The Properties of Light

Chapter 11

Our Window on the Universe
Light!

“And God said, Let there be light: and there was light.

“And God saw the light, that it was good…”

Genesis 1:3-4
Standing Waves

- We can create one dimensional standing waves using a rope
The vocabulary of standing waves

- Points of the medium that are permanently at rest are called Nodes.
- Points of the medium that have maximum oscillation are called Anti-Nodes.
- Only certain frequencies or modes produce standing waves. These are called resonance frequencies.
- The energy of a wave is associated with its frequency.
  - Higher frequencies have higher energy.
  - Example: wave machine.
Higher Dimensions

- Standing waves are possible in two dimensions as well
Video: Standing waves in soap bubbles
Standing Wave Modes in 2 Dimensions
Quiz:
Waves arrive at point B because of which of the following?

1. Diffraction of waves
2. Wave interference
3. Refraction of waves
4. Reflection of waves
5. The speed of light in empty space is a constant
The Tacoma narrows bridge revisited
The Doppler Effect
Wave frequency and wavelength change when the wave emitter or receiver is moving.

Higher frequency (shorter wavelength) if coming toward you

Lower frequency if moving away from you
Quiz:
Which picture represents refraction?
Quiz:
Which picture represents interference?
Quiz: Did you read most of Chapter 11 before class today?

A. Yes  
B. No
Light!

“And God said, Let there be light: and there was light.

“And God saw the light, that it was good…”

Genesis 1:3-4
Light

- has wavelength, frequency, amplitude and speed.
- reflects, refracts, interferes and diffracts.
- does more too.
- Is anything else in nature similar?
Speed of Light

- Romer used the seasonal variation in the timing of the eclipses of Jupiter’s moons.
- First precise measurement (1850) by Fizeau and Foucault was about 300,000 km/sec.
- The currently defined value is 299,792.458 km/sec.
Speed of Light

- This is fast enough to
  - Circumnavigate the globe in 0.13 seconds
  - Go to the moon and back in 2.6 seconds
  - Arrive from the sun in 8.3 minutes
  - Arrive from Voyager I in ~14 hours.

- An astronomical yardstick
  - 1 light year = 6 trillion miles

- A yardstick for radar.
  - distance = time × speed of light
Claim: light behaves like a transverse wave

- Speed stays the same.
The Electromagnetic Spectrum

Frequency (Hz cycles/sec)

10^22 10^20 10^18 10^16 10^14 10^12 10^10 10^8 10^6 10^4

Gamma rays → UV → Infrared → Microwave → Short-wave

X-rays → Visible

Wavelength (m)

10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^2 10^4

X-rays → UV → Infrared → Microwave → Short-wave

Visible → TV → AM

10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^2 10^4
Quiz: Infrared light has _____ than visible light

A. shorter wavelengths & higher frequencies

B. longer wavelengths & higher frequencies

C. longer wavelengths & lower frequencies
What causes light?

- E&M radiation is given off whenever electrons *accelerate*.
- It, in turn, causes other electrons to accelerate. (TV, microwave oven)
And what is “waving” and how?

- Recall that a moving charge (current) can produce a magnetic field. This means that a moving electric fields causes a magnetic field.
- Likewise, a moving magnetic field causes an electric field.
- Together, we get a “bootstrap” effect so that one produces the other and voila, we have *electromagnetic waves* or *electromagnetic radiation*.
- Take home lesson: no material needed.
So, if light is a wave ...

it should produce **diffraction** and **interference** patterns.
1. Single-slit diffraction

2. Diffraction of a laser beam
   - note how the light spreads more as the slit gets smaller
Interference: let’s experiment!

1) single slit
2) double slit
   ● Again, note the effect of changing the width of the slit.
Interference of light

- A nice example of laser interference from a double slit.
Conclusion:

Light exhibits wave characteristics.
Yes, but that doesn’t seem to be the whole story ...

- Photographs
- Photoelectric effect
Photos: let’s experiment

- How does photographic film work?
- How does film look when it is exposed to extremely low levels of light?
Photoelectric effect

- Under some conditions, shining light on charged metal will cause electrons to be ejected.

- What happens with:
  - white light?
  - brighter white light?
  - longer time?
  - dim UV light?
Photoelectric effect: summary

suggests light must be particulate!
Photoelectric effect

- Two outcomes of the experiment:
  1) Light has particle characteristics
  2) Energy of light packets (photons)
    \[ E = ( h ) \times ( \text{frequency} ) \]
    \( h \) is a very small constant.
Characteristics of photons

- no mass
- no charge
- associated with electromagnetic force
- \( E_{\text{photon}} = (\text{Planck’s constant})(\text{frequency}) \)
- \( h=6.626 \times 10^{-34} \text{ J} \cdot \text{s} \)
Explaining the photoelectric effect

Einstein: Nobel Prize, 1921

- Electrons are bound to a metal with a certain energy.
- Light interacts with the electrons one photon at a time.
- Low frequency (low energy) light does not discharge electrons.
- High frequency (high energy) light does discharge electrons
Photoelectric effect

- The effect **cannot** be explained by thinking light behaves as a **wave**!!!

**BUT**

- The effect **can** be explained by thinking light behaves as a stream of **particles**!!!
Photons and Interference

- Photons passing through two slits: more likely to travel some paths than others:
  - paths determined by slit width, frequency, collisions etc.
- Photons arrive at film in lumps, like particles
- Probability where lumps hit looks like amplitudes of interfering waves
Wave-Particle Duality

- Electromagnetic radiation is observed as particles
  - *photoelectric effect* & *dim image production*

- Where the particles land is described by waves of probability
  - *diffraction & interference*
Waves Striking Slits
Particles Striking Slits
What gives?

- How can a **particle** make an interference pattern?
- How can a **wave** make individual spots?
Wave-Particle Duality

- Light is both a wave and a particle.
  - It behaves like a wave when unobserved
    - It travels through both slits like a wave
  - It is detected like a particle
    - It hits the screen as individual dots

- Some perspectives:
  - Light is both
  - Light is neither
  - Light is light – it has properties that can be described by comparison with waves and it has other properties that can be described by comparison with particles.
  - Light is a quantum vector field