Quantum Computation

(In Brief)

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Exploiting Quantum Weirdness

"I think I can safely say that nobody understands quantum mechanics…

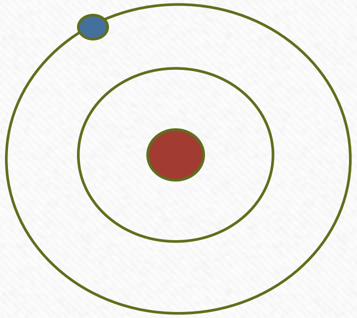
Exploiting Quantum Weirdness

"I think I can safely say that nobody understands quantum mechanics…

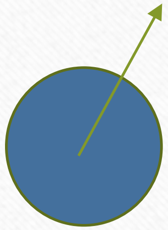
...BUT I know more about quantum mechanics than the generals do, believe me."

Key Ideas About Quantum Physics

- Certain properties can take on discrete values. Examples:



Energy Levels in atom: {ground state, 1st excited state,…}

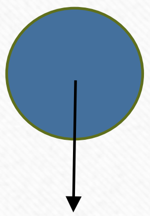
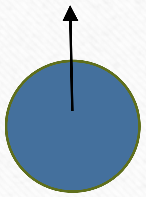


Component of spin about any given axis: {+1, -1} for electrons

- State of a particle described by a vector of length one: $|E_0\rangle$, $|0\rangle$, $|1\rangle$

Important Idea for Quantum Computers

- <u>Superposition</u>: Particle can be in any linear combination of states between measurements.

State = a *  + b * 

$\text{State} = a|0> + b|1>$, where the $|a|^2 + |b|^2 = 1$ (unit vector)

When a spin measurement is performed, State "collapses" to either $|0>$ with probability $|a|^2$ or $|1>$ with probability $|b|^2$.

Classical Computers vs Quantum Computers

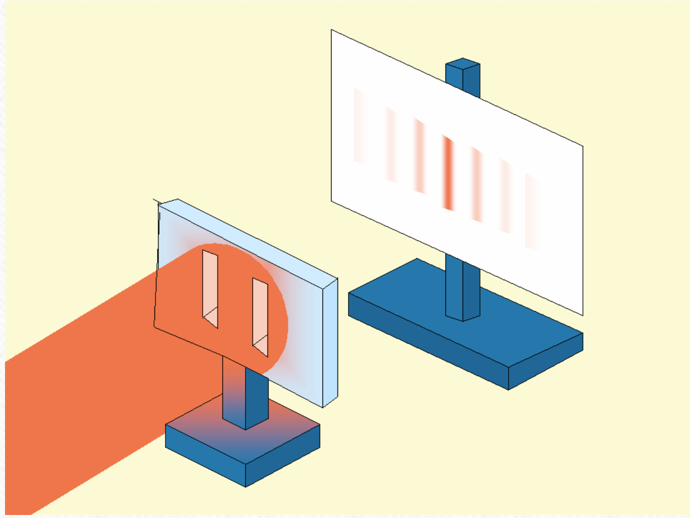
- Unit of information: “bit”…...0 or 1......high voltage or low voltage.....etc.

  Physical implementation: 2-state system in either one state or another.
- Classical computers/Logic gates process bits. Bits in, bits out.
- Quantum computers process bits in SUPERPOSITION. These are “quantum bits”, or qubits. Picture: electron “spin up” + “spin down”:

  Qubit state = a|0> + b|1>
- a and b are complex numbers (eg., 3 -2i, 5i, -145, 11) called “amplitudes”.
- Multiple qubits = multiple two-state quantum systems:
  - |01>, or |10>. In general: |00> + |01> + |10> + |11> (superposition properly normalized)

Interference is a Good Thing!

- In quantum mechanics, states can interfere with each other, cancelling in some places, and reinforcing in others (double-slit experiment with light)



What if we had a device that took every possible answer to a problem, made them interfere so that only the correct answer got reinforced?

That's what Quantum Computers are for!

General Process

Step 1: Input quantum state. Example, |00>. This represents a system of two particles: one spin down, the other also spin down.

Step 2: Apply a "quantum gate" turning the initial state into an equal combination of all the possible states: ½|00> + ½ |01> + ½ |10> + ½ |11>

Step 3: Repeatedly apply another transformation on this new state so that the amplitude for the right answer grows with each application of the transformation.

Step 4: Perform a measurement on the system. You will observe the correct answer with high probability.

Grover's Search Algorithm

- Unordered list of N items. Want to match a search query.
- Classical computers can match with O(N) at best.
- Quantum computers can do this with O($\sqrt{N}$)

- Suppose N = 2^n. We can write the i^{th} index of the list in binary. We can represent each index as a physical n qubit system.

Example: 8 entries in the list → The list indices are can be written as:
|000>, |001>, |010>, |011>, |100>, |101>, |110>, |111>. Think of each as 3 electrons, each of which can be spin down (0) or spin up (1).
By putting these in a uniform superposition, applying certain transformations, then measuring the system, we can arrive at the desired index with high enough probability. I.E. Suppose the desired index was 6. 6 = 110. So result of measurement will be the 3-qubit state |110>

Limitations

- System must be kept in a superposition for as long as the transformations need to work their interference MAGIC.
- Interactions between the qubits and the outside world will destroy the superposition!
- Quantum computers beat classical computers hands down only for certain tasks (eg., searching – Grover's algorithm; factoring – Shor's algorithm)
- Other tasks don't run any faster on a QC than on a CC (eg, our routine use)
- Just protecting the quantum nature of the systems you use as qubits will likely make the QC's slower than CC's for a long, long time.
- NSA likely has nothing to worry about.

National Security

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By Steven Rich and Barton Gellman January 2, 2014

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Is D-Wave's quantum computer actually a quantum computer?

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Programming Your Quantum Computer

The hardware doesn't yet exist, but languages for quantum coding are ready to go.

Brian Hayes

Shor's algorithm is implemented using five trapped ions

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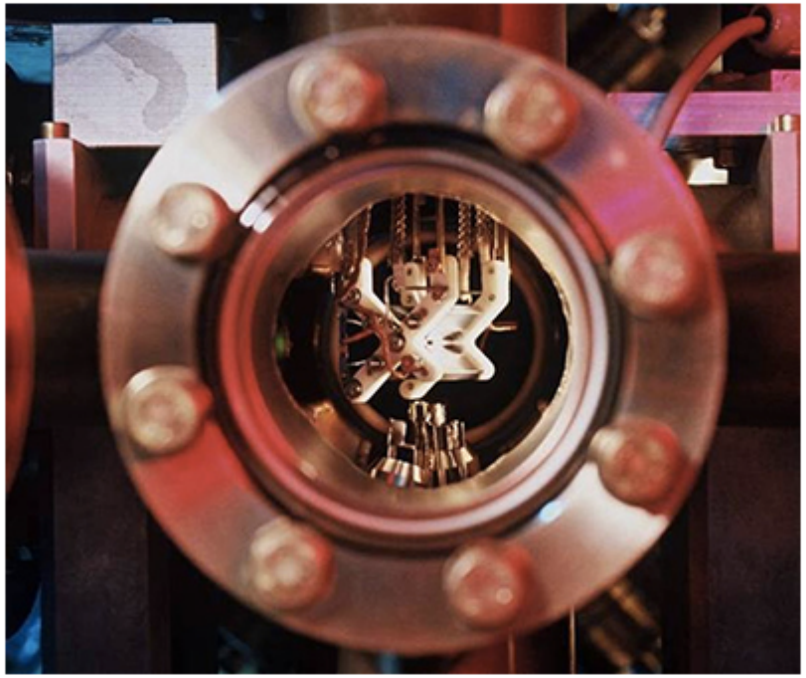

Quantum factor: the Paul trap used by Monz and colleagues

Nice blog post about Shor's algorithm for factoring large numbers and quantum computing:
http://www.scottaaronson.com/blog/?p=208

Scott Aaronson: Quantum Computing researcher at UT Austin – very cool blog if you're interested

A new quantum approach to big data

System for handling massive digital datasets could make impossibly complex problems solvable.

David L. Chandler | MIT News Office
January 25, 2016

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