

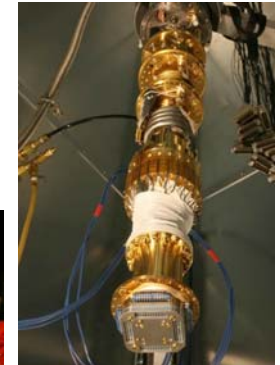
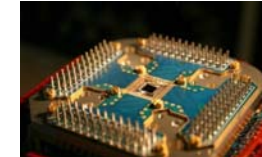
The Future is Quantum Computing ?

Professor John Kubiatowicz
University of California @ Berkeley
HotChips Panel
August 2007

Do quantum computers exist?

- Engadget headline: "World's first 'commercial' quantum computer solves Sudoku" (Feb 14th 2007)

- "As **expected**, Canada's D-Wave Systems has announced 'the world's first commercially viable **quantum computer**', and they seem to be pretty stoked about it. The achievement is notable, since they've managed to build a whole 16 qubit computer that actually does some simple computations, even if it's far less powerful than even the most basic of home computers."



- Clearly an important first problem to solve!
 - » Not clear that this machine actually works, however. A fair amount of suspicion that it is simply hype.
 - » Purports to use "Adiabatic Quantum Computing"

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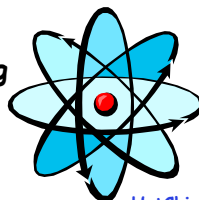
Ok, but why would you want a Quantum Computer?

- Suppose you want to:
 - Compute quantum properties of new materials in polynomial time
 - » So called "Quantum Simulation"
 - » This was the application that Richard Feynman proposed originally
 - Factor large numbers in polynomial time
 - » Shor's Algorithm
 - Find items in unsorted database in time proportional to square-root of n
 - » Grover's Algorithm



• Also: Its cool!

- Quantum Computers would be interesting from a theoretical standpoint
- Use properties of quantum mechanics to compute



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What are Quantum Computers?

- Use of Quantization and Superposition to compute:
 - Quantization: Only certain values or orbits are good
 - Superposition: Schizophrenic physical elements don't quite know whether they are one thing or another
- Bits can be in a combination of "1" and "0":
 - Written as: $\Psi = C_0|0\rangle + C_1|1\rangle$, called a "qubit"
 - The C 's are *complex numbers!*
 - » Important Constraint: $|C_0|^2 + |C_1|^2 = 1$ [think probability]
- Measurement (looking at bit) forces bit to be 0 or 1
- **n-bit register can hold 2^n values simultaneously!**
 - Called "Entanglement" between bits
 - 3-bit example:

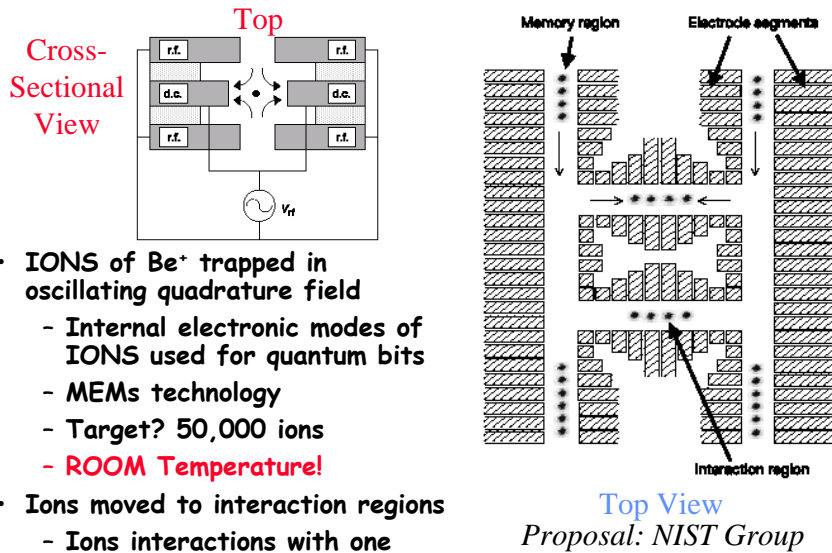
$$\Psi = C_{000}|000\rangle + C_{001}|001\rangle + C_{010}|010\rangle + C_{011}|011\rangle + C_{100}|100\rangle + C_{101}|101\rangle + C_{110}|110\rangle + C_{111}|111\rangle$$
 - **Multi-bit gates work on coefficients between bits.**
 - » Universal set of gates required for arbitrary computation
- **Fundamental Issue: Arbitrary Entanglement fragile!**
 - **Requires all information to be coded in QECC codes**

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ION Trap Quantum Computer: Promising technology



- IONS of Be^+ trapped in oscillating quadrature field
 - Internal electronic modes of IONS used for quantum bits
 - MEMs technology
 - Target? 50,000 ions
 - **ROOM Temperature!**
- Ions moved to interaction regions
 - Ions interactions with one another moderated by lasers

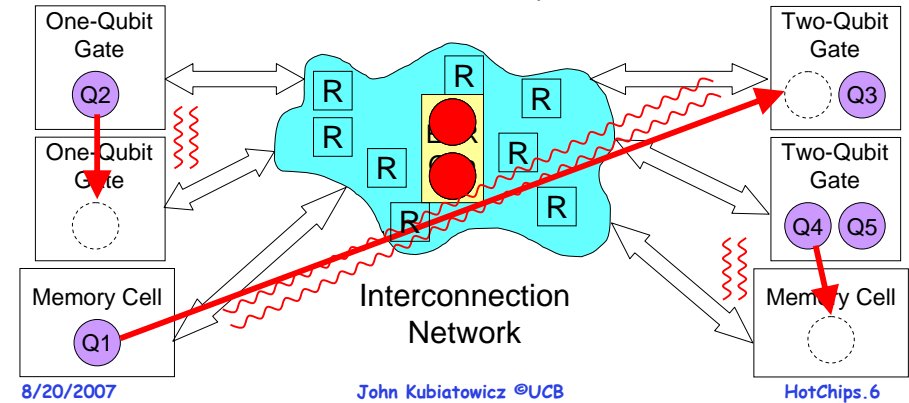
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Interesting fact #314159: Use of Teleportation for cross-chip communication

- Short-range communication is ballistic (movement)
- Errors accumulate with distance \Rightarrow Long-range communication via "Teleportation"
 - Teleportation uses EPR ("Einstein, Podolsky, Rosen") pairs of qubits at source and destination
 - EPR distribution network takes place of wires



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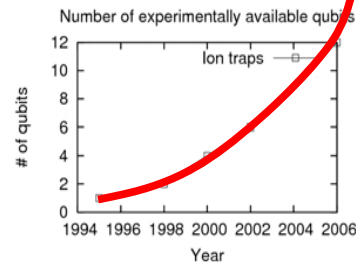
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Following a Moore's law of increase?



Courtesy of Monroe group at U. Mich.



- DARPA Roadmap predicts 50 qubits by 2012
 - Ion traps: 30 qubits by 2008
- Quantum circuit design done by hand so far
- However:
 - Potential Complexity of layout and control
 - Verification of fault-tolerant properties
 - \Rightarrow Automation (CAD) desirable?

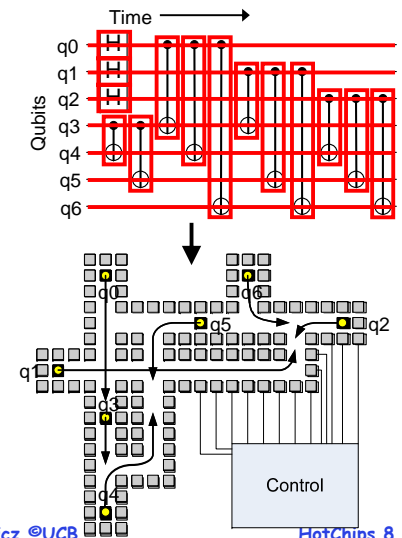
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Use of CAD for Ion Trap Physical Layout

- Input: Gate level quantum circuit
 - Bit lines
 - 1-qubit gates
 - 2-qubit gates
- Output:
 - Layout of channels
 - Gate locations
 - Initial locations of qubit ions
 - Movement/gate schedule
 - Control for schedule



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Closing Thoughts

- Quantum Computing is a “meta technology”
 - Any technology can be used if it:
 - » exhibits entanglement and is sufficiently insulated from environment
 - » Supports a basic set of operations between qubits
 - Ion traps are fairly promising technology
- Architecture of Quantum Computers actually an interesting topic with interesting challenges
 - Errors, Control, Communications
 - Not too early to be working on it
 - » Might be able to help with building first *real* quantum computer
- Quantum Entanglement very interesting property
 - Called “spooky action at a distance” by Einstein
 - Bits widely separated still “communicate” with each other
- Some papers:
 - <http://qarc.cs.berkeley.edu/publications>