From Last Time...
Wavefunctions and probabilities
square of wavefunction = probability
Tunneling
Purely quantum effect
Applied in scanning tunneling microscope

The wavefunction and quantum ‘jumps’
• A quantum system has only certain discrete quantum states in which it can exist.
• Each quantum state has distinct wavefunction, which extends throughout all space
• It’s square gives probability of finding electron at a particular spatial location.
• When particle changes it’s quantum state, wavefunction throughout all space changes.

Hydrogen atom quantum jump

The electron jumps from one quantum state to another, changing its wavefunction everywhere. During the transition, we say that the electron is in a superposition between the two states.

Classical particle in a box
• Box is stationary, so average speed is zero.
• But remember the classical version

Particle bounces back and forth.
- On average, velocity is zero.
- But not instantaneously
- Sometimes velocity is to left, sometimes to right

Quantum version
• Quantum state is both velocities at the same time

Ground state is a standing wave, made equally of
- Wave traveling right ( positive momentum +h/λ )
- Wave traveling left ( negative momentum - h/λ )

Quantum ground state is equal superposition of two very different motions.
Making a measurement

Suppose you make multiple measurements of the speed (hence, momentum) of the quantum particle in a tube. How often will you measure the particle moving to the left?

A. 0% (never)
B. 33% (1/3 of the time)
C. 50% (1/2 of the time)

The wavefunction

- Wavefunction $= \Psi = |\text{moving to right}> + |\text{moving to left}>
- The wavefunction for the particle is an equal 'superposition' of the two states of precise momentum.
- When we measure the momentum (speed), we find one of these two possibilities.
- Because they are equally weighted, we measure them with equal probability.

A Measurement

- We interpret this as saying that before the measurement, particle exists equally in states - momentum to right - momentum to left
- When we measure the momentum, we get a particular value (right or left).
- The probability is determined by the weighting of the quantum state in the wavefunction.
- The measurement has altered the wavefunction. The wavefunction has 'collapsed' into a definite momentum state.

Double-slit particle interference

- Reduce intensity until only single photon at a time goes through slits.
- Which slit does the photon go through?

Interference of a single photon

In the two-slit experiment with one photon, which slit does the photon go through?

A. Left slit
B. Right slit
C. Both slits
Photon on both paths

Path 1: photon goes through left slit
Path 2: photon goes through right slit

Wavefunction for the photon is a superposition of these two states.

Quantum mechanics says photon is simultaneously on two widely separated paths.

Superposition of quantum states

- We made a localized state made by superimposing (‘adding together’) states of different wavelength (momenta).
- Quantum mechanics says this wavefunction physically represents the particle.
- The amplitude squared of each contribution is the probability that a measurement will determine a particular momentum.
- Copenhagen interpretation says that before a measurement, all momenta exist. Measurement ‘collapses’ the wavefunction into a particular momentum state (this is the measured momentum).

Measuring which slit

Measure induced current from moving charged particle

- Suppose we measure which slit the particle goes through?
- Interference pattern is destroyed!
- Wavefunction changes instantaneously over entire screen when measurement is made.

A superposition state

\[ \frac{1}{\sqrt{2}} (|\text{Margarita}\rangle + |\text{Beer}\rangle) \]

- Margarita or Beer?
- This QM state has equal superposition of two.
- Each outcome (drinking margarita, drinking beer) is equally likely.
- Actual outcome not determined until measurement is made (drink is tasted).

What is object before the measurement?

- What is this new drink?
- Is it really a physical object?
- Exactly how does the transformation from this object to a beer or a margarita take place?
- This is the collapse of the wavefunction.

Quantum dice game

Suppose we have a six-sided quantum die. It is not fair, but comes up ‘2’ most often. It’s wavefunction could be

A. \[1.2|1\rangle + 1.3|2\rangle + 1.3|3\rangle + 1.7|4\rangle + 0.8|5\rangle + 1.1|6\rangle\]
B. \[1.1|1\rangle + 1.4|2\rangle + 1.3|3\rangle + 1.3|4\rangle + 0.8|5\rangle + 1.1|6\rangle\]
C. \[1.4|1\rangle + 1.3|2\rangle + 1.6|3\rangle + 1.4|4\rangle + 0.9|5\rangle + 1.3|6\rangle\]
Not universally accepted

- Historically, not everyone agreed with this interpretation.
- Einstein was a notable opponent
  - ‘God does not play dice’
- These ideas hotly debated in the early part of the 20th century.
- Particularly famous venue was 1927 Solvay conference in Belgium

A “home movie” shot by Irving Langmuir, (the 1932 Nobel Prize winner in chemistry). It captures 2 minutes of an intermission in the proceedings. Twenty-one of the 29 attendees are on the film.

Voice-over is by Nancy Thorndike Greenspan.

Solvay movie

Schroedinger’s cat

- Some founders of quantum mechanics were not happy with this interpretation.
- Schroedinger developed scenario involving a living object to illustrate his skepticism.

His scenario involved a cat, a radioactive atom, and a canister of poison gas.

A cat, along with a decaying radioactive nucleus, a radiation detector, and a flask of poisonous gas are enclosed in a box.

The radiation detector will break the flask if it detects emission from decay of nucleus (which decays with 50% probability). This kills the cat.

But maybe it doesn’t decay (also with 50% probability). This doesn’t kill the cat.

This wavefunction is a superposition of

- A nucleus that has not decayed
- A radiation detector that has not detected radiation
- An unbroken flask
- A live cat

and

- A decayed nucleus
- A radiation detector that has detected radiation
- A broken flask
- A dead cat
**Wavefunction collapse**
- This wavefunction collapses into one or the other state with 50% probability when you open the box and observe the situation.
- How can the cat be both dead and alive?
- Wouldn’t it know?

Who qualifies as making the measurement, the cat or the box opener?

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**Quantum computing**
- In the last several years, it has been discovered that these superposition ideas could be used in a novel way to do complex calculations.
- A normal computer uses bits
  - Each bit can take a value of 0 or 1.
- A qubit (quantum bit) is a physical device that is in a linear superposition of two quantum states.
- Can think of these two quantum states as the 0 and 1 of a classical binary computer.

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**Qubits**
- Qubits - label two levels of an atom as $|0\rangle$ and $|1\rangle$
  
  $|0\rangle$  | $|1\rangle$

- Superposition state $|\psi\rangle = a |0\rangle + b |1\rangle$
- Create a superposition state of 2 atoms, for example $|\psi\rangle = a |00\rangle + b |11\rangle$
- This is an entangled state.

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**Quantum computing**
- Create superposition state of $N$ atoms
- Function applied to superposition state acts on all components simultaneously.
- Parallel processing of quantum data.