Lecture 13
(Rays, Reflection and Refraction)

Physics 2130-01 Spring 2020

Douglas Fields

https://phet.colorado.edu/sims/blackbody-spectrum/blackbody-spectrum_en.html

https://phet.colorado.edu/en/simulation/legacy/discharge-lamps

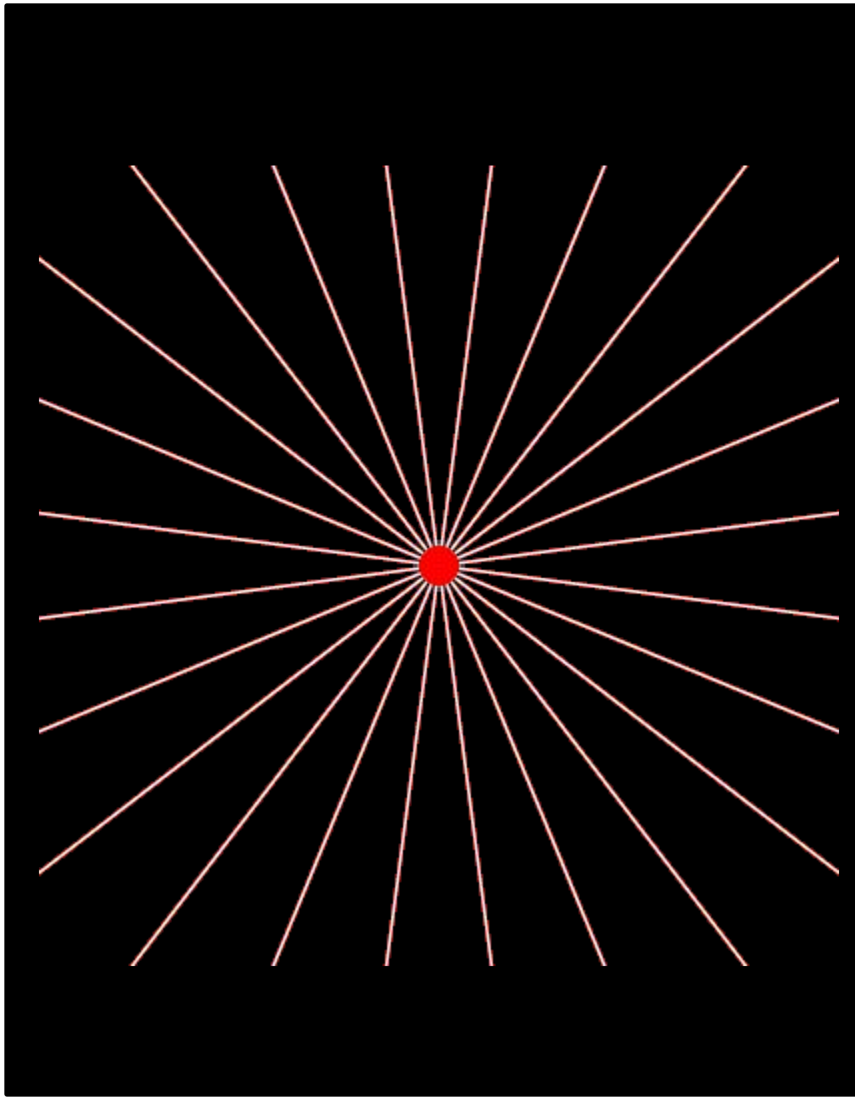
https://phet.colorado.edu/en/simulation/legacy/radio-waves

https://phet.colorado.edu/sims/html/bending-light/latest/bending-light_en.html

Sources

- The fundamental source of electromagnetic radiation is accelerated charges.
- The total power radiated goes as the charge times the acceleration squared:

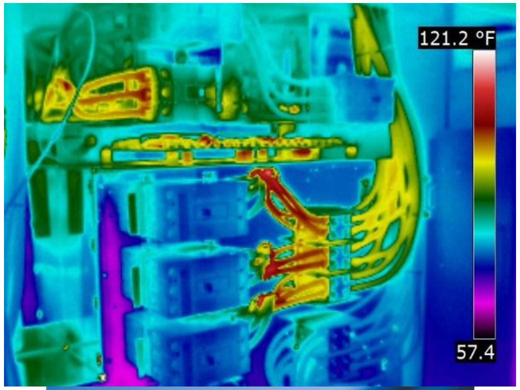
$$P = \frac{2}{3}\frac{q^2 a^2}{4\pi\varepsilon_0 c^3} = \frac{q^2 a^2}{6\pi\varepsilon_0 c^3} \text{ (SI units)}$$

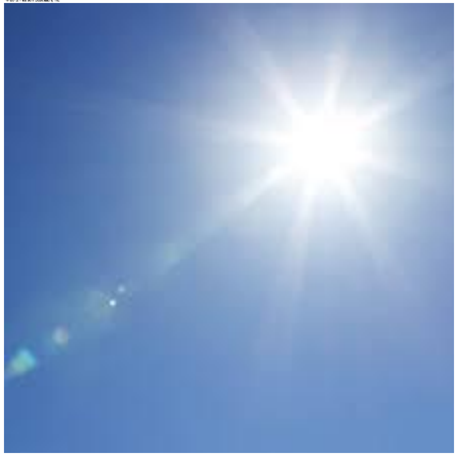


http://www.tapir.caltech.edu/~teviet/Waves/field_a.gif

Sources – Thermal Radiation

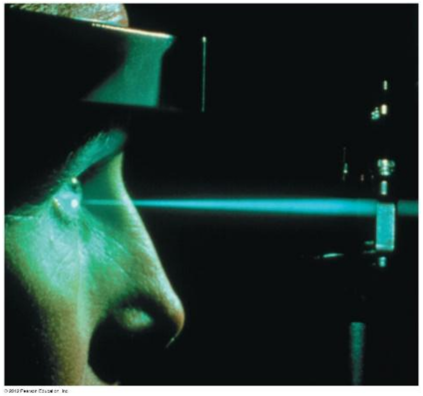
- As mentioned earlier, EM waves are caused by accelerated charges. But what are the sources of acceleration?
- Remember from thermodynamics that temperature is a measure of the average kinetic energy of the constituent particles.
- So, higher temperatures mean higher (average) kinetic energies (with some distribution).
- As these constituents move, they can suffer collisions, and if they are charged, these collisions represent accelerated charged particles.
- There is then a distribution of wavelengths of EM waves emitted.
- The hotter the object, the more shorter wavelengths (higher frequency) are emitted.



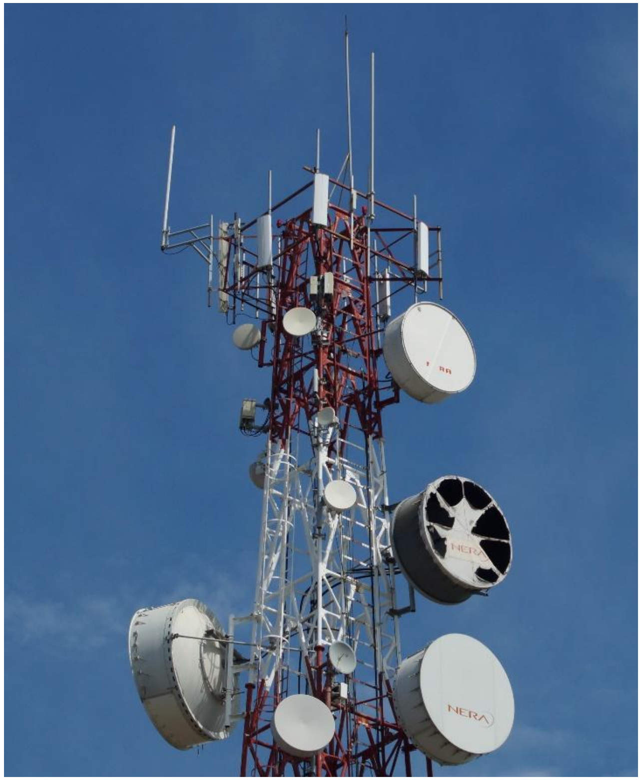


Sources – Atomic transitions

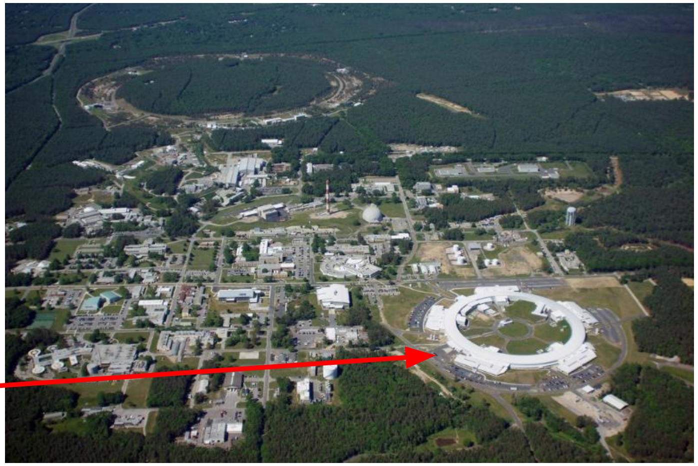
- When electrons bound in an atom make transitions from one state to a lower energy state, they emit light (photons).
- This can happen through chemical reactions, induced emission (lasers), or by exciting the atoms of a gas by passing a current through it.
- In all cases, the electrons go from a higher energy state to a lower one through the emission of light.



Sources – Transmitters

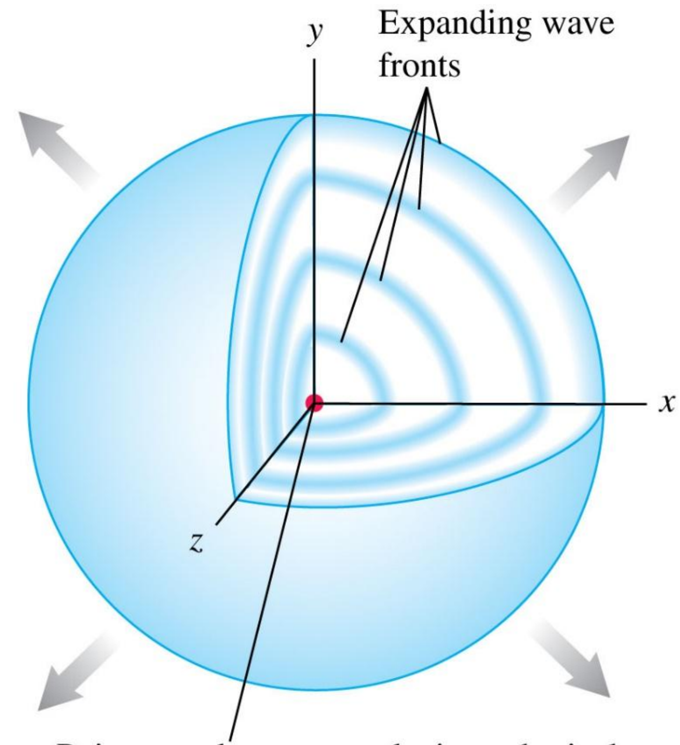


- Electrons in a conductor can be accelerated by an applied electric field, thus emitting EM waves.
- This is the idea behind radio and microwave transmitters.
- If you have a circulating beam of electrons, then they are undergoing acceleration.
- This causes the emission of synchrotron radiation, and is the idea behind Brookhaven National Lab's National Synchrotron Light Source II.



Waves and Wave fronts

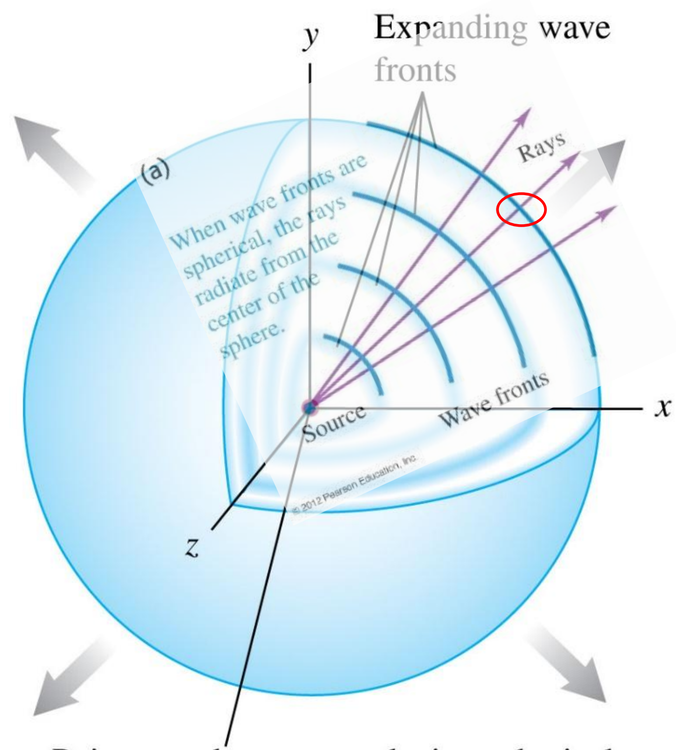
- Let's first consider a point source of waves.
- Doesn't matter what type of waves (sound, light…).
- We can visualize the expanding (in 3D) waves as a series of concentric shells, each growing out in space.
- We call these wave fronts, although they don't (have to) represent the "front" of the wave.



Point sound source producing spherical sound waves (alternating compressions and rarefactions of air)

Waves and Wave fronts

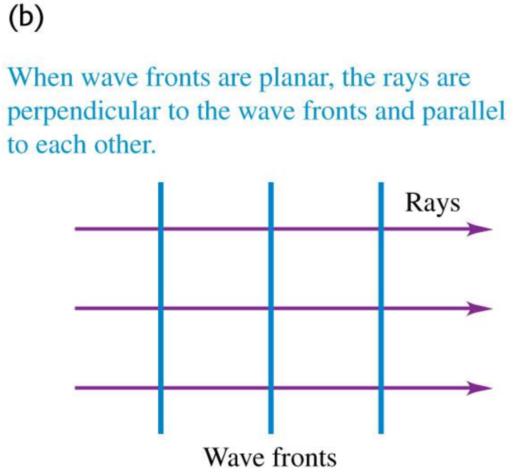
- Now, since we have to often work in two dimensions when we draw or write, lets take a cross-section of these shells (I'm showing only a quarter of a cross-section), and draw the wave fronts as arcs of the circle that would be represented by a complete wave front cross-section.
- Now, if we draw arrows from the source in the direction of the wave travel, notice that these "rays" are everywhere perpendicular to the wave fronts.
- These rays will provide us with a very useful representation of the waves when we deal with optics.
- If we zoom in on the circled area…

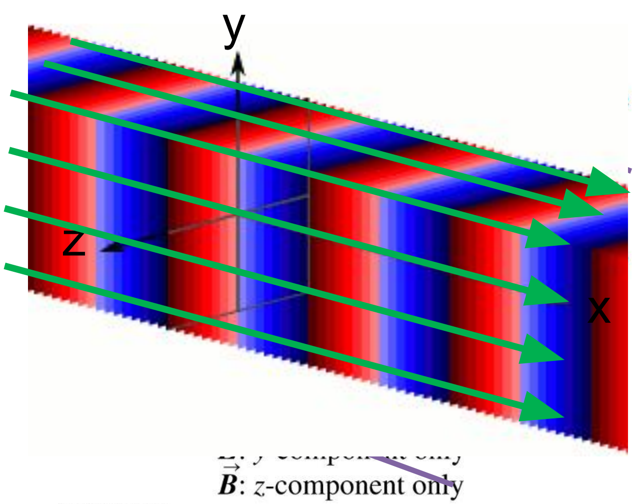


Point sound source producing spherical sound waves (alternating compressions and rarefactions of air)

Waves and Wave fronts

- We get an approximation of a plane wave.
- In this case, the rays are all parallel to one another (in the approximation).
- Don't confuse rays with photons or something!
- Rays don't really exist, they are just a way for us to visualize the direction of the wave motion.
- Think of them in the same way we think of wind-tunnel lines of fluid flow.
- Their spacing is unimportant, and their number is arbitrary.

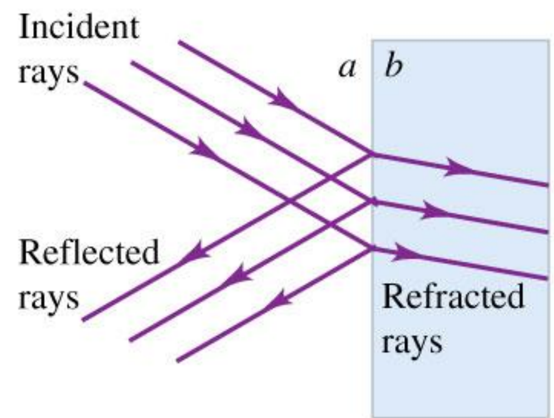




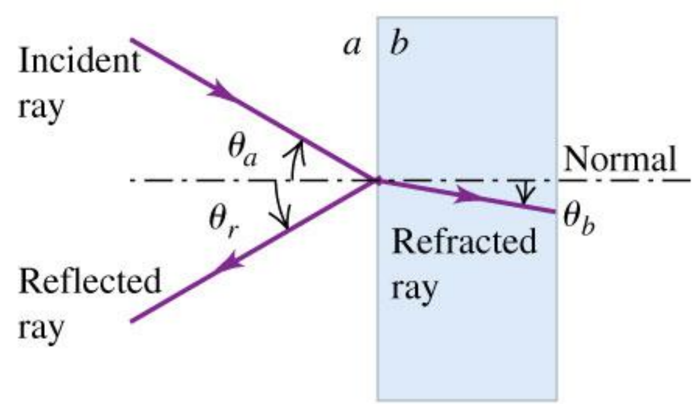
Reflection and Refraction

- Now, we are going to discuss reflection and refraction (transmission) of EM waves at the interface between two materials.
- [I’d rather discuss Huygens's Principle now, but I will keep with the order of the book.]
- Remember what we learned about mechanical waves at boundaries (using the wave table).
  - At boundaries between two materials with different wave speeds (determined by the index of refraction), there will be both reflection and transmission.
- But in 3D materials where the wave fronts don’t necessarily strike the interface head-on, what happens to the waves?

(b) The waves in the outside air and glass represented by rays



(c) The representation simplified to show just one set of rays



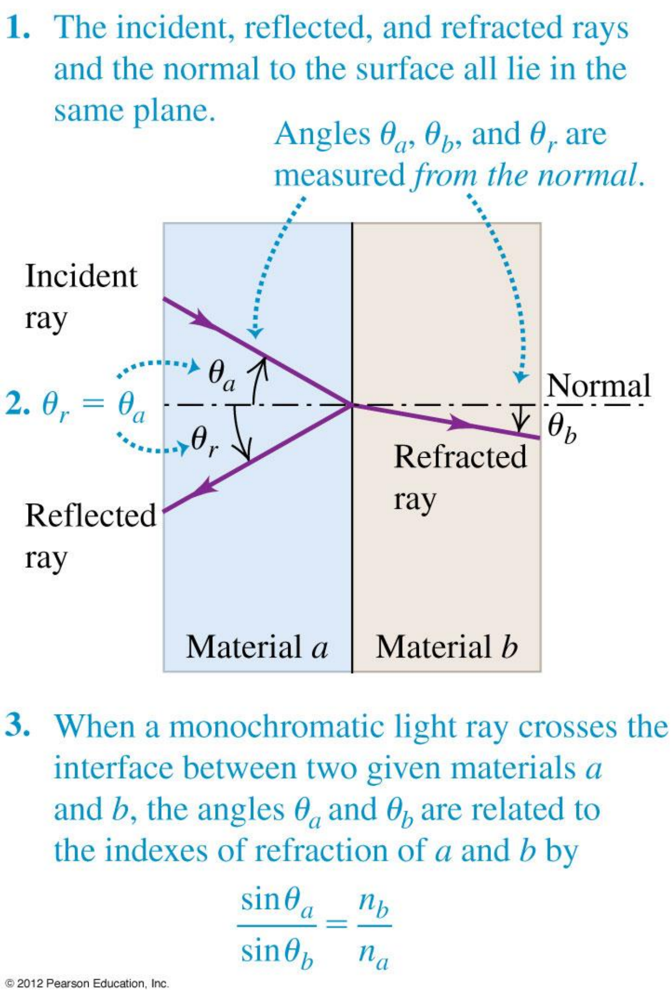
Laws of Reflection and Refraction

- For the time being, let's just give the experimental results:
  - The incident, reflected and refracted rays and the normal to the surface all lie in the same plane.
  - The angle of reflection is equal to the angle of incidence for all wavelengths and for any pair of materials.

$$\theta_r = \theta_a$$

  - For monochromatic light, and for a given pair of materials, a and b:

$$n_a \sin\theta_a = n_b \sin\theta_b$$

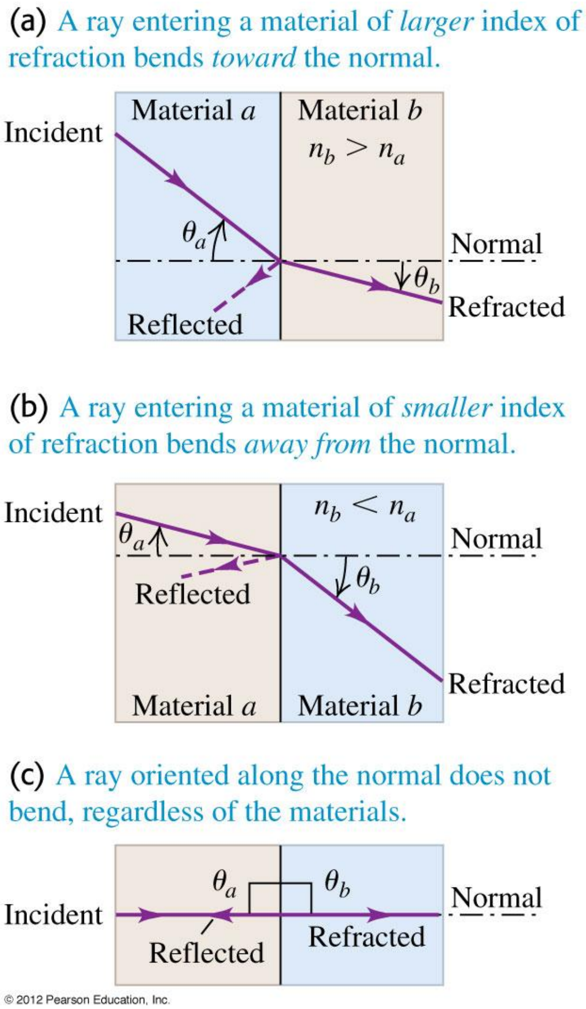


Laws of Reflection and Refraction

$$\theta_r = \theta_a$$

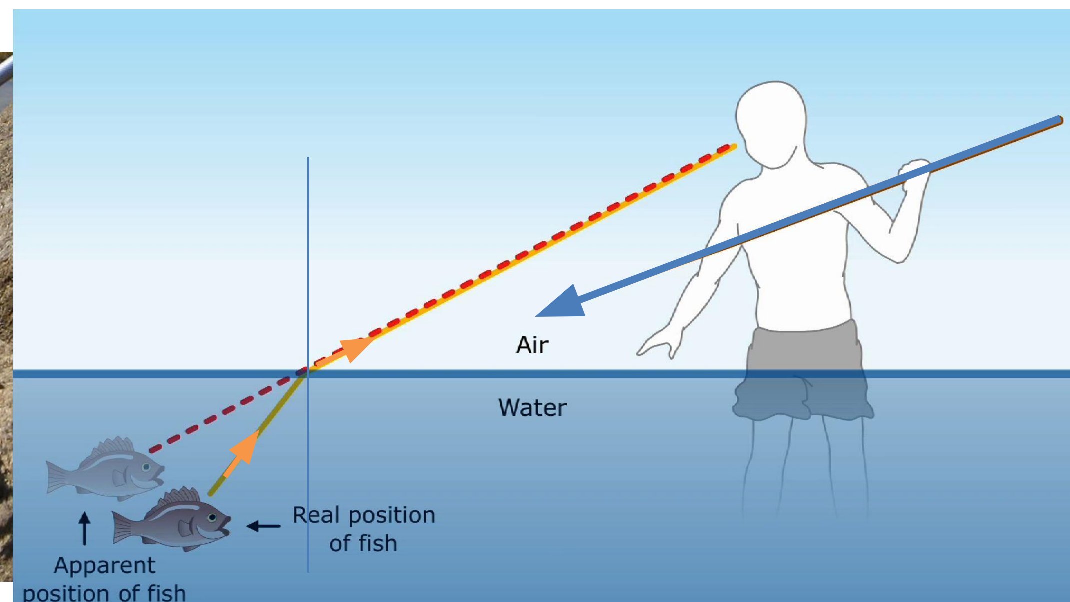
$$n_a \sin\theta_a = n_b \sin\theta_b$$

- Three examples.
  - Material b has a larger index of refraction:
  - Material a has a larger index of refraction:
  - The angle of incidence is zero



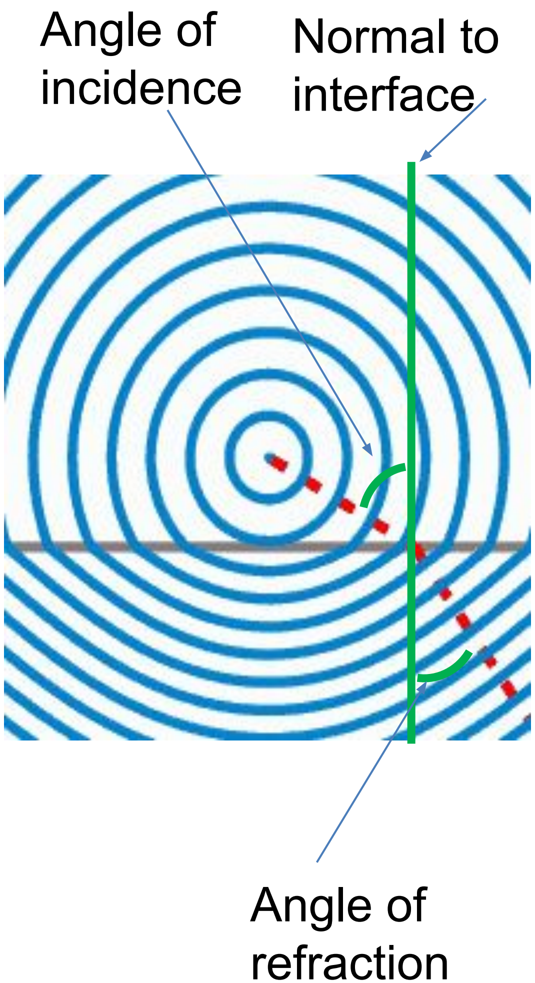
Laws of Reflection and Refraction

- These Laws (what used to be called Snell's Laws) can account for many phenomena we see daily.
- The concept isn't difficult, but sometimes is confusing.
- Must keep in mind how the angles are defined!



Examples

- Remember that it is the wave velocity (not the frequency of oscillations) that change in going from one medium into another.
- So, since $\lambda_0 = \frac{v_0}{f}$ and $\lambda = \frac{v}{f}$.
- Then with $v = \frac{v_0}{n}$, we get $\lambda = \frac{\lambda_0}{n}$ in the new medium.



Indices of Refraction

- Vacuum: n = 1
- Air at STP: n = 1.0003 ~ 1
- Acrylic?

Table 33.1 Index of Refraction for Yellow Sodium Light, $\lambda_0 = 589$ nm

Substance	Index of Refraction, n
Solids	
Ice (H_2O)	1.309
Fluorite (CaF_2)	1.434
Polystyrene	1.49
Rock salt (NaCl)	1.544
Quartz (SiO_2)	1.544
Zircon ($ZrO_2 \cdot SiO_2$)	1.923
Diamond (C)	2.417
Fabulite ($SrTiO_3$)	2.409
Rutile (TiO_2)	2.62
Glasses (typical values)	
Crown	1.52
Light flint	1.58
Medium flint	1.62
Dense flint	1.66
Lanthanum flint	1.80
Liquids at 20°C	
Methanol (CH_3OH)	1.329
Water (H_2O)	1.333
Ethanol (C_2H_5OH)	1.36
Carbon tetrachloride (CCl_4)	1.460
Turpentine	1.472
Glycerine	1.473
Benzene	1.501
Carbon disulfide (CS_2)	1.628