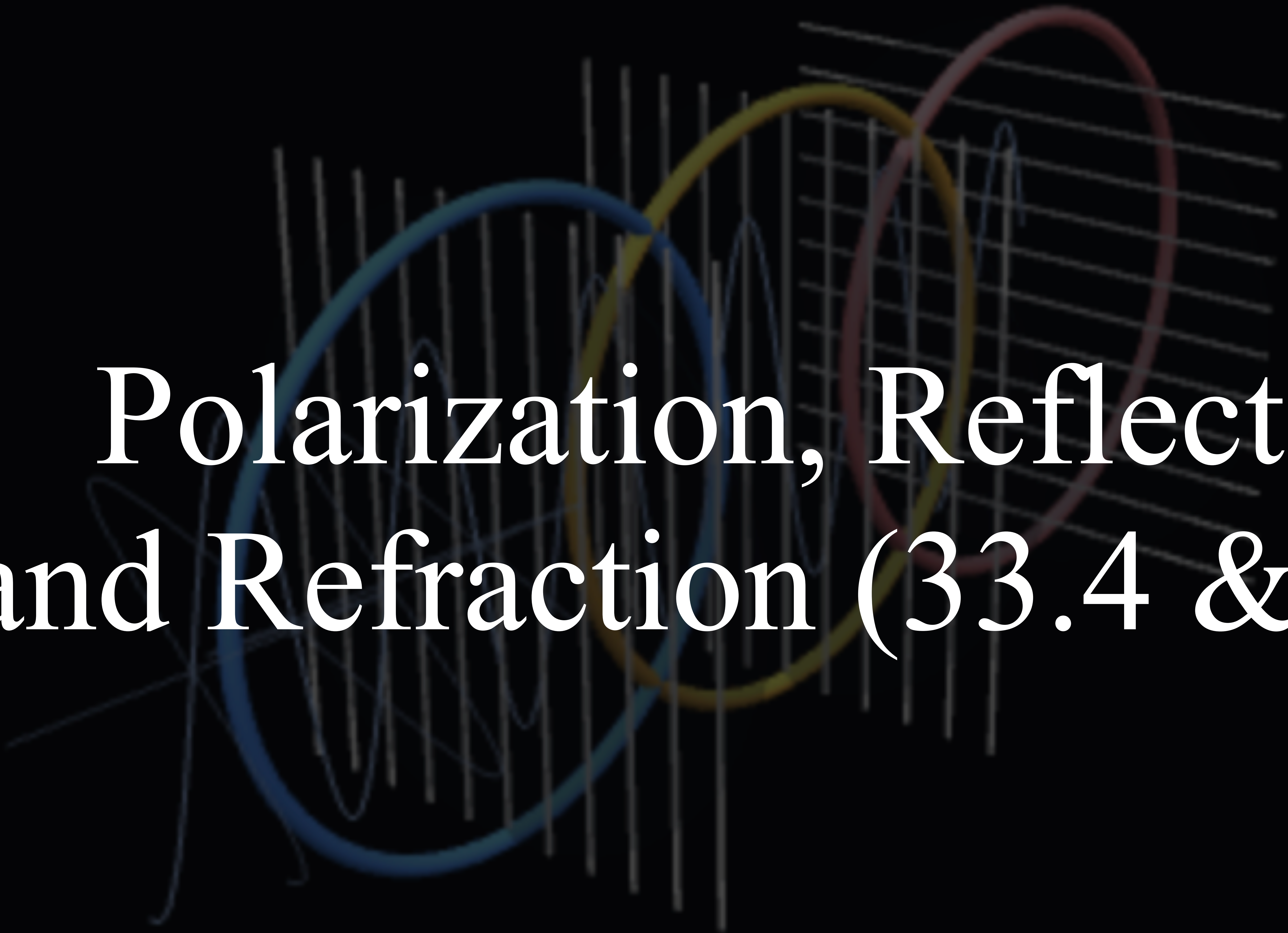
No class

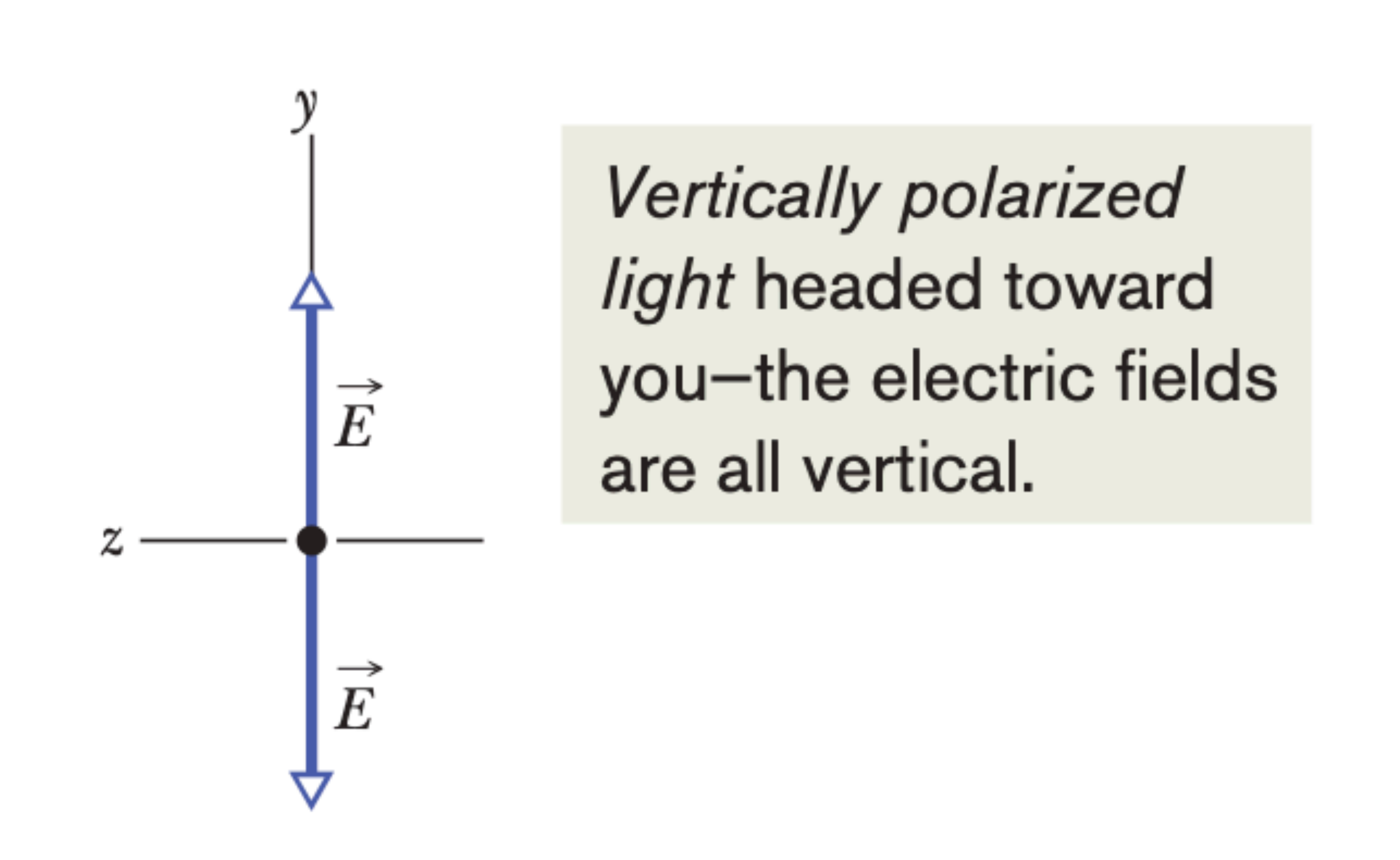
Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
April	6 Midterm 2 ✅	7	8 HWG due	9	10 Lecture 15 ✅	11	12
	13 Lecture 16 ✅	14	15 HWH due	16	17 Lecture 17 ✅	18	19
	20 Lecture 18 ✅	21	22 HWI due	23	24 Lecture 19	25	26
May	27 Lecture 20	28	29 HWJ due	30	1 Lecture 21	2	3
	4 Lecture 22	5 Lecture 23	6	7	8	9	10

Polarization, Reflection, and Refraction (33.4 & 33.7)

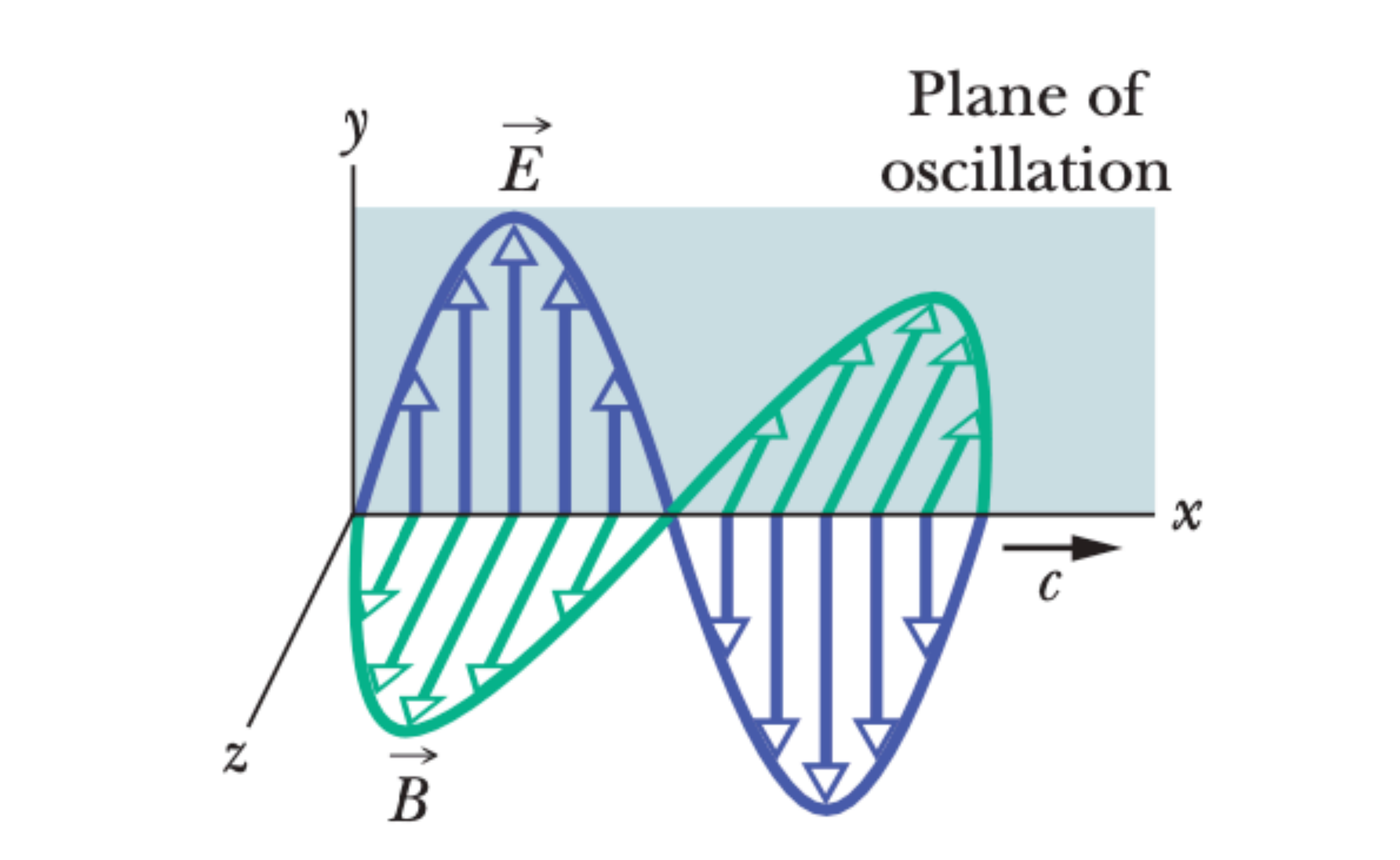


Key concepts: Polarization

- Plane of oscillation:
  - The plane containing the $\vec{E}$ vectors is called the plane of oscillation



(b)



(a)

Key concepts: Polarization

- 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

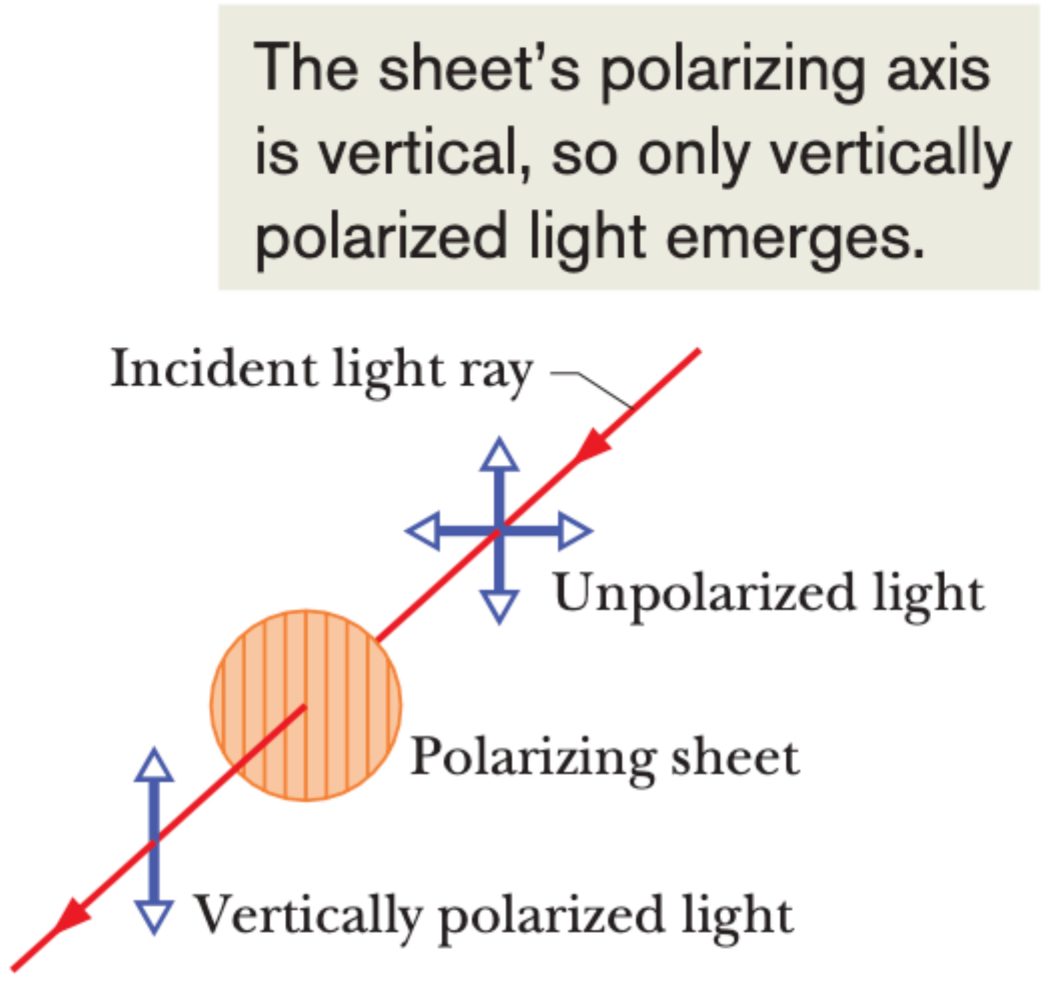


Figure 33-11 Unpolarized light becomes polarized when it is sent through a polarizing sheet. Its direction of polarization is then parallel to the polarizing direction of the sheet, which is represented here by the vertical lines drawn in the sheet.

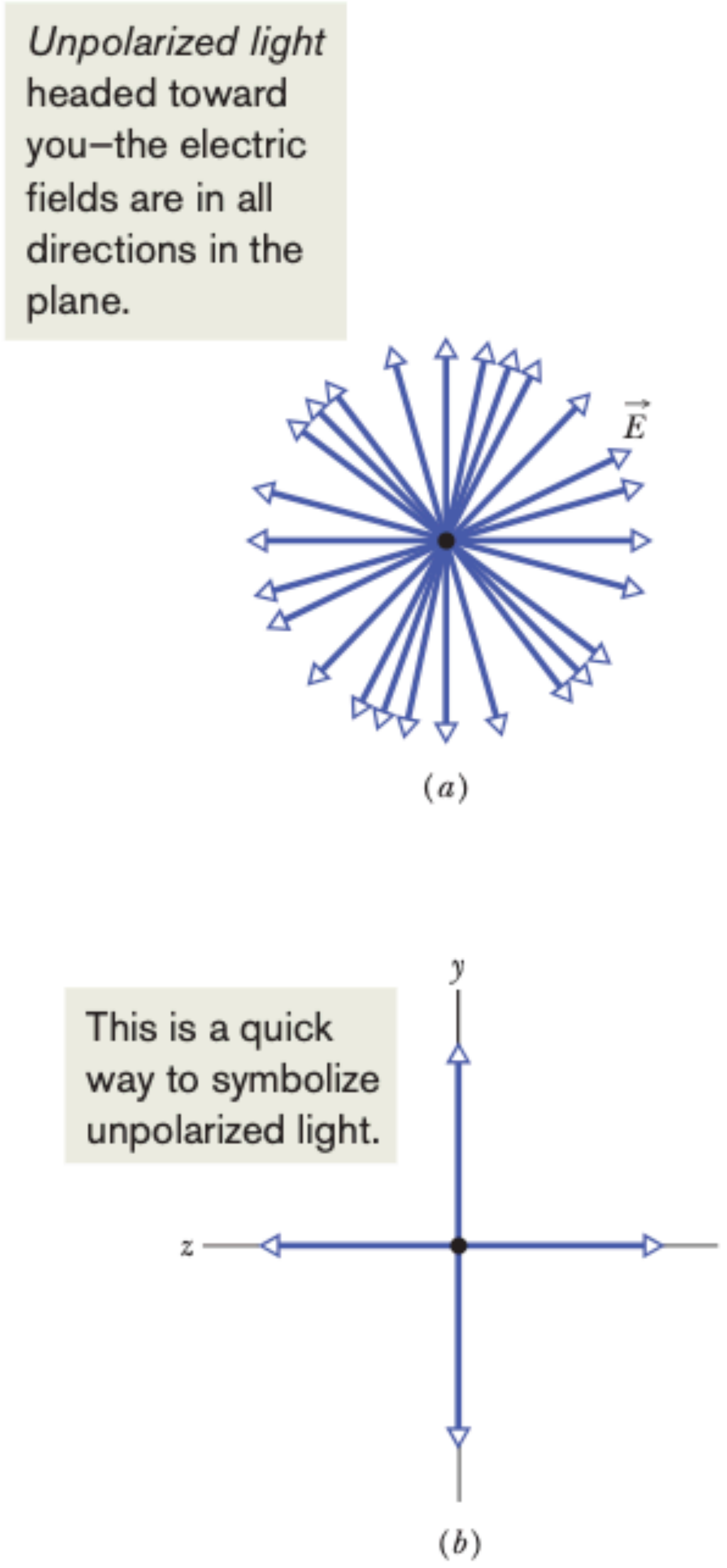


Figure 33-10 (*a*) Unpolarized light consists of waves with randomly directed electric fields. Here the waves are all traveling along the same axis, directly out of the page, and all have the same amplitude E. (*b*) A second way of representing unpolarized light—the light is the superposition of two polarized waves whose planes of oscillation are perpendicular to each other.

Key concepts: Polarization

- 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:
  - $I = \frac{1}{2} I_0$
- Let us call this the *one-half rule;* we can use it *only* when the light reaching a polarizing sheet is unpolarized

Key concepts: Polarization

- If the light is polarized:
  - Transmitted parallel component is:
    - $E_y = E\cos\theta$
  - Recall that the intensity of an electromagnetic wave (such as our light wave) is proportional to the square of the electric field's magnitude
    - $I = E_{\mathrm{rms}}^2 / c\mu_0$
    - $I \propto E_y^2$
    - $I \propto I_0 \cos^2\theta$

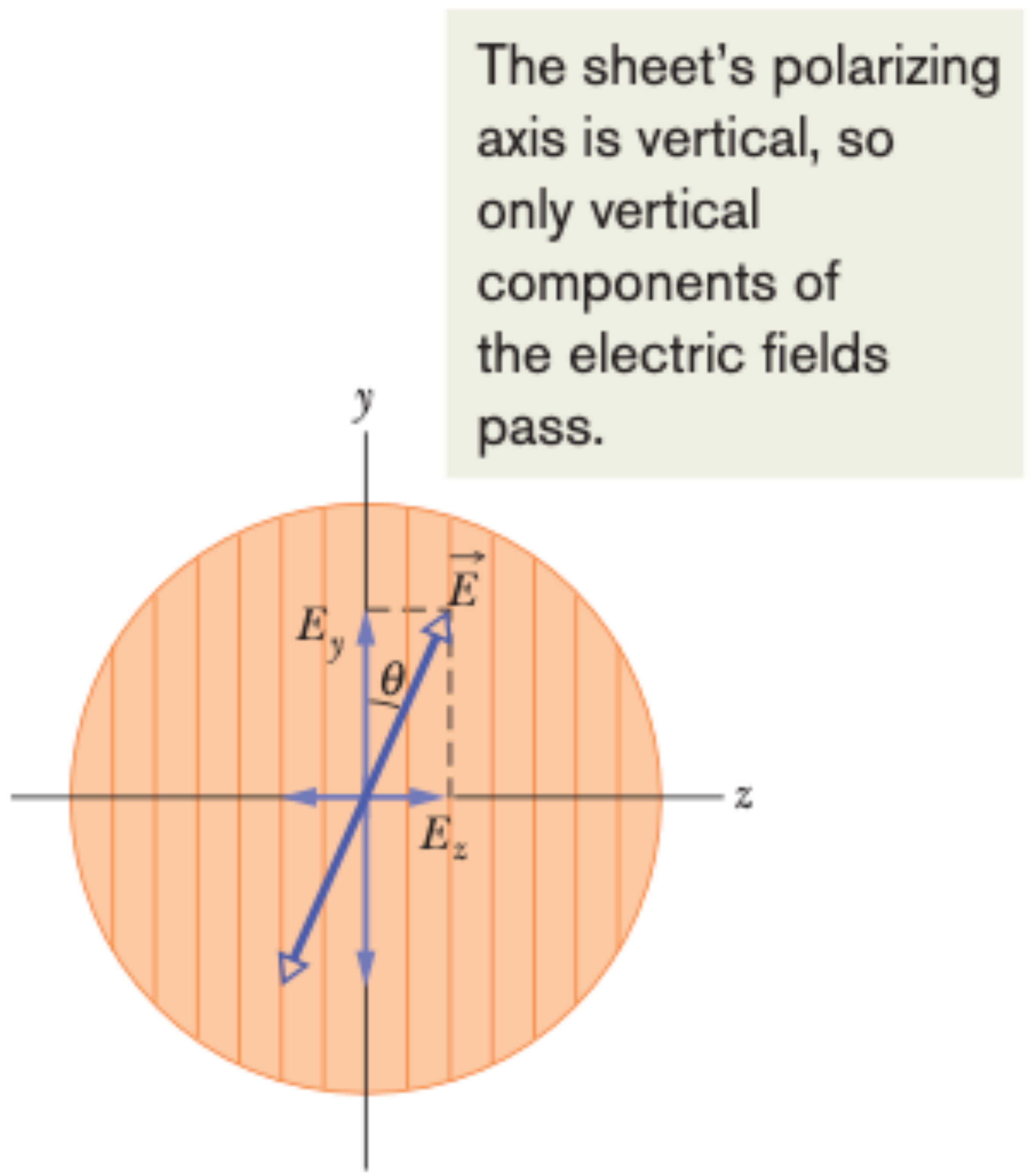


Figure 33-12 Polarized light approaching a polarizing sheet. The electric field $\vec{E}$ of the light can be resolved into components E_y (parallel to the polarizing direction of the sheet) and E_z (perpendicular to that direction). Component E_y will be transmitted by the sheet; component E_z will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

Key concepts: Polarization

- Two polarizing sheets
- 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 navi- gate 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.

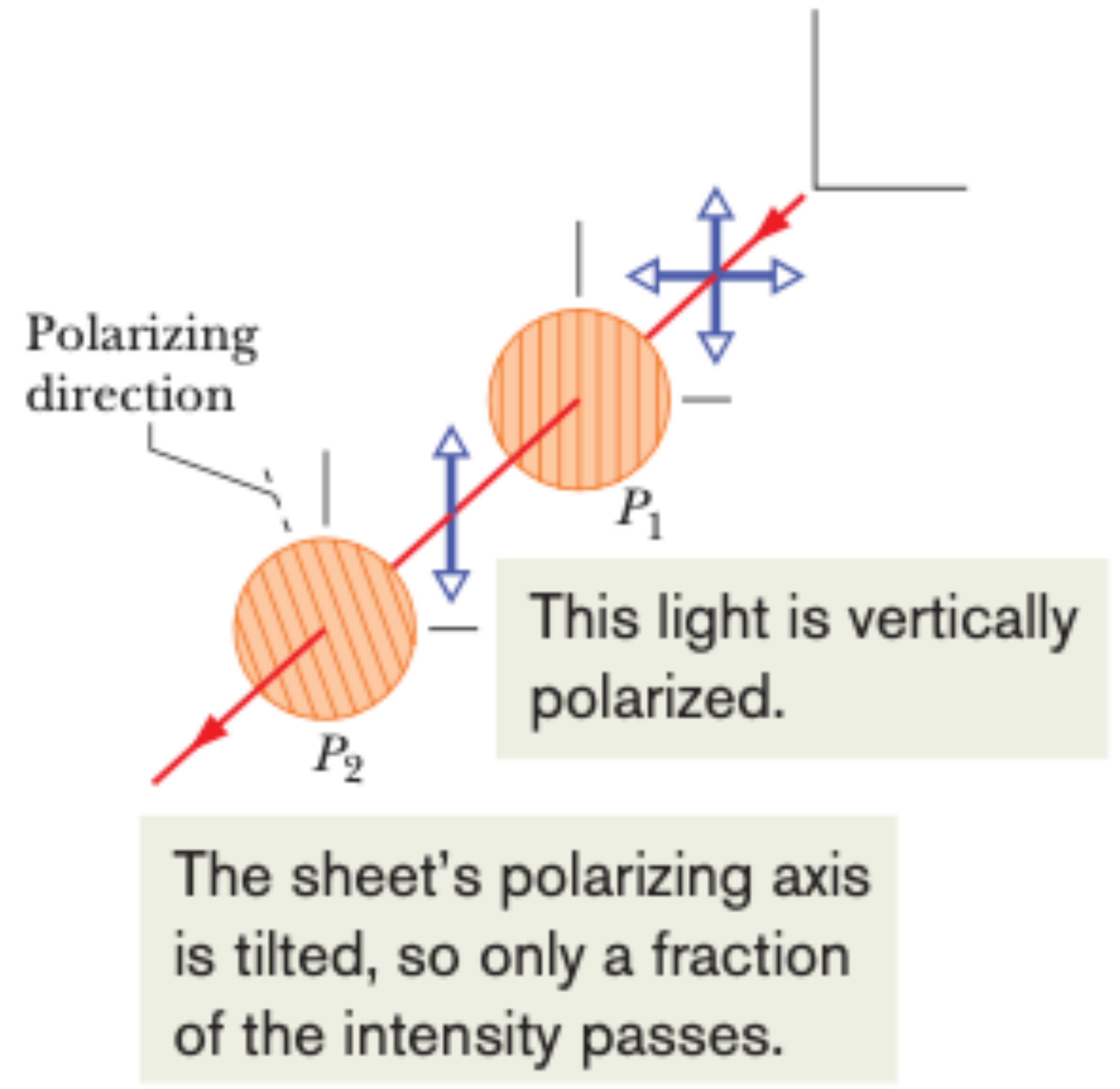
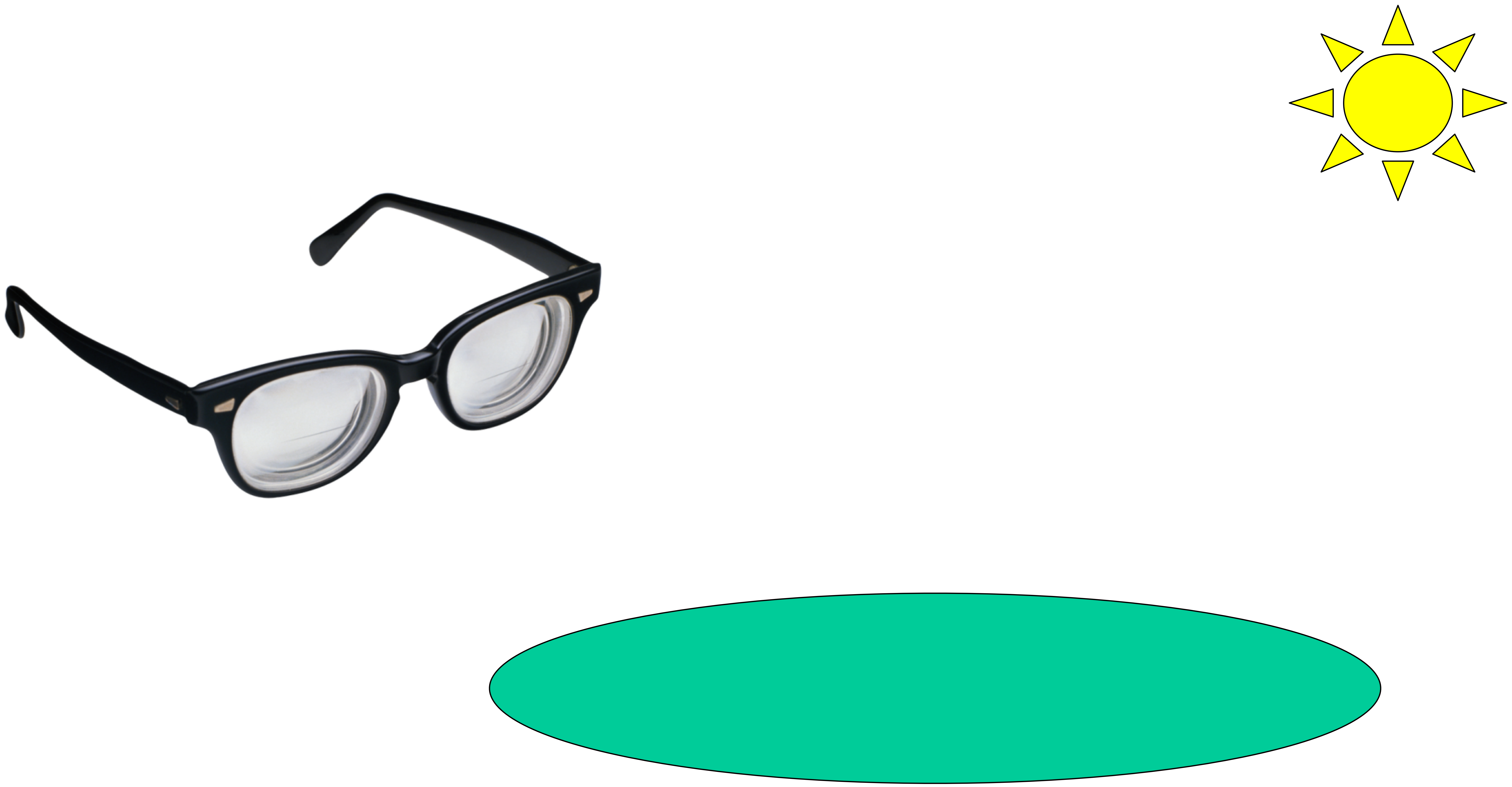
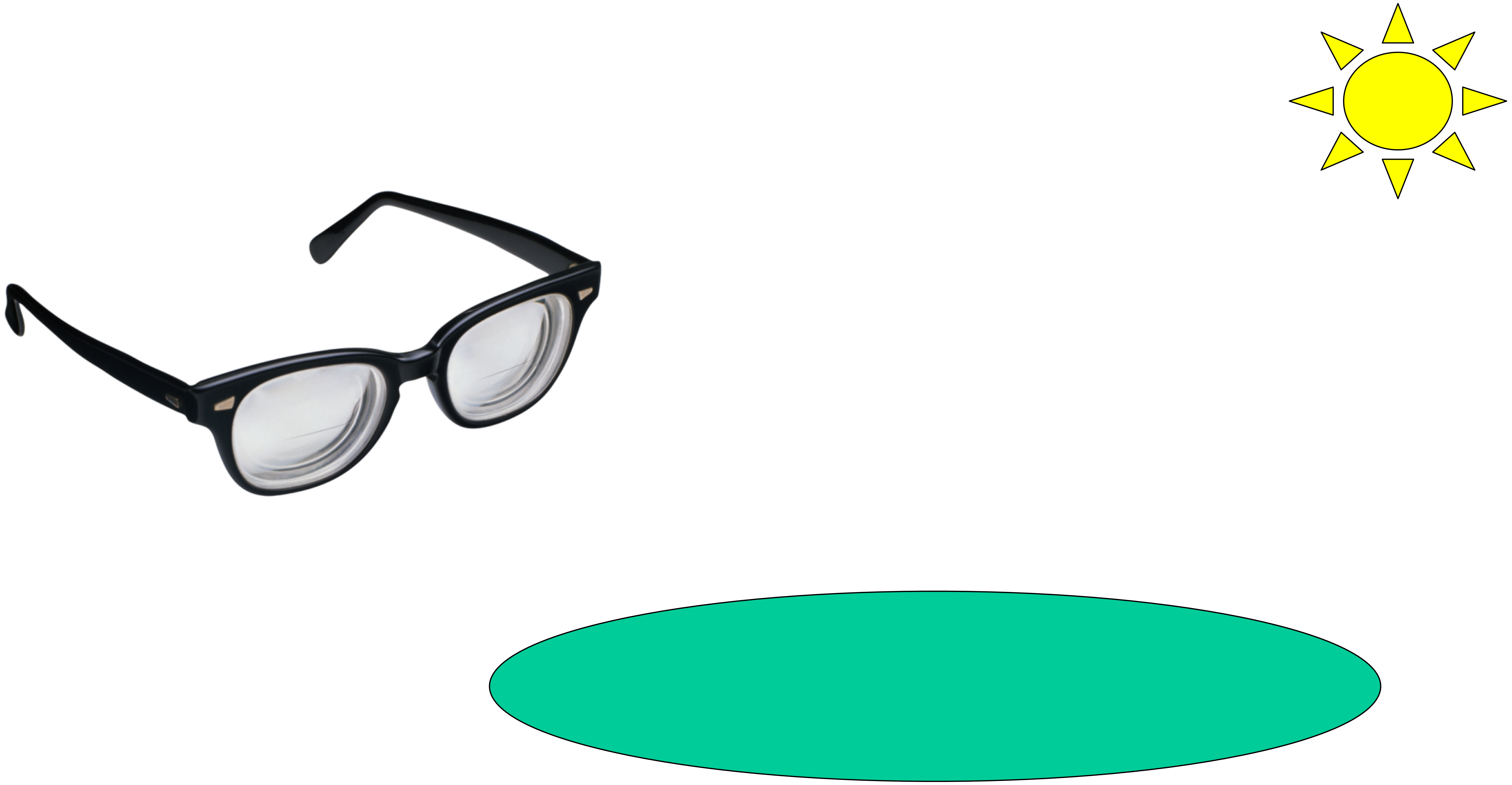


Figure 33-13 The light transmitted by polarizing sheet P_1 is vertically polarized, as represented by the vertical double arrow. The amount of that light that is then transmitted by polarizing sheet P_2 depends on the angle between the polarization direction of that light and the polarizing direction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



To reduce glare off the lake, should the polarization axis of these sunglasses be

A)Vertical B) Horizontal C) Makes no difference



To reduce glare off the lake, should the polarization axis of these sunglasses be

A) Vertical   B) Horizontal   C) Makes no difference

The correct answer is **A) Vertical**.

Explanation

When unpolarized sunlight reflects off a flat, horizontal surface like a lake, the physics of the reflection changes the light's properties. The reflected light becomes partially or fully polarized in the **horizontal** direction (parallel to the surface of the water). This concentrated, horizontally polarized light is what we perceive as harsh glare.

To effectively eliminate this glare, polarized sunglasses are manufactured with a **vertical** transmission axis. Here is how they interact with the light:

- **Targeting the Glare:** Because the filter's axis is vertical, it acts as a microscopic picket fence that blocks the horizontally oscillating light waves reflecting off the lake.
- **Allowing Ambient Light:** The glasses still allow vertically polarized light (and the vertical components of unpolarized ambient light) to pass through, ensuring you can still clearly see your surroundings.

If the sunglasses had a horizontal polarization axis, they would actually transmit the glare rather than block it.

Reducing the glare from a lake

Suppose you have light going through two crossed polarizers.

What will happen if a third polarizer is placed in between the two with polarization angle of 45° ?

A) nothing will change

B) the transmitted light will decrease

C) the transmitted light will increase

D) the transmitted light will go to zero

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This is one of the most famous and counterintuitive experiments in classical optics! It feels like adding *more* filters should block *more* light, but polarization doesn't work like standard light dimming.

Here is the step-by-step breakdown of why this happens:

1. The Initial State (Crossed Polarizers)

Imagine the first polarizer is oriented vertically (0 deg). It blocks all horizontal light and only lets vertical light through. The second polarizer is "crossed," meaning it is oriented horizontally (90 deg). Because the light reaching it is 100% vertical, the horizontal polarizer blocks it completely.

- **Result:** 0% of the light gets through.

2. Inserting the Middle Polarizer

Now, you insert a third polarizer in the middle at a 45 angle.

- **Step 1:** Unpolarized light hits the first polarizer (0 deg). The light that passes through is now perfectly vertical.
- **Step 2:** That vertical light hits the new middle polarizer (45 deg). Here is the trick: a vertical wave actually has a *diagonal component*. The middle polarizer absorbs the perpendicular component but allows the 45◦ diagonal component to pass.
- **Step 3:** The light is now polarized diagonally at 45 deg This diagonal light hits the final horizontal polarizer (90◦). Because diagonal light has both a vertical and a *horizontal* component, the final polarizer allows that horizontal component to pass through!

The Math (Malus's Law)

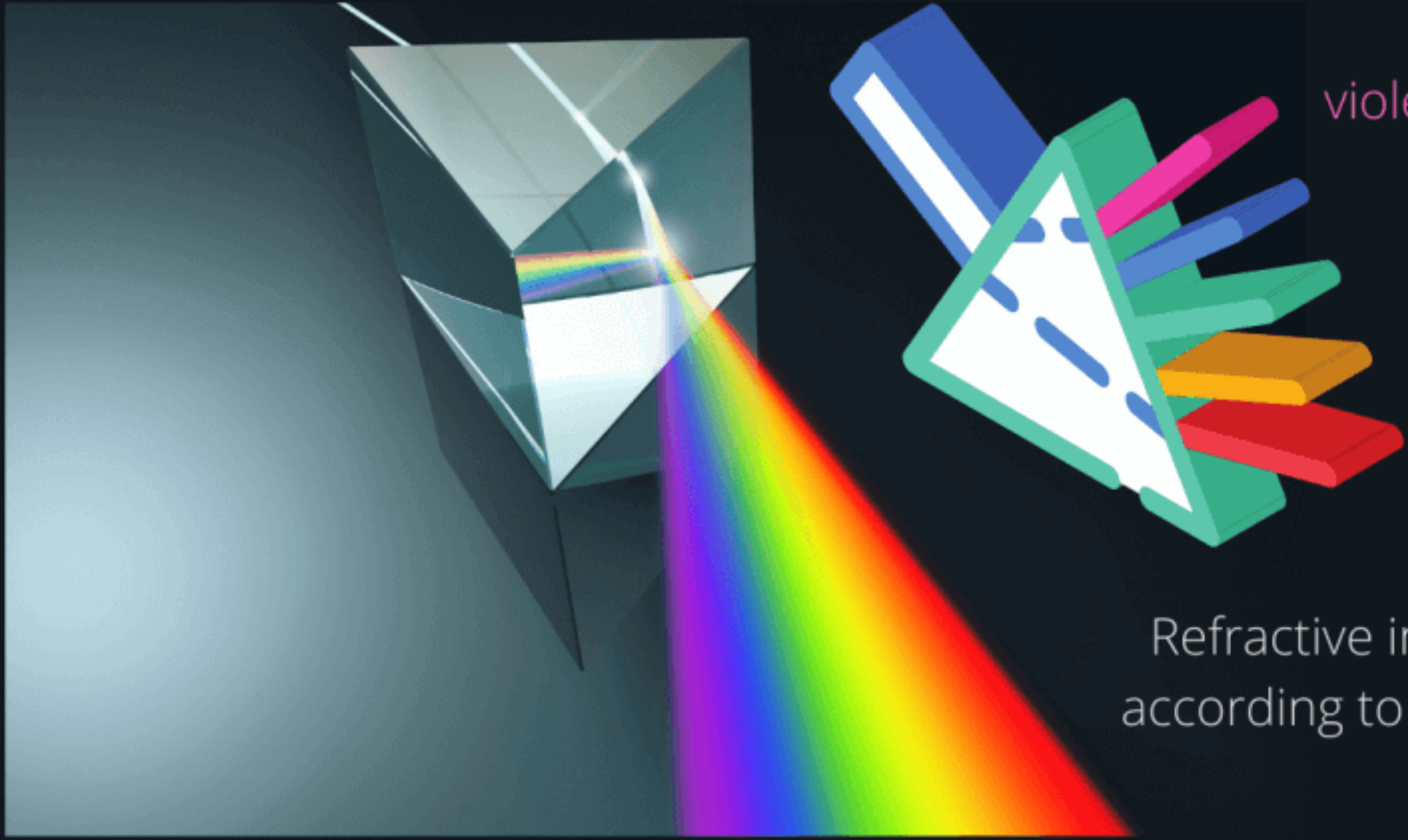
The intensity of polarized light passing through a filter is given by Malus's Law: I=I0 cos2(θ), where θ is the angle between the light's polarization and the filter's axis.

1. **After Filter 1 (0):** Intensity is I_1.
2. **After Filter 2 (Middle, 45◦):** The angle difference is 45−0=45◦. Intensity = $I_1 \cos^2(45^\circ)= I_1(0.5)$. The light is now at 45◦.
3. **After Filter 3 (End, 90◦):** The angle difference between the light (45) and the filter (90) is 45◦. Final Intensity =I2 cos2(45◦)=$I_2 \cos^2(45^\circ) = [I_1(0.5)] \times [0.5] = 0.25\ I_1$

By inserting a filter, you took the final transmitted light from **0** to **25%** of I1 . The transmitted light increased!

Refraction

Refraction is the change in the speed and direction of a wave passing from one medium into another.



Refractive index varies according to wavelength.

Key concepts: Reflection

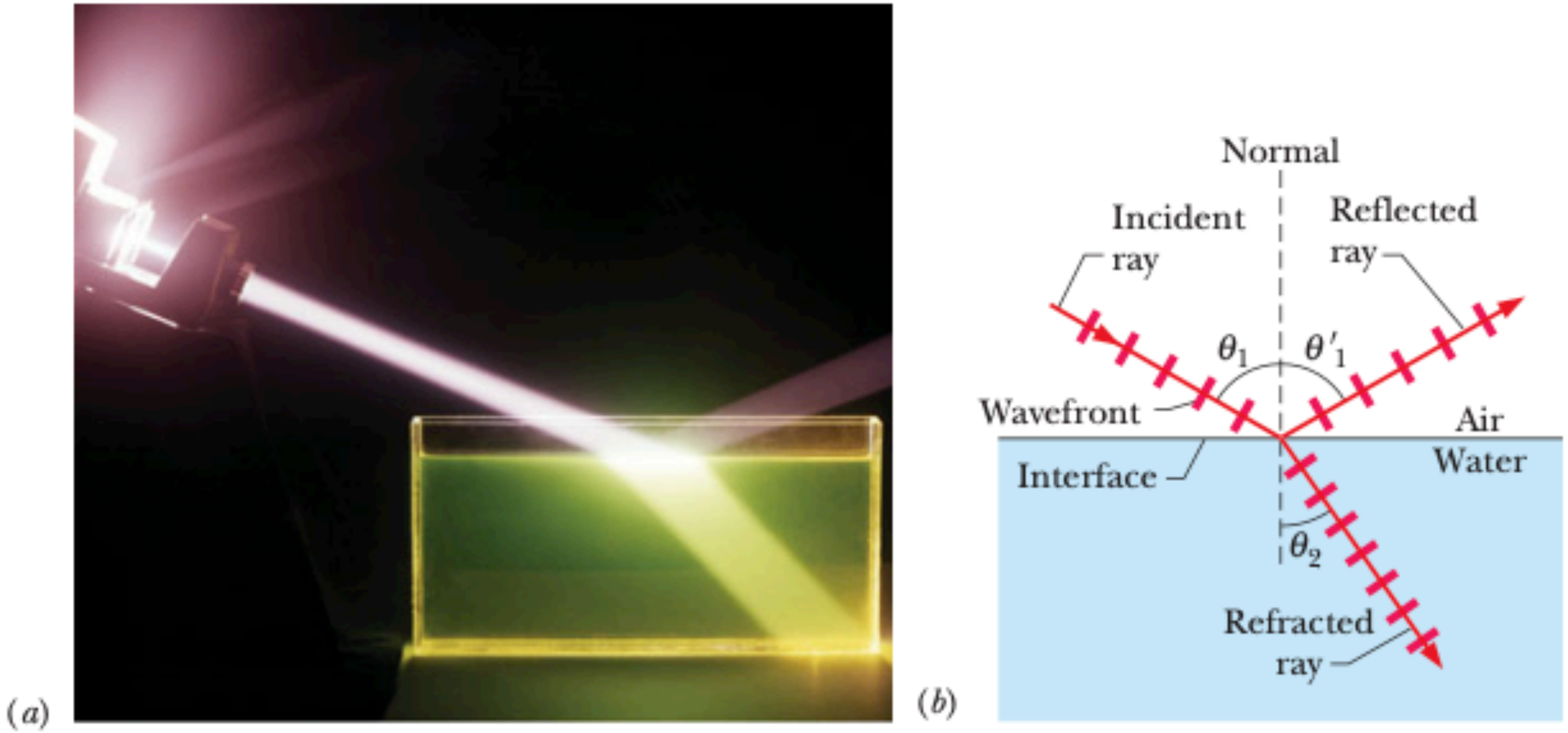


Figure 33-16 (*a*) A photograph showing an incident beam of light reflected and refracted by a horizontal water surface. (*b*) A ray representation of (*a*). The angles of incidence (θ_1), reflection (θ'_1), and refraction (θ_2) are marked.

Key concepts: Reflection

- Angle of incidence = Angle of reflection
  - $\theta_1^{'} = \theta_1$

Key concepts: Refraction

- Snell's law:
  - $n_2 \sin \theta_2 = n_1 \sin \theta_1$
  - n = index of refraction

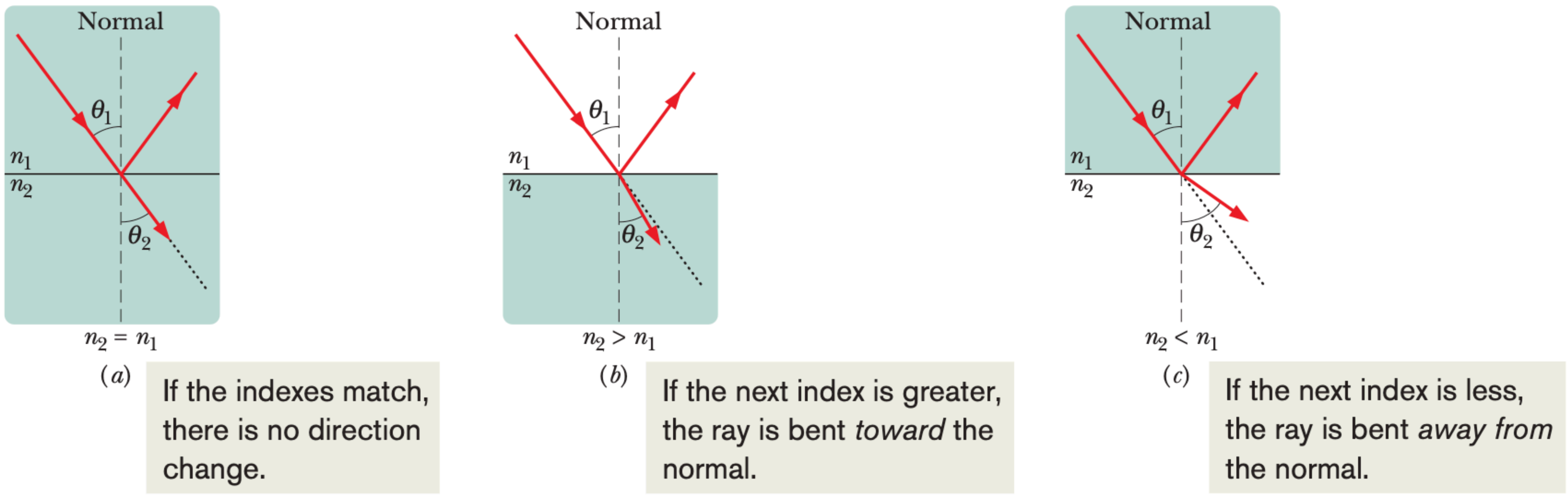
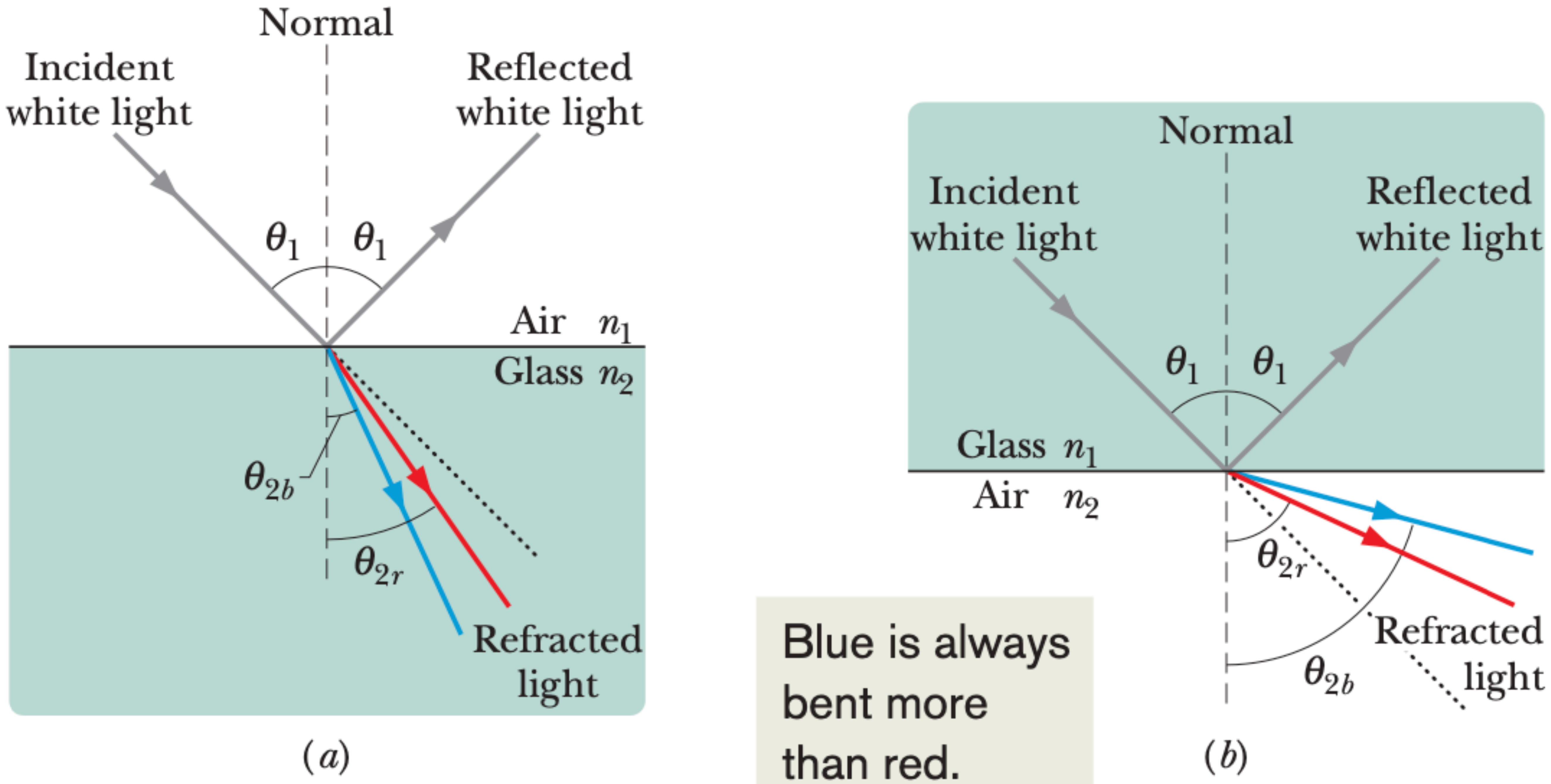


Figure 33-17 Refraction of light traveling from a medium with an index of refraction n_1 into a medium with an index of refraction n_2. (*a*) The beam does not bend when $n_2 = n_1$; the refracted light then travels in the *undeflected direction* (the dotted line), which is the same as the direction of the incident beam. The beam bends (*b*) toward the normal when $n_2 > n_1$ and (*c*) away from the normal when $n_2 < n_1$.

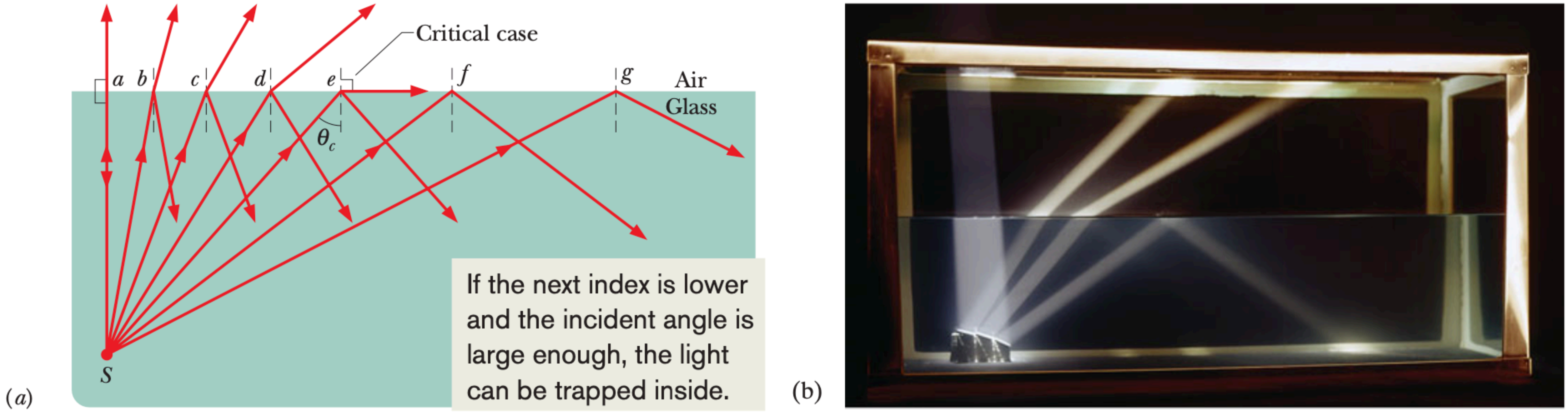
Key concepts: Refraction

Figure 33-19 Chromatic dispersion of white light. The blue component is bent more than the red component. (*a*) Passing from air to glass, the blue component ends up with the smaller angle of refraction. (*b*) Passing from glass to air, the blue component ends up with the greater angle of refraction. Each dotted line represents the direction in which the light would continue to travel if it were not bent by the refraction.



Blue is always bent more than red.

Key concepts: Total internal reflection



Ken Kay/Fundamental Photographs

- Snell's law:
  - $n_2 \sin\theta_2 = n_1 \sin\theta_1, \theta_2 = 90°$
  - $\theta_c = \sin^{-1}\dfrac{n_2}{n_1}$

Key concepts: Total internal reflection

- Reflected wave will be fully polarized, with its $\overrightarrow{E}$ vectors perpendicular to the plane of incidence, if it strikes a boundary at the Brewster angle θ_B, where:
- $\theta_B = \tan^{-1} \frac{n_2}{n_1}$

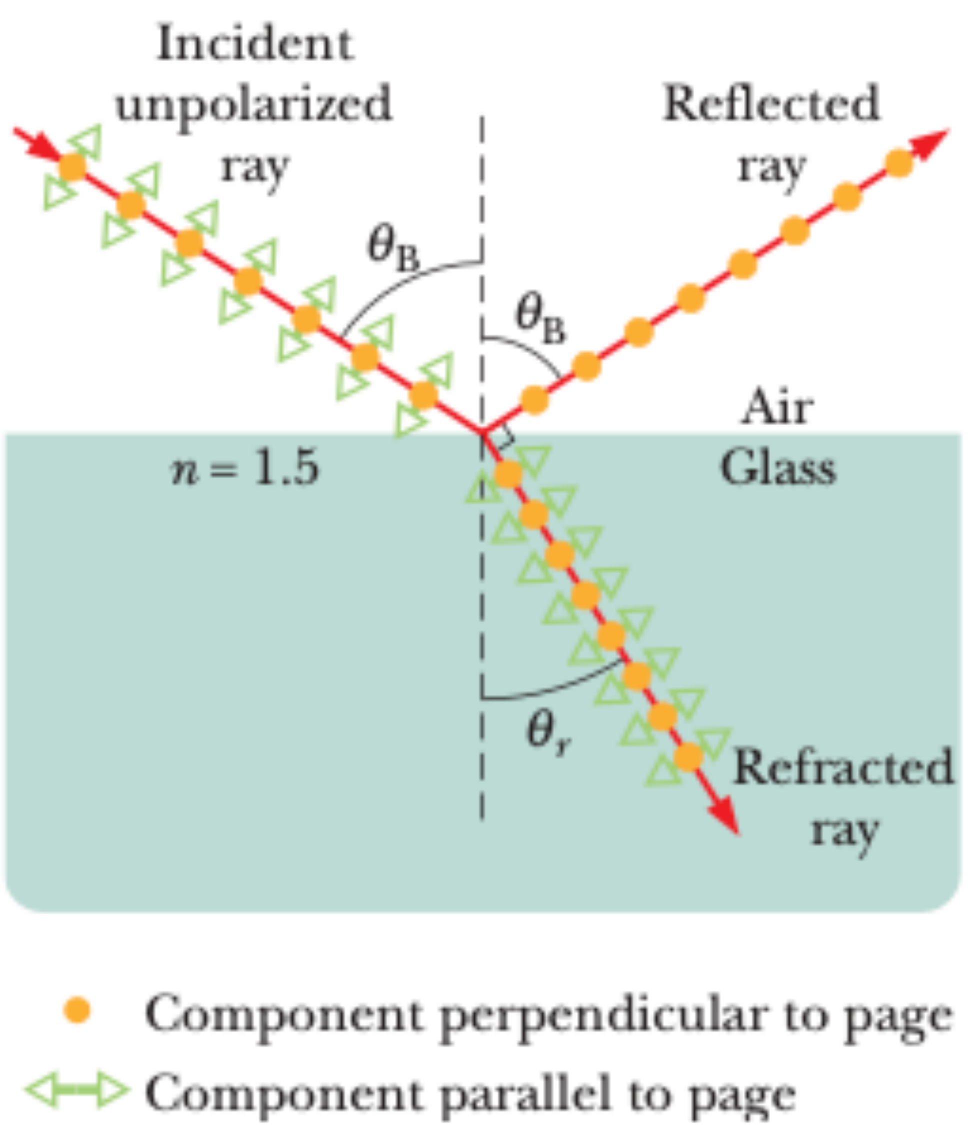


Figure 33-25 A ray of unpolarized light in air is incident on a glass surface at the Brewster angle θ_B. The electric fields along that ray have been resolved into components perpendicular to the page (the plane of incidence, reflection, and refraction) and components parallel to the page. The reflected light consists only of components perpendicular to the page and is thus polarized in that direction. The refracted light consists of the original components parallel to the page and weaker components perpendicular to the page; this light is partially polarized.

An EM plane wave in free space comes from the left towards a vertical interface.

Which statement is true?

A. Only certain frequencies are allowed.
B. You are free to choose the wave speed.
C. A compensating wave must travel towards the interface from the right too.
D. You may independently select the frequency and the ***k***-vector.
E. None of the above.

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E. None of the above.

The correct choice is the final option: **None of the above.**

Here is a breakdown of the physics explaining why each of the preceding statements is false:

- **"Only certain frequencies are allowed."** In free space, there are no boundary conditions to quantize the allowed modes of the electromagneti field. An EM plane wave can take on a continuous spectrum of any frequency.

- **"You are free to choose the wave speed."** The speed of an EM wave in free space is a fundamental constant, c, dictated by the permittivity ar permeability of the vacuum (c=1/μ0 ϵ0). It cannot be arbitrarily chosen.
- **"A compensating wave must travel towards the interface from the right too."** When a wave hits an interface from the left, boundary conditions will typically give rise to a *reflected* wave (traveling back to the left) and a *transmitted* wave (traveling forward to the right). There no physical requirement for an independent wave to originate from the right side and travel leftward toward the interface.
- **"You may independently select the frequency and the k-vector."** While you can choose the *direction* of the wave vector k its magnitude k (the wavenumber) and the angular frequency ω are strictly locked together by the dispersion relation for free space: ω=ck. Therefore, they are not independent variables.

Since all four specific claims violate fundamental principles of electromagnetism in free space, "None of the above" is the only true statement.

For reflected and transmitted waves $\omega_R = \omega_T = \omega_I$.

What can we conclude about the wavelengths of the transmitted and reflected waves?

A. $\lambda_R = \lambda_T = \lambda_I$
B. $\lambda_R = \lambda_T \neq \lambda_I$
C. $\lambda_R \neq \lambda_T = \lambda_I$
D. $\lambda_R = \lambda_I \neq \lambda_T$
E. Need more information

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E. Need more information

1. **The Relationship Between Variables:** The speed of a wave (v) is related to its angular frequency (ω) and wavelength (λ) by the equation:
   $v=\omega\lambda/2\pi$

   Since the problem states that the frequency is constant across all three waves ($\omega R = \omega T = \omega I$), the wavelength is directly proportional to the wave speed in a given medium ($\lambda \propto v$).
2. **Incident and Reflected Waves:** The incident wave and the reflected wave both travel in the *same* medium. Because wave speed is determined by the properties of the medium, their speeds must be identical ($vI = vR$). With the same speed and the same frequency, they must have the same wavelength:
   $\lambda R = \lambda I$
3. **Transmitted Wave:** The transmitted wave enters a *new* medium across the interface. Assuming the media have different physical properties (which is what causes the reflection and transmission in the first place, such as a change in the index of refraction), the wave speed will change (vT / vI). Because the frequency remains constant while the speed changes, the wavelength must also change:
   $\lambda T / \lambda I$

Combining these facts gives the final relationship: **$\lambda R = \lambda I \neq \lambda T$** .