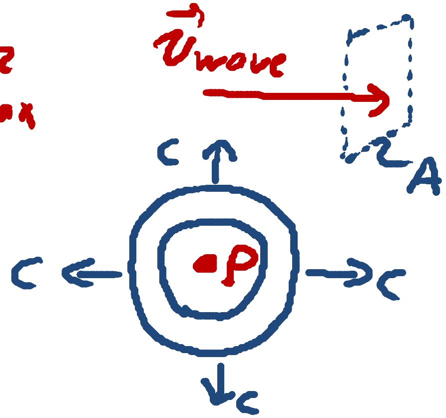
Recap

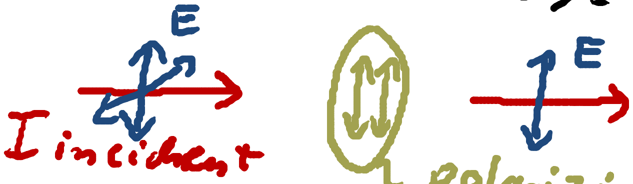
Lecture 27

- Energy transport by EM wave:
  - Intensity $= I = \dfrac{\text{average power}}{\perp \text{ area } A} = \frac{1}{2} c \varepsilon_0 E_{max}^2$
  - for isotropic point source: $I = \dfrac{P_{\text{point source}}}{4\pi r^2}$



- Polarization and ideal polarizing filter:
  - Polarizing filter: only electric field component parallel to the filter's transmission (polarization) axis is passed

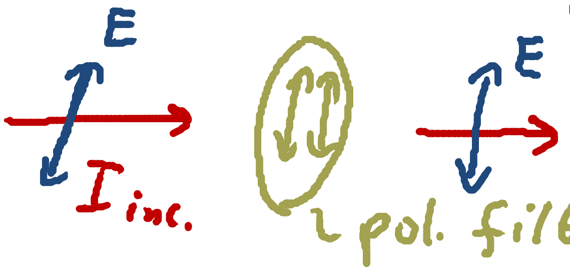
⇒ for randomly polarized incident wave:



$I_{transmitted} = \frac{1}{2} I_{incident}$

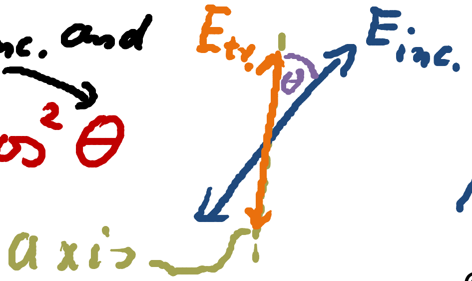
polarizing filter with vertical transm. axis

⇒ for incident plane-polarized wave:



angle between $\vec{E}_{inc.}$ and transm. axis

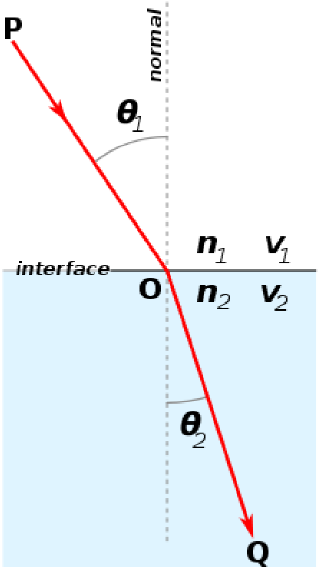
$I_{transm.} = I_{inc.} \cos^2\theta$



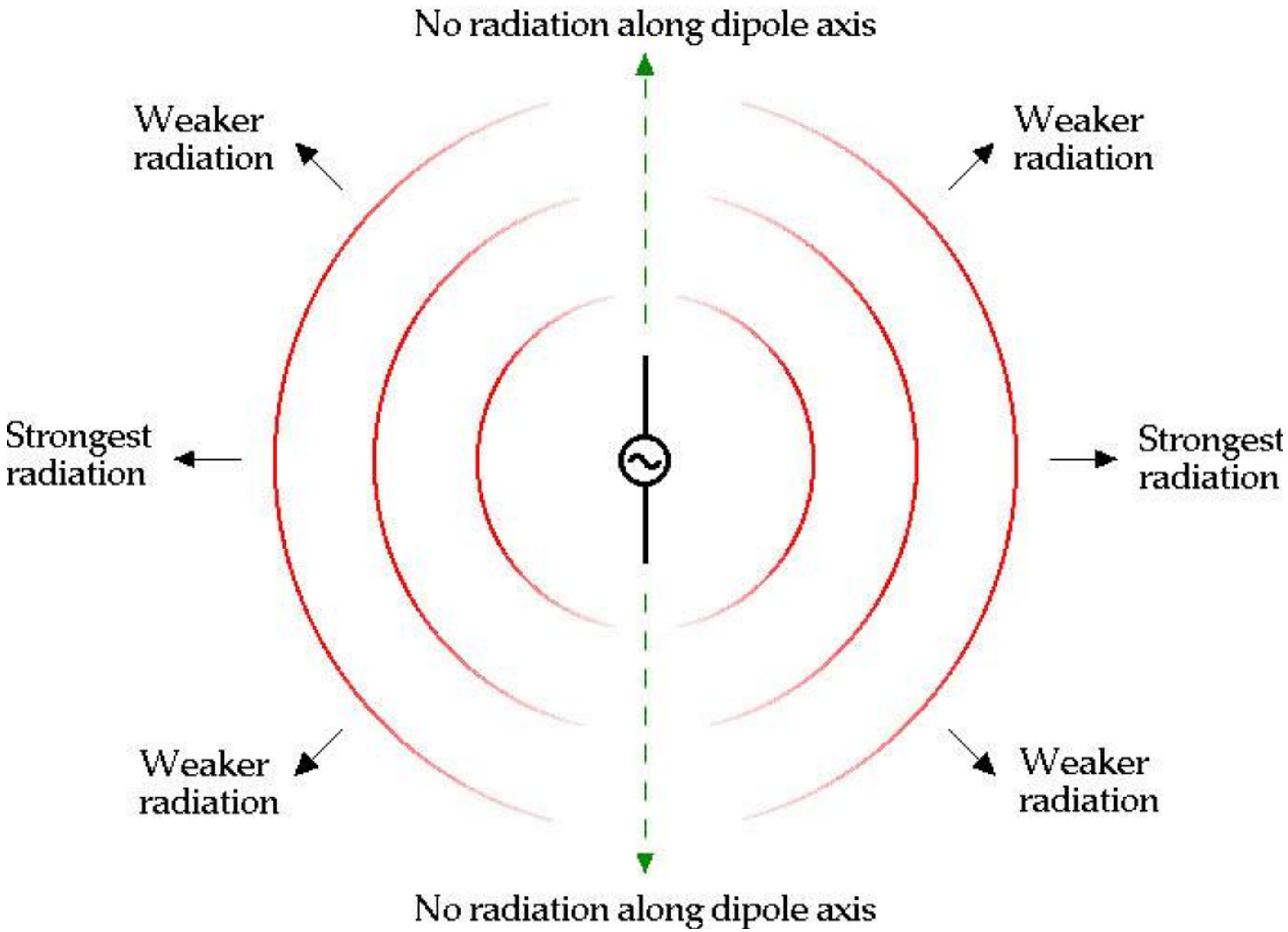
electric field after the filter always points along the filter's transmission axis!

Today:

- Polarization of EM waves
  - Why is the sky blue, and why does it turn dark blue at 90 degrees from the sun?
- Reflection and refraction
  - Snell’s law



Electric Dipole Radiation Pattern



No radiation along dipole axis

Weaker radiation

Weaker radiation

Strongest radiation

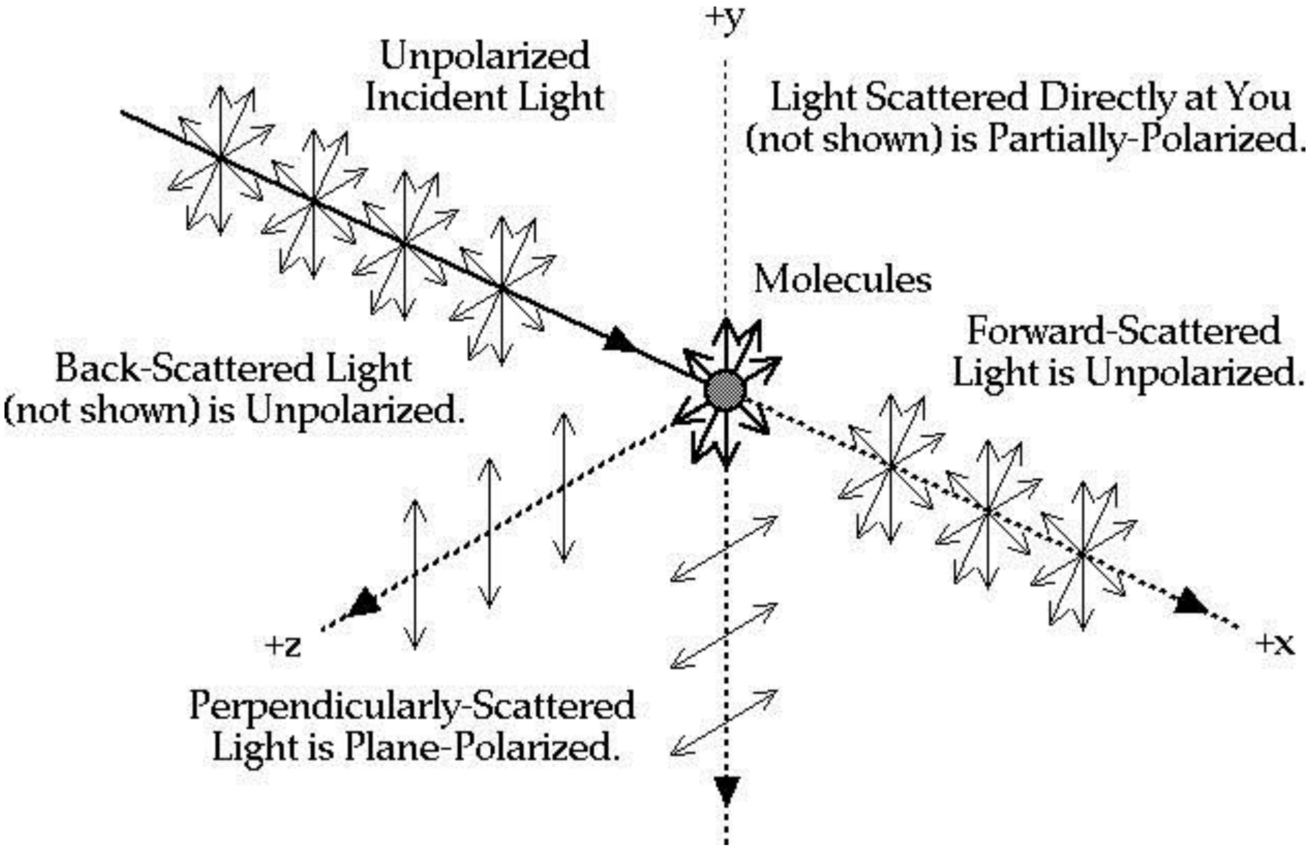
Strongest radiation

Weaker radiation

Weaker radiation

No radiation along dipole axis

Polarization of Light by Scattering



Arrows (↔) show $\vec{E}$ oscillation directions in light. Unpolarized light is a mixture of all polarizations. Bold arrows (**↔**) show electric charge (dipole) oscillations in molecules due to $\vec{E}$ oscillations from incident light. These charge oscillations capture incident light energy and re-radiate or “scatter” it in all directions with polarizations as indicated.

Blue light is scattered more than visible light of other colors (lower frequencies).
That’s why the sky is blue…

Photo without polarization filter

Photo taken with polarization filter

Notice that the sky turns dark blue at 90 degrees from the sun!

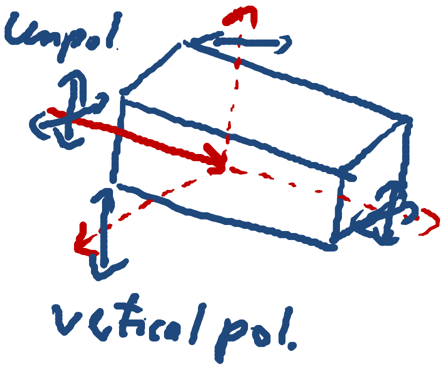
An unpolarized beam of light is directed into the side of an aquarium containing cloudy water. Light scattered by the cloudy water out of the front of the aquarium is to be observed through a polarizing filter.

Which orientation of the transmission direction of the filter will transmit the most light?

A. Horizontal. [✓ B. Vertical.]

C. 45° to horizontal.

D. All orientations will transmit the same amount of light.



Geometrical Optics

- In the following, we assume:
  - (1) Light beams with width $\gg \lambda_{light}$
  - (2) Obstacles/apertures/objects with size $\gg \lambda_{light}$

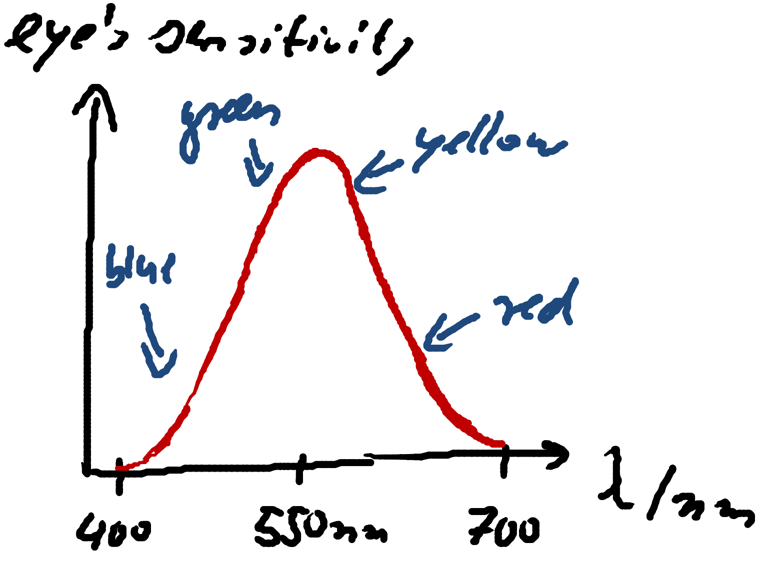
⇒ Light travels in straight-line paths ("rays") through vacuum and homogeneous isotropic materials

- Visible light:

$\lambda \approx 400\,nm$ to $700\,nm$

violet ↗ (400 nm), red ↑ (700 nm)

Perceived color of light is determined by its wavelength



- Speed of light:

- in vacuum: $v_{light} = c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = 3.0 \cdot 10^8 \, m/s$

- in a material:

$$\boxed{v_{light} = \frac{c}{n}} < c$$

with index of refraction $n \geq 1$ of the material

$\Rightarrow$ Speed of light is different in different materials!

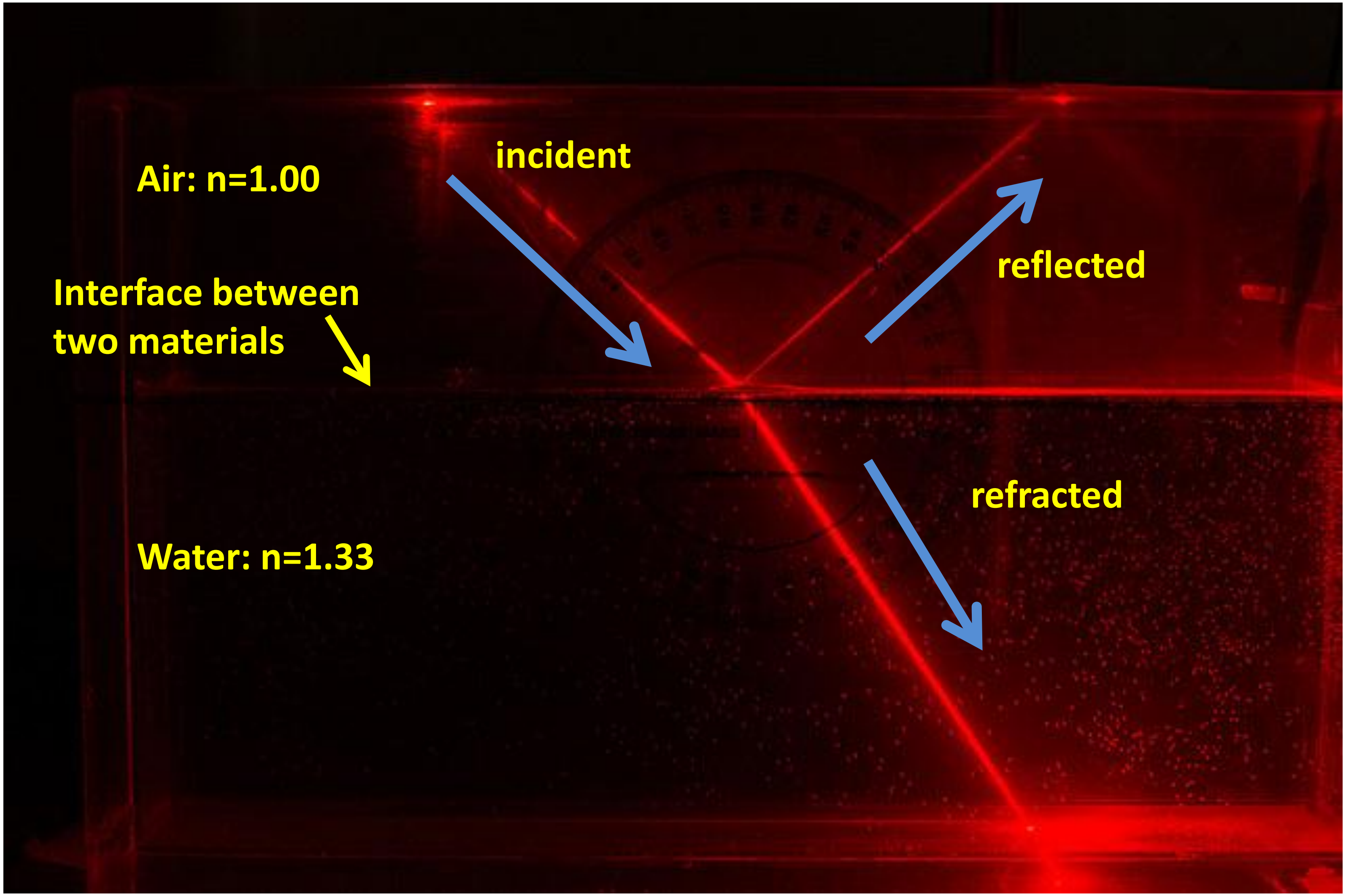
Examples: $n_{glass} = 1.5$ to 1.9

$n_{water} = 1.33$

$n_{air} = 1.0003$

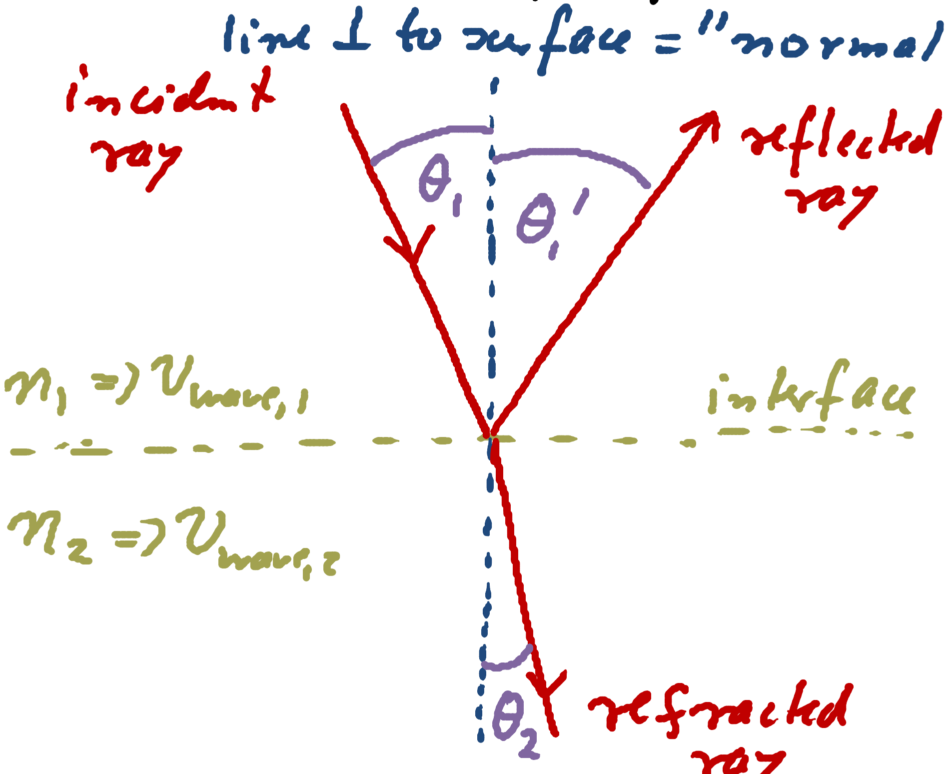
$\Rightarrow$ This has several important consequences!

Reflection and Refraction



Reflection and Refraction

Consider a beam of light traveling from one medium (with index of refraction n_1) into a second medium (with index of refraction n_2)



at interface (where speed of wave changes):

- part of the light is <u>reflected</u>
- rest of the light will be transmitted into medium 2 ⇒ <u>refracted</u> ray

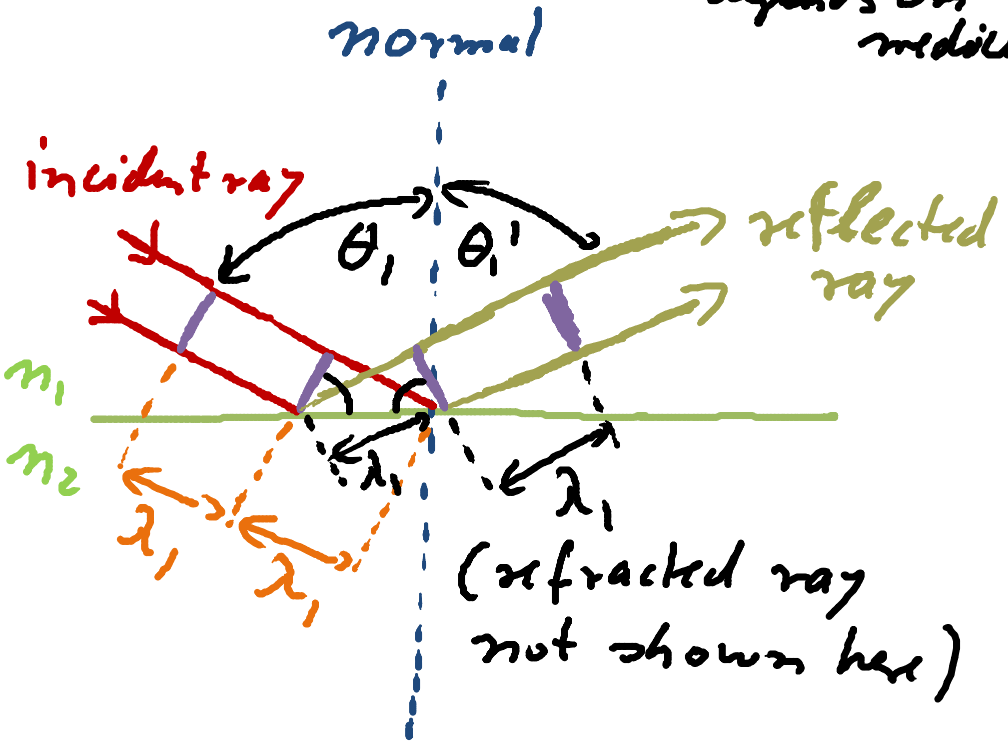
<u>Note:</u> Frequency of light is the <u>same</u> in both media, but wavelength λ is different if $n_1 \neq n_2$, since then $v_{wave,1} \neq v_{wave,2}$

How are θ_1, θ_1', and θ_2 related to each other?

→Consider traveling light:

- within time $T = \frac{1}{f}$, light travels by distance $= \lambda$

$$\left(\text{distance between ``wave fronts''}\right) = \lambda = \underset{\text{depends on medium}}{v_{wave}} / \underset{\text{fixed}}{f} = \frac{c}{nf}$$



(refracted ray not shown here)

Incident and reflected ray are in the <u>same</u> medium

⇒ travel by same distance λ_1 in $\Delta t = 1/f = T$

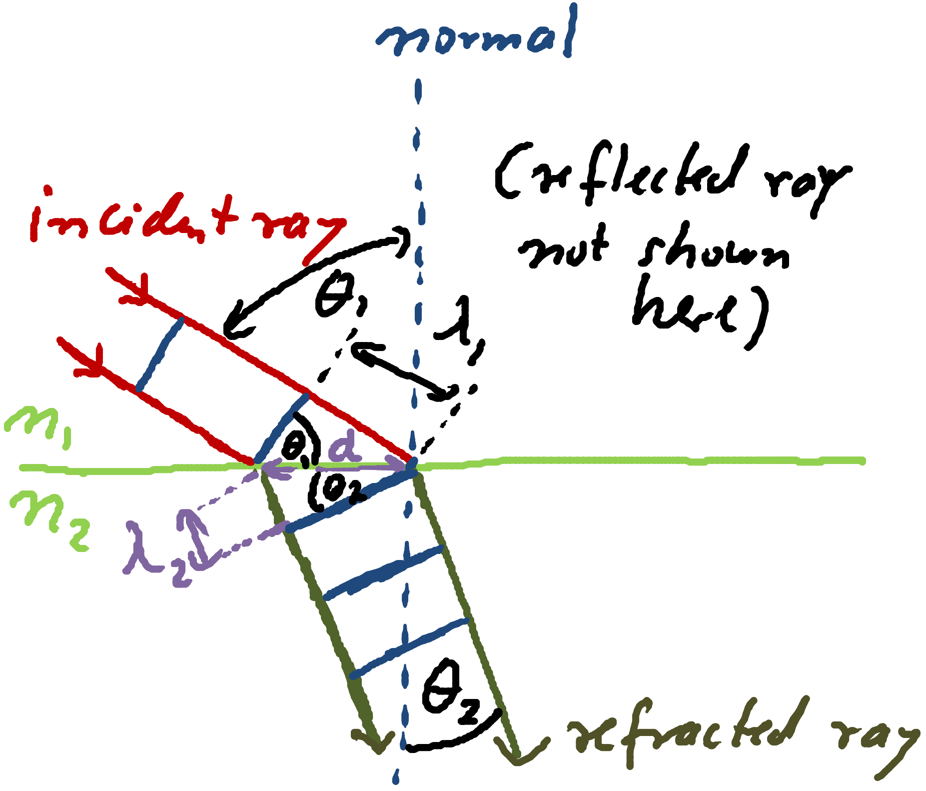
⇒ angle of reflection $\overset{!}{=}$ angle of incidence

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

(Law of reflection)

Plane containing the normal and incident ray: plane of incident

→ similar for refracted ray:



- In time interval $\Delta t = 1/f = T$
  - incident ray travels by distance $\lambda_1 = d \sin\theta_1$
  - refracted ray travels by distance $\lambda_2 = d \sin\theta_2$

$$\Rightarrow \frac{\sin\theta_1}{\sin\theta_2} = \frac{\lambda_1 d}{\lambda_2 d} = \frac{\lambda_1}{\lambda_2}$$

$$= \frac{v_{wave,1} f}{v_{wave,2} f} = \frac{n_2}{n_1}$$

$\nearrow$ $v_{wave} = \frac{c}{n} = \lambda f$

⇒ Law of refraction (Snell's Law) $\boxed{n_1 \sin\theta_1 = n_2 \sin\theta_2}$

Note: All angles are measured relative to the normal!

Refraction: Example