Physics 202, Lecture 23

Today’s Topics

- Lights and Laws of Geometric Optics
  - Nature of Light
  - Reflection and Refraction
  - Law of Reflection
  - Law of Refraction
  - Index of Reflection, Snell’s Law
  - Total Internal Reflection
  - Dispersion and Prisms
Spectrum of EM Waves

\[ \lambda f = c \]

- **GHz**
  - TV, FM
  - Microwave
- **MHz**
  - AM
  - Long wave

**Speed of light:**
- \( v = c \) in vacuum
- \( v < c \) in medium

**Wavelength:**
- depends on medium
- Frequency: unchanged in medium

- \( \lambda = 400 \text{nm} \)
- \( 1 \text{ nm} = 10^{-9} \text{ m} \)
- \( \lambda = 700 \text{nm} \)

Color of lights: frequencies of waves

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Light And Optics

- Nature of Light
  - Light as rays
  - Light as EM waves: f, \( \lambda \), \( \phi \), v, A, interference …
  - Light as group of photons (Quantum Theory)

- Propagation of Light
  - Geometric Optics: Treat light as rays. (Ch. 31,32)
    → Ray approximation.
  - Wave Optics: Wave properties become important
    Interference, diffraction…(Ch. 33.)
Ray Approximation (1)

- When the wavelength of the light is much smaller than the size of the optical objects it encounters, it can be treated as (colored) rays.

Ray approximation is valid when $\lambda << d$

Ray approximation is not valid near the gap when $\lambda \sim d$. OK elsewhere.
Ray Approximation (2)

- Basic features of ray approximation
  - Light rays travel in straight lines in a uniform medium
  - Light rays change direction at the boundary of media
    \( \rightarrow \) Reflection and refraction
  - Light rays travel at speed of light in the medium
  - Trace of rays are reversible
  - Frequency (color) remains the same along the path.
  - Wavelength changes as light enters a different medium
  - When two set of light rays meet, they pass through each other, interference is not considered.
  - Phases are usually not a concern.
Light rays at a boundary

- At a boundary, three things may happen:
  - Rays are reflected. (Reflection)
  - Rays are refracted. (Refraction)
  - Rays are absorbed. (Absorption)

\[ I_{\text{in}} = I_{\text{reflection}} + I_{\text{refraction}} \ (\ + \ I_{\text{absorption}} ) \]

Note: Frequency is unchanged in reflection and refraction
Reflection

- Law of reflection: On a smooth boundary, the angle of reflection equals the angle of incidence ($\theta_1 = \theta_1'$).

![Diagram showing reflection at smooth and rough surfaces.](image)
Refraction

- what happens when light penetrates into a denser medium?
- the rays are kinked towards the normal

\[ \theta_{\text{air}} = \text{angle of incidence} \]
\[ \theta_{\text{water}} = \text{angle of refraction} \]
Refraction: Deflection of light ray depends on index of refraction $n$

- speed of light in medium is $c/n$
- $n$ depends on the medium

- air $n = 1$
- water $n = 1.33$
- glass $n = 1.52$

(n also depends slightly on the color of the light: $n$ for glass is 1.53 for blue light and 1.51 for red light)
Refraction: Snell’s law

\[ \frac{\sin \theta_{\text{air}}}{\sin \theta_{\text{water}}} = \frac{n_{\text{water}}}{n_{\text{air}}} \]

- \( \theta_{\text{air}} \) = angle of incidence
- \( \theta_{\text{water}} \) = angle of refraction
- \( n \) = index of refraction
Refraction: Snell’s law

\[
\frac{\sin \theta_\text{air}}{\sin \theta_\text{water}} = \frac{n_\text{water}}{n_\text{air}}
\]

\( \theta_\text{air} = \) angle of incidence
\( \theta_\text{water} = \) angle of refraction
\( n = \) index of refraction

inverted ray: water-air case

normal

interface
Light rays going from water to air are deflected so that they are farther away from the normal to the interface.
Refraction: Snell’s law

\[ \frac{\sin \theta_{\text{air}}}{\sin \theta_{\text{water}}} = \frac{n_{\text{water}}}{n_{\text{air}}} \]

\( \theta_{\text{air}} = \text{angle of incidence} \)

\( \theta_{\text{water}} = \text{angle of refraction} \)

\( n = \text{index of refraction} \)

inverted ray: water-air case
Relative Intensity of Reflected and Refracted Light

- Maxwell’s equations can be used to calculate how much light is reflected and how much is refracted.
- For light at normal incidence with intensity $I_0$, the intensity $I$ of the reflected light is:

$$I = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2 I_0$$

The fraction of light that is reflected depends on the angle of incidence.
Total internal reflection

- When light goes from water to air, Snell’s law says that is deflected farther away from the normal. When the angle of incident light is so high that Snell’s law cannot be satisfied, then all the light is reflected:
  - TOTAL INTERNAL REFLECTION
Total internal reflection

inverted ray: water-air case

\[
\frac{\sin \theta_{\text{air}}}{\sin \theta_{\text{water}}} = \frac{n_{\text{water}}}{n_{\text{air}}}
\]

\(\theta_{\text{air}} = \) angle of incidence

\(\theta_{\text{water}} = \) angle of refraction

\(n = \) index of refraction
Refraction and total internal reflection

http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/totint.html
Total internal reflection is the key to fiber optics
Refraction: examples

Does the fish appear to be above or below its real position?
Refraction: examples

Does the fish appear to be above or below its real position?
Refraction: examples

Underwater objects appear to be closer to the surface than they really are.

Apparent position is above real position.
Index of Refraction

- Index of refraction: \( n \equiv \frac{c}{v} \)
  - vacuum \( \rightarrow n = 1 \)
  - low \( v \) \( \rightarrow \) high \( n \)
  - all media have \( n > 1 \)
  - \( \lambda_1 n_1 = \lambda_2 n_2 \)

- Snell’s law of refraction

\[
n_1 \sin \theta_1 = n_2 \sin \theta_2
\]

Frequency is unchanged when light enters into a different medium.
Dispersion

- For a given material, the index of refraction \((n=c/v)\) is a function of frequency (color) of the light.
  - It is called dispersion,
  - Refraction angle depends on color
- Examples:

Prism

Rainbow
Huygen’s Principle

- All points on a given wave front are taken as point sources for the production of spherical secondary waves, called wavelets, that propagate outward through a medium with speeds characteristic of waves in that medium. After some time interval has passed, the new position of the wave front is the surface tangent to the wavelets.
Fermat’s Principle

- The path taken by light traveling from one point to another is such that the time of travel is a minimum. That is, light travels along the path of least time.

Both Huygen’s principle and Fermat’s principle can be derived from Maxwell’s equations.