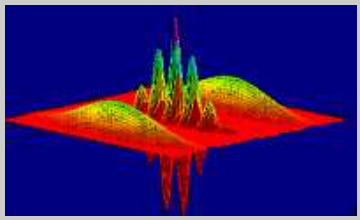
Los Alamos
National Laboratory



Quantum Computation

An effort from T6 and CIC3

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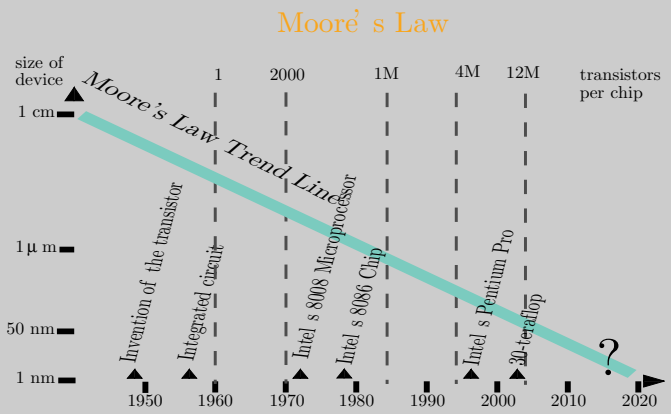
http://qso.lanl.gov/qc

Outside Collaborators: D. Cory, D. DiVincenzo, S. Lloyd, P.Shor

- Study of the fragility of quantum computers, (decoherence): Physics Today, October 1991
  Science, 270, 1633, 1995.
- Study of how to make quantum computers robust; Resilient Quantum Computation:
  Science, 279, 342, 1998
- Experimental verification: First implementation of quantum error correction (worldwide) and first working quantum computer prototype at the laboratory (quant-ph/9802018)

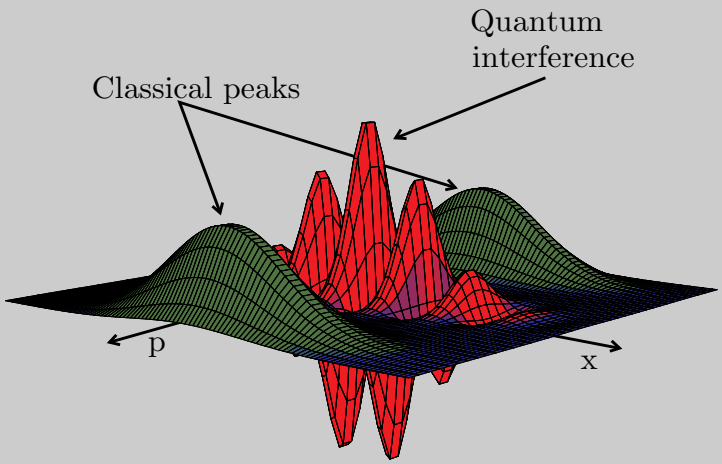
Overview

From the first realisations of computers, Los Alamos has always had the most powerful machines. The speed of computers has been increasing steadily; every 18 months since the 1950s the number of transistors per chip doubles (Moore's law). We are therefore going toward the barrier defined by the laws of quantum physics as transistors shrink to atomic size. The quantum computation program short-circuits that constraint by exploiting the quantum laws to advantage rather than regarding them as obstacles.



The size of transistors is decreasing rapidly, around 2010 they will be of atomic size.

A quantum computer accepts any superposition of its inputs as an input, and processes the components simultaneously, performing a sophisticated interference experiment of classical inputs. This "quantum parallelism" allows one to explore exponentially many trial solutions with relatively modest means, and to select the correct one. This capability has a particularly dramatic effect on factoring of large integers, which lies at the core of the present-day encryption strategies (public key) used in diplomatic communication and increasingly in business. As demonstrated approximately three years ago, quantum computers could yield the most commonly used encryption protocols obsolete. Since then, it has also been realized that quantum computation can lead to breakthroughs elsewhere, including simulations of quantum systems and implementation of novel encryption strategies (quantum cryptography), as well as applications such as sorting.



Wigner function of a superposition of two gaussian states. Quantum computers utilize in an essential way the fragile interference of superpositions of wave functions

Implementations of quantum computers are hampered by the fragility of quantum states due to decoherence, which destroys the ability of a quantum computer to act as an interferometer and implement the quantum parallelism required (albeit to a varying degree) by the above-mentioned applications. Recent rapid progress in addressing this concern was achieved as a result of collaborations between physicists, computer scientists, material scientists and chemists who use techniques adaptable to quantum computing (such as nuclear magnetic resonance (NMR)) for other purposes. These interdisciplinary techniques make quantum computing an ideal Los Alamos project.

Recent Achievements (97-98)

It has been known for some time that error rates in quantum computers will be much larger than in their classical counterparts. One of the most important source will be decoherence and a good part of our effort is aimed at undersanding this phenomena. To keep tight control on the evolution of a quantum computer error correction will be essential. But will errors occuring in the attempt to implement error correction tilt the process unfavorably? The answers is no, at least if the error rate is small enough (see Science, vol.279, p.342). In other words imperfections and imprecisions of a quantum computer are not obstacles for quantum computation.

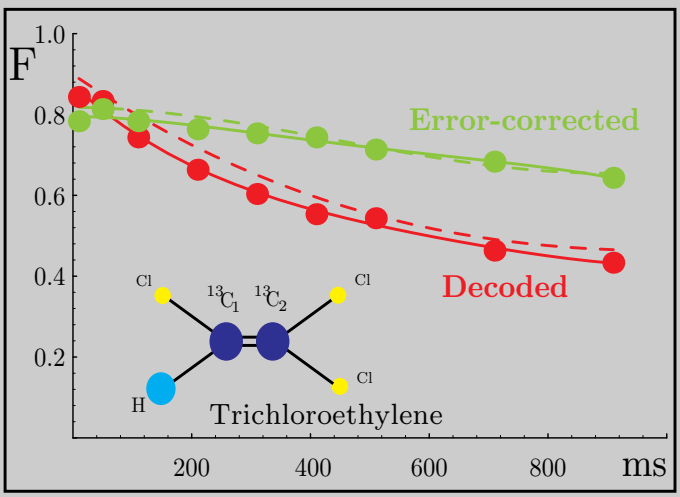
Bruker DRX-500 spectrometer at Los Alamos

We have implemented the simplest of quantum error correcting code: the 3-bit code correcting for phase errors. This has been done using NMR technology. The quantum bits in this experiment are the hydrogen and carbon nuclei of trichloroethylene. The figure shows the fidelity (the probability to be in the right state) as a function of decoherence time allowed. The dotted curve is the theoretical prediction, the full line the experiment.

Accuracy Threshold Theorem:

A quantum computation can be as long as required with any desired accuracy as long as the noise level is below a threshold value.

There have been many proposals for the experimental implementation of quantum computers. The best known are the ion trap, cavity quantum electrodynamics, Josephson junctions and NMR. Each proposal's goal is to be able to routinely manipulate quantum states involving 10-20 qubits at the turn of the century. Of these proposals, NMR is likely to be the first to achieve this goal as it is already "off-the-shelf" technology. It has matured a great deal since its invention 50 years ago and is now routinely used to manipulate large numbers of spins in molecules for structure determination. State-of-the-art NMR spectrometers are available at the Laboratory. Doing quantum computation using NMR is currently the cheapest option and the most straightforward to implement.



Selected publications

16 Janury 1998, Volume 279, pp. 342-345 **SCIENCE**

RESEARCH ARTICLES

RESILIENT QUANTUM COMPUTATION

EMANUEL KNILL, RAYMOND LAFLAMME, WOJCIECH H. ZUREK

(15 May 1997; accepted 21 November 1997)

VOLUME 79, NUMBER2 PHYSICAL REVIEW LETTERS 14 JULY 1997

Programmable Quantum Gate Arrays

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(Received 18 March 1997)

VOLUME 78, NUMBER20 PHYSICAL REVIEW LETTERS 19 MAY 1997

Quantum Computation with Phase Drift Errors

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(Received 30 December 1996)

PHYSICAL REVIEW A VOLUME 55, NUMBER 2 FEBRUARY 1997

Theory of quantum error-correcting codes

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VOLUME 78, NUMBER22 PHYSICAL REVIEW LETTERS 24 FEBRUARY1997

Quantum Analog of the MacWilliams Identities for Classical Coding Theory

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(Received 28 October 1996)

VOLUME 77, NUMBER22 PHYSICAL REVIEW LETTERS 25 NOVEMBER 1996

Quantum Logical Operations on Encoded Qubits

Wojciech Hubert Zurek and Raymond Laflamme
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Decoherence Bounds on Quantum Computation with Trapped Ions

Richard J. Hughes, Daniel F.V. James, Emanuel H. Knill, Raymond Laflamme, and Albert G. Peetschek
University of California, Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(Received 8 April 1996, revised manuscript received 27 August 1996)

VOLUME 77, NUMBER1 PHYSICAL REVIEW LETTERS 1 JULY 1996

Perfect Quantum Error Correcting Code

Raymond Laflamme[1], Cesar Miquel, Juan-Pablo Paz and Wojciech Hubert Zurek[1]
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Reversibility and stability of information processing systems

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Theoretical Astrophyics,T-6, MS B288, Los Alamos National Laboratory, Los Alamos, New Mexico 87545
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15.) Quantum computers possible by John Fleck, Albuquerque Journal (Top page), January 16, 1998.

14.) Lab scientists describe error-correction method for quantum computers By the Associated Press, Los Alamos Monitor, p.6, January 16,1998.

13.) In Subatomic Logic: Researchers nudge closer to the goal of quantum computing, by Corey S. Powell on the Scientific American web site (http://www.sciam.com/explorations/091696explorations.html).

12.) Quantum Computation in Wirtschaftswoche, a weekly German business magazine, in the 17th of July 1997 issue.

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