November 11th

Electromagnetic Waves - Chapter 34

Review - EM Waves

- Poynting vector, *S* – rate of energy transported per unit area:

$$\vec{S} = \frac{1}{\mu_0}\vec{E}\times\vec{B}$$

- Instantaneous energy flow rate

$$S_{peak} = \frac{1}{\mu_0 c}E_m{}^2$$

$$E_{rms} = \frac{E_m}{\sqrt{2}}$$

- Intensity – average value of S

$$\boxed{I = \frac{1}{\mu_0 c}E_{rms}^2}$$

Review: Radiation pressure

- For total absorption, force, momentum and radiation pressure on the object are

$$\boxed{F = \frac{IA}{c}} \qquad \Delta p = \frac{\Delta U}{c} \qquad \boxed{p_r = \frac{I}{c}}$$

- For total reflection back along original path, force, momentum and radiation pressure are

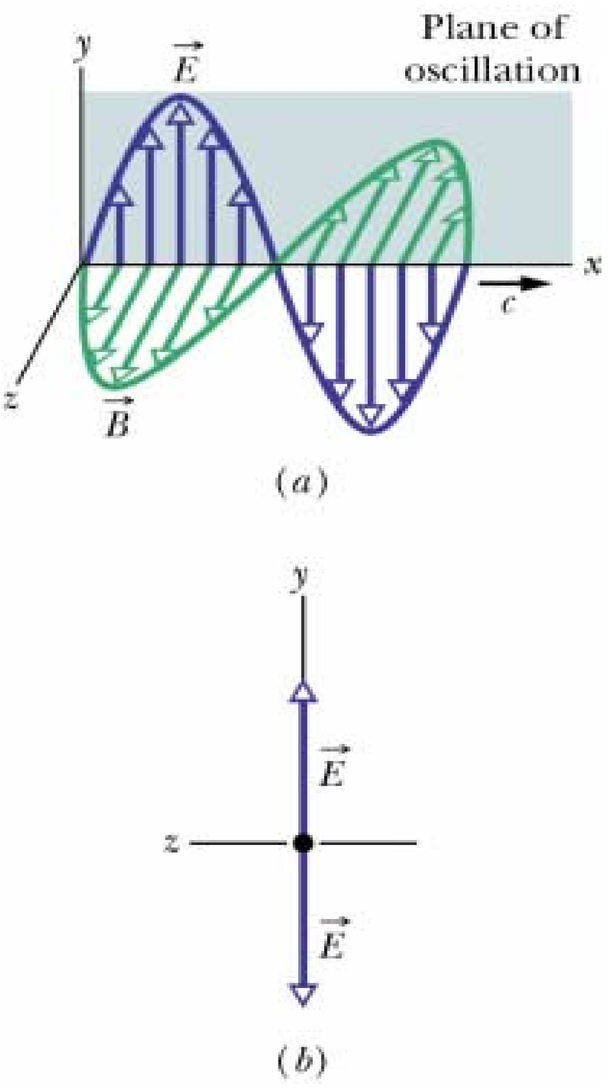
$$\boxed{F = \frac{2IA}{c}} \qquad \Delta p = \frac{2\Delta U}{c} \qquad \boxed{p_r = \frac{2I}{c}}$$

EM Waves: Polarization (Fig. 34-10)

- Source emits EM waves with *E* field always in same plane wave is polarized

- Indicate a wave is polarized by drawing double arrow

- Plane containing the *E* field is called plane of oscillation

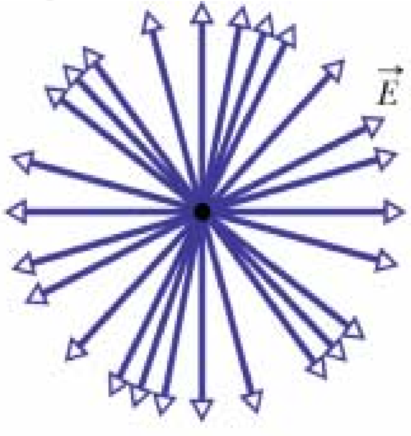


(a)

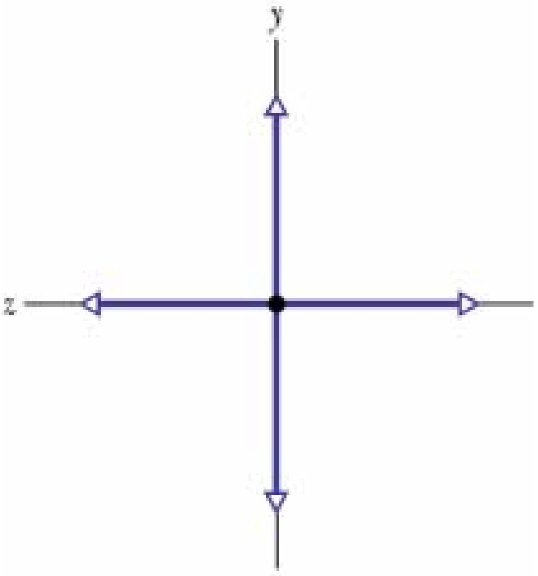
(b)

EM Waves: Polarization (Fig. 34-11)

- Source emits EM waves with random planes of oscillation (E field changes direction) is unpolarized
  - Example, light bulb or Sun
- Resolve E field into components
- Draw unpolarized light as superposition of 2 polarized waves with E fields $\perp$ to each other

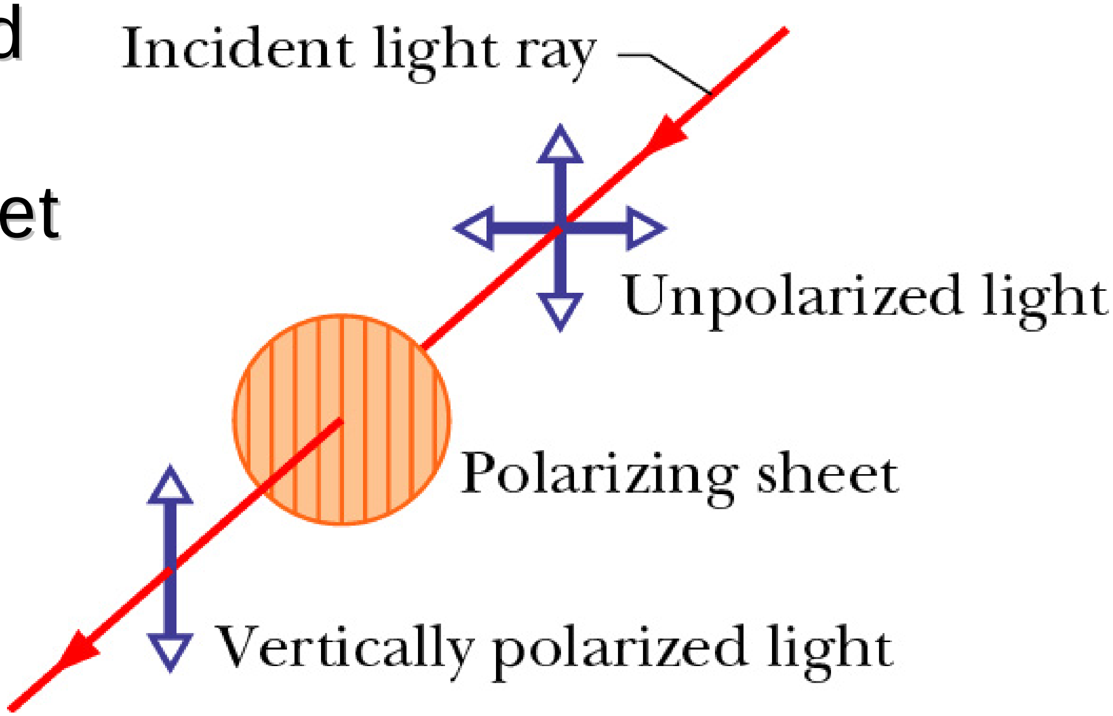


(a)



(b)

EM Waves: Polarization (Fig. 34-12)

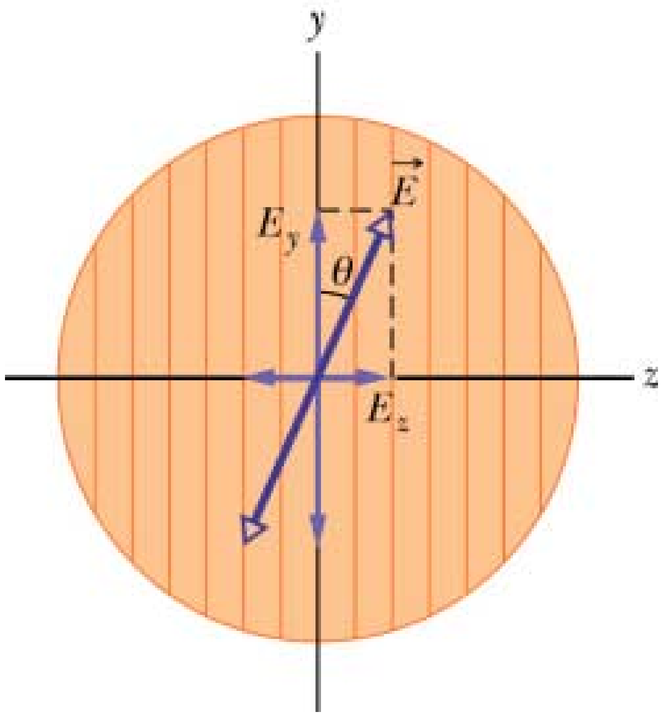


- Transform unpolarized light into polarized by using a polarizing sheet
- Sheet contains long molecules embedded in plastic which was stretched to align the molecules in rows
- *E* field component || to polarizing direction of sheet is passed (transmitted), but ⊥ component is absorbed
- So after the light goes through the polarizing sheet it is polarized in the same direction as the sheet.

EM Waves: Polarization (Fig. 34-13)

- What is the intensity, *I* of the light transmitted by polarizing sheet?
- For initially polarized light, resolve *E* into components

$$E_y = E_{||} = E\cos\theta$$



- Transmitted || component is

$$I = \frac{1}{c\mu_0}E_{||}^2 = \frac{1}{c\mu_0}E^2\cos^2\theta = I_0\cos^2\theta$$

- Cosine-squared rule: Intensity of polarized wave changes as $\cos^2\theta$

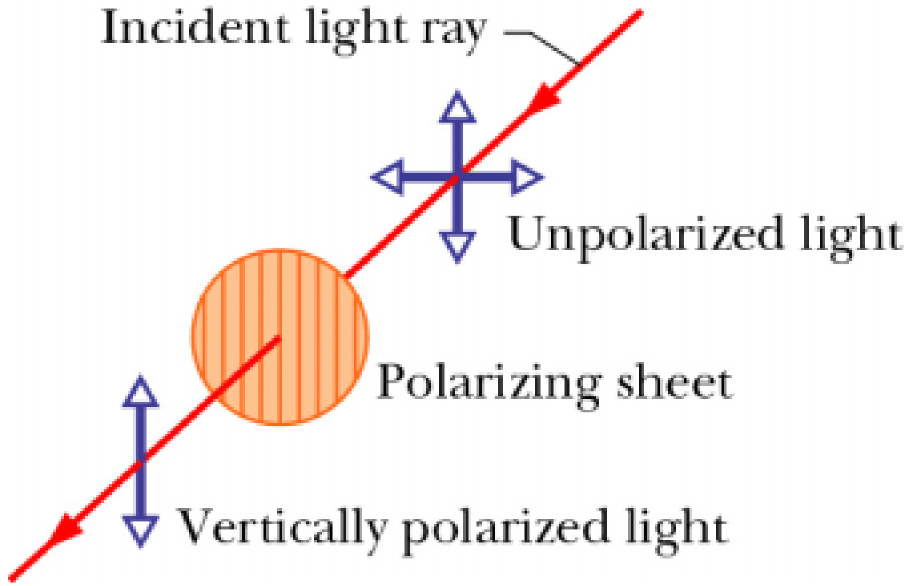
$$\boxed{I = I_0\cos^2\theta}$$

EM Waves: Polarization (Fig. 34-12)

- For unpolarized light, average over $\cos^2\theta$

$$\boxed{I = \tfrac{1}{2} I_0}$$

- Only light || to polarizer is transmitted



- One-half rule: Intensity of unpolarized wave after a polarizer is half of original

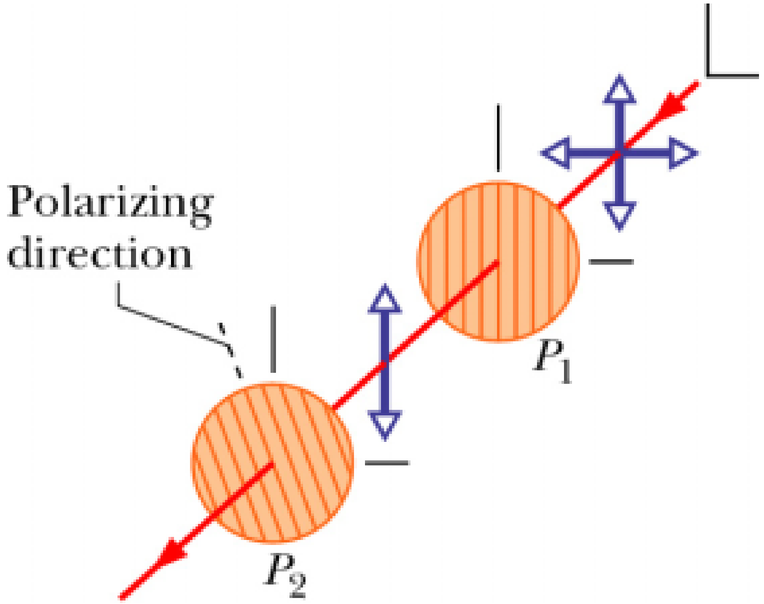
EM Waves: Polarization (Fig. 34-14)

- Have 2 polarizing sheets
  - First one called polarizer
  - Second one called analyzer
- Intensity of unpolarized light going through first polarizer is

$$I_1 = \tfrac{1}{2} I_0$$

- Light is now polarized and intensity of light after second analyzer is given by

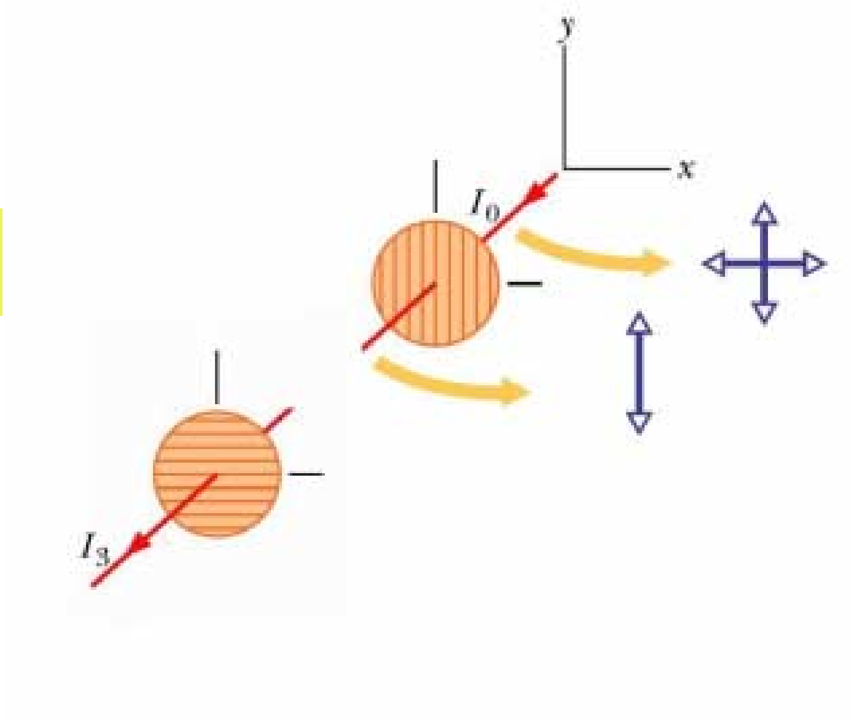
$$I_2 = I_1 \cos^2\theta = \tfrac{1}{2} I_0 \cos^2\theta$$



An interesting demo

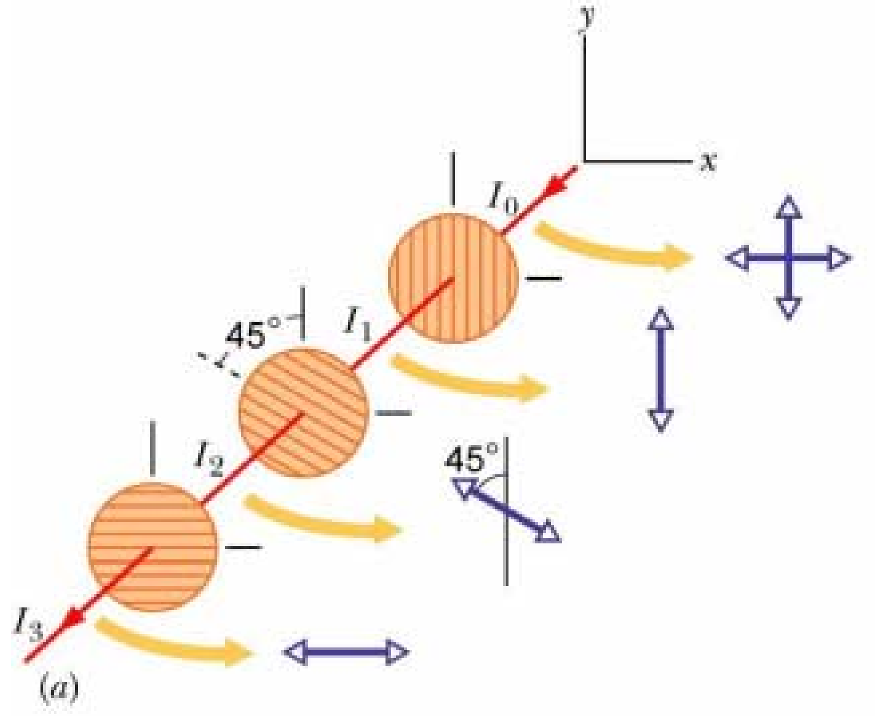
- Effect of P_1 and P_3
- Take $\theta_1 = 0^o$ and $\theta_3 = 90^o$
- After P_1 $I_1 = \frac{1}{2} I_0$
- After P_3

$$I_3 = I_1 \cos^2(90^o) = 0$$



An interesting demo

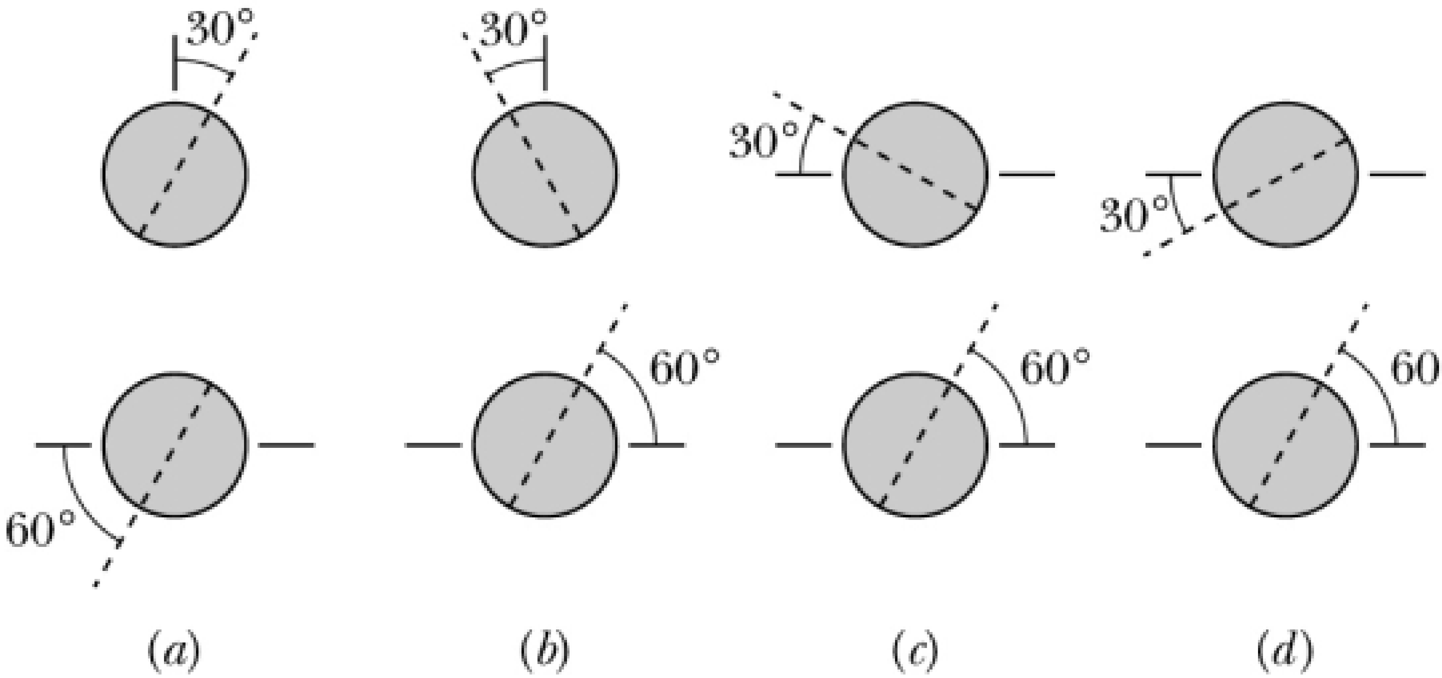
- Keep $\theta_1 = 0^o$ $\theta_3 = 90^o$
- Now insert P$_2$ in between P$_1$ and P$_3$ with $\theta_2 = 45^o$



- After P$_1$ $I_1 = \frac{1}{2} I_0$
- After P$_2$ $I_2 = I_1 \cos^2(45^o) = \frac{1}{4} I_0$
- After P$_3$ $I_3 = I_2 \cos^2(45^o) = \frac{1}{8} I_0$

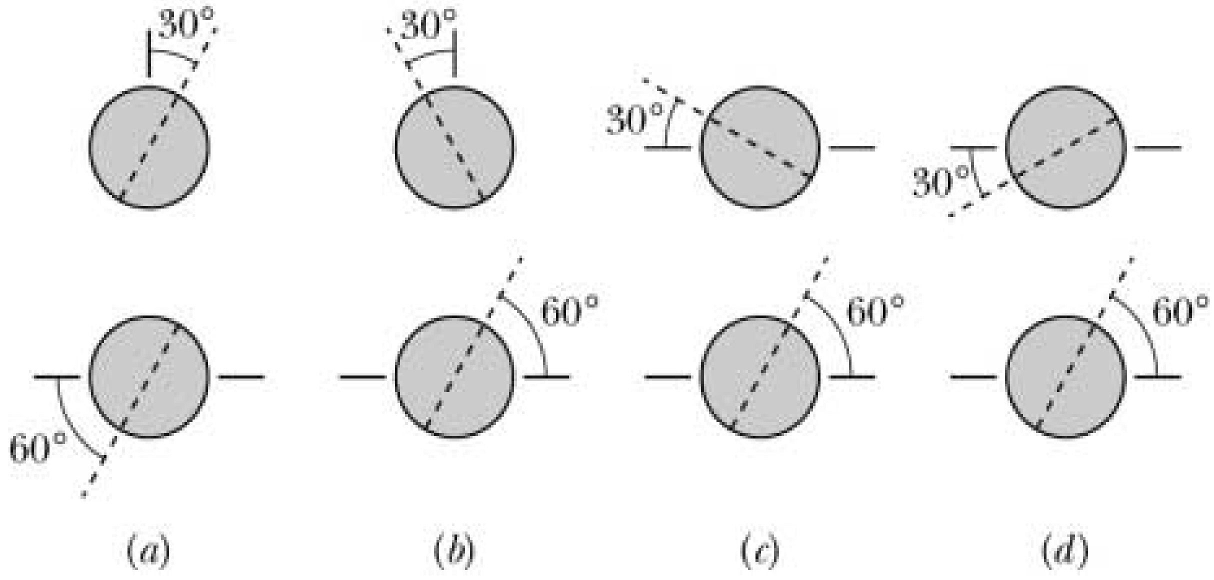
Checkpoint #4

- Unpolarized light hits a polarizer and then an analyzer. The polarizing direction of each sheet is indicated by dashed line. Rank pairs according to fraction of initial intensity which is passed, greatest first.



Checkpoint #4

- Look at relative orientation of polarization direction between the 2 sheets.
- What is the intensity if the sheets are...
  - Polarized || – all light passes
  - Polarized ⊥ to each other – no light passes
  - For angles in between – get more light if closer to ||



a,d,b,c

Optical activity

- Certain materials rotate the plane of polarization
- The rotation angle may depends on the frequency (color)
- This is due to molecular asymmetry - e.g. molecules with spiral shapes
- Karo syrup and scotch tape

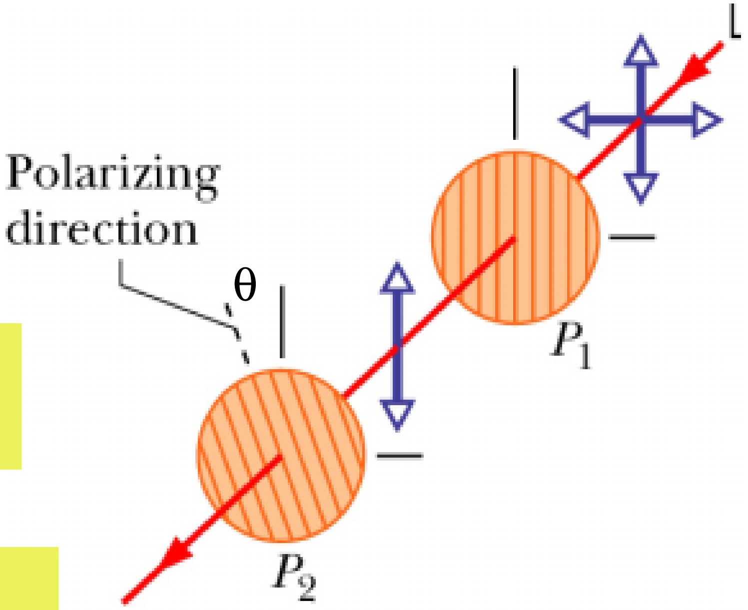
Example of Polarized Light

- Two polaroids are placed in an unpolarized beam of light with angle θ=10° between their axes. What percent of the incident light makes it through?

$$I_1 = \tfrac{1}{2} I_0$$

$$I_2 = I_1 \cos^2\theta = \tfrac{1}{2} I_0 \cos^2\theta$$

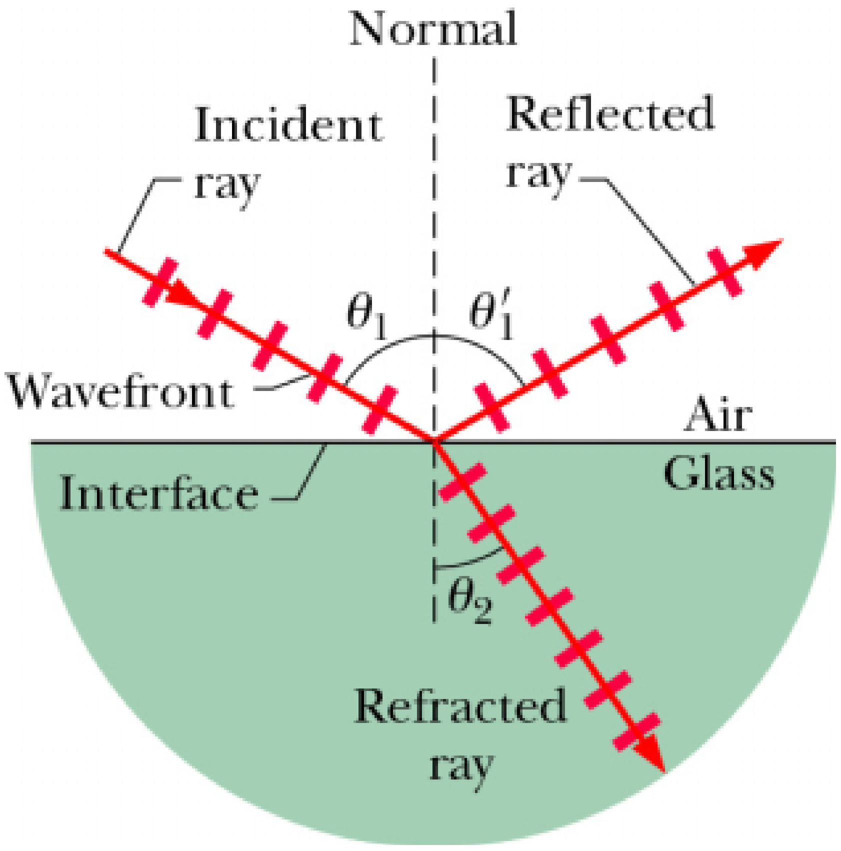
$$\frac{I_2}{I_0} = \tfrac{1}{2}\cos^2\theta = \tfrac{1}{2}\cos^2(10) = 0.4849$$



$$\frac{I_2}{I_0} = 48.49\ \%$$

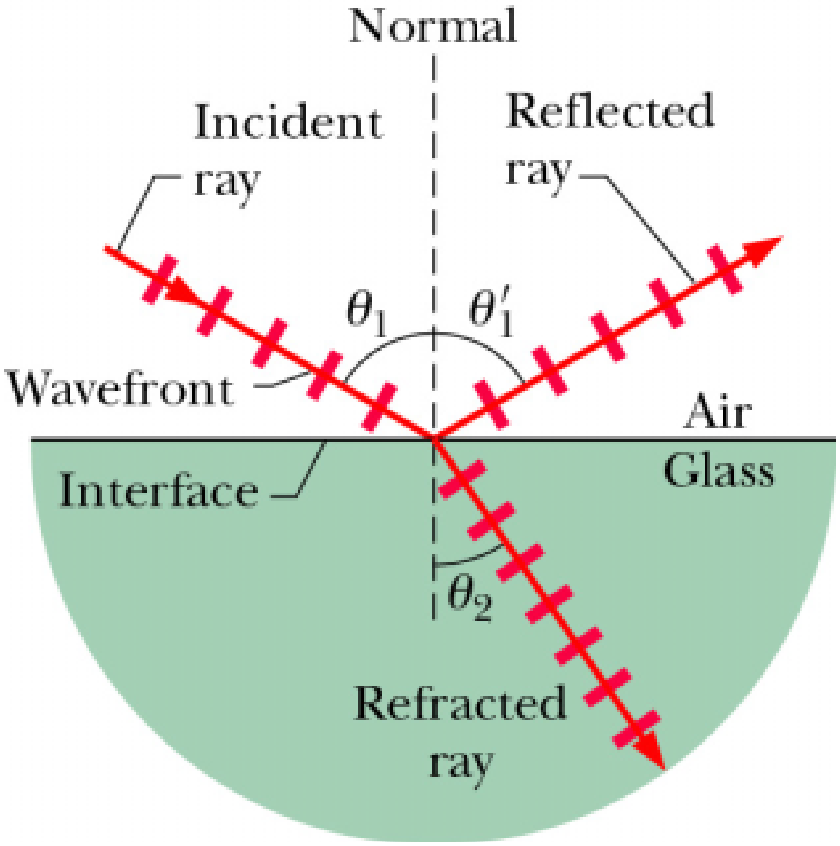
Reflection & Refraction (Fig. 34-17)

- Represent light waves as straight lines or rays
- If incident (incoming) light wave hits surface of different material some light will
  - Be reflected back
  - Travel through and be refracted



Reflection & Refraction (Fig. 34-17)

- Define a line, the normal, which is ⊥ to surface at point where the incident beam hits the surface
- Angles relative to normal
  - Angle of incidence θ_1
  - Angle of reflection θ_1'
  - Angle of refraction θ_2
- Plane containing incident ray and normal is plane of incidence



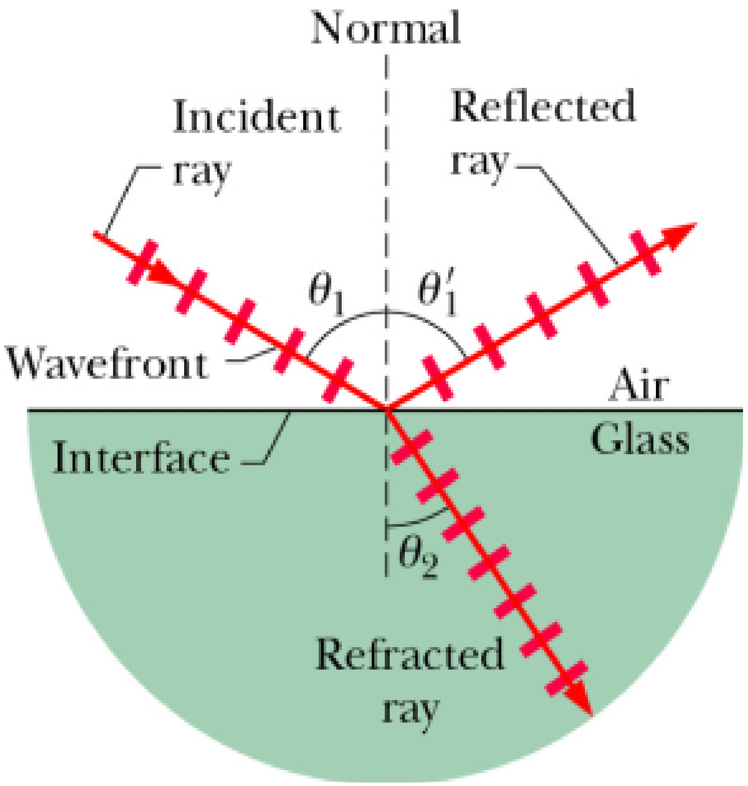
Reflection & Refraction (Fig. 34-17)

- Law of reflection: Reflected ray lies in plane of incidence and angle for reflection is equal to angle of incidence

$$\boxed{\theta_1' = \theta_1}$$

- Law of refraction: Refracted ray lies in plane of incidence and angle of refraction is related to angle of incidence by Snell's law

$$\boxed{n_2 \sin\theta_2 = n_1 \sin\theta_1}$$



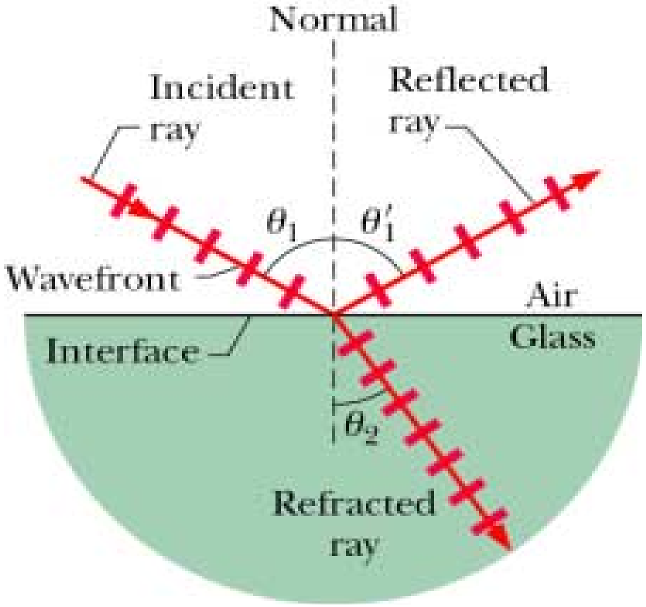
Reflection & Refraction (Fig. 34-17)

$$n_2 \sin\theta_2 = n_1 \sin\theta_1$$

- n is dimensionless constant called index of refraction
- Index of refraction, n for given medium is defined as

$$\boxed{n = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}} = \frac{c}{v}}$$

- Nothing has n <1, velocity of wave in medium is always less than the speed of light



Medium	Index, n
Vacuum	Exactly 1
Air	1.00029
Glass	1.52
Diamond	2.42
Water	1.33