Chapter 33

- The nature and propagation of light

Michael Wong – PHY 1122 Spring 2023

Chs. 33 – 36: Optics

- Chapter 33 – **Nature of light** and ray/wave optics
  - Reflection, refraction, polarization, dispersion, and scattering.
- Chapter 34 – Image formation
  - Creating real and virtual images using mirrors and lenses and combinations of both.
- Chapters 35 & 36 – Wave optics
  - Interference and diffraction of light and applications.

Learning goals

- Light rays, wave fronts, plane waves
- **Reflection** and **refraction** of light when it crosses a boundary between materials.
  - **Snell's law**.
- **Total internal reflection**
- **Polarization of light – Malus' Law**
- Scattering of light*

Introduction

- A diamond sparkles brilliantly with lots of colours.
- Compared to air, light in the diamond travels at a slower speed.
  - Different colours also travel at slightly different speeds.
- Optics is the study of how light behaves. It explains why we see rainbows, a blue sky, mirages, holograms, and our reflection when we look in a mirror.
  - Also lots of technology based on optics – photonics.

Light and optics

- Historical models for the nature of light.
  - **Particles** or **waves** or both?

- Measurement of the **speed of light** ($c = 2.998 \times 10^8$ m/s)
  - methods by Galileo (early 1600s), Roemer (1675), and Fizeau (1849).

- The **ray approximation** → "Ray Optics" or "Geometric Optics" , explains:
  - Reflection and refraction
  - Dispersion
  - Total internal reflection (applications)

The nature of light (brief history)

- Pre-1800, **light was considered to be a stream of particles** emitted by luminous objects to the eyes of the viewer.
  - **Newton** was champion of the particle model ("Opticks" published in 1704).
  - Particles left the object and stimulated the "sense of sight".
  - Phenomena such as reflection/refraction could be explained well.
  - In late 1600s, **Huygens** showed the **wave model** could also explain reflection/refraction.

- In 1801, **Thomas Young** showed first experimental demonstration of the wave nature – the **double-slit experiment** where light rays interfere.

- **Maxwell** determined light to be electromagnetic radiation (1873).
  - Confirmed experimentally by **Hertz** in 1887.
  - The wave model was accepted by most.

Dual nature of light

- In the early 1900s, new experiments indicated light also has a particle nature.
  - **Photoelectric effect** (see Ch. 39) when light strikes a metal surface and electrons are ejected.
- **Einstein** proposed the **quantization model** where light particles (photons) have energy based on their frequency ($E = hf$).
- Now we regard light as having a **dual nature**, both particle *and* wave.
- Chs. 35/36 expand on the wave nature of light (**wave optics**).

Measurements of the speed of light

- Early methods were unsuccessful since light travels so fast.
  - **Galileo** (early 1600s) tries two observers separated by 10 km.
  - Reaction time of observers was greater than transit time.

- **Roemer** (1675) used astronomical observations to estimate the speed of light (period of revolution of Jupiter's moon as Jupiter revolved around the sun).
  - Approximated speed to be $2.3 \times 10^8\ \mathrm{m/s}$

- **Fizeau** (1849) used a rotating toothed wheel to transmit and then allow or block reflection of the light.
  - Found a value of $c = 3.1 \times 10^8\ \mathrm{m/s}$ (not bad!)
  - Subsequent investigations yielded better and better results.

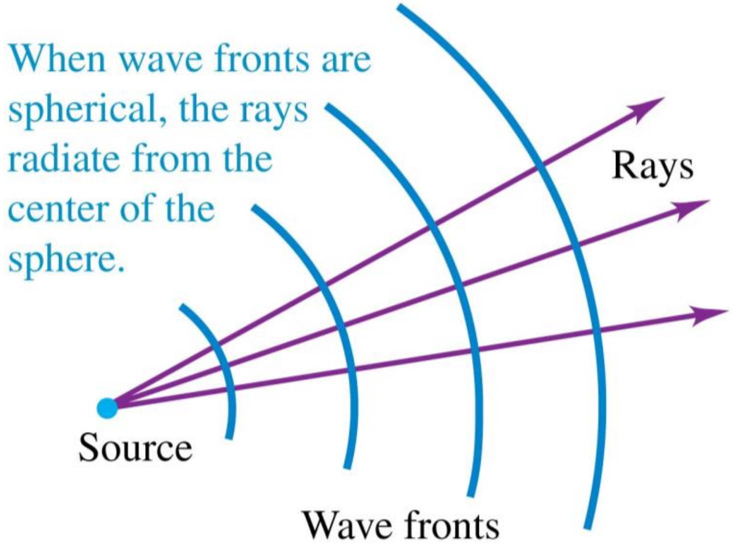
- Current accepted value is $\boxed{c = 2.998 \times 10^8\ \mathrm{m/s}}$.

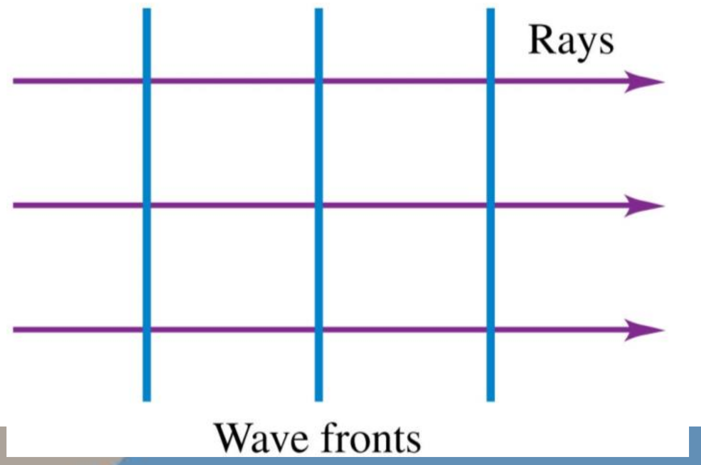
Waves, wave fronts, and plane waves

- We can use the idea of **rays** to describe light propagation.
  - Rays travel in straight lines and a point source emits rays in all directions **(ray approximation)**.
  - Perpendicular to the rays are surfaces of "phase" called **wave fronts** (similar to potential surfaces).
  - The *phase* is the same at all points on a wave front.

- This idea can be used to describe both mechanical and **electromagnetic waves**.
  - Note: rays are imaginary but "convenient" to use.

- When we're far away from a source, the wave fronts are "parallel" to each other and are treated as a set of planes.
  - This known as a **plane wave** and rays all point together.
  - This branch of optics is also known as **geometric optics**.

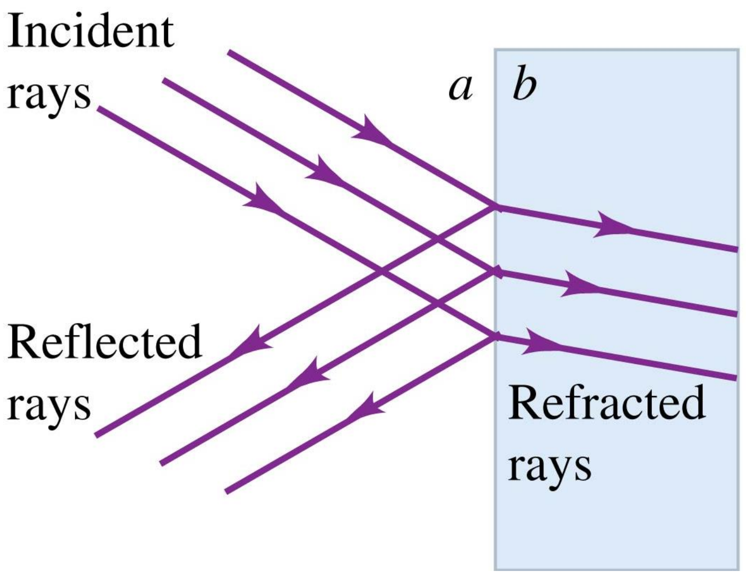


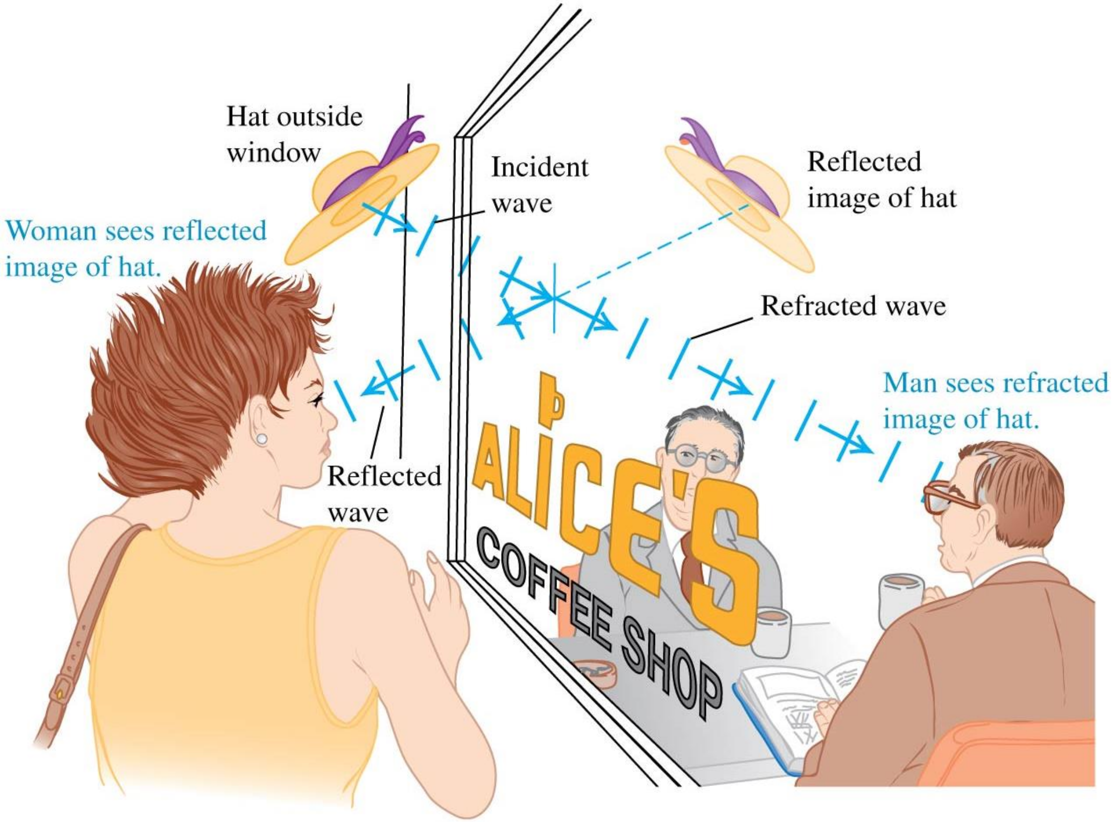


Reflection and refraction

- When a light wave strikes a smooth interface (eg. air and glass), part of the wave is *reflected* and part is *refracted*.

- Bundles of rays form *beams* of light.

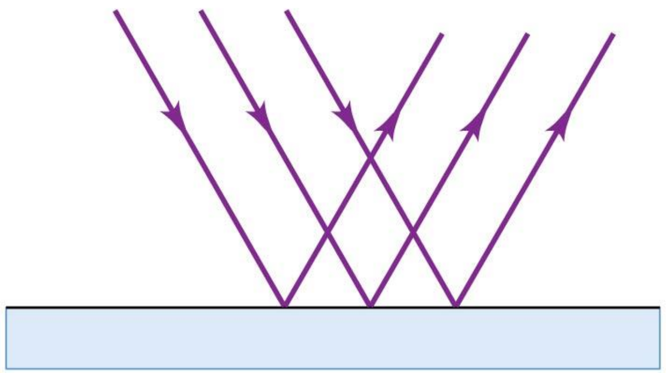




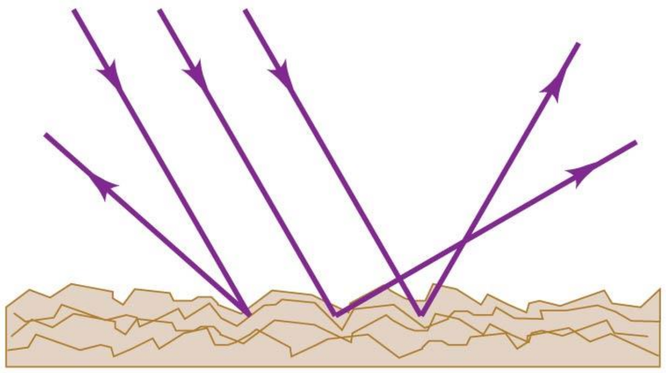
Two types of reflection

- For a smooth interface, we have **specular reflection** where the reflected light rebounds in a definite direction.
- For a rough interface, the incident light is scattered away and we have **diffuse reflection**.
- For reflection problems in this chapter, we only will use specular reflection.

(a) Specular reflection



(b) Diffuse reflection



The law of reflection and refraction 1

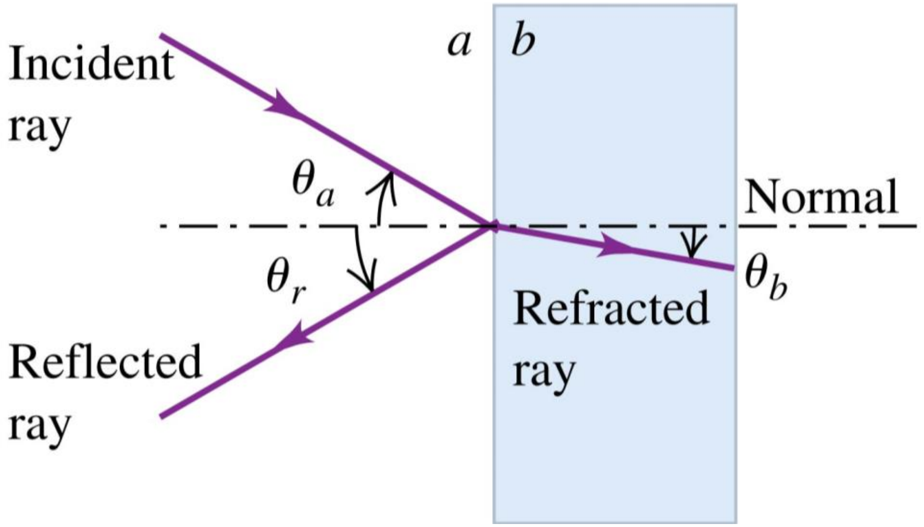
- The incident, reflected, and refracted rays and the normal line to the surface are all in the same "incidence plane".
- **Law of reflection**: the angle of reflection is equal to the angle of incidence.

$$\boxed{\theta_r = \theta_a}$$

- The angle of the refracted ray is related to the speed of light in the two mediums.

  Example:
  if $v_b < v_a$, then $\theta_b < \theta_a$

  θ_a and θ_b measured wrt the Normal.



The law of reflection and refraction 2

- The **index of refraction** (or refractive index) of a material relates the speed of light in vacuum to the speed of light in that material.

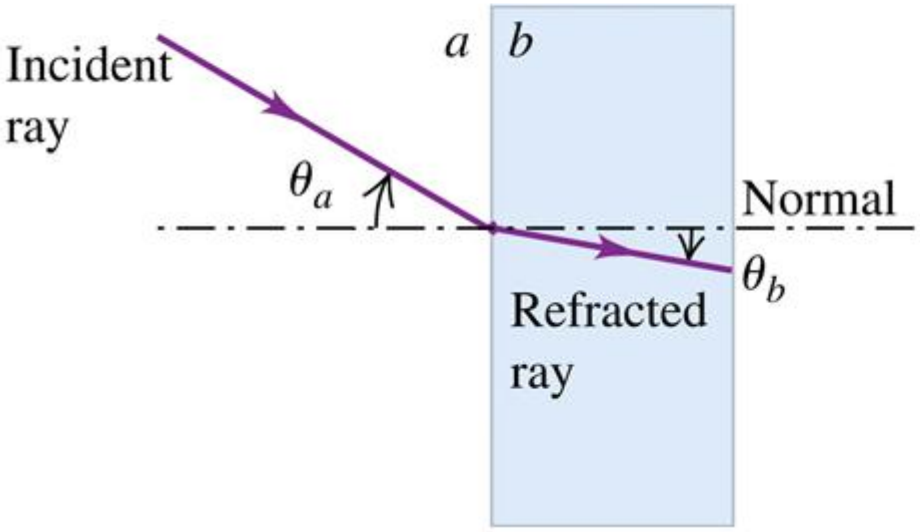
$$\boxed{n = \frac{c}{v}}$$

where $n \geq 1$ has no units, and we assume $n = 1$ for air or vacuum.

- Our law of refraction is:

$$\boxed{n_a \sin\theta_a = n_b \sin\theta_b}$$

otherwise known as **Snell's Law**.

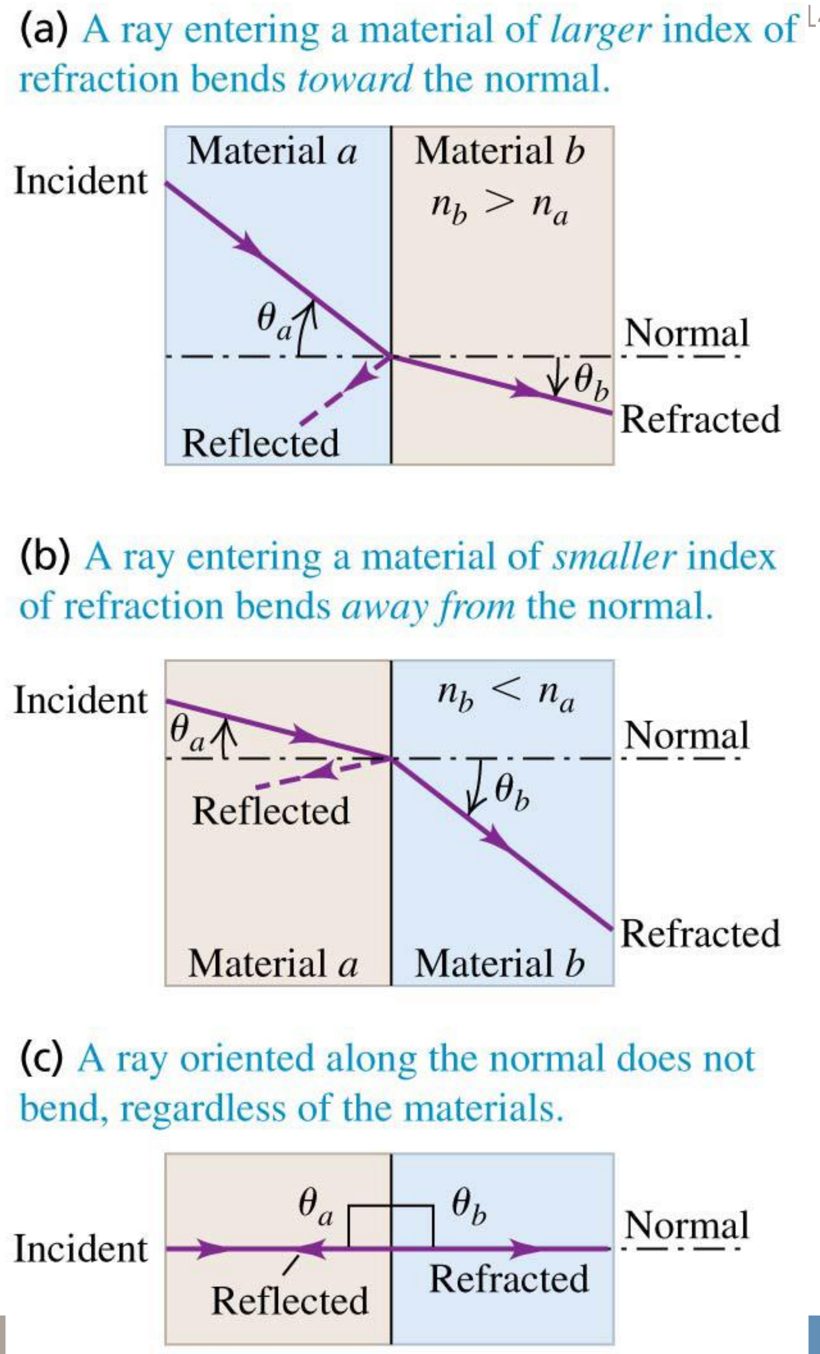


Refraction (3 cases)

- If $n_a < n_b$ (such as for light in air traveling into water)
  - Light bends *towards* the normal.

- If $n_a > n_b$, light bends *away from* the normal.

- For $\theta_a = 0$ then there is *no bending* at the interface.

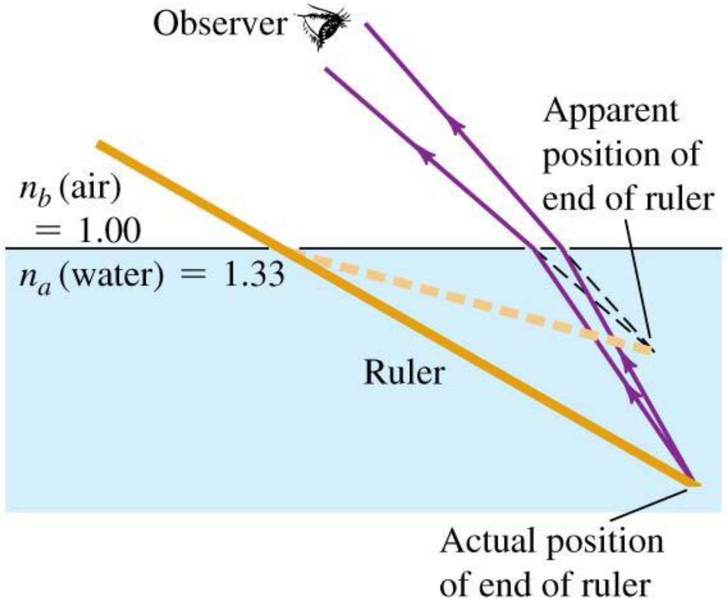


Example: Half-immersed ruler

- The straight ruler "appears" to bend at the surface of the water.
- Because light rays bend when they exit the water, the ruler *appears* to be closer to the surface than it actually is.

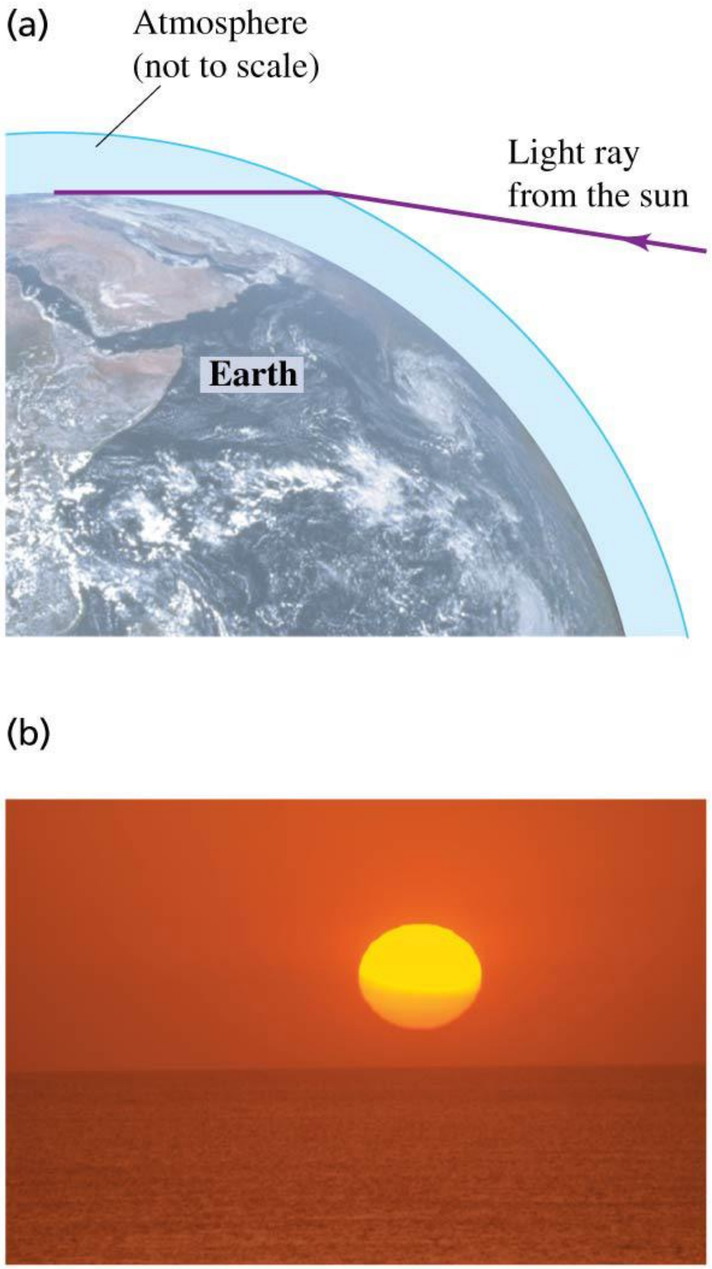
(a) A straight ruler half-immersed in water

(b) Why the ruler appears bent



Example: Flattened sun

- Light rays from the sun bend downwards when they encounter our atmosphere (n slightly > 1).
- Stronger refraction occurs for light from lower part of the sun than the top.
- Result is a slightly "flattened" sun.

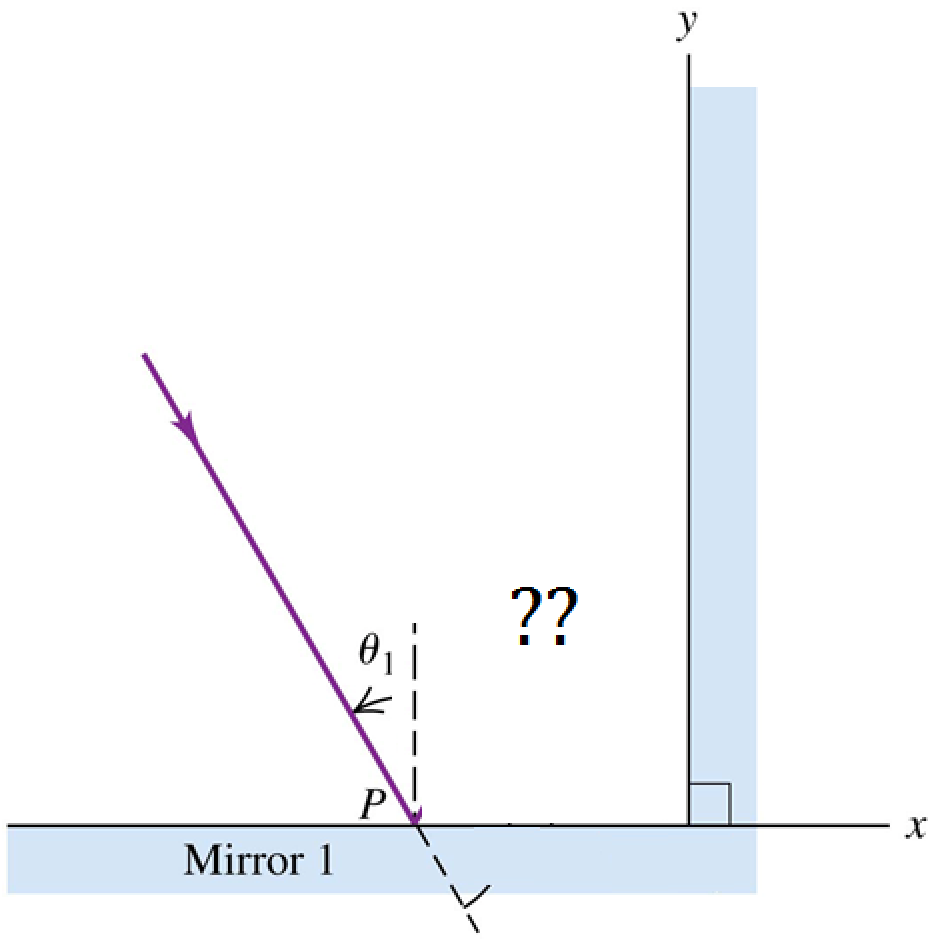


Ex. 33.3 – Twice-reflected ray

- Solving reflection problems requires basic knowledge of geometry.

- Right angle is $90°$
- Two right angles is $180°$
- Three angles in a triangle add up to $180°$
- Etc…

- Two mirrors at $90°$ to each other is called a retro-reflector. Applications:
  - Tail-lights, stop signs
  - Measuring distance from Earth to moon.



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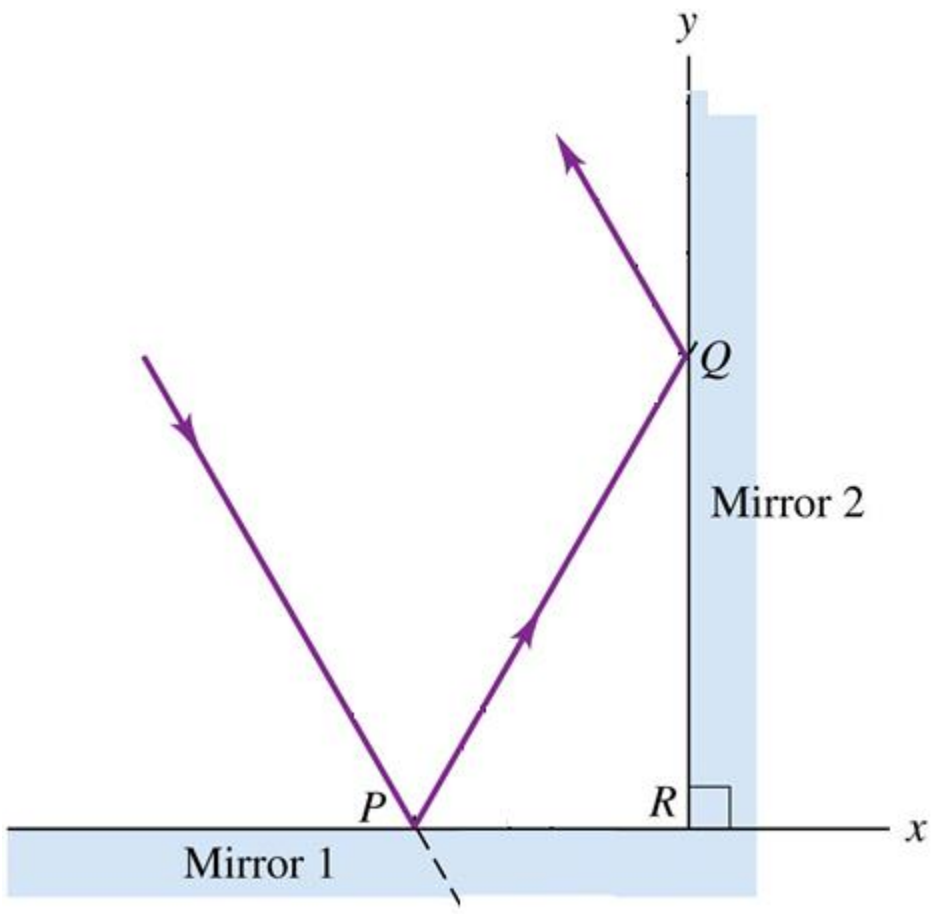

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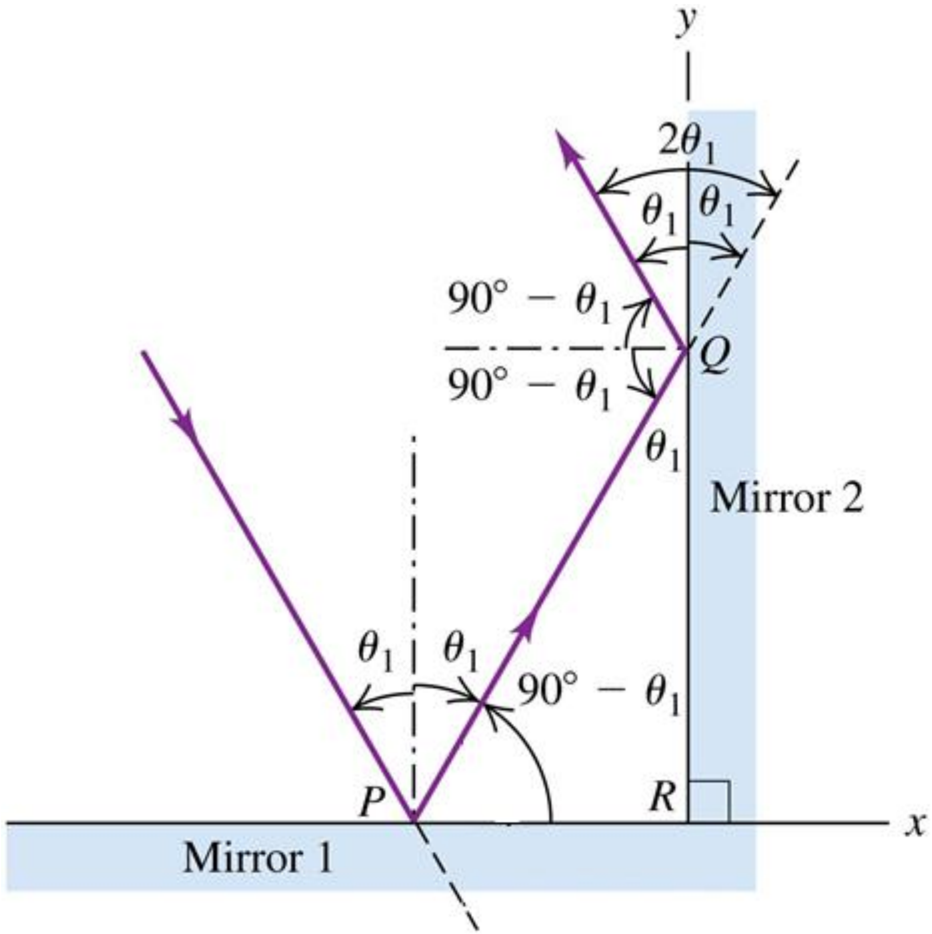
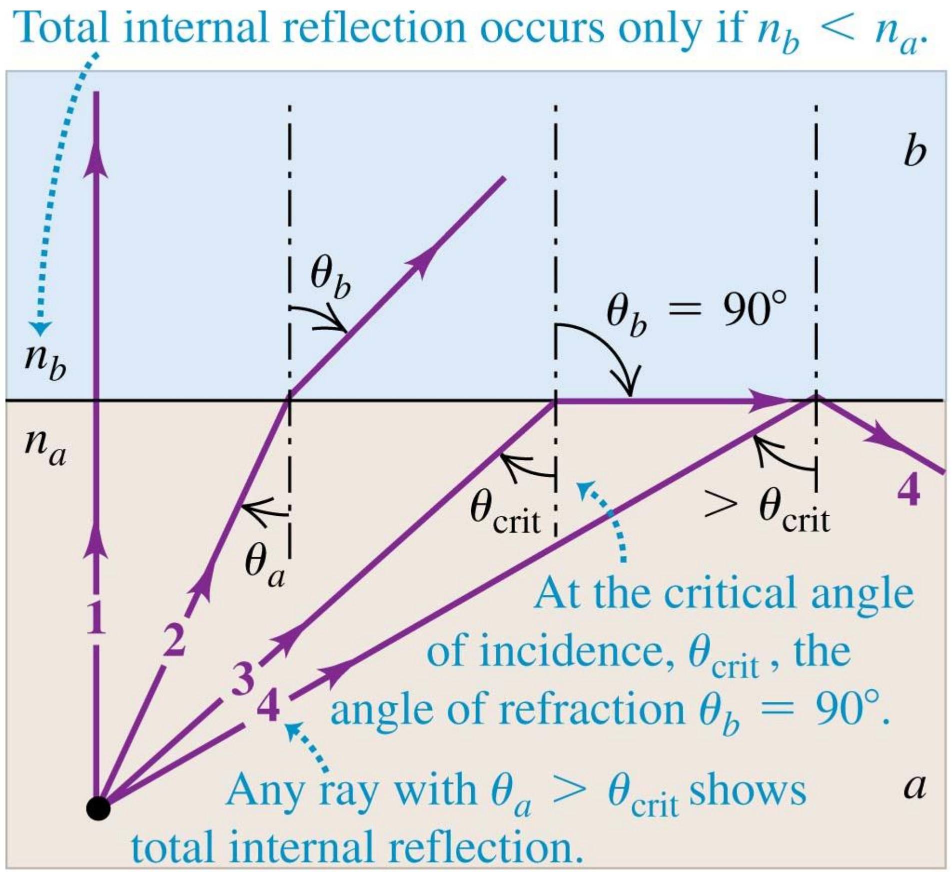


Total internal reflection

- Under certain circumstances, all the light can be reflected back from an interface (**total**ly **internal**ly **reflect**ed - TIR).
- Conditions:
  - Wave must first be travelling in high-index medium ($n_a > n_b$).
  - Angle of refraction θ_b is $\geq 90°$.
- Figure to the right:
  Rays 3 and 4 show TIR.

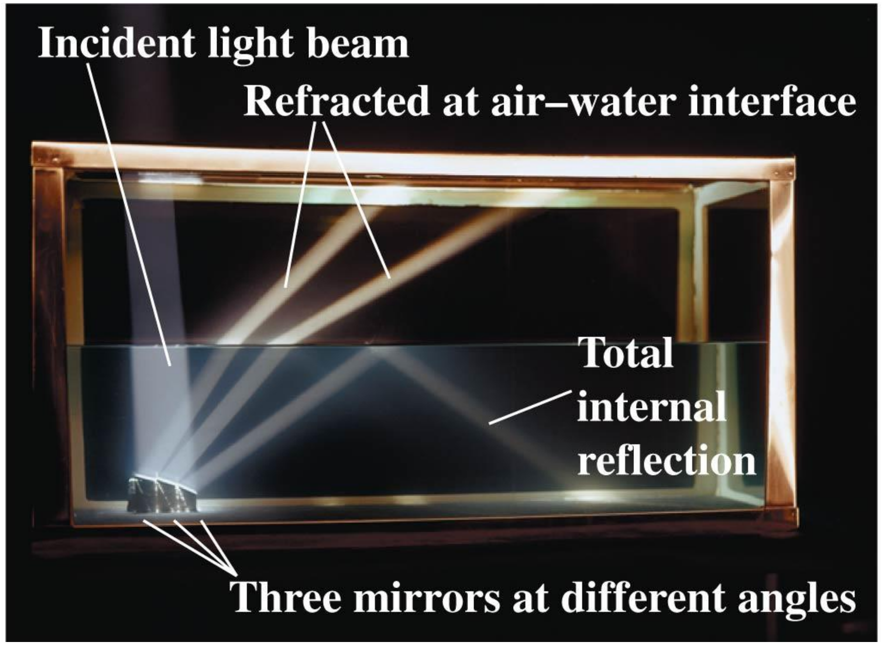


Total internal reflection

- The equation to find the critical angle depends only on the two indices of refraction for the materials.

$$\boxed{\sin\theta_{crit}} = \frac{n_b}{n_a}\sin 90° = \boxed{\frac{n_b}{n_a}}$$

and we require that the wave is first travelling in the high index medium ($n_a > n_b$).

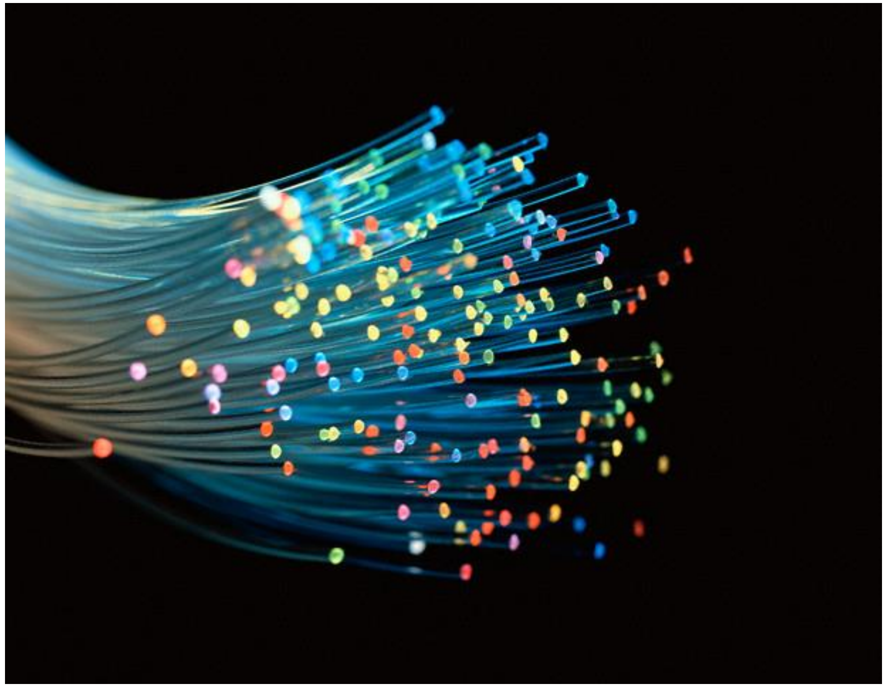


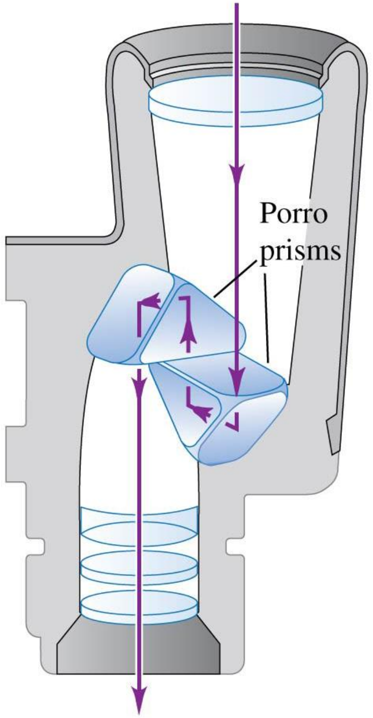
- In terms of velocity, $\sin\theta_{crit} = v_a/v_b$.

- This phenomenon occurs for mechanical waves as well.
  - Ie. Sound on concrete.

Examples of total internal reflection

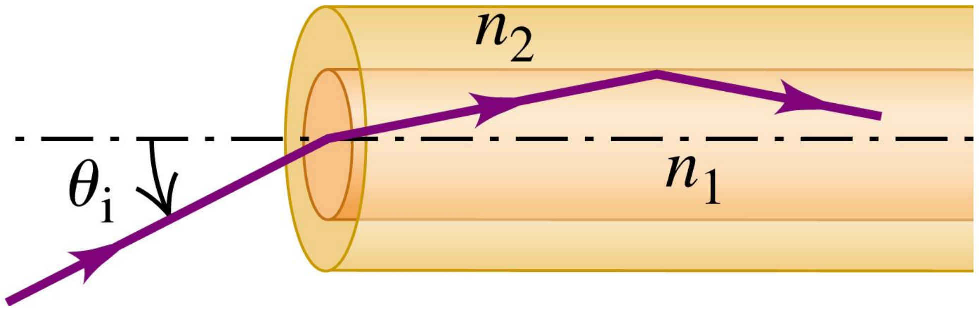
- Fiber optics, binoculars, light reflecting in diamonds, mirages in the desert, and many, many more.



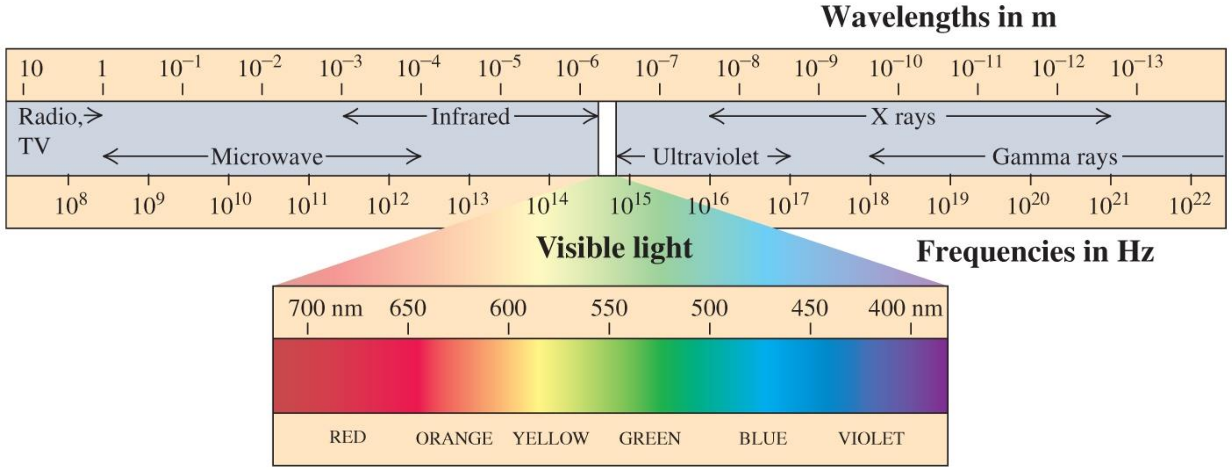


Fiber-optic cables

- Similar to electric cables/wires but they carry **light** instead of current.
- Light travels through the core of the cable by **total internal reflection**.
- There are numerous applications in telecommunications:
  - high speed internet, cable TV, telephone wires, etc…
- We can calculate the critical angle and the numerical aperture (θ_i) based on the indices of refraction for the **core** and **cladding**.
  - See DGD problem 33.46.



Dispersion

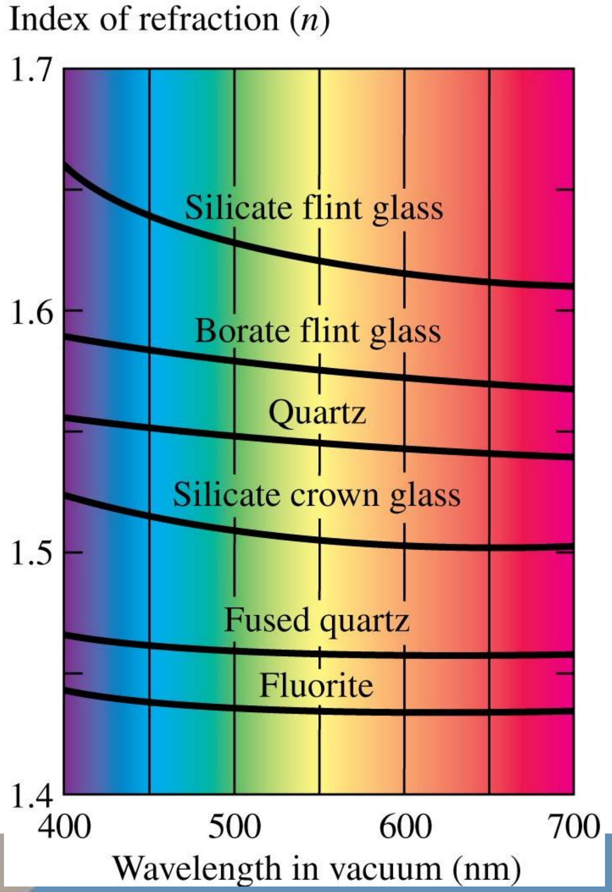


- Light is electromagnetic radiation (visible light, infrared, ultraviolet, x-rays, gamma rays, microwaves…).

- The speed of light in vacuum, c, is the same for all wavelengths but in a material it is different (due to n).

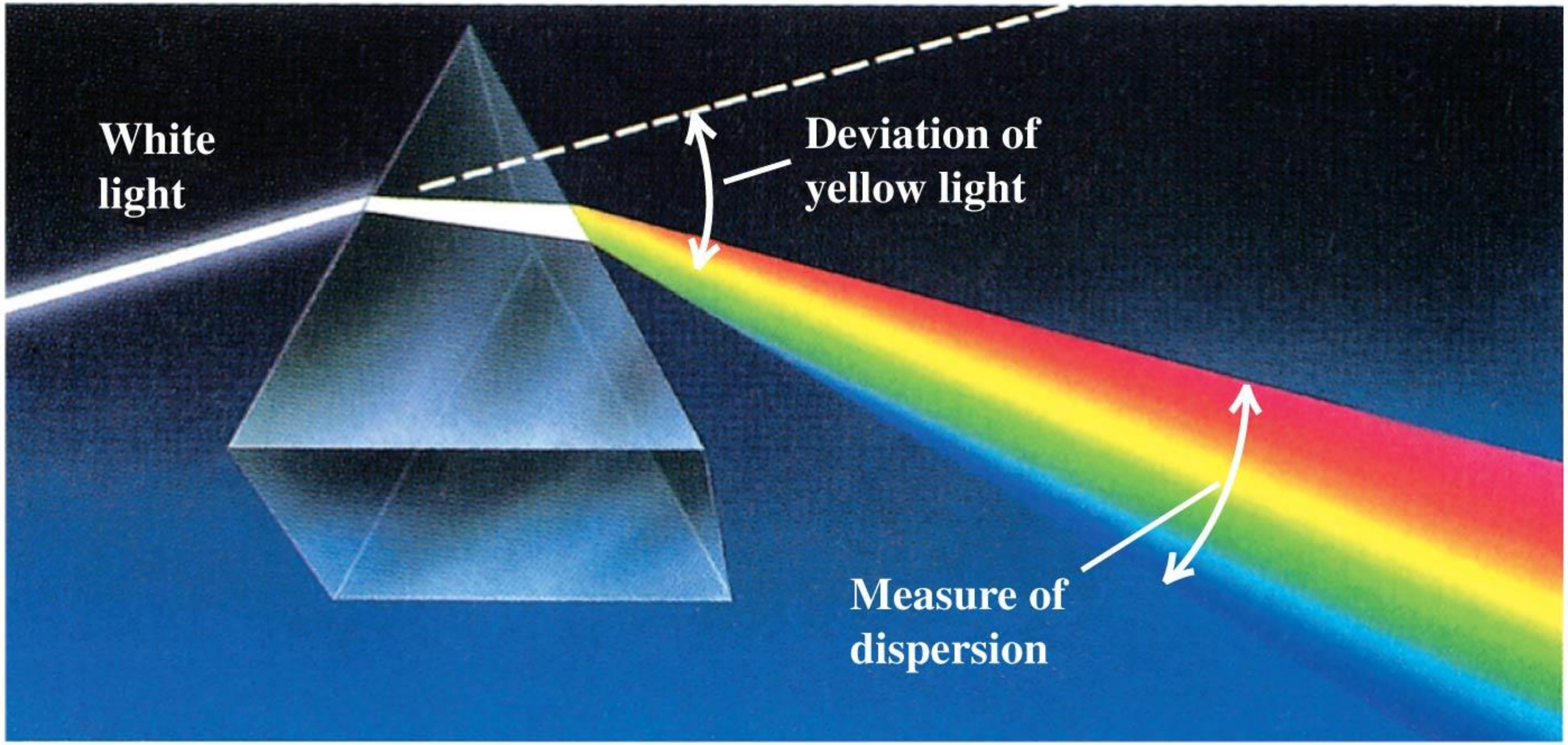
- The dependence of v (or n) on λ is called **dispersion**.

- In most materials, n decreases for longer wavelengths (see figure).



Dispersion by a prism

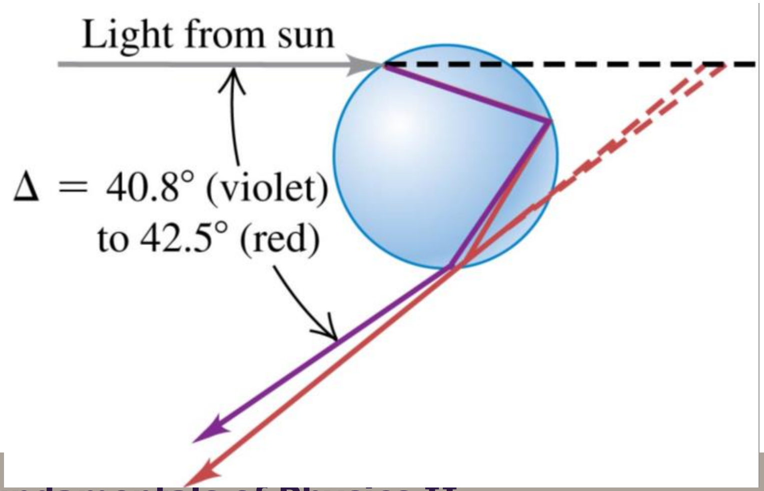
- The double refraction when white light enters then exits the prism causes separation of white light into a **spectrum**.

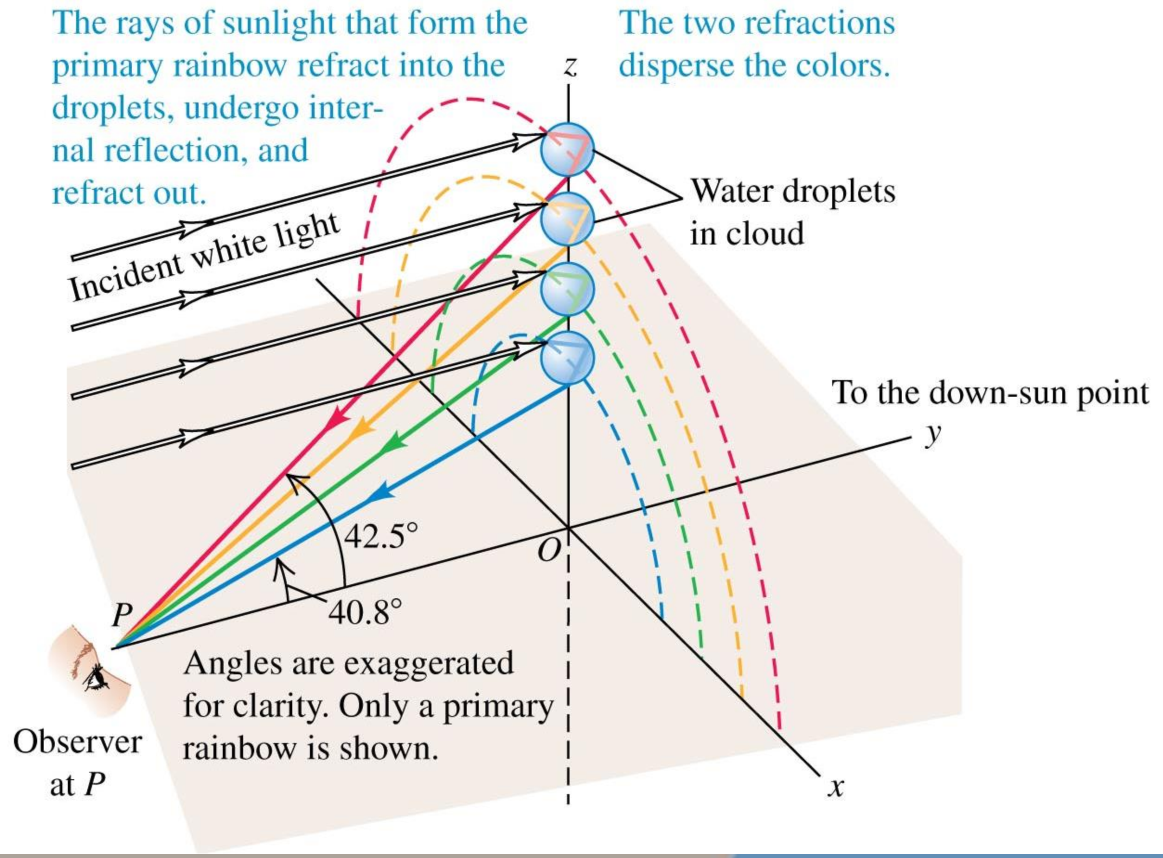


Rainbows

- When sunlight enters a spherical water droplet, it is partially reflected from the back surface then refracted again.

- Different wavelengths travel at different speeds (have different n) so they refract at different angles.

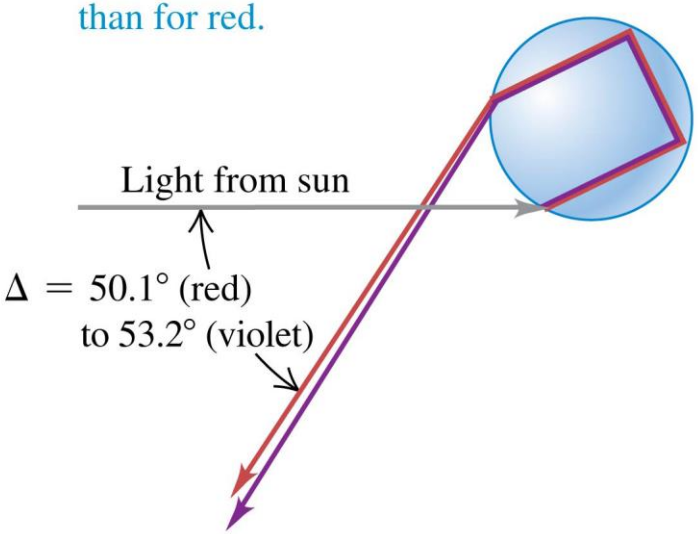


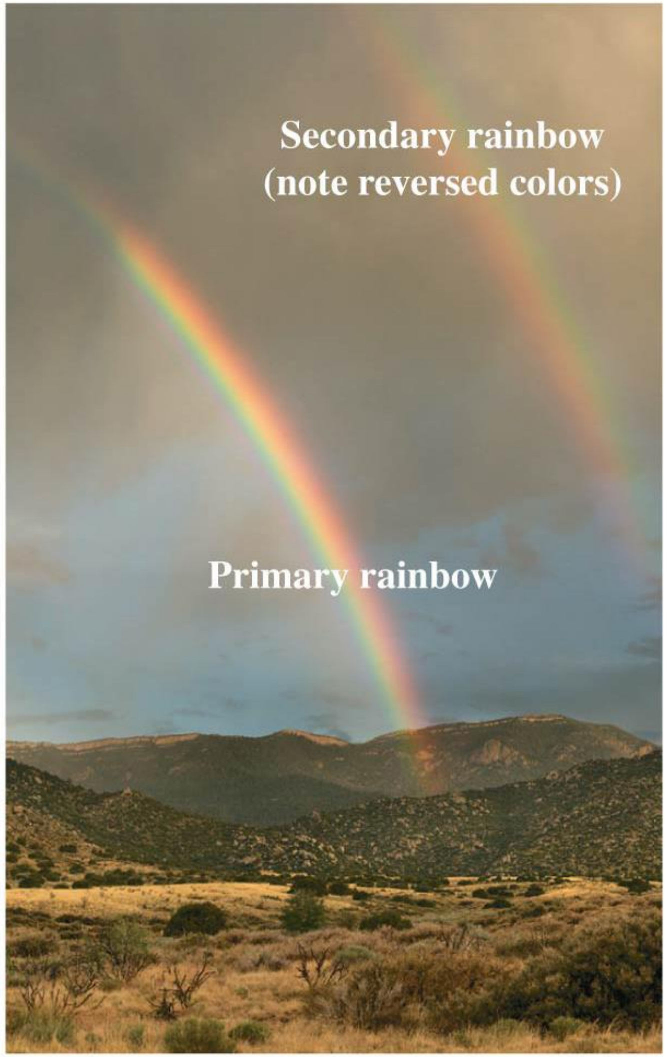


Double rainbows!!!

- Sometimes a second, fainter rainbow can be seen due to two refractions and two internal reflections inside a water droplet.

(e) A secondary rainbow is formed by rays that undergo two refractions and *two* internal reflections. The angle Δ is larger for violet light than for red.





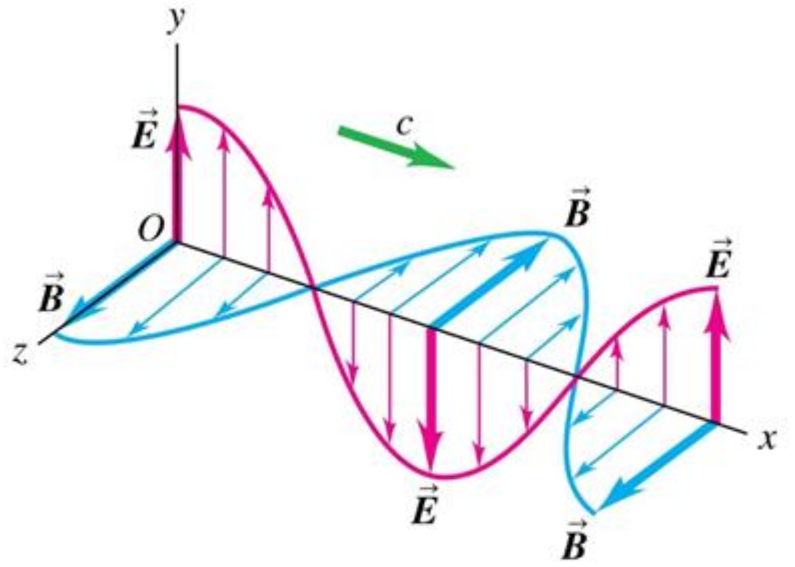
Electromagnetic waves and polarization

- An **electromagnetic wave** propagates in space at constant intensity.

- Consider the **linearly polarized** light in the figure.
  - As the wave travels along direction x, the electric field oscillates in the xy plane.

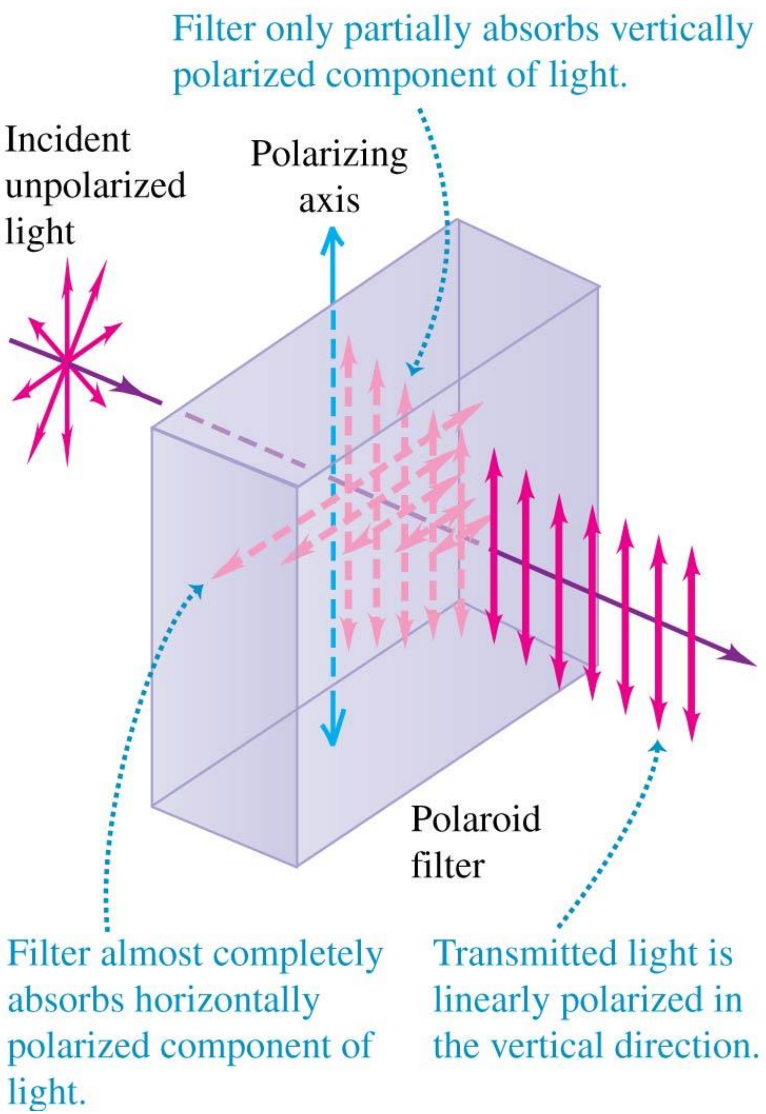
- For **polarization** we only consider the electric field (not the magnetic field).

- Normal light is **unpolarized** – made of up waves with e-fields oscillating in every direction of yz.



Polarization

- White light from most sources is **unpolarized**. It is made of waves with electric fields in all directions, randomly distributed.
- Transmission through a **polarizing filter** will produce linearly polarized light.
  - Ie. it will "linearly polarize" the light in the direction of the **polarizing axis**.
- The **intensity** of the transmitted light is exactly **one half** the intensity of the incident light.
- Different types of polarizers: absorptive, beam splitters, thin films, etc…



Malus' law

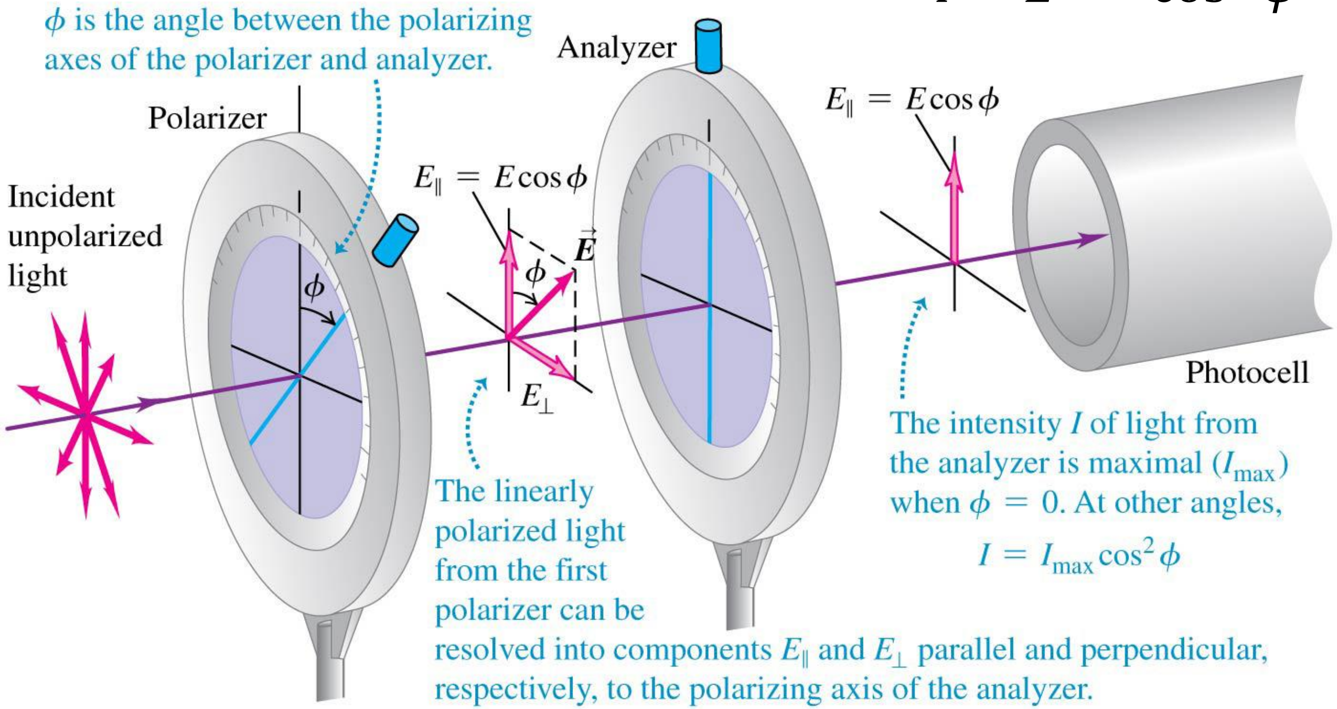
- When incident unpolarized light is put through two polarizers, the first polarizer converts the light to **linear polarization** while the second polarizer **filters** only a certain amount of the resulting light.

$$I \propto E^2 \propto \cos^2 \phi$$

- The **intensity** (power per area) of the light passing through the 2nd polarizer is given by Malus' Law:

$$\boxed{I = I_{max} \cos^2 \phi}$$

in units W/m² (or W/cm²).

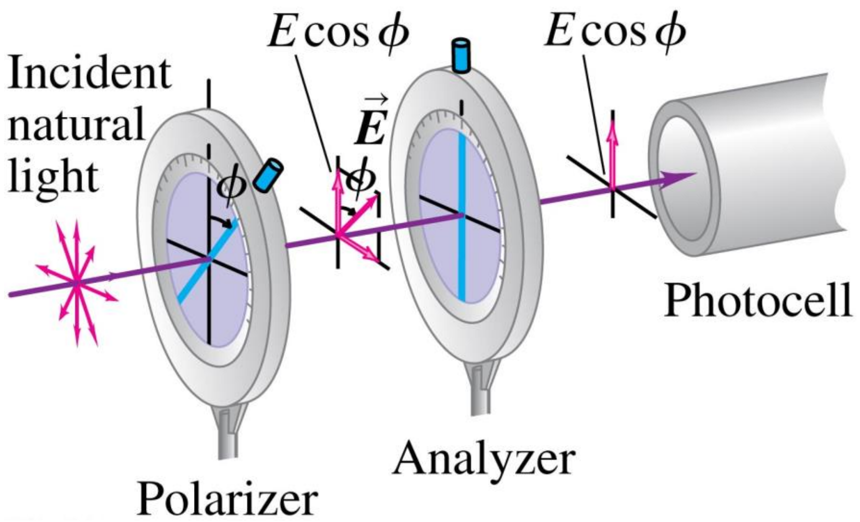


Ex. 33.5 – Combo of 2 polarizers

- Light with intensity I_0 is incident on a combination of 2 polarizers where the angle between them is $\phi = 30°$.

  Find the intensity of the transmitted light.

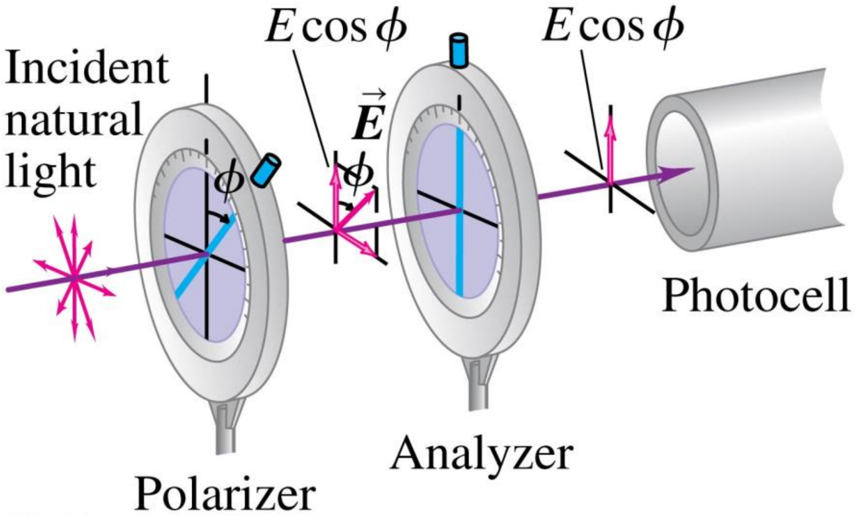
  NB. Remember that unpolarized light is incident on a polarizer, the transmitted light is $I_0/2$.



Ex. 33.5 – Combo of 2 polarizers

- The initial intensity is I_0 so the intensity entering the analyser is $I_0/2$.

$$\boxed{I} = \frac{I_0}{2}\cos^2 30° = \frac{I_0}{2}\left(\frac{3}{4}\right) = \boxed{\frac{3I_0}{8}}$$



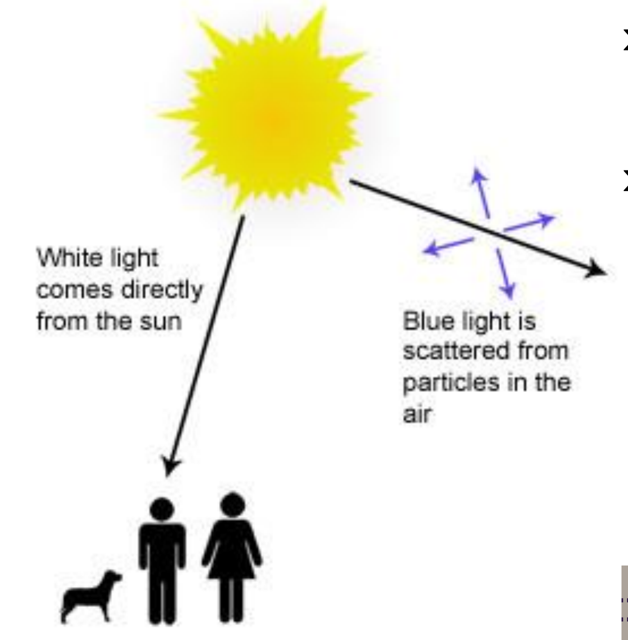
Circular and elliptical polarization

- When the electric field vector of a light wave rotates around the direction of light propagation, the polarization is circular or elliptical.
- Circular polarization can be separated into left and right-hand circular polarization.
- The lenses on 3D movie glasses either allow transmission of left or right circularly polarized in order to see depth on the screen.

Scattering of light

- When light from the sun hits our atmosphere, it gets absorbed then re-radiated out in a variety of directions.
  - This process is called **scattering**.

- Blue light has shorter wavelength (and more energy) and is scattered more than red light (longer wavelength).



» When looking up during the daytime, we see that the sky appears blue.

» During a sunset, the sky appears red/orange because the blue light is scattered out due to large distance travelled.