Conceptual Physics

Luis A. Anchordoqui

Department of Physics and Astronomy
Lehman College, City University of New York

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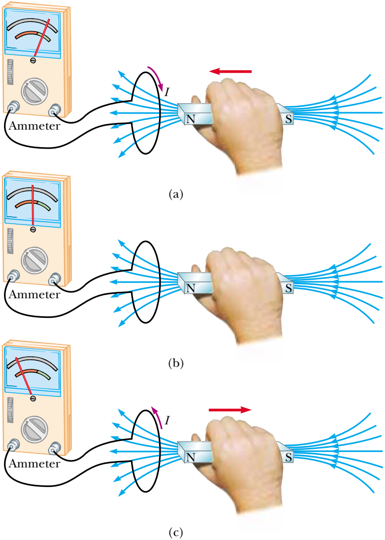
- In mid-1800's ☞ Faraday observed that
  a changing magnetic field creates an electric field

- Magnet is moved inside loop
  ☞ ammeter deflects indicating current is induced in loop

- Magnet is held stationary
  ☞ there is no current induced

- Magnet moved away from loop
  ☞ ammeter deflects indicating induced current is
  in opposite direction

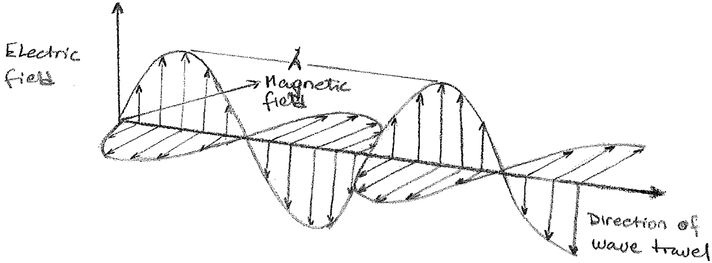


- Shortly after Faraday's discovery ☞ Maxwell hypothesized that
  a changing electric field creates a magnetic field

- Putting all these together ☞ Maxwell predicted that
  if you begin changing $\vec{E}$ and $\vec{B}$ in any region of space
  wave of changing fields propagates at speed of light

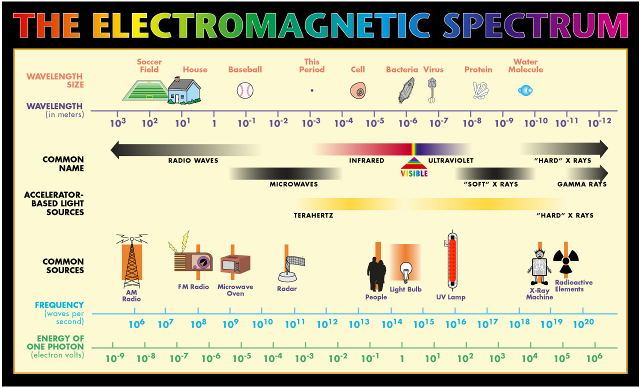
$$c \simeq 3 \times 10^8 \text{ m/s}$$

outward from region where change first took place



- E.g. ☞ moving an electron causes a change in $\vec{E}$
  which causes a change in $\vec{B}$... etc...
- These changing fields zip over to a second electron
  which was jiggled by $\vec{E}$ field that arrives at microscope time later
- In 1888 Maxwell's prediction passed important test
  when Hertz generated and detected EM waves in laboratory
- He performed a series of experiments that
  not only confirmed existence of electromagnetic waves
  but also verified that they travel at speed of light

- Light itself consists of electric and magnetic fields of this kind
- But what about photons? ☞ Good question
- We will deal with this soon ☞ But meanwhile... note important fact: we have a means of transporting energy through empty space without transporting matter
- *Electromagnetic waves* propagate any time an electron is jiggled



- We just learned that light is a wave
- Unlike particles ☞ waves behave in funny ways
  e.g. ☞ they bend around corners
- However ☞ smaller wavelength λ is $\Rightarrow$ weaker funny effects are
- λ of light is about 100 times smaller than diameter of human hair!
- For a long time ☞ no one noticed "wave nature" of light at all
- This means that for most physics phenomena of everyday life
  we can safely ignore wave nature of light
- Light waves travel through and around obstacles
  whose transverse dimensions are much greater than wavelength
  and wave nature of light is not readily discerned
- Under these circumstances ☞ behavior of light
  is described by rays obeying set of geometrical rules
- This model of light is called ray optics
- Ray optics is limit of wave optics
  when wavelength is infinitesimally small

- To study more *classical* aspects of how light travels:
  - We will ignore time variations ☞ (10^{14} Hz too fast to notice)
  - We will assume light travels through a transparent medium in straight line
  - Light can change directions in 3 main ways:
    1. Bouncing off objects (reflection)
    2. Entering objects (e.g. glass) and bending (refraction)
    3. Getting caught and heating the object (absorption)
- In other words
  - We consider that light travels in form of rays
  - Rays are emitted by light sources and can be observed when they reach an optical detector
  - We further assume that optical rays propagate in optical media
  - To keep things simple ☞ we will assume that media are transparent

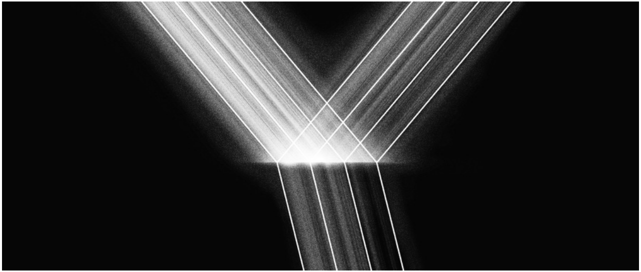
- Light only travels at $c \simeq 3 \times 10^8$ m/s in vacuum
- In materials ☞ it is always slowed down
- *Index of refraction* ☞ how fast light travels through material

$$\text{index of refraction} = n = \frac{\text{speed of light (in vacuum)}}{\text{speed of light (in medium)}}$$

- The bigger the n ☞ the slower the light travels

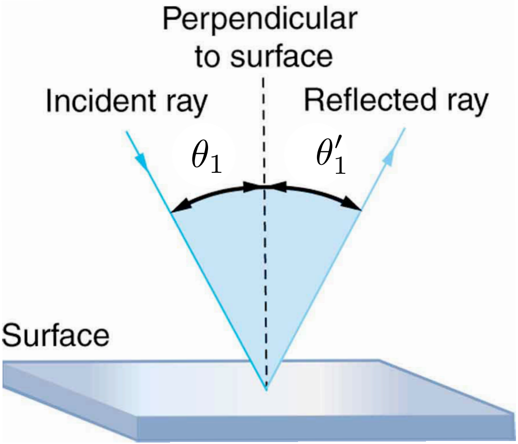
Material	Index of Refraction (n)
Vacuum	1.000
Air	1.000277
Water	1.333333
Ice	1.31
Glass	About 1.5
Diamond	2.417

- When ray of light traveling through transparent medium encounters boundary leading into another transparent medium part of energy is reflected and part enters second medium
- Ray that enters second medium is bent at boundary and is said to be refracted
- Incident ray, reflected ray, and refracted ray all lie in same plane



Experiments show ☞ angle of reflection θ_1' equals angle of incidence θ_1

$$\theta_1' = \theta_1$$



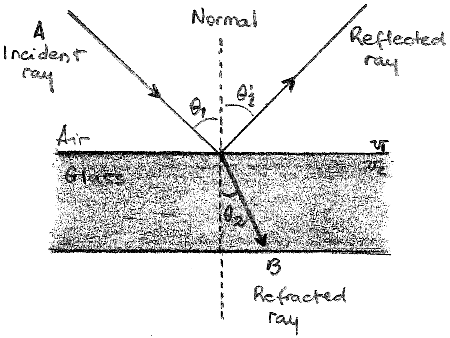
- Angle of refraction depends on: $\begin{cases} \text{properties of two media} \\ \text{angle of incidence through} \end{cases}$

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1} = \text{constant}$$

v_1, v_2 ☞ speed of light in first and second medium

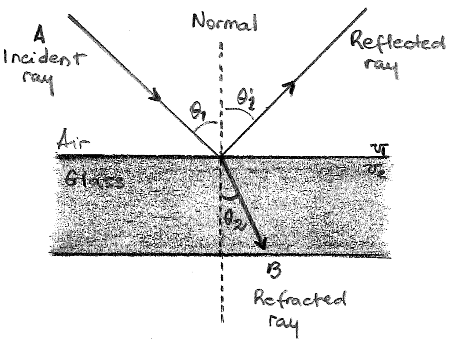
- Replacing v_2/v_1 with ratio of refractive indexes n_1/n_2

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

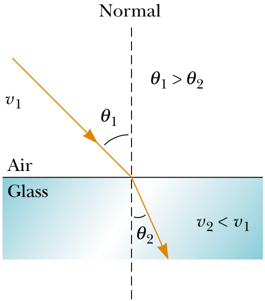


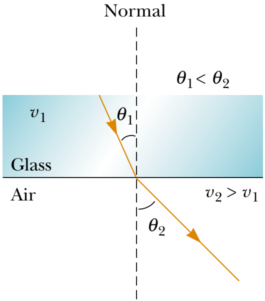
Path of a light ray through a refracting surface is reversible

- Ray travels from point A to point B
- If ray originated at B ☞ it would have traveled to left along line BA to reach point A
- Reflected part would have pointed downward and to left in glass



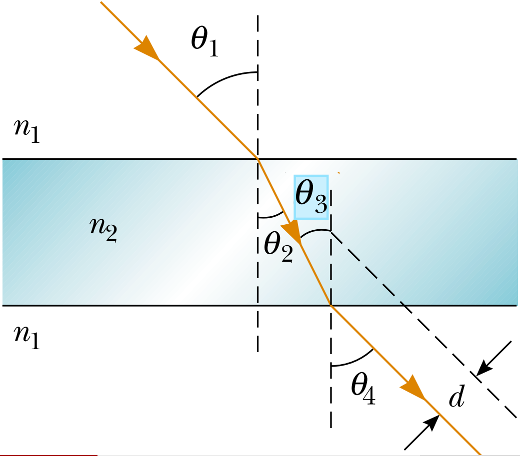
- Light rays can pass through several boundaries
- E.g. ☞ you might have a sheet of glass:
  light ray from n_1 enter to larger n_2 and exit n_2 to smaller n_1
- At each boundary ☞ refraction law will hold
- At left boundary we have ☞ $n_1 \sin\theta_{\rm in} = n_2 \sin\theta_2$
  when light beam moves from air into glass
  light slow down entering glass and its path is bent toward normal
- At right boundary we have ☞ $n_2 \sin\theta_3 = n_1 \sin\theta_{\rm out}$
  light speeds up entering air and its path bends away from normal





- Geometry tells us (if walls are parallel) that $\theta_2 = \theta_3$
- This means $\sin\theta_2 = \sin\theta_3$
- So $n_1 \sin\theta_{\rm in} = n_2 \sin\theta_2 = n_2 \sin\theta_3 = n_1 \sin\theta_{\rm out}$
- This means (compare far left with far right of equation)

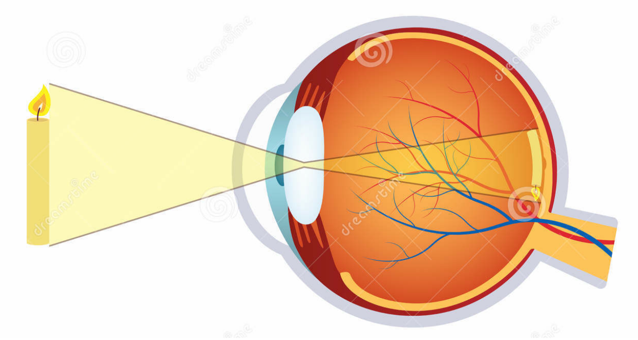
$\sin\theta_{\rm in} = \sin\theta_{\rm out}$ ☞ which says $\theta_{\rm in} = \theta_{\rm out}$



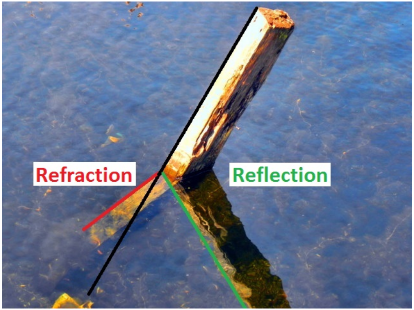
- What if you have glass with walls that are not parallel?
- This is idea behind lenses
- As light enters ☞ it is bent and rays come out different depending on where and how they strike
- Focal length of optical system measures of how strongly system converges or diverges light
- For optical system in air ☞ focal length is distance over which initially collimated (parallel) rays are brought to a focus
- Lens geometry usually looks complicated (and it is!) but for thin lenses ☞ result is relatively simple

$$\frac{1}{\text{object distance}} + \frac{1}{\text{image distance}} = \frac{1}{\text{focal length}}$$

- How do you know where objects are? How do you see them?
- You deduce direction and distance in complicated ways
  but arises from angle and intensity of *bundle* of light rays
  that make it into your eye
- Eye is adaptive optical system
- Crystalline lens of eye changes its shape to focus light
  from objects over a great range of distances

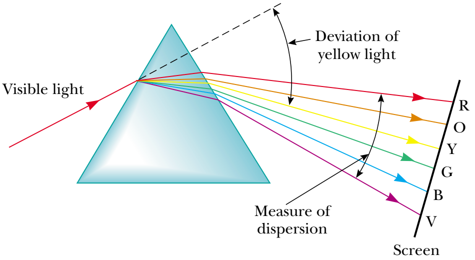


Summary of reflection and refraction



Prisms

- Triangular cut of glass produce rainbow of color from sun light
- Narrow beam of white light
  incident at non-normal angle on one surface of glass is refracted
- Different colors of light have different speeds in glass
- Separated rays emerge from other interface
  spread in familiar rainbow pattern



Light as composite of colors

- Newton placed prism in path of narrow beam of sunlight
- As expected ☞ beam was spread over band of angles
- He inserted second prism and allowed spread beam to enter it
- When arranged carefully
  second prism reconstituted original beam in original direction
- He labeled the different colors
  with continuously varying parameter that had the units of time
- λ and $\mathcal{T}$ characterizing given color connected by speed of light

$$\lambda/\mathcal{T} = c/n$$