Spring 2009 EE 710: Nanoscience and Engineering

Part 6: Quantum Computing
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Current Technology Contenders

- Ion/atom trap arrays
- Photonic structures
- Spintronic arrays
- Superconducting arrays
- Molecular arrays
Quantum Computing

Interference Patterns
The latent possibilities within a superposition can actually interfere with each other, constructively reinforcing or destructively canceling each other to form the final definite state. The programmer of a quantum computer must choreograph the calculation in such a way that computational paths leading to a "wrong" answer will destructively interfere with each other, canceling each other out and leaving only the "right" answers to be observed.

Finding an Answer
The ability of quantum objects to simultaneously hold multiple, seemingly conflicting values is at the heart of quantum computing. This state is called a quantum superposition (at right). Superpositions occur all the time at the quantum level. In fact, any isolated quantum object like an atom or a photon is in a superposition. But as soon as the object interacts with something else, such as another atom or photon, the superposition is liable to collapse. The collapse of a superposition is called decoherence. Decoherence is essentially an act of measurement, where all possible states in the superposition collapse into the one ultimately observed. If the quantum computer's qubits suffer too much decoherence before the calculation is completed, the information will be irretrievably lost and the probability of producing a correct answer becomes essentially zero.

Perform a measurement, collapsing the qubits' superpositions. By repeating these steps and combining the results, we can reliably obtain the factors of a very large number.

Intel co-founder Gordon Moore famously observed nearly half a century ago that miniaturization may ultimately lead to quantum computers which use...
QUANTUM COMPUTING

WHAT PROBLEMS CAN A QUANTUM COMPUTER SOLVE?

Computer scientists classify problems by the number of computational steps an algorithm requires to solve them. Problems that a classical computer can quickly solve are called P (polynomial time) problems. NP problems are the class of problems that quantum computers can efficiently solve. Factoring the product of two large prime numbers is an example of a problem that is both an NP and a QP problem.

THE ISSUE: CAN WE BUILD A SOPHISTICATED QUANTUM COMPUTER?

A company called D-Wave Systems has exhibited what it controversially calls the world’s first commercial quantum computer, but most experts treat these claims with considerable skepticism. Some of the best minds in physics today are struggling to build simple quantum computers, and computer scientists are still seeking their ideal applications. It seems even if practical, powerful quantum computers existed today, we probably wouldn’t know how to best use it. Ironically, if building sophisticated quantum computers turns out to be impossible in principle, this may be the biggest breakthrough of all, as it would imply that our fundamental understanding of the quantum world is incorrect.
Computational Requirements for Calculations at the Nanoscale

Simulated Quantum Computation of Molecular Energies
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Superconducting Technologies

- Liquid He cooled chips
- Use Al or Nb superconductor materials
- Circuits comprised of two superconducting quantum interference devices (SQUID) in parallel to one another.
- UCSB published phase matched superconducting wires for transmission lines in Nature on Sept. 19th 2008

1 quantum flux filling only 1 state

$\frac{1}{2}$ of a quantum flux inductively coupled into the squid

Prospects for Quantum Coherent Computation Using Superconducting Electronics

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University of Rochester, Department of Electrical Engineering, Rochester, New York, USA
**SQUIDS**

**SIN Tunnel Junctions**

Fig. 10
Tunneling between two superconductors with different energy gaps at a temperature lower than \( T \) K. A. No voltage is applied between the two junctions. B. As a voltage

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D-wave’s Quantum Computer

- Uses 4 x 4 arrays of SC SQUID qubits tied to nearest neighbors and next nearest neighbors to provide computation
- Lasted release (Jan 2009) is a 32 bit CPU (?)

http://dwave.wordpress.com/
Atomic Traps

- Paul Traps use quadripole fields and laser cooling to slow and bunch atoms within the local field minimum.
- Lasers and/or electromagnetic fields can then be used to guide the atoms around a chip.

Ion Chip: 5 electrodes, silver on quartz
Ion height: 150 μm
Trap frequencies: 1.92, 1.94, 0.76 MHz
At \( V_d = 240 \text{V} \), \( V_{sc} = \pm 16 \text{V} \)

Lifetime: ~11 hours at \( T = 4 \text{K} \)
Laser Cooling
Optical Design Required for Laser Cooling of Traps

UC Boulder Web Publication on Laser Cooling

Figure 5. Overall optical layout for laser trap experiment including both saturated absorption and Raman lasers.

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Fields Present in Planar Traps

Fig. 4. Trapping atoms with a magnetic field.

Fig. 6. Trapping an atom with a persistent supercurrent atom chip.
Planar Ion Traps

Fig. 1: Schematic illustrations of (a) a two-level linear RF Paul trap representative of what is currently used in quantum computation experiments, and (b) a five-electrode planar ion trap. Ions are trapped along the trap axis, shown as a dotted line. An RF potential is applied to the red electrodes to provide radial confinement, and DC potentials are applied to the blue control electrodes to provide axial confinement and to shuttle ions along the trap axis. Typical dimensions for current two-level traps are a slot width $s$ of 200 to 400 microns.


Experimental investigation of planar ion traps

FIG. 19. (Color online) Turning a corner. The arrows point to the position of the ion (a) before and (b) after turning the corner. This operation takes about 50 ms.

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2-D array traps for more complex mobility functions


Fig. 2: Top view of a two-dimensional Paul trap array. Ions can either be confined to points or free to move along lines, depending on the RF and ground connections. The connections shown (right inset) trap ions above the dots. Left inset: Microspheres are trapped in the 2D array, and seven are shown illuminated by the laser beam. The four-rod loading trap is visible above and to the right.

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Experimental Investigation of Planar Ion Traps

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A Two-Dimensional Lattice Ion Trap for Quantum Simulation

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(Dated: September 16, 2008)

FIG. 7: Experimental setup for the macroion experiment (Section IV). (a) 3-D schematic of lattice trap setup. (b) The lattice RF plate, as mounted for the microsphere experiment. The hole diameter is 1.14 mm and the hole spacing is 1.67 mm. The trap is supported by a printed circuit board.

FIG. 9: Image from above of ions in the lattice. The dark holes are the holes in the rf electrode; the grounded plane is 1.4 mm beneath them. Single macroions appear as white dots that are levitated above the plane of the rf electrode and are illuminated by 832 nm laser radiation at 8 mW. White dots on the surface of the rf electrode are due to stray light scatter. The left image was taken at \( V = 300 \) V and \( \Omega/2\pi \approx 1200 \) Hz and the right image was taken at \( V = 300 \) V and \( \Omega/2\pi \approx 1960 \) Hz. In the left figure, in the top well, two ions are shown repelling each other in the same well.
Magnetic Atom Traps

Electro-Optical Nanotrap for Neutral Atoms

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FIG. 1 (color online). The nanotrap. A suspended carbon nanotube, attached at each end to an electrode, supports two Ag nanospheres across a gap in a silicon nitride membrane. An illuminating laser field excites plasma oscillations in the spheres, and large electric fields near the structures are generated. In addition, a dc voltage is applied to the electrodes to create a toroidal trapping region (red). The radius of the toroid can be controlled with nanometer precision and the trap may be loaded directly from an incident atom beam.
Magnetic Atom Traps

Narrow-line magneto-optical cooling and trapping of strongly magnetic atoms

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FIG. 1: (Color online) Potential energy for a magnetic atom in a narrow-line MOT. $U(z)$ is in units of $\hbar \kappa T_{0}/2$. At the top, counterpropagating laser beams are labeled by their left-hand circular (LHC) helicity. Curves are shown for an atom with $J = 6$, for red or blue detuning and various values of $m_J$. For an atom in state $m_J$, the curve at higher (lower) energy [$\delta > 0$ ($\delta < 0$)] represents the potential for $\delta > 0$ ($\delta < 0$). Optical pumping stabilizes the stretched trap states ($m_J = \pm J$), since blue (red)-detuned trapping lasers tend to drive atoms toward the upper (lower) potential energy curve. Increasing line thickness (from dashed to thin to thick lines) represents increasing population of a state due to optical pumping. Insets a) and b) show the resonant optical transitions at trap minima labeled a and b. Here, for $m_J = J$, $\gamma_0 = 1/2$ in the absence of gravity; the gravitational force is 20% of the magnetic force.

FIG. 2: (Color online) Potential energy for a magnetic atom in a narrow-line MOT. $U(z)$ is in units of $\hbar \kappa T_{0}/2$. At the top, counterpropagating laser beams are labeled by their left-hand circular (LHC) helicity. Curves are shown for an atom with $J = 6$, for red or blue detuning and various values of $m_J$. For an atom in state $m_J$, the curve at higher (lower) energy [$\delta > 0$ ($\delta < 0$)] represents the potential for $\delta > 0$ ($\delta < 0$). Optical pumping stabilizes the stretched trap states ($m_J = \pm J$), since blue (red)-detuned trapping lasers tend to drive atoms toward the upper (lower) potential energy curve. Increasing line thickness (from dashed to thin to thick lines) represents increasing population of a state due to optical pumping. Insets a) and b) show the resonant optical transitions at trap minima labeled a and b. Here, for $m_J = J$, $\gamma_0 = 1/2$ in the absence of gravity; the gravitational force is 20% of the magnetic force.

FIG. 5: (Color online) Oscillation of the atomic cloud during release into the magnetic trap. (Upper) Cloud images at early times. (Lower) z position of maximum density together with a fit to the expected trajectory.