# Chapter 33

# The Nature and Propagation of Light

## 33.1 Light Wave Terminology and Basics

8/10:

- **Geometric optics**: The study of situations in which EM radiation interacts with objects (possibly with holes) such that $\lambda <<$ size of obstacles, holes.
- **Physical optics**: The study of situations in which EM radiation interacts with objects (possibly with holes) such that $\lambda \approx$ size of obstacles, holes.
- **Ray**: An imaginary line, perpendicular to the wave fronts, that indicates the direction of propagation.
- Any time a wave hits a medium, you get reflection and transmission.
- **Huygens principle**: All points on a wavefront act as point sources of spherical wavelets. After a time $\Delta t$, the new position of the wavefronts is the surface of tangency of the wavelets.

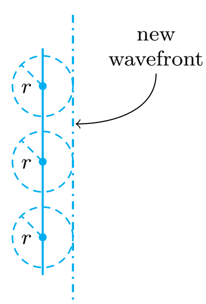
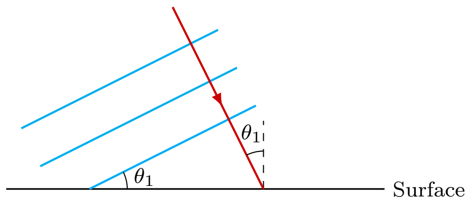
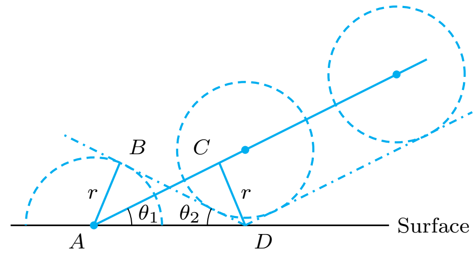



Figure 33.1: Huygens principle.

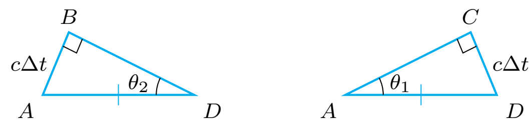
  - The radius $r$ of the wavelets, in terms of the time $\Delta t$ from their creation, is $r = c\Delta t$.
- Light rays hitting a surface (see Figure 33.2).
  - Since the triangles containing the **angle of incidence** and the **angle of reflection** ($\triangle ACD$ and $\triangle ABD$, respectively) share $\overline{AD}$, $r$, and a right angle (see Figure 33.2c), we have that they are identical.
  - Thus, $\theta_1 = \theta_2$.
  - Since light rays have a constant phase offset (specifically, 90°) from light waves, it follows that light rays also reflect off of surfaces with their original angle of incidence.
- **Angle of incidence**: The angle with which wavefronts hit a surface, or the angle a light ray makes with a normal to a surface.




(a) Waves hit a surface.




(b) Invoking Huygens principle.




(c) Proving identical triangles.

Figure 33.2: Properties of reflecting waves.

- The quantity $\theta_1$ in Figure 33.2.

- **Angle of reflection**: The angle with which the reflected wavefront intersects with a surface.
  - The quantity $\theta_2$ in Figure 33.2b.
- **Law of reflection**: The principle that $\theta_1 = \theta_2$.

## 33.2 Reflection

- Corner reflector:

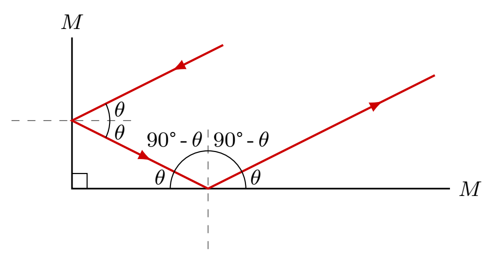



Figure 33.3: Corner reflector.

  - The law of reflection implies that the ray entering at an angle $\theta$ will exit at the same angle, just displaced a bit.
- If you don't want radar to detect planes:
  - Eliminate right angles (they're corner reflectors).
  - Make the surface something that absorbs radiation (hi tech ceramic).
- Mirrors create images; tie to projective geometry.
  - Seeing an object in the mirror is equivalent to seeing it as far behind the mirror as the thing is in front of the mirror.
  - This is **ray tracing**!

- **Virtual image**: An image that is created by light rays that don't really exist, i.e., projected light rays.
- Mirrors don't reverse left and right; they reverse front and back.

## 33.3 Refraction

- Light waves and glass.
  - Light waves enter glass, shake the atoms therein, and then those atoms emit their own light.
  - However, the light emitted by the atoms goes in all directions.
  - When you sum up all the secondary sources in a horrible integral, you end up with an effective wave propagating to the right, but at a speed less than the speed of light.
- **Index of refraction**: The quotient of the speed of light in a vacuum and the speed of light in a particular medium. *Denoted by* $\boldsymbol{n}$.
$$n = \frac{c}{v}$$
  - Since light can never travel faster than the speed of light, $n \geq 1$.
  - Some common $n$ values:
    - $n_{\text{water}} \approx 1.33$.
    - $n_{\text{glass}} \approx 1.5$.
    - $n_{\text{diamond}} \approx 2.5$.
    - $n_{\text{air}} \approx 1.003 \approx 1$.
- In materials, $v$ changes and $f$ remains constant, so $\lambda$ changes.
  - $c = f\lambda$ and $v = f\lambda'$ imply that
$$\lambda' = \lambda \cdot \frac{v}{c} = \frac{\lambda}{n}$$
- In a surface, the wavefront gets bent.

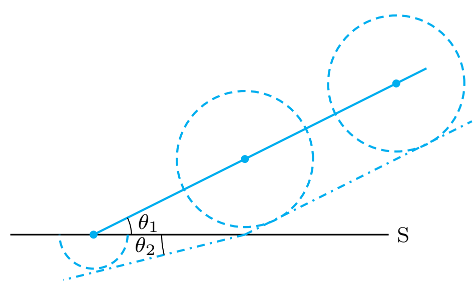



Figure 33.4: Properties of refracting waves.

  - Similarly, the ray gets bent.
  - When looking from air into a different surface, $\theta_2 < \theta_1$.
  - Explains why when you reach for something in water, it appears closer and in a different spot — you're reaching for the virtual image!
- **Angle of refraction**: The angle with which the refracted wavefront intersects with a surface.
  - The quantity $\theta_2$ in Figure 33.4.
- **Snell's law**: The formula $n_1 \sin\theta_1 = n_2 \sin\theta_2$. *Also known as* **law of refraction**.

- **Critical angle**: The angle of incidence such that light will be refracted at 90°.
  - If $\theta_{\text{inc}} > \theta_{\text{crit}}$, you only get reflection!
  - From Snell's Law,
$$\theta_{\text{crit}} = \sin^{-1}(n_2/n_1)$$
- **Total Internal Reflection**: Conditions such that all light is reflected and none is refracted. *Also known as* **TIR**.
  - Only a possibility when the light wave is moving to a medium with a lower index of refraction.
- If you have a glass rod and you put light in at one end at an angle greater than the critical angle, it will be trapped and can only come out at the other end.
  - Total internal reflection allows us to redirect light however we want.
  - Light "flowing" through this construction is analogous to water flowing through a pipe.
  - As long as the angle we bend the light pipe at isn't too sharp, it will stay trapped in the light pipe.
  - In a well-designed light pipe, you will loose very little intensity.
  - This is the principal behind fiber optics.
  - You lose current in a wire due to resistance, but you don't lose much intensity in a light pipe.

## 33.4 Office Hours (Pandey)

8/11:
- Can you explain the upwards and downwards displacement currents in Figure 32.3?
  - Not really.

## 33.5 Dispersion

8/12:
- The way that atoms shake in a material with light passing through it depends on the frequency of the light.
- Thus, $n = n(f)$.
  - For example, $n_{\text{blue}} \neq n_{\text{red}}$.
- In general, $n$ increases as $f$ increases (or $\lambda$ decreases).
  - Thus, $n_{\text{blue}} > n_{\text{red}}$, for example.
- Thus, if you have light made up of all kinds of different colors, every color will travel through the material at a different speed.

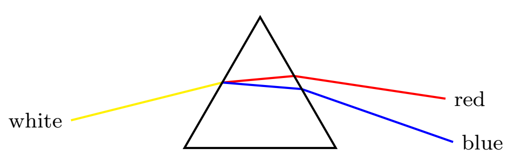



Figure 33.5: A prism dispersing light.

  - This is the principle behind a **prism**.
- **Dispersion**: The dependence of the index of refraction on the frequency of light.

- When light passes through water droplets in the sky, it gets refracted by different amounts, depending on the color of the light. This is what creates a rainbow!
- **Fermat's Principle**: Light follows the path that takes the least time.
- Light traveling between $A$ and $B$ via a mirror.
  - In this case, least time implies shortest distance.
  - And indeed, the path with the shortest distance via the mirror is the one where $\theta_1 = \theta_2$, as can be proven with optimization and calculus.
- Light traveling between $A$ and $B$ via a change of medium.
  - In this case, shortest distance *does not* imply least time.
  - If $n_1 < n_2$, you can travel faster in $n_1$ then you can in $n_2$, so you want to minimize the time you spend in $n_2$ without going too far out of your way.
  - It follows that the path with the least time will be the one given by Snell's law.
- Why does light take the path of least time?
  - Fermat says, "because it does."
  - Quantum physics has a more bizarre reason for this.
- How does light know which path to take?
  - It doesn't — it tries all paths and only one succeeds.

## 33.6 Polarization

8/13:
- Midterm on Tuesday.
  - 80 minutes, more questions.
  - HW 1-3.
  - Chapter 15-16, 33-34.
- **Polarized** (wave) **in the *xy*-plane**: A wave where both the medium and displacement are entirely contained in the $xy$-plane. *Also known as* **vertically polarized** (wave).
- If you shake a string up and down, you will create a polarized wave in the $xy$-plane.
- If you shake electrons up and down, you will create a vertically polarized EM wave, with $\vec{E}_{\text{trans}}$ entirely contained in the vertical plane.
  - If you face said wave parallel to the propagation, you only see movement up and down.
- A metal comb running vertically blocks vertically polarized microwaves since the microwaves lose energy creating currents in the metal.
  - Works with microwaves since they're long, but wouldn't with visible light.
  - However, a polaroid does work with the visible spectrum.
- A polaroid filter is composed of long, stretched out organic molecules analogous to the teeth on the metal comb.
  - If the **transmission axis** is vertical, all vertical waves get through.
  - If it is horizontal, they all get blocked.

- If it is rotated at some angle $\phi$ from the vertical, decompose the radial vector into parallel and perpendicular components.
  - The perpendicular component is totally blocked, and the parallel component is totally transmitted.
  - It follows that $\vec{E} = \vec{E}_{\|} = \vec{E}_{\text{polarized}} \cos\phi$, so the wave amplitude of vertically polarized light decreases by $\cos\phi$.

- Since $I \propto A^2$, we get the following.
- **Law of Malus**: The following formula, where $I_2$ is the intensity of light that gets past the polaroid filter and $I_1$ is the initial intensity.
$$I_2 = I_1 \cos^2\phi$$
- For unpolarized light, $I_{\text{trans}} = I_{\text{unpol}} \cos^2\phi$, but for light at every angle $\phi$.
  - Thus, if we average $\cos^2\phi$ over all $\phi$, we get that
$$I_{\text{trans}} = \frac{1}{2} I_{\text{unpol}}$$
  - Note that the above result is for a **perfect filter**. In reality, stacking filters causes some additional loss of intensity.
- If you put a two filters on top of each other at perpendicular angles, it will entirely eliminate the intensity.
  - At some angle $\phi$ in between, you'll have a variable loss of intensity.
- If you put a third filter at an angle between two perpendicular filters, you'll regain some intensity.