Defining signature of waves!

INTERFERENCE & DIFFRACTION OF WAVES + 3 BASIC TENETS OF QUANTUM MECHANICS

- What does interference mean? (Sections 17.1 & 17.5)
  - Constructive and Destructive interference
  - Both Transverse and Longitudinal Waves interfere

- Standing Waves & the *1st basic tenet of QM:* Energy Quantization
  - Standing Waves created by 2 traveling waves in opposite direction; Nodes and Antinodes (Sections 17.2, 17.3, Figs. 17.5, 17.6, 17.9)
  - The energy-levels of an atom are quantized (Bohr model) because the electron is a wave! (classnotes)

- Beats & the *2nd basic tenet of QM:* Wave-Particle Duality
  - Waves can behave like Particles
    - Consider Beats (Demo with tuning forks) (Section 17.8).
    - Many sinusoidal waves added together yield a wavepacket.
    - Time-duration of wavepacket and frequency bandwidth of the source are related.
    - Spatial extent of wavepacket – deBroglie wavelength (Section 38.4 and 39.5)
    - Can the deBroglie wavelength of an electron, or of an atom, equal the optical wavelength?
  - Particles can behave like Waves
    - Consider the two-slit interference experiment (Remember the "Fabric of Cosmos" video?)
    - Electrons interfere! Demo: Davisson-Germer expt
    - Atoms interfere! New state of Matter – Bose-Einstein condensate (1997, 2001 Physics Nobels)

- Diffraction and the *3rd basic tenet of QM:* Heisenberg Uncertainty Principle (Sec. 39.6)
  - Waves diffract, i.e., bend around obstacles

Defining signature of waves!

INTERFERENCE & DIFFRACTION OF WAVES + 3 BASIC TENETS OF QUANTUM MECHANICS

- What does interference mean? (Sections 17.1 & 17.5)
  - Constructive and Destructive interference
  - Both Transverse and Longitudinal Waves interfere

- Standing Waves & the *1st basic tenet of QM:* Energy Quantization
  - Standing Waves created by 2 traveling waves in opposite direction; Nodes and Antinodes (Sections 17.2, 17.3, Figs. 17.5, 17.6, 17.9)
  - The energy-levels of an atom are quantized (Bohr model) because the electron is a wave! (classnotes)

- Beats & the *2nd basic tenet of QM:* Wave-Particle Duality
  - Waves can behave like Particles
    - Consider Beats (Demo with tuning forks) (Section 17.8).
    - Many sinusoidal waves added together yield a wavepacket.
    - Time-duration of wavepacket and frequency bandwidth of the source are related.
    - Spatial extent of wavepacket – deBroglie wavelength (Section 38.4 and 39.5)
    - Can the deBroglie wavelength of an electron, or of an atom, equal the optical wavelength?
  - Particles can behave like Waves
    - Consider the two-slit interference experiment (Remember the "Fabric of Cosmos" video?)
    - Electrons interfere! Demo: Davisson-Germer expt
    - Atoms interfere! New state of Matter – Bose-Einstein condensate (1997, 2001 Physics Nobels)

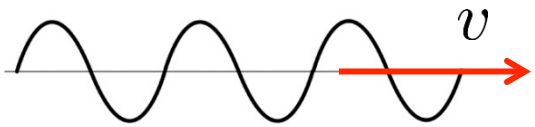
- Diffraction and the *3rd basic tenet of QM:* Heisenberg Uncertainty Principle (Sec. 39.6)
  - Waves diffract, i.e., bend around obstacles

Sec. 17.2: Standing Waves

We can form a **Standing Wave** by superposing (i.e. adding together) two travelling waves of the same amplitude, wavelength, and frequency, but travelling in the opposite directions. 1D case: Watch a video.

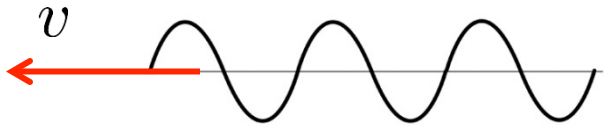
The name Standing Wave comes from the fact that the resultant wave has an amplitude that oscillates in place.

Right Travelling Wave



$$D_R(x,t) = a\sin(kx - \omega t)$$

Left Travelling Wave



$$D_L(x,t) = a\sin(kx + \omega t)$$

The Resultant Wave: $D(x,t) = D_R(x,t) + D_L(x,t)$

$$D(x,t) = \underbrace{2a\sin kx}\cos\omega t$$

$A(x)$, amplitude function

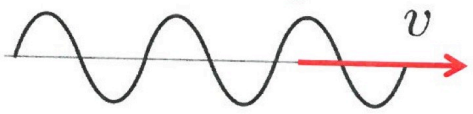
What does this look like In 2D and 3D?!

Sec. 17.2: Standing Waves

We can form a **Standing Wave** by superposing (i.e. adding together) two travelling waves of the same amplitude, wavelength, and frequency, but travelling in the opposite directions.

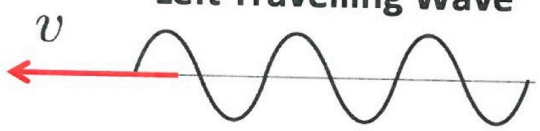
The name Standing Wave comes from the fact that the resultant wave has an amplitude that oscillates in place.

Right Travelling Wave



$$D_R(x,t) = a\sin(kx - \omega t)$$

Left Travelling Wave



$$D_L(x,t) = a\sin(kx + \omega t)$$

$\sin A + \sin B = 2\sin\left(\frac{A+B}{2}\right)\cos\left(\frac{A-B}{2}\right)$

The Resultant Wave: $D(x,t) = D_R(x,t) + D_L(x,t)$

$= a[\sin(kx-\omega t) + \sin(kx+\omega t)]$

$= 2a\sin kx\cos(-\omega t)$

$\cos(-\theta) = \cos\theta$

NOTE!
NO MATTER WHAT TIME,
STANDING WAVE
IS ZERO AT LOCATIONS
WHERE $\sin kx = 0$

$$D(x,t) = \underbrace{2a\sin kx}_{\equiv}\cos\omega t \quad \checkmark$$

$A(x)$, amplitude function

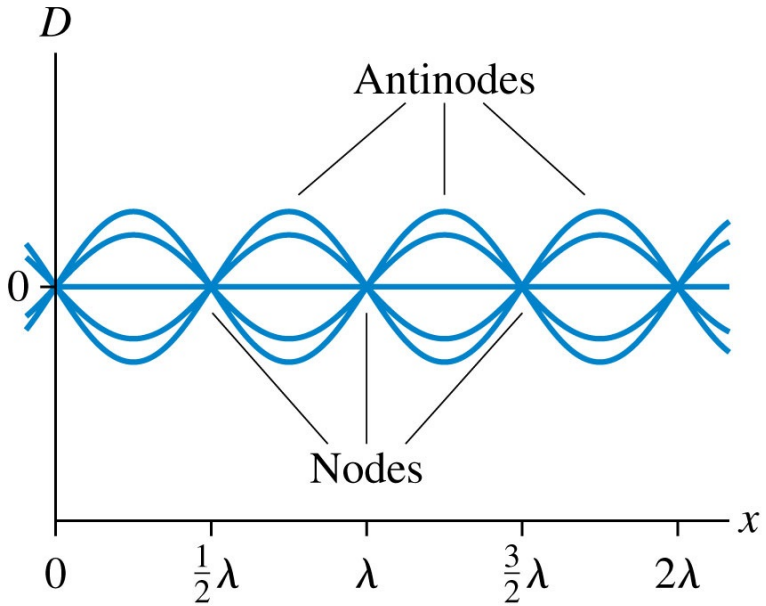
What does this look like?
In 2D and 3D?!

(Back to 1D) Standing Wave Terminology

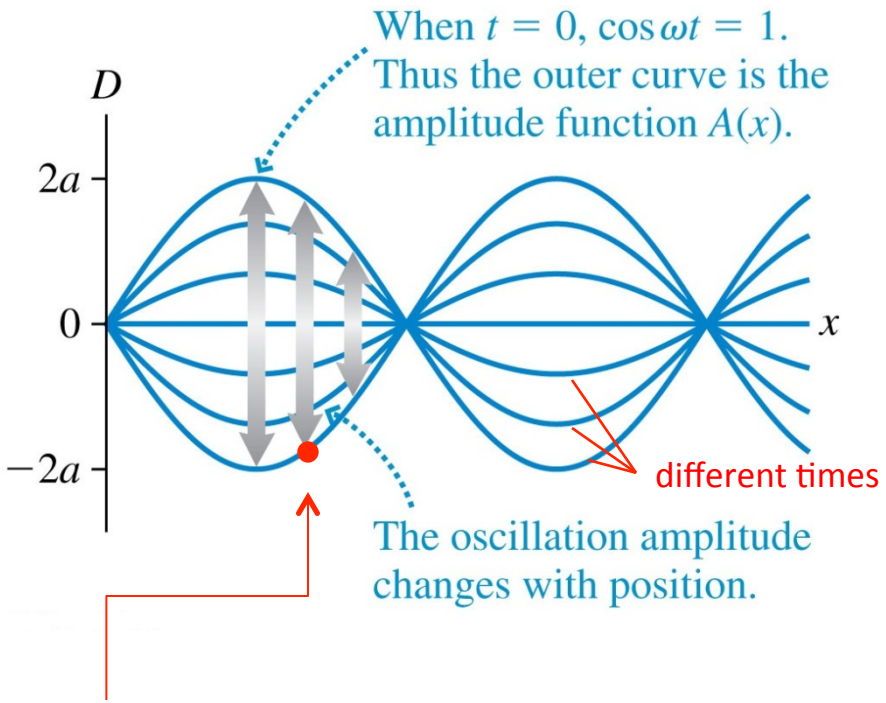
$$D(x,t) = 2a\sin kx\cos\omega t = 2a\sin\frac{2\pi x}{\lambda}\cos\omega t = A(x)\cos\omega t$$

When $\frac{x}{\lambda} = 0, \frac{1}{2}, 1, \frac{3}{2}, 2, \ldots \Rightarrow$ No displacement, a **Node**

When $\frac{x}{\lambda} = \frac{1}{4}, \frac{3}{4}, \frac{5}{4}, \frac{7}{4}, \ldots \Rightarrow$ Displacement is maximum, an **Antinode**



The nodes and antinodes are spaced $\lambda/2$ apart.



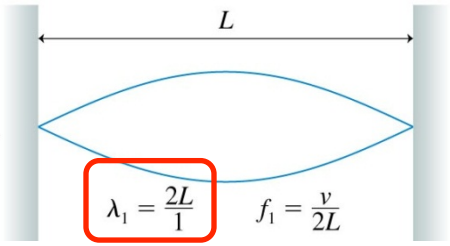
A point here has SHM with Amplitude A(x)

Sec. 17.3: Standing Waves on a String

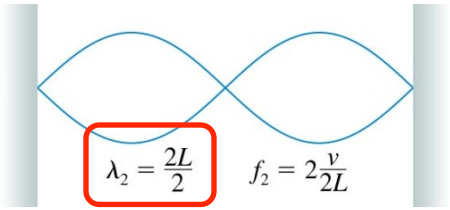
For a string clamped at both ends, what are the wavelengths and frequencies of the allowed standing waves?

Standing wave condition: Both ends must be a node. So an integer number of half wavelengths can fit on the string.

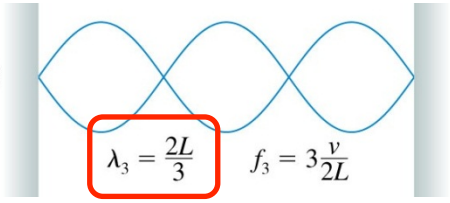
"Fundamental" (longest wavelength)



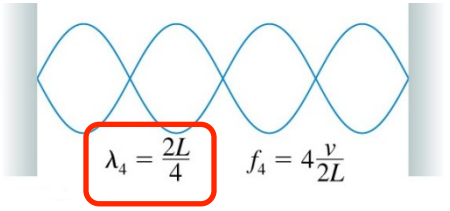
"Second Harmonic"



"Third Harmonic"



"Fourth Harmonic"



So, following the pattern, the allowed wavelengths are:

$$\lambda_n = \frac{2L}{n}$$, where n = 1, 2, 3…

And the allowed frequencies (v = wavespeed) are:

$$f_n = v / \lambda_n = n\, v / (2L) = n\, f_1$$

where: $f_1 = \frac{v}{2L}$

Note the important fact:

The n^{th} harmonic has n antinodes.

THE FIRST BASIC TENET OF QUANTUM MECHANICS: ENERGY QUANTIZATION
(simplified description of Sections 38.4 & 38.5)

An electron is a wave.

Q: How should I draw an atom now?

THE FIRST BASIC TENET OF QUANTUM MECHANICS: ENERGY QUANTIZATION

(simplified description of Sections 38.4 & 38.5)

An electron is a wave.

Q: How should I draw an atom now?

A: The concept of ENERGY QUANTIZATION

(where do the Bohr levels of an atom come from?)

THE FIRST BASIC TENET OF QUANTUM MECHANICS: ENERGY QUANTIZATION
(simplified description of Sections 40.2 – 40.4)

An electron is a wave.

Q: How should I draw an atom now?

A: The concept of ENERGY QUANTIZATION

(where do the Bohr levels of an atom come from?)

Replace  by a simpler 1-D atom

Electron going back&forth like a "particle in a box".

See Fig. 38.14

THE FIRST BASIC TENET OF QUANTUM MECHANICS: ENERGY QUANTIZATION (simplified description of Sections 38.4 & 38.5)

An electron is a wave.

Q: How should I draw an atom now?

A: The concept of ENERGY QUANTIZATION

(where do the Bohr levels of an atom come from?)

Replace  by a simpler 1-D atom

Electron going back&forth like a "particle in a box".

- Electron wavefunction $\Psi(x,t) = A\sin(kx - \omega t + \phi)$

See Fig. 38.14

THE FIRST BASIC TENET OF QUANTUM MECHANICS: ENERGY QUANTIZATION (simplified description of Sections 38.4 & 38.5)

An electron is a wave.

Q: How should I draw an atom now?

A: The concept of ENERGY QUANTIZATION

(where do the Bohr levels of an atom come from?)

Replace  by a simpler 1-D atom

Electron going back & forth like a "particle in a box".

- Electron wavefunction $\psi(x,t) = A\sin(kx - \omega t + \phi)$
- Electron does not exist outside walls

$\therefore \quad \psi(x \leq 0) = \psi(x \geq L) =$ ____

$\Rightarrow \psi$ has _____ at both ends.

See Fig. 38.14

THE FIRST BASIC TENET OF QUANTUM MECHANICS: ENERGY QUANTIZATION (simplified description of Sections 38.4 & 38.5)

An electron is a wave.

Q: How should I draw an atom now?

A: The concept of ENERGY QUANTIZATION

(where do the Bohr levels of an atom come from?)

Replace  by a simpler 1-D atom

Electron going back & forth like a "particle in a box".

- Electron wavefunction $\Psi(x,t) = A\sin(kx - \omega t + \phi)$
- Electron does not exist outside walls

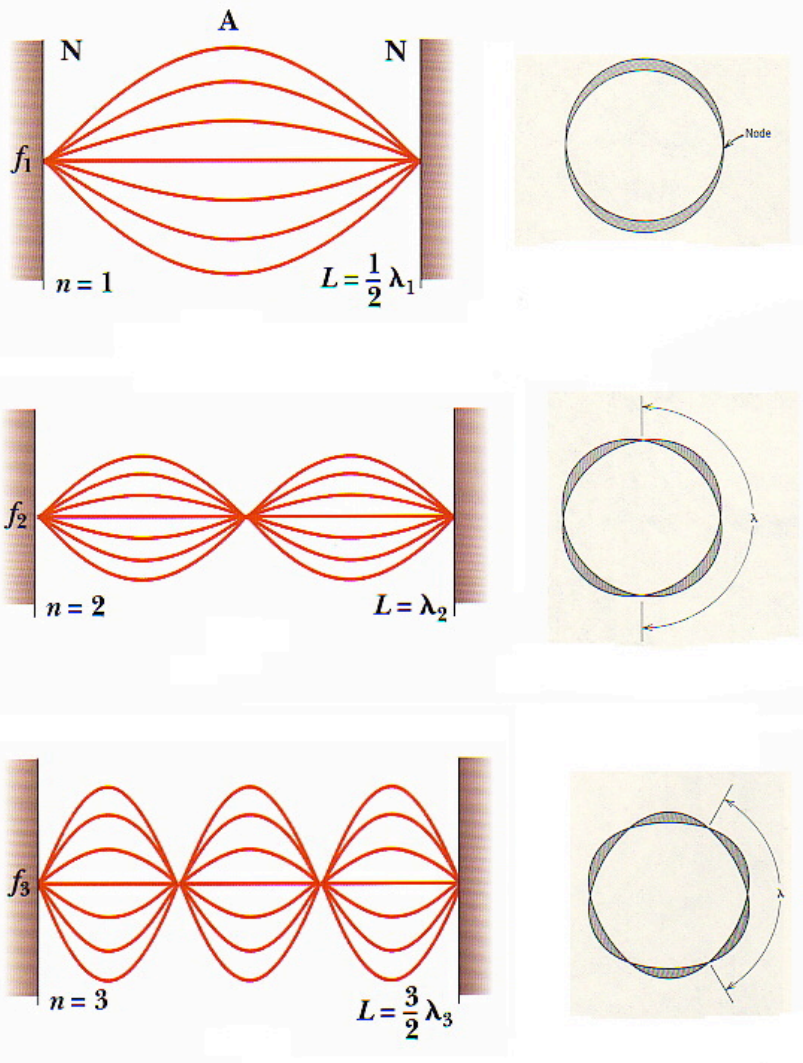
$\therefore \quad \Psi(x \leq 0) = \Psi(x \geq L) =$ _____

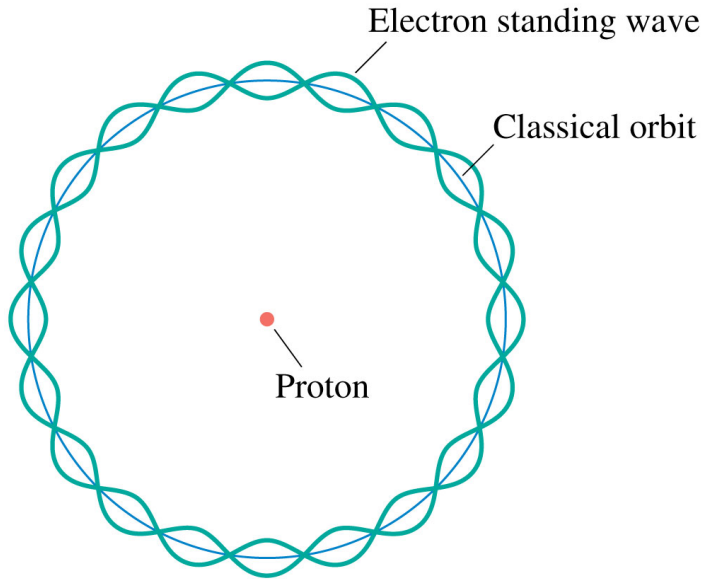
$\Rightarrow$ Ψ has _____ at both ends.

- Ψ is beginning to remind us of _____ _____ !!

See Fig. 38.14

Sec. 38.4: BOHR MODEL - THE ENERGY-LEVELS OF AN ATOM ARE QUANTIZED! (see Fig. 38.18)





An $n = 10$ electron standing wave around the orbit's circumference.

- In a Bohr hydrogen atom, the wave-like electron sets up a circular standing wave.
- The orbital circumference is an integer number (10 in this case) of the electron's wavelength

$\lambda_n = 2L / n$, where n = 1, 2, 3…

Defining signature of waves!

INTERFERENCE & DIFFRACTION OF WAVES + 3 BASIC TENETS OF QUANTUM MECHANICS

- What does interference mean? (Sections 17.1 & 17.5)
- Constructive and Destructive interference
- Both Transverse and Longitudinal Waves interfere

- Standing Waves & the *1st basic tenet of QM:* Energy Quantization
- Standing Waves created by 2 traveling waves in opposite direction; Nodes and Antinodes (Sections 17.2, 17.3, Figs. 17.5, 17.6, 17.9)
- The energy-levels of an atom are quantized (Bohr model) because the electron is a wave! (classnotes)

- Beats & the *2nd basic tenet of QM:* Wave-Particle Duality
- Waves can behave like Particles
  - Consider Beats (Demo with tuning forks) (Section 17.8).
  - Many sinusoidal waves added together yield a wavepacket.
  - Time-duration of wavepacket and frequency bandwidth of the source are related.
  - Spatial extent of wavepacket – deBroglie wavelength (Section 38.4 and 39.5)
  - Can the deBroglie wavelength of an electron, or of an atom, equal the optical wavelength?
- Particles can behave like Waves
  - Consider the two-slit interference experiment (Remember the "Fabric of Cosmos" video?)
  - Electrons interfere! Demo: Davisson-Germer expt
  - Atoms interfere! New state of Matter – Bose-Einstein condensate (1997, 2001 Physics Nobels)

- Diffraction and the *3rd basic tenet of QM:* Heisenberg Uncertainty Principle (Sec. 39.6)
- Waves diffract, i.e., bend around obstacles

Defining signature of waves!

INTERFERENCE & DIFFRACTION OF WAVES + 3 BASIC TENETS OF QUANTUM MECHANICS

- What does interference mean? (Sections 17.1 & 17.5)
  - Constructive and Destructive interference
  - Both Transverse and Longitudinal Waves interfere

- Standing Waves & the *1st basic tenet of QM:* Energy Quantization
  - Standing Waves created by 2 traveling waves in opposite direction; Nodes and Antinodes (Sections 17.2, 17.3, Figs. 17.5, 17.6, 17.9)
  - The energy-levels of an atom are quantized (Bohr model) because the electron is a wave! (classnotes)

- Beats & the *2nd basic tenet of QM:* Wave-Particle Duality
  - Waves can behave like Particles
    - Consider Beats (Demo with tuning forks) (Section 17.8).
    - Many sinusoidal waves added together yield a wavepacket.
    - Time-duration of wavepacket and frequency bandwidth of the source are related.
    - Spatial extent of wavepacket – deBroglie wavelength (Section 38.4 and 39.5)
    - Can the deBroglie wavelength of an electron, or of an atom, equal the optical wavelength?
  - Particles can behave like Waves
    - Consider the two-slit interference experiment (Remember the "Fabric of Cosmos" video?)
    - Electrons interfere! Demo: Davisson-Germer expt
    - Atoms interfere! New state of Matter – Bose-Einstein condensate (1997, 2001 Physics Nobels)

- Diffraction and the *3rd basic tenet of QM:* Heisenberg Uncertainty Principle (Sec. 39.6)
  - Waves diffract, i.e., bend around obstacles

Defining signature of waves!

INTERFERENCE & DIFFRACTION OF WAVES + 3 BASIC TENETS OF QUANTUM MECHANICS

- What does interference mean? (Sections 17.1 & 17.5)
  - Constructive and Destructive interference
  - Both Transverse and Longitudinal Waves interfere

- Standing Waves & the *1st basic tenet of QM:* Energy Quantization
  - Standing Waves created by 2 traveling waves in opposite direction; Nodes and Antinodes (Sections 17.2, 17.3, Figs. 17.5, 17.6, 17.9)
  - The energy-levels of an atom are quantized (Bohr model) because the electron is a wave! (classnotes)

- Beats & the *2nd basic tenet of QM:* Wave-Particle Duality
  - Waves can behave like Particles
    - Consider Beats (Demo with tuning forks) (Section 17.8).
    - Many sinusoidal waves added together yield a wavepacket.
    - Time-duration of wavepacket and frequency bandwidth of the source are related.
    - Spatial extent of wavepacket – deBroglie wavelength (Section 38.4 and 39.5)
    - Can the deBroglie wavelength of an electron, or of an atom, equal the optical wavelength?
  - Particles can behave like Waves
    - Consider the two-slit interference experiment (Remember the "Fabric of Cosmos" video?)
    - Electrons interfere! Demo: Davisson-Germer expt
    - Atoms interfere! New state of Matter – Bose-Einstein condensate (1997, 2001 Physics Nobels)

- Diffraction and the *3rd basic tenet of QM:* Heisenberg Uncertainty Principle (Sec. 39.6)
  - Waves diffract, i.e., bend around obstacles

Use Videos to prove: "Particles can behave like Waves"

- Recall from the pbs-nova video: Brian Greene's "Fabric of the Cosmos" that you watched just after Thanksgiving that the **double-slit interference experiment** with *electrons* (not just water waves) yields an interference pattern!

  This means electrons must be waves, not particles!

- Let's re-watch a ~7 minute segment from 14:07 to 20.33 from Brian Greene's "Fabric of the Cosmos" located at https://www.youtube.com/watch?v=eCFTVdExxPA

- Next, let's watch another video on the double-slit experiment, with electrons. http://www.youtube.com/watch?v=DfPeprQ7oGc

  In class, during the last few minutes, we watched this video https://www.youtube.com/watch?v=nAGPAb4obs8 which shows that not just electrons but atoms too can be shown to behave like waves, producing a Bose-Einstein condensate. These condensates represent a new state of matter – neither gas, nor liquid, nor solid, nor plasma – and their discovery was awarded a Nobel Prize in physics in 2001. These condensates have since been used to demonstrate atom lasers, quantum computers, slow light crawling at few m/s, etc. etc. etc., leading to two further Nobels in 2005 and 2012.

WE KINDA ABRUPTLY STOPPED HERE