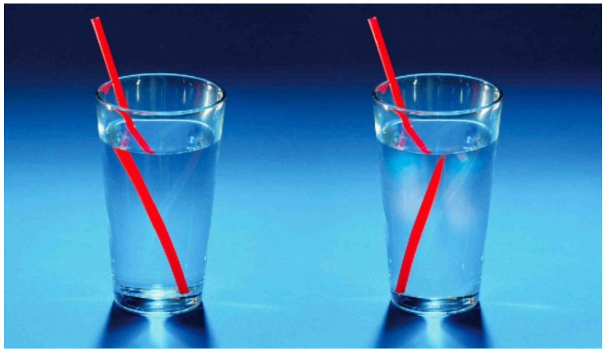

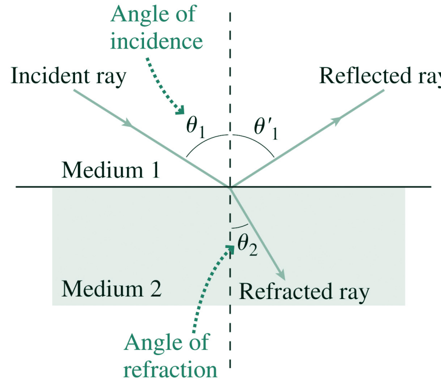


# University Physics 227N/232N

# Chapters 30-32: Optics

**Homework "Optics 1" Due This Friday at Class Time**

**Quiz This Friday**

Dr. Todd Satogata (ODU/Jefferson Lab)

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http://www.toddsatogata.net/2014-ODU

Monday, April 14 2014

Happy Birthday to Abigail Breslin, Joe Haden, Sarah Michelle Gellar,
Greg Maddux, Pete Rose, Alan MacDiarmid (Nobel prize 2000) and Christiaan Huygens!

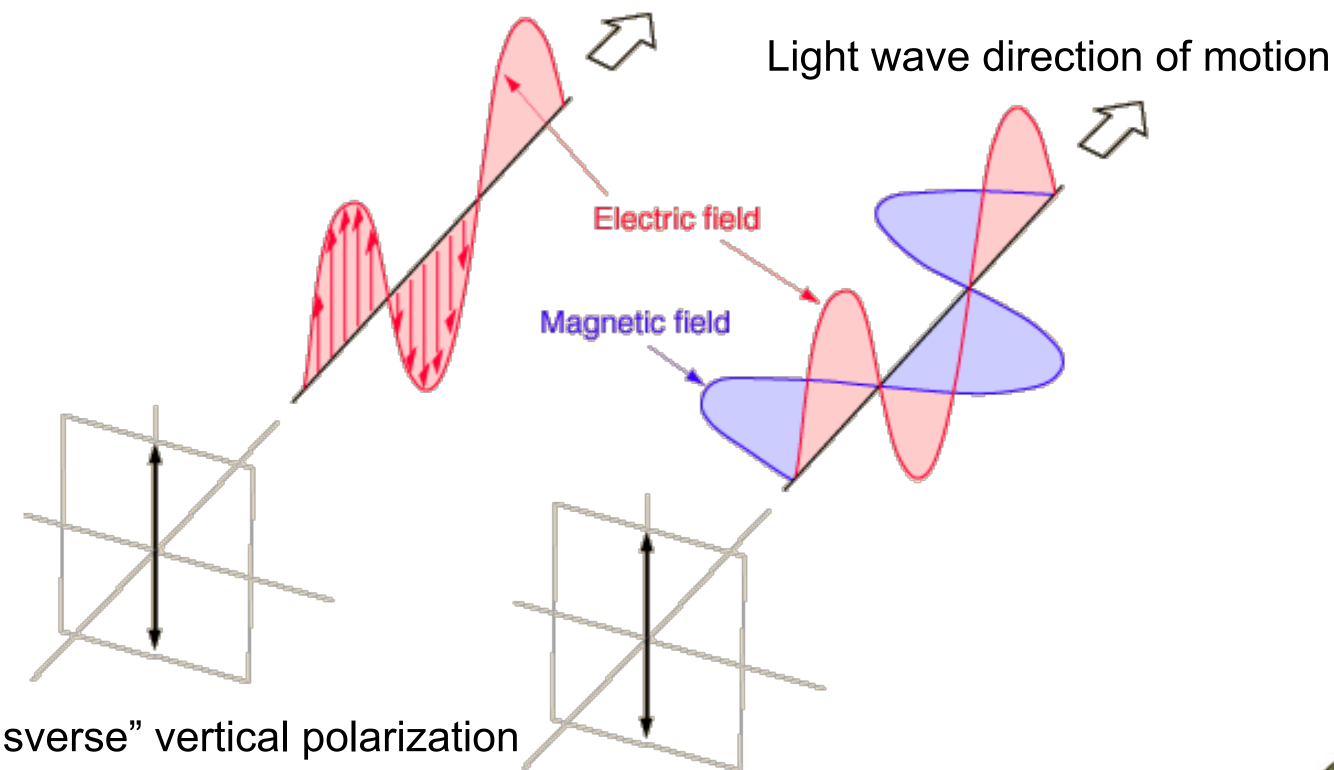
# The Remaining Semester

| | | | | |
|---|---|---|---|---|
| M Apr 14 | 30 | [-- Mb] | Optics: Reflection/Refraction, Snell's Law | |
| W Apr 16 | 30 | [-- Mb] | Optics: Dispersion | |
| F Apr 18 | 31 | [-- Mb] | Optics: Mirrors and Lenses | Quiz |
| M Apr 21 | 31 | [-- Mb] | Optics: Mirrors and Lenses | |
| W Apr 23 | 32 | [-- Mb] | Optics: Interference and Diffraction | |
| F Apr 25 | 32 | [-- Mb] | Optics: Interference and Diffraction | Quiz |
| M Apr 28 | All | [-- Mb] | Review | |
| W Apr 30 | -- | -- | Reading Period, No class, Office Hours at request | |
| F May 2 | -- | -- | Reading Period, No class, Office Hours at request | |
| M May 5 | FINAL | 08:30-11:30 | | |

- We only have six classes left! (plus one final review session)
- Yes, the final exam is comprehensive…
- … but it has the same rules of engagement as midterm 3
  - Very similar to homework; cheat sheet(s) posted Mon Apr 28
- Homework journals are due Fri Apr 25
  - To be returned Mon Apr 28
  - Can be turned in earlier at your discretion (to get back earlier)

# A Short Excursion: Electromagnetic Waves

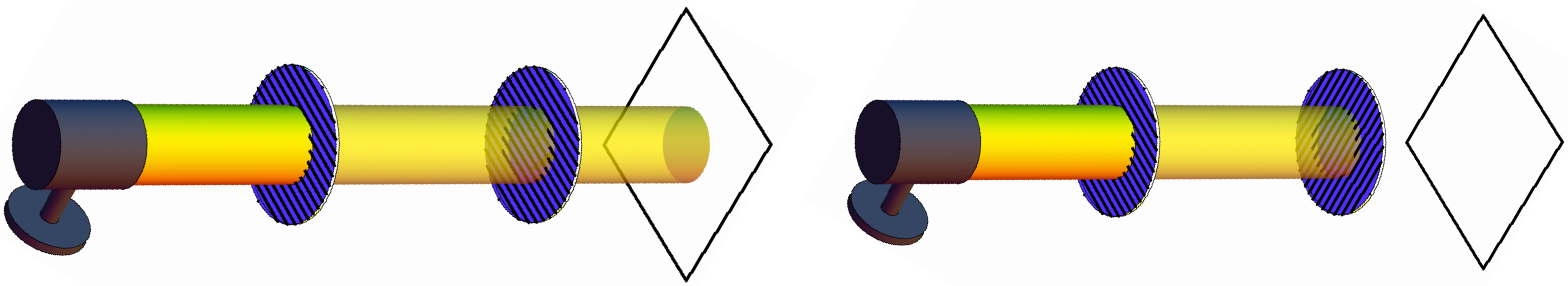
- For our purposes in learning about optics, we can treat light as an **electromagnetic wave**
  - Light is really waves of **transverse electric and magnetic fields**
    - Changing B field creates changing E field, which creates changing B field..
  - The fields and direction of motion are all perpendicular to each other
  - The direction of the electric field oscillation is called **polarization**




"Transverse" vertical polarization

# Polarized Light

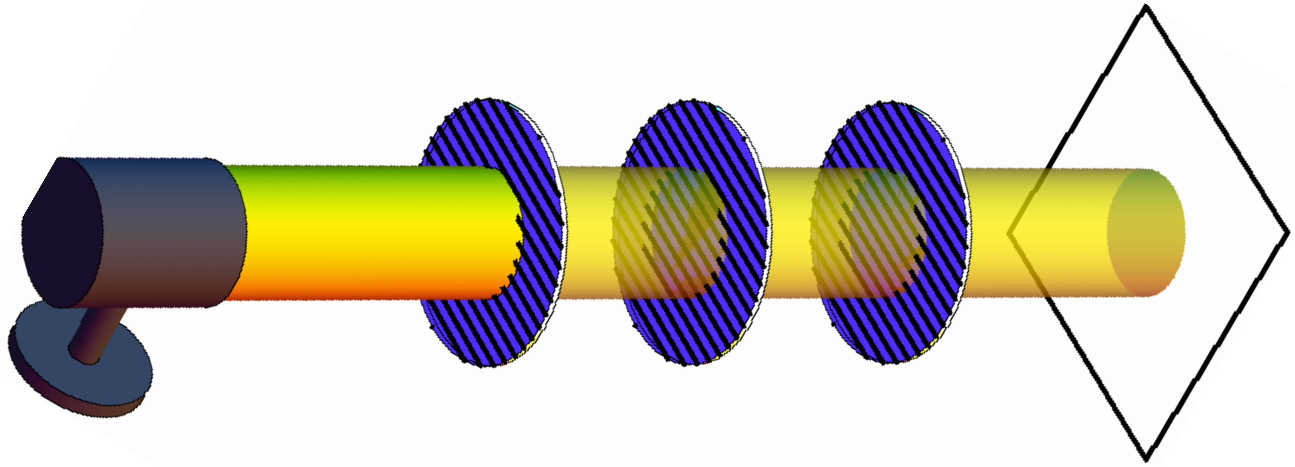
- Polarized light has many applications
  - Polarized filters: let only one direction of polarization through.
  - We'll see that light reflecting off certain surfaces in certain ways becomes linearly polarized
    - Polarized sunglasses block some of this reflected "glare" (demo!)
    - Two linearly polarized filters rotated 90 degrees block all light



Demo from http://demonstrations.wolfram.com/LightBeamsThroughMultiplePolarizers/

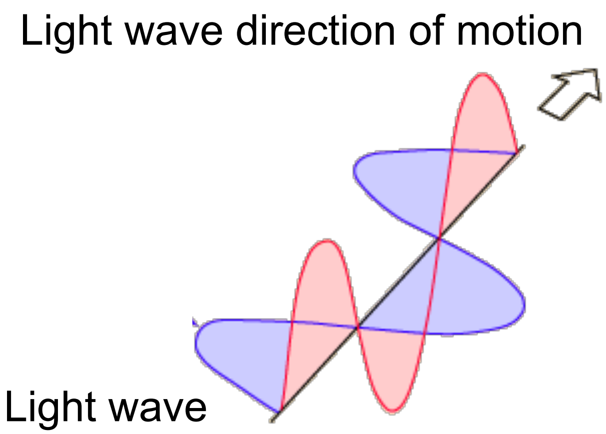
  - 3D cinema/TVs also commonly uses polarized glasses
    - Two different images are broadcast with two different polarizations
    - Separate polarizations in lenses give each eye a different image: 3D!
  - Material stress testing: https://www.youtube.com/watch?v=3LNJmuYhA0s

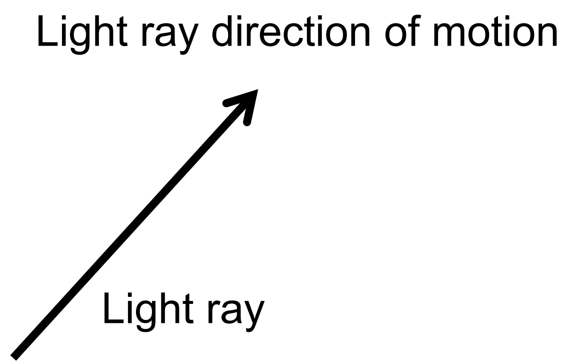
# Ponderable



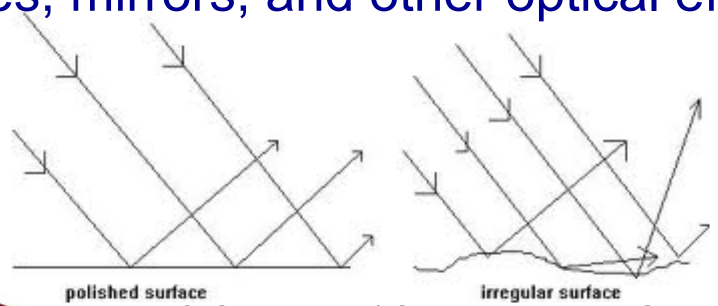
- We've seen that two polarized filters rotated 90 degrees apart block all light transmission. What happens if I put in a third polarized filter between those two and rotate it through 90 degrees?
  - A. All light is always blocked since it was all blocked with just the two filters.
  - B. All light is always transmitted because it's the least intuitive answer and Todd likes to be tricky.
  - C. Some light is always transmitted.
  - D. All light is sometimes blocked.

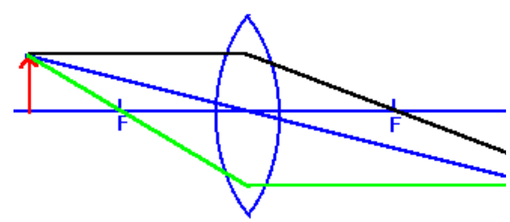
# Electromagnetic Waves and Geometric Optics



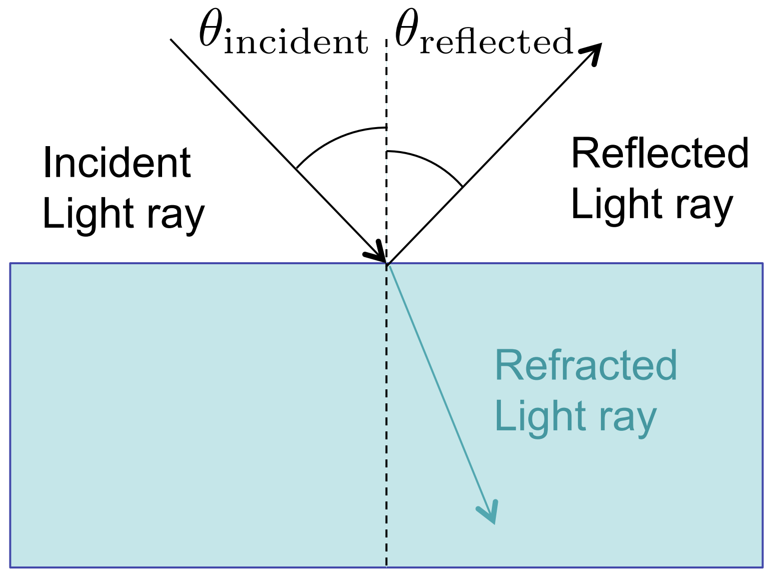




- We'll mostly use an approach to optics called **geometric optics**
  - Waves are complicated, and EM waves are even more complicated.
  - We really just care where the light goes!
  - Light in a vacuum (or close to a vacuum) travels in straight lines
    - So use these straight lines (**rays**) to describe where light rays go
  - This approach of "ray tracing" will let us describe reflection, refraction, lenses, mirrors, and other optical effects



# Reflection




Dotted line: **normal** to surface

- Let's start optics with **reflection**
- We're pretty familiar with reflection!
  - For smooth surfaces, incident and reflected rays have the same angle **as measured to the normal to the surface**

$$\boxed{\theta_{\text{reflected}} = \theta_{\text{incident}}}$$

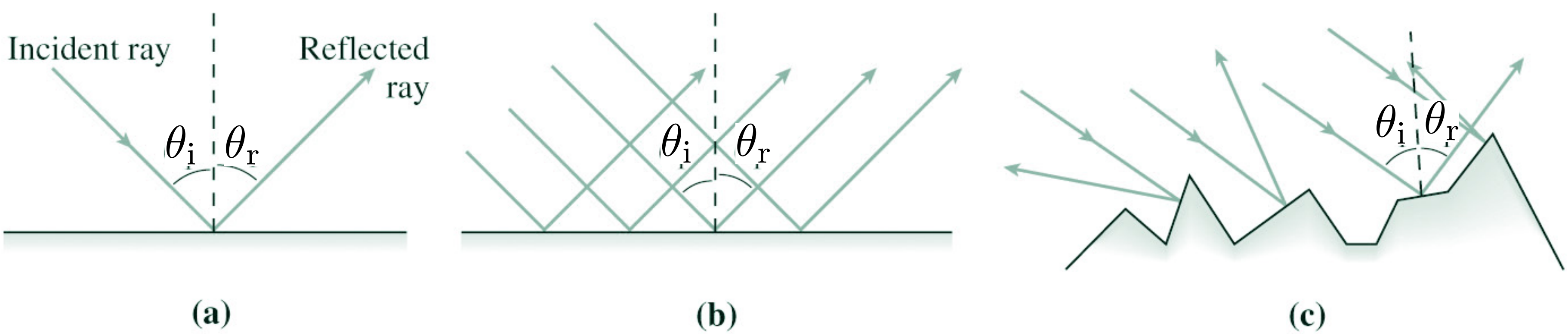
  - Equal angle reflection is seen in more than just optics
    - e.g. elastic collisions such as billiards

# Reflection

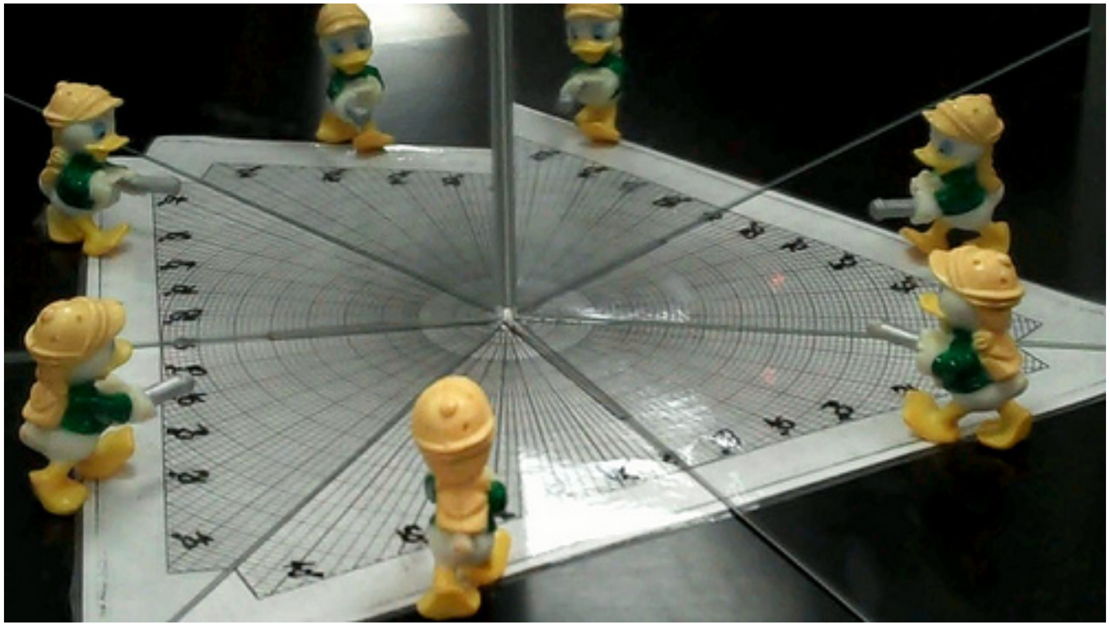
- When light reflects from a surface, the incident and reflected rays make the same angle with the normal to the surface (figure (a)):

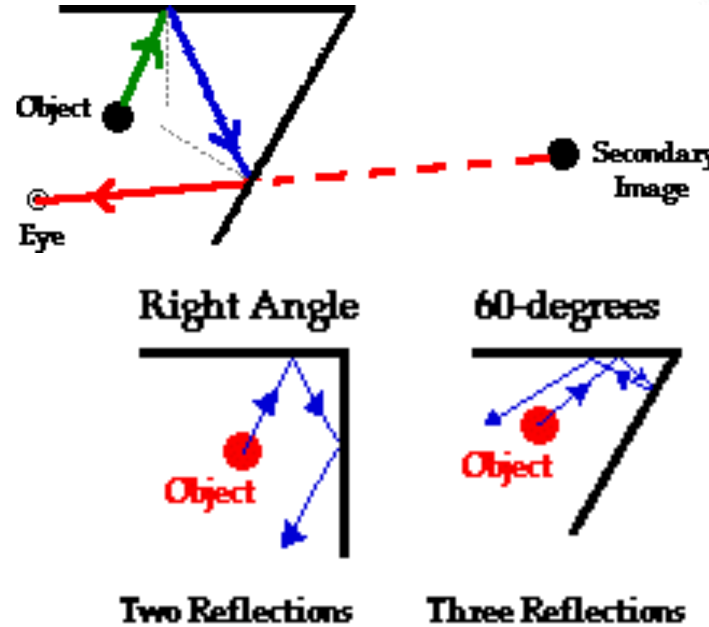
$$\boxed{\theta_{\text{reflected}} = \theta_{\text{incident}}}$$

  - For smooth surfaces, parallel rays all reflect at the same angle.
    - The surface then looks shiny and can form **images**. Oooo shiny!
    - This is called **specular reflection** (figure (b)).
  - The angles are equal even for rough surfaces.
    - But because of the roughness, the light comes off in random directions.
    - This is called **diffuse reflection** (figure (c)). Not so shiny!



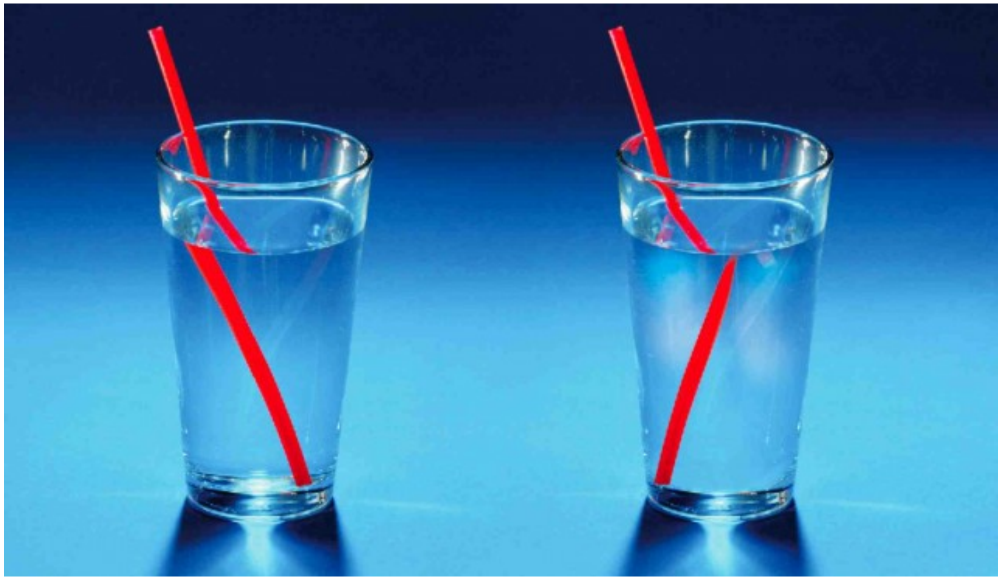
# Reflection and Images

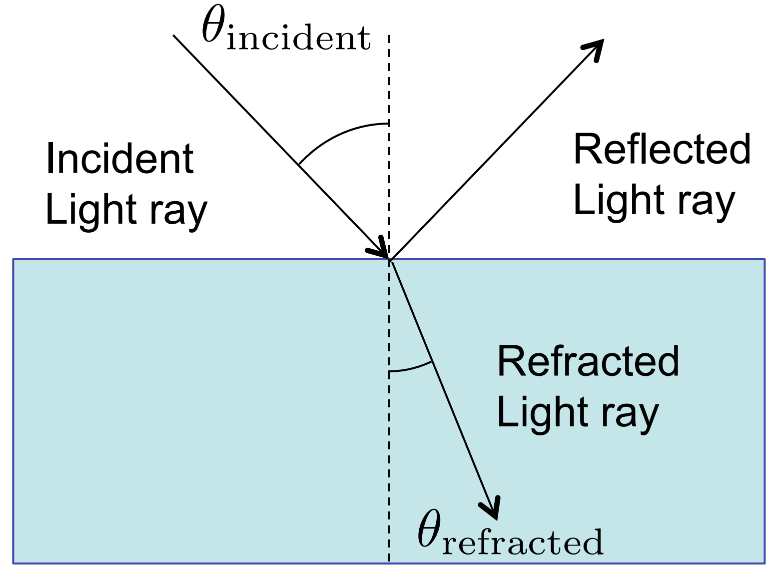





- A single mirror produces a single reflection: that's straightforward.
- Multiple mirrors require you to trace multiple reflections.
  - Your brain thinks the light is going straight when it's really reflecting, so you "see" an image of an object as though the light traveled in a straight line the entire time.
  - Two mirrors at a 90 degree angle always reflect light back out parallel to the original incoming rays
    - You can do some geometry to prove that. ☺

# Index of Refraction






- **Refraction** is the bending of light as it crosses an interface between two different transparent media
  - Occurs because the apparent light wave speed changes between the two media.
  - **Index of refraction n:** $\boxed{n \equiv \frac{c}{v}}$
  - *c* is the speed of light in a vacuum
    - So n=1 for a vacuum, n>1 for all other materials

# Some Indexes of Refraction

- Index of refraction really depends on many details
  - Temperature and pressure
  - Wavelength of light
  - Density and composition of material
- New nanotech metamaterials have even been fabricated to have "negative" index of refraction
- We'll mostly discuss air (n=1.00), water (n=1.33), and glass (n=1.50) in this class

| Substance | Index of Refraction, *n* |
|---|---|
| Gases | |
| Air | 1.000293 |
| Carbon dioxide | 1.00045 |
| Liquids | |
| Water | 1.333 |
| Ethyl alcohol | 1.361 |
| Glycerine | 1.473 |
| Benzene | 1.501 |
| Diiodomethane | 1.738 |
| Solids | |
| Ice ($H_2O$) | 1.309 |
| Polystyrene | 1.49 |
| Glass | 1.5–1.9 |
| Sodium chloride (NaCl) | 1.544 |
| Diamond (C) | 2.419 |
| Rutile ($TiO_2$) | 2.62 |

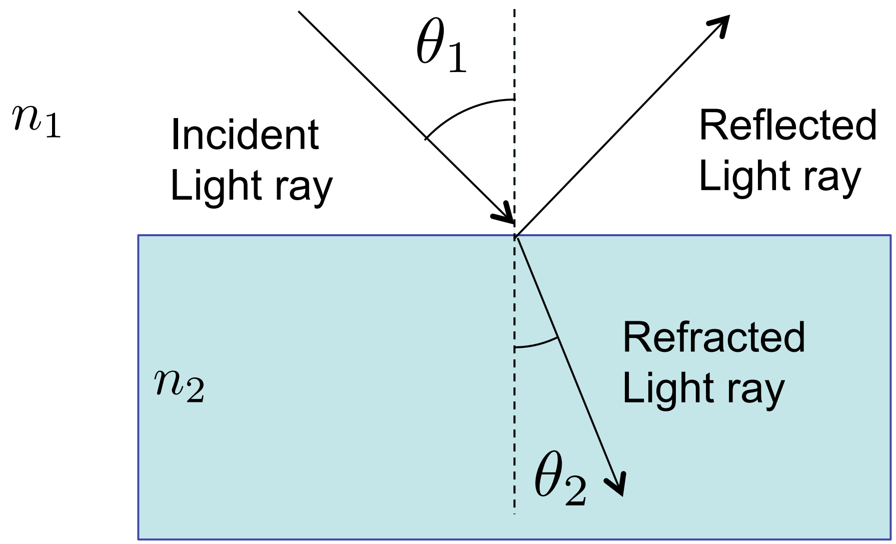
*At 1 atm pressure and temperatures ranging from 0°C to 20°C, measured at a wavelength of 589 nm (the yellow line of sodium).

# Refraction: Snell's Law

- The angles of incidence and refraction and the indexes of refraction for two materials are related by **Snell's Law**:

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

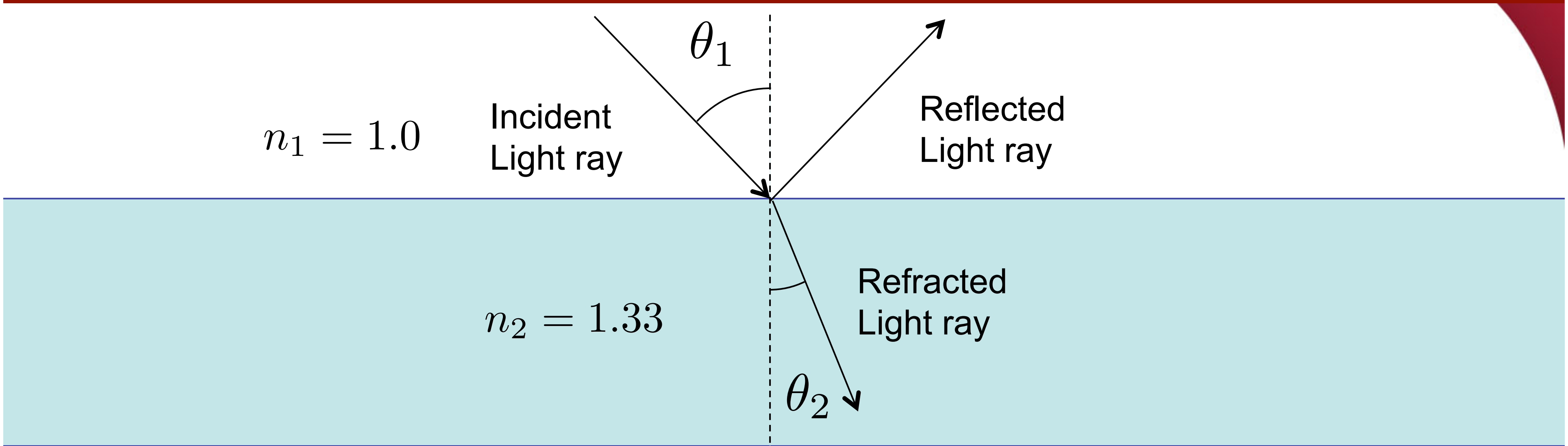
  - Remember that the angles are measured from the **normal** to the surface.
  - There is also a reflected light ray from the surface.




If $n_1 < n_2$ then $\theta_1 > \theta_2$

If $n_1 > n_2$ then $\theta_1 < \theta_2$

# Example




- You are looking for a ring you accidentally dropped in your pool, so you shine a laser pointer at the pool surface at an angle of 30 degrees from vertical. What is the angle of the laser ray in the pool?

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

$$(1.0)\sin(30^\circ) = 1.33\sin\theta_2 \quad \Rightarrow \quad \boxed{\theta_2 = 22^\circ}$$

# (Refraction Example: Slab Displacement)

- Refraction through a plane slab of glass doesn't change the direction of rays but displaces them slightly

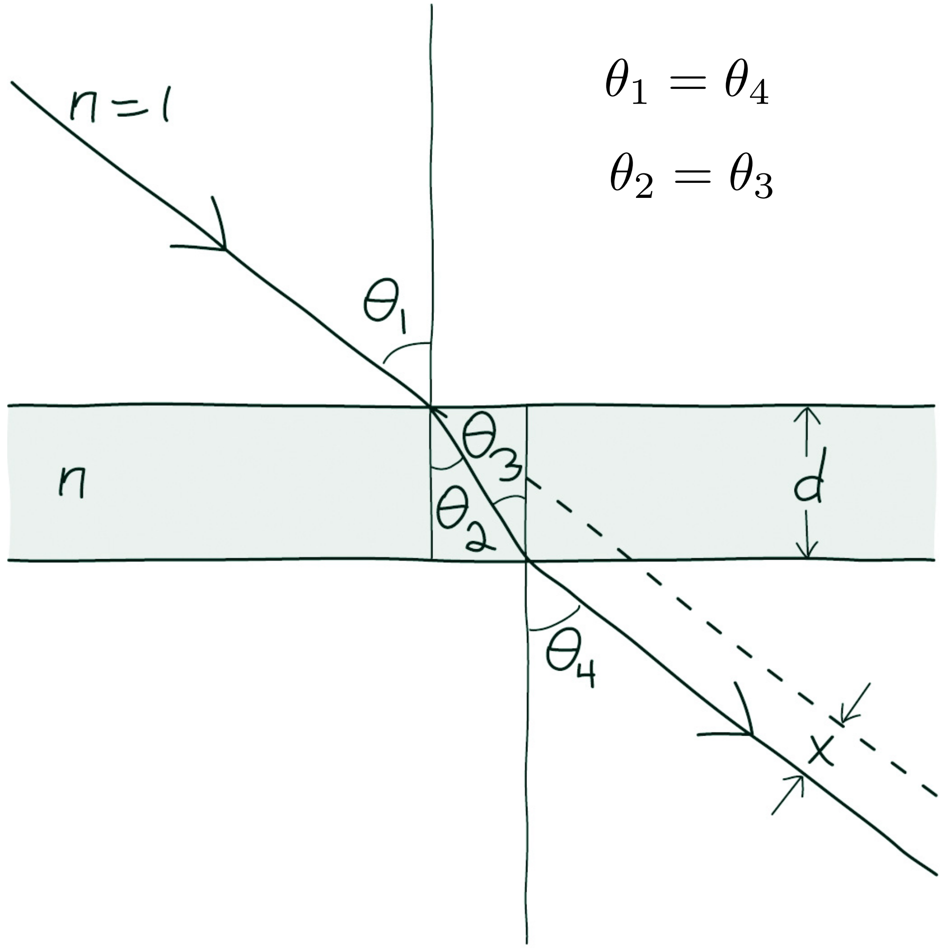
$$\cos\theta_2 = \frac{d}{l} \quad \Rightarrow \quad \frac{1}{l} = \frac{\cos\theta_2}{d}$$

$$\sin(\theta_1 - \theta_2) = \frac{x}{l} = \frac{x\cos\theta_2}{d}$$

$$\sin(\theta_1 - \theta_2) = \sin\theta_1\cos\theta_2 - \cos\theta_1\sin\theta_2$$

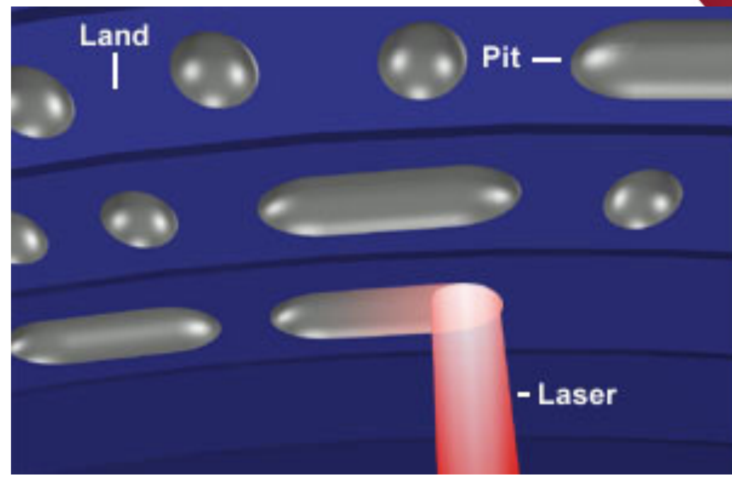
$$\frac{x}{d} = \sin\theta_1 - \cos\theta_1\tan\theta_2$$

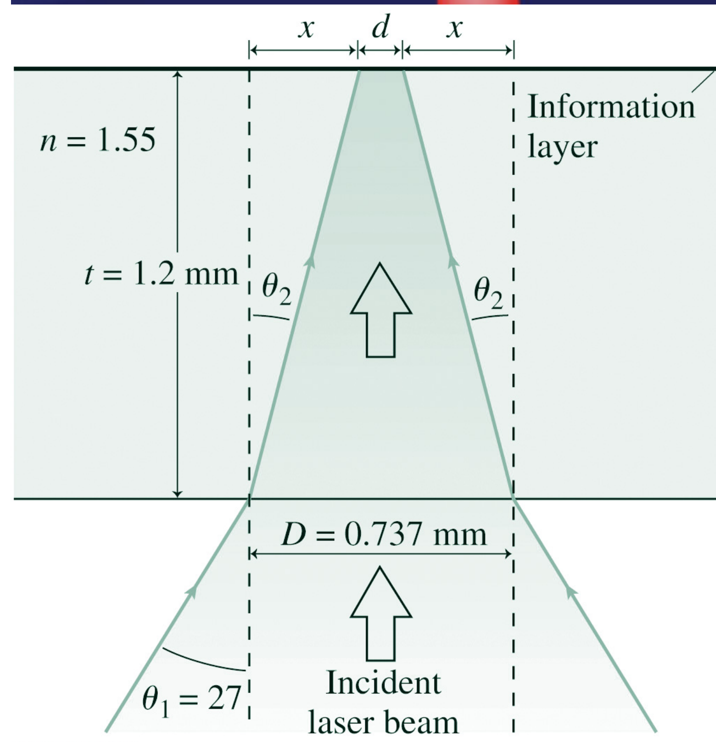
$$\frac{x}{d} = \sin\theta_1\left[1 - \frac{\cos\theta_1}{\sqrt{n^2 - \sin^2\theta_1}}\right]$$



# Refraction Example: CD Encoding

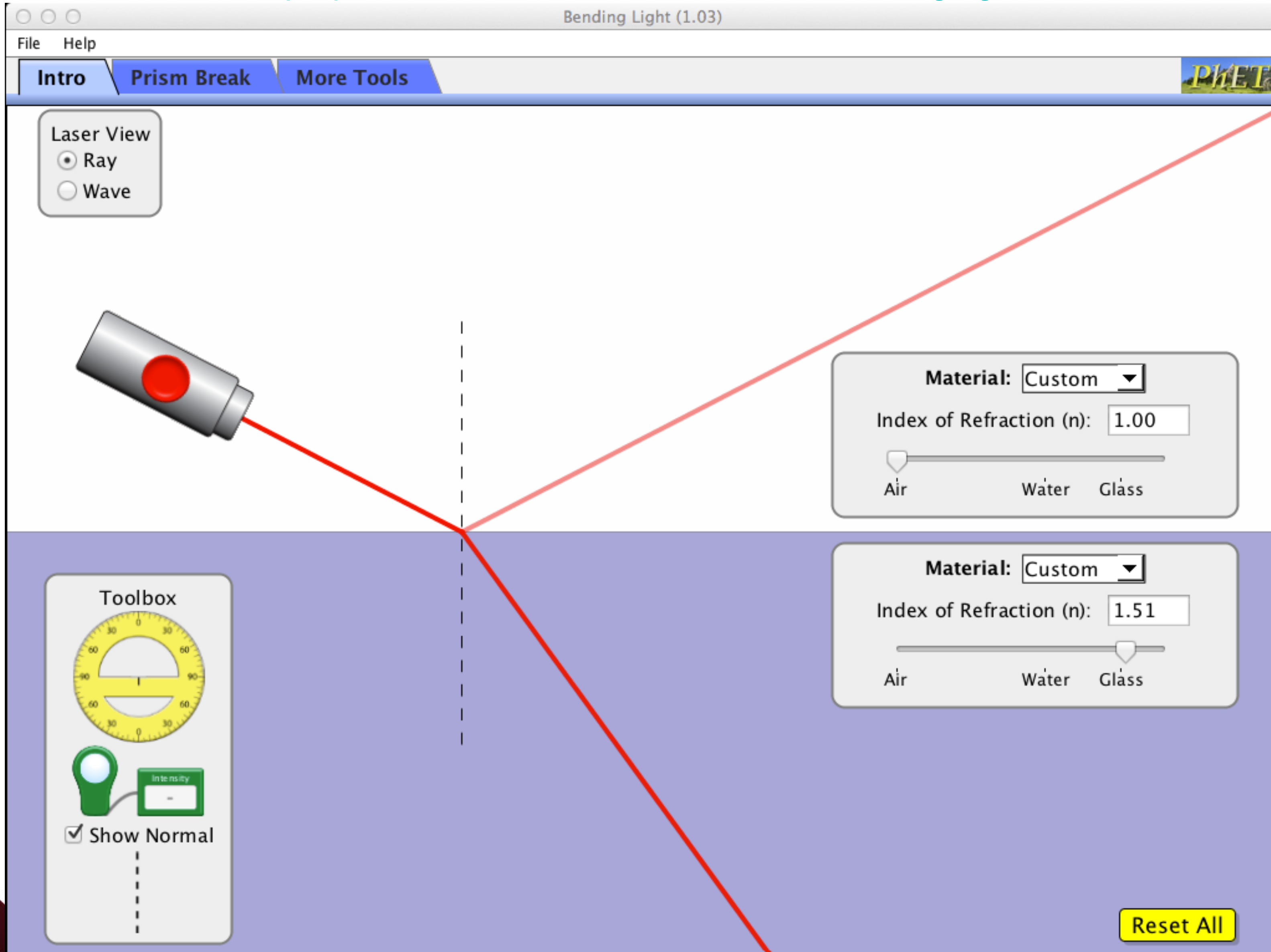
- Refraction in a compact disc helps make the disc relatively immune to dust.
  - Dust specks settle on the top layer of the semi-transparent surface
  - The laser beam is broad there – less interference from dust specks
  - But refraction makes beam small at the "information layer" to read small pit encoding




# Applet ~~Wednesday~~ Monday: Refraction

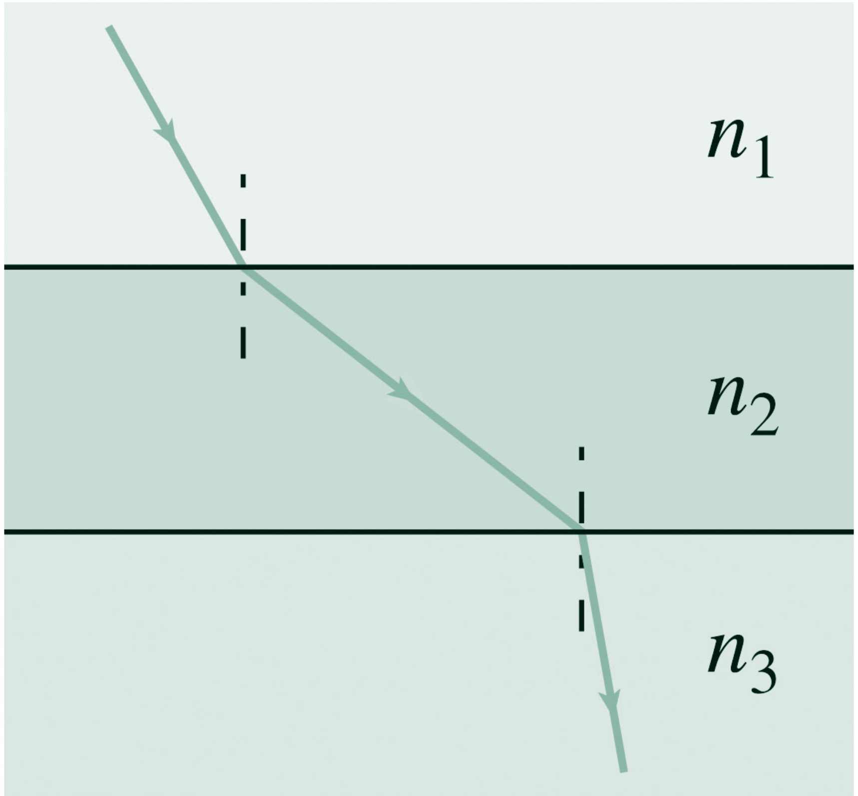
http://phet.colorado.edu/en/simulation/bending-light



# Quick Question

- The figure shows the path of a light ray through three different media. Rank the media in order of their refractive indices.

A. n1 > n2 > n3
B. n3 > n1 > n2
C. n3 > n2 > n1
D. n2 > n1 > n3





Remember, light bends further towards the normal in a higher refractive index medium.

# Quick Question

- The angle of incidence

A. is always greater than the angle of refraction.
B. must equal the angle of refraction.
C. is always less than the angle of refraction.
D. may be greater than, less than, or equal to the angle of refraction.

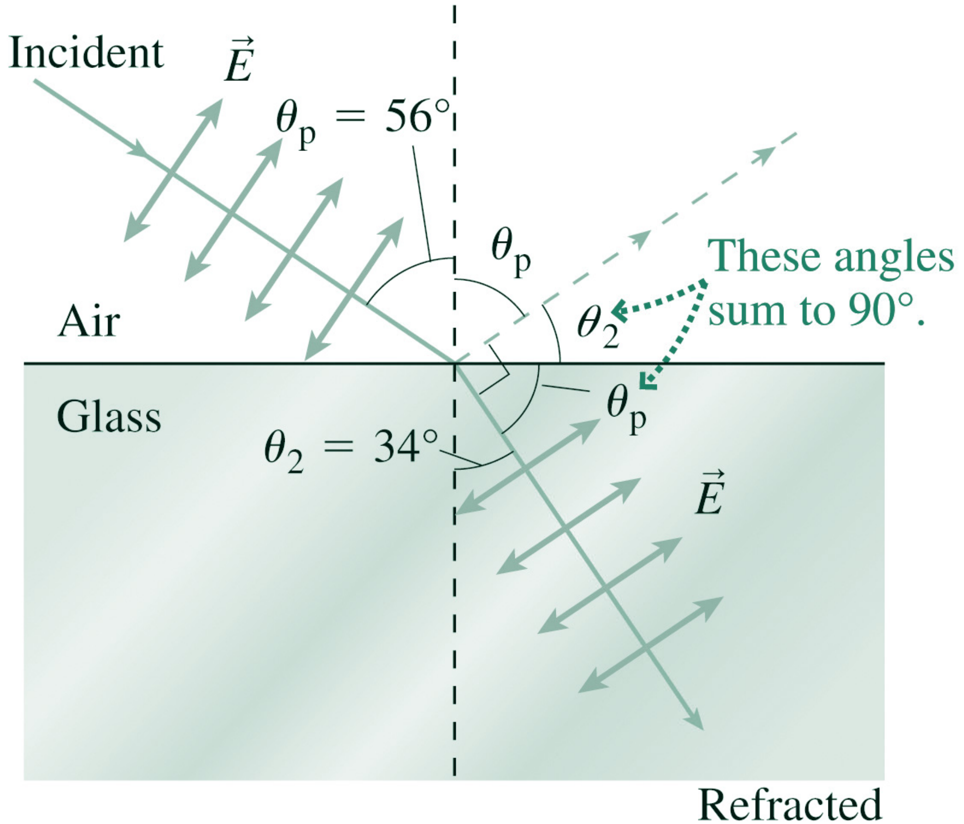
# Polarization and the Brewster Angle

- When the angle of incidence is equal to the **polarizing angle**,

$$\boxed{\tan\theta_{\mathrm{P}} = \frac{n_2}{n_1}}$$

also called the **Brewster angle**, the reflected beam has no polarization in the plane defined by the incident and reflected rays.

  - The polarizing angle occurs when the reflected and refracted beams are perpendicular.
  - Then the molecular dipoles in the material are oscillating along the reflected direction, and there's no radiation in this direction.

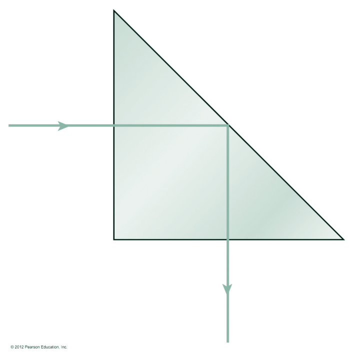


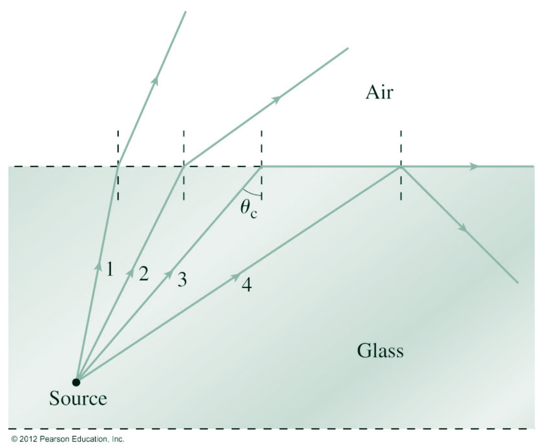
# Total Internal Reflection

- **Total internal reflection** (TIR) occurs at the interface from a material with greater refractive index to one with lesser refractive index.
  - TIR occurs when the incidence angle is greater than the critical angle given by

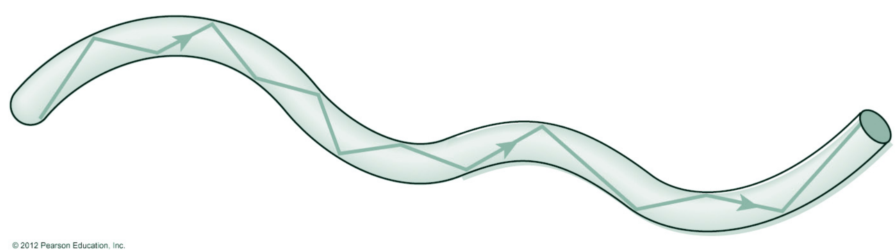
$$\boxed{\sin\theta_c = \frac{n_2}{n_1}}$$

  - TIR is used in prism-based reflectors.

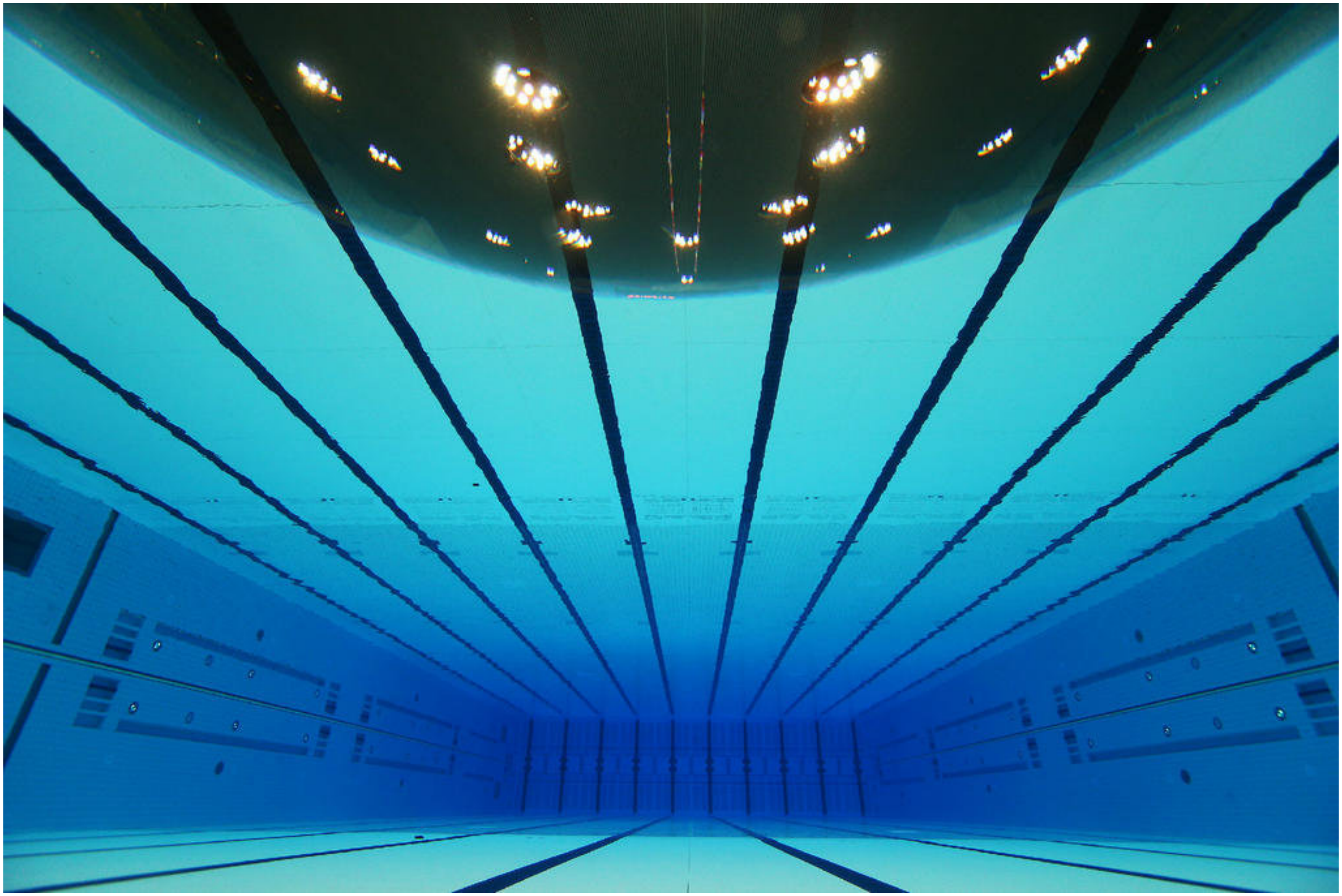



  - TIR is the basis of optical fibers, guiding light along the fibers that, among other applications, carry data on the internet.



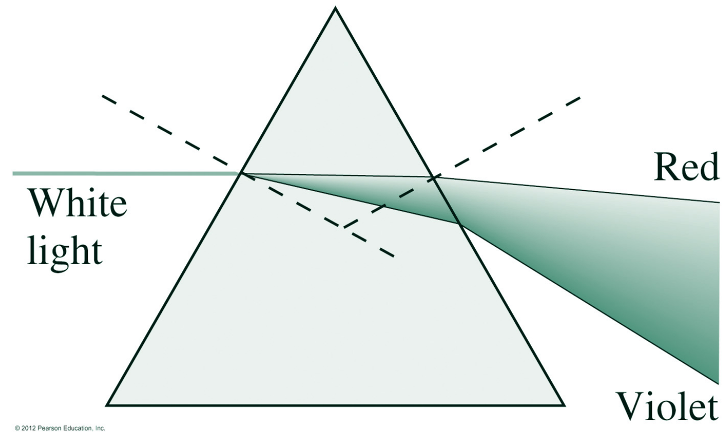
# Total Internal Reflection



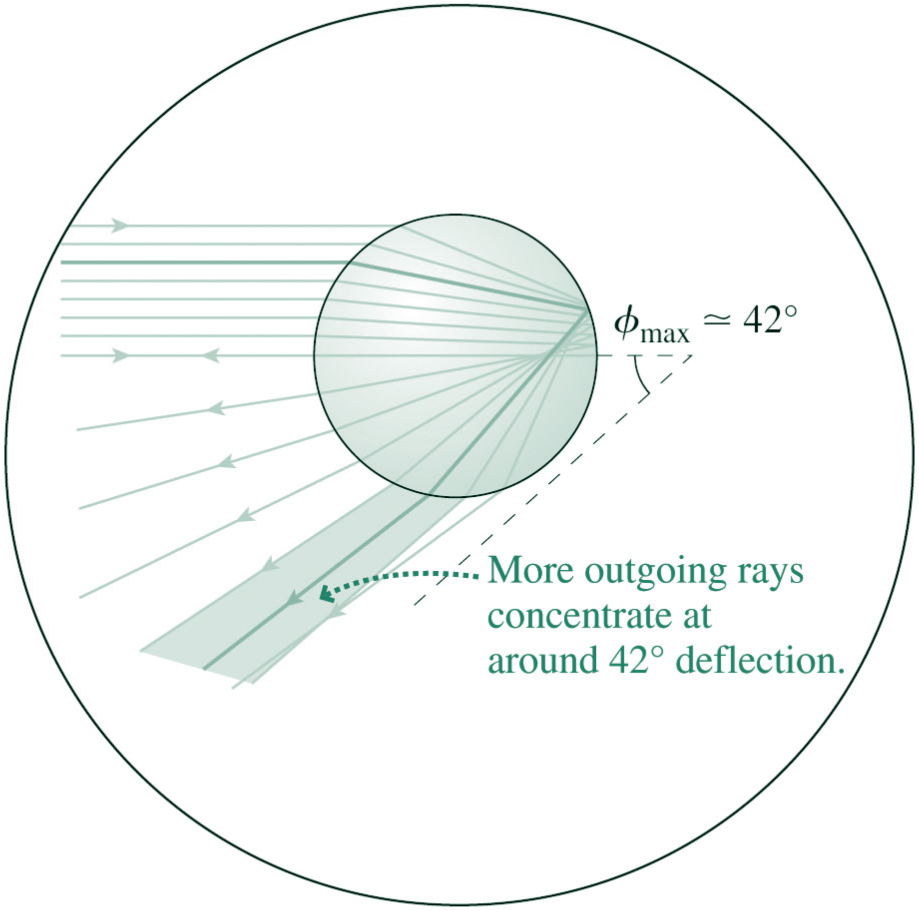
- Total internal reflection is why a swimming pool's surface looks like a mirror from underwater, but not from above.

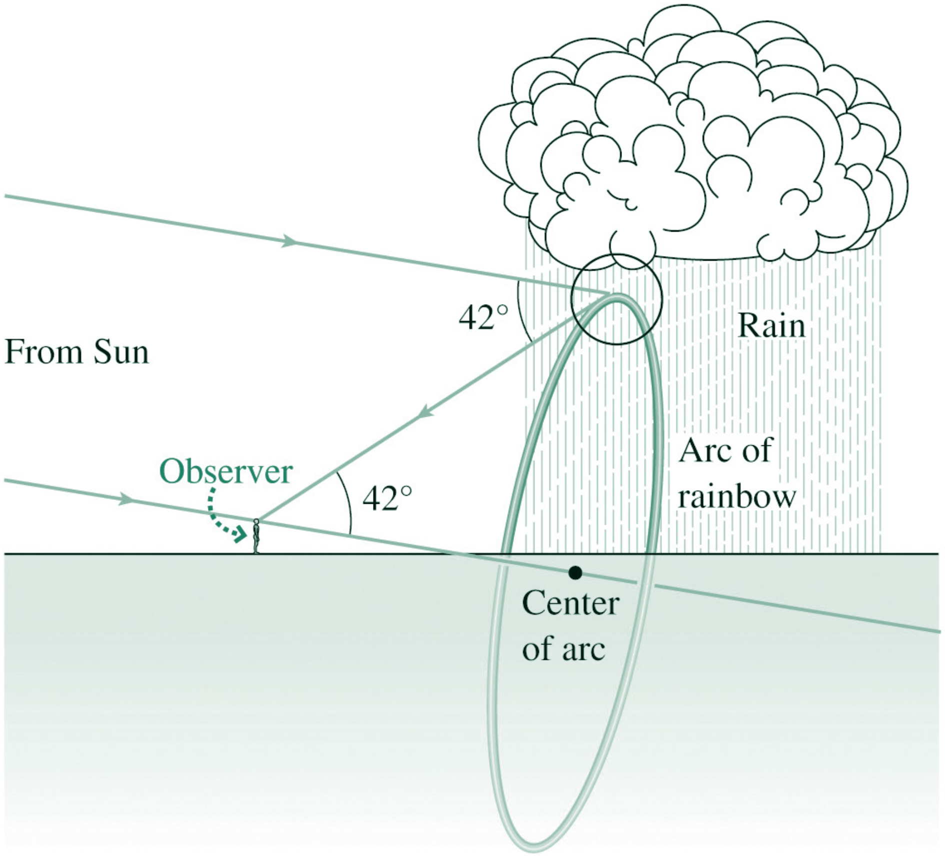
# Dispersion

- The refractive index depends on wavelength, and therefore refraction disperses the different wavelengths in slightly different directions.
  - That’s why a prism produces a spectrum of color from white light.
  - Dispersion and total internal reflection in raindrops cause the rainbow.




# Dispersion: Rainbows




- This reflection and dispersion is why rainbows appear with the sun behind you, and at a certain particular height in the sky.