The precise formulation of the time space laws of [electromagnetic] fields was the work of Maxwell (1870s). Imagine his feelings when the differential equations he had formulated proved to him that the electromagnetic fields spread in the form of polarized waves and with the speed of light! - Albert Einstein

How do I know a wave is a wave?

Today:
“Classical” wave-view of light & its interaction with matter
• Pre-quantum
• Still useful in many situations.

HW01 due, beginning of class; HW02 assigned today

Reminders:
- HW01 due today
- HW02 assigned today
- Problem-Solving Sessions on Tuesdays

Next week:
Special Relativity → Michelson-Morley experiment
Universal speed of light
Length contraction, time dilation

How to generate light?

Stationary charges →
constant E-field, no magnetic (B) field
(We don’t see charges glow in the dark)

Charges moving at a constant velocity →
Constant current through wire creates a B-field
but B-field is constant. (We don’t see DC.)

Accelerating charges →
changing E-field and changing B-field
(EM radiation → both E and B are oscillating)
We talked briefly about Maxwell equations

Electromagnetic waves carry energy

\[ E(x,t) = E_{\text{max}} \sin(ax-bt) \]

Light shines on a black tank full of water. How much energy is absorbed?

Intensity = Power = energy/time \( \sim (E_{\text{avg}})^2 \)
area

\( \sim (\text{amplitude of wave})^2 \sim E_{\text{max}}^2 \)

Light shines on three black barrels filled with water:

Which barrel will heat up the fastest?

Use \( E_{\text{max}} = E_{\text{peak}} > E_{\text{avg}} \)

A) \( 2 > 1 > 3 \)  
B) \( 1 > 2 > 3 \)  
C) \( 1 > 2 > 3 \)

Intensity = power/area \( \sim E_{\text{max}}^2 \)

Does not depend on frequency/color!
Classical waves: Intensity $\sim E_{max}^2$

Classically:
Time average of the E-field squared: same... independent of frequency.

Intensity only depends on the E-field amplitude but not on the color (or frequency) of the light!

Goals for waves
- Superposition
- Interference
- Double-Slit Experiment
- Polarization
- Interferometers

Wave or Particle?
Question arises often throughout course:
- Is something a wave, a particle, or both?
- How do we know?
- When best to think of as a wave? as a particle?

In classical view of light, EM radiation is viewed as a wave (after lots of debate in 1600-1800's).
In what sense does it act as a wave?

What is the most definitive observation we can make that tells us something is a wave?

EM radiation is a wave
What is most definitive observation we can make that tells us something is a wave?

Observe interference.

Constructive interference: (peaks are lined up and valleys are lined up)

1-D interference

What happens with 1/4 phase interference?
Two-Slit Interference

1. A plane wave is incident on the double slit.

2. Waves spread out behind each slit.

3. The waves interfere in the region where they overlap.

4. Bright fringes occur where the combined waves interfere on the viewing screen.

Double-Slit Experiment with Light

Recall solution for Electric field (E) from the wave equation:

\[ E = A \cos(kx - \omega t) \]

Let's forget about the time-dependence for now:

\[ E = A \cos(kx) \]

Euler's Formula says:

\[ \exp(ikx) = \cos(kx) + i\sin(kx) \]

For convenience, write:

\[ E = A \exp(ikx) \]

Before Slits

\[ E = A \exp(ikx) \]

After Slits

\[ E_1 = A_1 \exp(ikx_1) \quad \& \quad E_2 = A_2 \exp(ikx_2) \]

\[ \Rightarrow \quad E_{\text{Total}} = E_1 + E_2 = A_1 \exp(ikx_1) + A_2 \exp(ikx_2) \]

\[ I = |E_{\text{Total}}|^2 = |E_1|^2 + |E_2|^2 + 2|E_1||E_2|\cos(\varphi) \]

\[ \varphi = k(x_2 - x_1) \]

• For waves, we add the individual amplitudes to find the amplitude of the total wave (\( E_{\text{Total}} \)).

• We square the sum (\( E_{\text{Total}} \)) to find the intensity.
Double-slit experiment

Determining the space between peaks ($H$)

For constructive

$$\Delta r = r_2 - r_1 = m\lambda \quad (\text{where } m=1,2,3,...)$$

If screen far away

$$\Theta_1 = \Theta_2 = \Theta$$

If we change from blue light (high $f$) to red (small $f$)
what happens to the spacing between peaks, $H$?

A) Increases  B) Stays the same  C) Decreases

E-field describes probability of finding light there

Electromagnetic wave (e.g. hitting screen of double slit)

Describe EM wave spread out in space.

Probability of detection (peak / trough) ~ (Amplitude of EM wave)$^2$

What are these waves?

**EM Waves**

- Amplitude $E = \text{electric field}$
- $|E|^2$ tells you the intensity of the wave.
- Maxwell’s Equations:
  - $\frac{\partial^2 E}{\partial t^2} = \frac{1}{c^2} \frac{\partial^4 E}{\partial x^4}$
- Solutions are sine/cosine waves:
  - $E(x,t) = A\sin(kx - \omega t)$
  - $E(x,t) = A\cos(kx - \omega t)$

Superposition:

If $E_i(x,t)$ is a solution, and $E_j(x,t)$ is also a solution, then

$E_i(x,t) + E_j(x,t)$ is also a solution.
So far...
very 2D .. What about 3-D

Note: light is transverse wave .. Not longitudinal
E-field cannot oscillate in direction of propagation

Light is generally unpolarized

Light is generally oscillating every which way...
Simplify by having just two components

Now imagine looking end on... down the x-axis

Could also be
Or more generally

Light is generally unpolarized

Polarizers

What happens if I run it through another filter:

A) All light passes
B) All light passes & becomes unpolarized
C) 1/2 of light passes
D) No light passes

Polarization

What happens if I run it through another filter:

Hint:

Now add:

yields:

Nothing, right?
But what if I put this in the middle
Put this together....
Interferometers

1881 Michelson invented a device now known as the 'Michelson Interferometer.' (Nobel Prize, 1907)

We will see it in action in the famous Michelson-Morley experiment, which will lead us to the special relativity theory. So the interferometer had a huge impact!!

Such interferometers are nowadays widely used for various precision measurements. State-of-the-art visible-light interferometers achieve resolutions of ~100pm! (X-ray interferometers are ~1pm).

(100pm = 1Å = diameter of a Hydrogen atom.)

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**Electromagnetic waves**

E-field (for a single color):

\[ E(x,t) = E_0 \sin(\omega t + \frac{2\pi y}{\lambda} + \phi) \]

\[ \lambda = \frac{2\pi c}{\omega} \]

Wavelength \( \lambda \) of visible light is:

\( \lambda \approx 350 \text{ nm} \ldots 750 \text{ nm} \)

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**Constructive interference**

\[ E_{\text{sum}}(x,t) = \frac{1}{2} \cdot E_0 \sin(\omega t + 2\pi x / \lambda + \phi) + \frac{1}{2} \cdot E_0 \sin(\omega t + 2\pi x / \lambda + \phi) = ? \]

\[ = E_0 \sin(\omega t + 2\pi x / \lambda + \phi) = E_{\text{light source}}(x,t) \]

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**Unequal arm lengths**

\[ \Delta L \]

\[ \Delta L / 2 \]
Destructive interference

\[ E_{\text{surf}}(x,t) = \frac{1}{2} E_0 \sin(\omega t + 2n\pi x / \lambda + \phi) + \frac{1}{2} E_0 \sin(\omega t + 2n\pi (x+\Delta x) / \lambda + \phi) \]

if \( \Delta x = \lambda / 2 \):

\[ \sin(x+\pi) = -\sin(x) \]

Moving mirror: What do you see?

Light source

Tilted mirror: 'Fringes!

Light source

Gravitational wave detectors

Summary

Michelson interferometers allow us to measure tiny displacements. Displacements of less than 100 nm are made visible to the eye!

Interferometers find many applications in precision metrology such as for displacement, distance and stress measurements as well as flatness measurements.

Interferometers have played an important role in physics:

- Michelson-Morley experiment \(\rightarrow\) special relativity
- Testing general relativity: Gravitational wave detection

To here, 1/20