From Last Time...

- Heisenberg Uncertainty principle
- Arises from wave nature of particles.
- Particle cannot have precise position and momentum.
- Highly accurate momentum (wavelength) means position is uncertain
- Can localize particle by superimposing many wavelengths, so momentum is uncertain.
- Quantum mechanical tunneling.
The wavefunction and quantum ‘jumps’

- Saw that particle 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.
Example: hydrogen atom

\[ n=1 \quad n=2 \quad n=3 \quad n=4 \]

Photon emitted
\[ hf = E_3 - E_1 \]

Wavefunction changes from 3p to 1s throughout all space.
Example: ‘Particle’ wavepacket

A measurement determining particle location to within $\Delta x$

Original wavefunction of moving particle

Resulting wavefunction
Double-slit particle interference

- Wave propagates through both slits.
- Film records point impact, building up interference pattern.
- Impact point determined probabilistically from wavefunction.
Measuring the wavefunction

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

- Attenuated candle - one photon at a time through slits
- Interference still seen!
- Conclusion each photon goes through both slits.
- Experiment with 3 months exposure  G.I. Taylor 1909
What does Quantum Mech. Mean?

- Particle going through slits, interference pattern.
- Probability of hitting screen. But when it is detected, it has hit in one particular place.
- Don’t measure half an electron, or 0.1 electron.
- How does this happen?
Measurement and interactions

- Suggests that the measurement is changing the wavefunction.
- We will see that this may be true in some sense, but not the most obvious one.
- In the past several years, subtle experiments have been devised to probe these effects.
- They reveal unusual quantum-mechanical effects difficult to understand in terms of classical ideas of how objects are ‘correlated’.
A puzzling experiment

Photon 'splitter'

Photon from source travels toward nonlinear region along both of these paths (i.e. it is a wave).
Photon 1 travels along both of these paths. Interference is observed.
The nonlinear regions split the photon into two photons. The photons are ‘entangled’.
Photon 2 travels along both of these paths. If we measure a photon we don’t know which path.
Block 2A. Then if we measure photon 2, photon 1 is on path B, and vice versa. No interference.
Even with no detector, blocking 2A gives no interference.
Nonlocal effect of observation

• Barrier is quite far from slits and interfering region, and detector and barrier apparently interact only w/photon 2.

• Yet interference arising from photon 1 is destroyed.

• Detector is not even necessary. Inserting barrier destroys interference, even if we don’t make a physical observation to determine the path of photon 1.

• Arises from entanglement of the two photons, and the nature of quantum mechanics.
Quantum entanglement

- When two particles are quantum entangled, they become a single quantum system with a single ‘shared’ wavefunction.

- This ‘shared’ wavefunction undergoes ‘quantum jumps’ in a way similar to a hydrogen atom, or electron wavepacket.

- As long as shared wavefunction is not disturbed, this ‘shared’ character is preserved over any distance.

- In this sense entangled particles behave as a single quantum object.
What does this mean?

• Experiment has verified ‘quantum jumps’
• Experiment has verified that jumps can be ‘communicated’ instantaneously over vast distances.
• How can this be reconciled with, for instance, relativity and faster than light travel?
• No energy and no information is transferred.
Quantum Teleportation

Entangled beams are used for teleportation. New experiments in 2004 have done this with atoms.
Superposition quantum states

- Localized state made by superimposing (‘adding together’) states of different wavelength (momenta).
- Quantum mechanics says this wavefunction physically represents the particle.
- The amplitude 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.
Physics meeting 1920’s
A superposition state

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

- Margarita or Beer?
- This QM state has equal superposition of two states.
- 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?

\[ \frac{1}{\sqrt{2}} \left( \begin{array}{c} \text{\begin{center} \includegraphics[width=1cm]{margarita.png} \end{center}} \\ + \begin{center} \includegraphics[width=1cm]{beer.png} \end{center} \end{array} \right) \]

- 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.
Schroedinger’s cat

• Some founders of quantum mechanics were not happy with this interpretation.

• Schroedinger developed this scenario to point out some of the confusing aspects.
Schroedinger’s cat

- Cat in a box with a nucleus that can decay and emit a photon.
- Detector then triggers a hammer that releases poison and kills the cat.
- Atom is in superposition of being excited or not.
- Thus cat is both dead and alive.
- Determined when we measure.
Schroedinger Cat State

• 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 \textbf{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?
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.
Qubits

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

$\begin{align*}
|0\rangle & \quad \text{and} \quad |1\rangle \\
|0\rangle & \quad \text{and} \quad |1\rangle
\end{align*}$

- 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.
Quantum computing

• Create superposition state of N atoms
• Parallel processing of quantum data.
Quantum computing algorithms

• If we could do this with 10,000 qubits we could factor a number with Shor’s algorithm that is larger than any classical computer can.

• Uses quantum mechanics so it is probabilistic.

• Other algorithms for searching data bases and for simulating Quantum mechanical systems.

• So far people can do experiments with <10 qubits.
Building a Quantum Computer

- **Atoms**
  - Choose two convenient energy levels for qubit
  - 1-qubit operations with laser light
  - 2-qubit operations with vibrational mode coupling (ion traps) or interchange of photons (cavity QED) or atomic collisions

- **Superconductors**
  - Qubit is presence or absence of flux
  - 1-qubit operations with applied field
  - 2-qubit operations with exchange of flux

- **Electrons on Liquid Helium**
  - Electron spin as qubit
  - 1-qubit operations with applied fields
  - 2-qubit operations with spatial overlap

- **Nuclear Magnetic Resonance**
  - Nuclear spins as qubits
  - 1-qubit operations with applied fields
  - 2-qubit operations by means of naturally present exchange interactions
One Successful Quantum Computer

7 qubit implementation of Shor’s algorithm.
Molecule chemically synthesized to factor 15 in prime factors.
Nuclear spin plays role of Qubit.
Detected by nuclear magnetic resonance technique.

“Experimental realization of Shor's quantum factoring algorithm using nuclear magnetic resonance”
LIEVEN M. K. VANDERSYPEN, MATTHIAS STEFFEN, GREGORY BREYTA, COSTANTINO S. YANNONI, MARK H. SHERWOOD & ISAAC L. CHUANG
Nature 414, 883 - 887 (20 December 2001);
Scenario for coupled solid state Qubits

(Courtesy Prof. M. Eriksson, UW-Madison Physics)

Uncoupled
\[ J \approx 0 \]

Swap
\[ J > 0 \]
Double quantum dot in Si/SiGe
Progress toward two coupled Qubits. (M. Erikkson, UW Physics)
Atomic qubits
(Profs. Mark Saffman and Thad Walker, UW-Madison Physics)

Optical traps for atoms.
Review question

Our quantum computer has $N$ qubits. How many different states can be represented at one time.

A. $N$
B. 1
C. $N/2$
D. $2^N$
E. 4 $N$