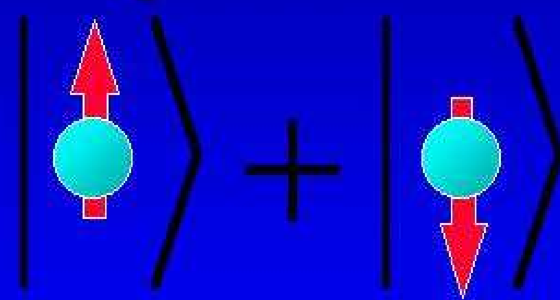
Towards quantum computation: a 215 Hz 5-qubit quantum processor

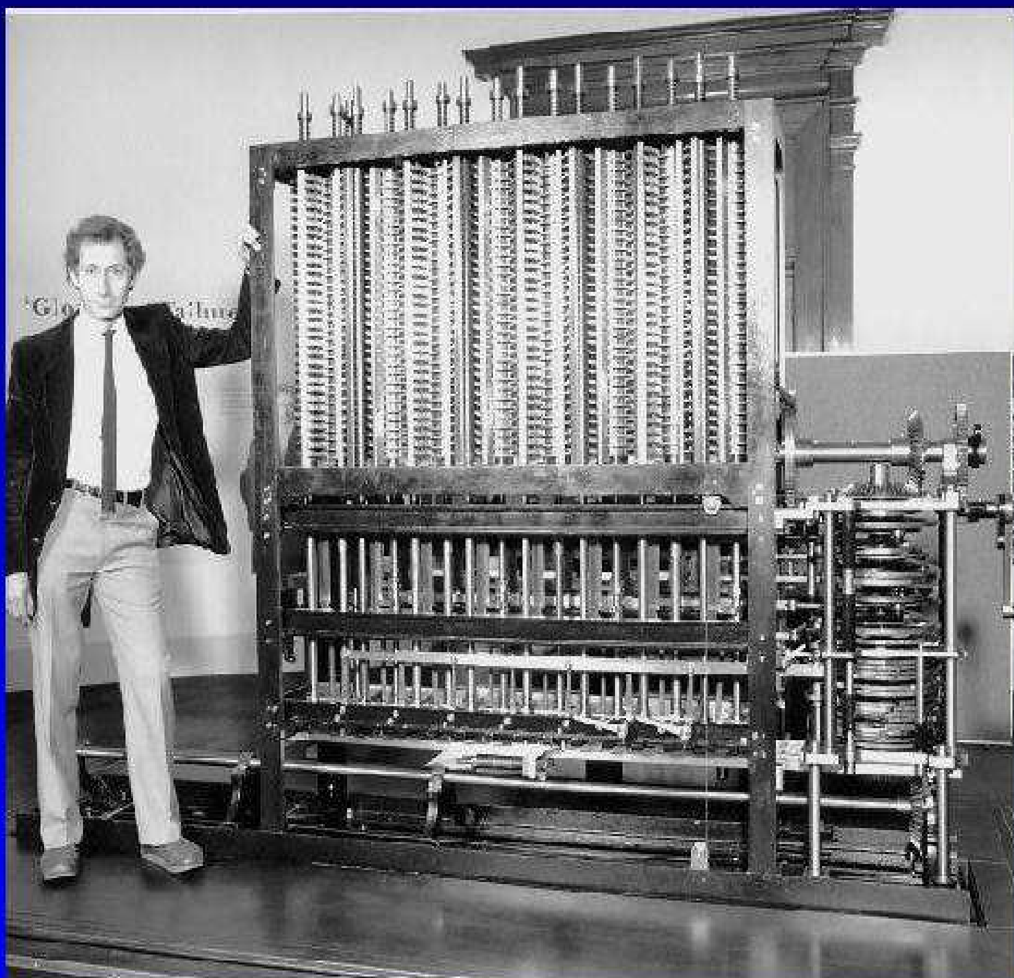
Isaac Chuang



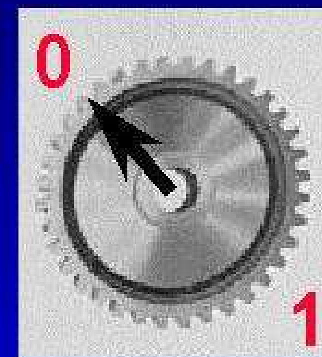
Lieven Vandersypen, Matthias Steffen, Gregory Breyta, Costantino Yannoni, and Richard Cleve

IBM Almaden Research Center

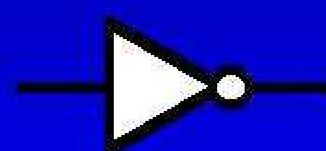
Classical Computers



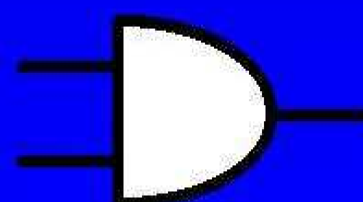
Difference Engine (1879)



NOT



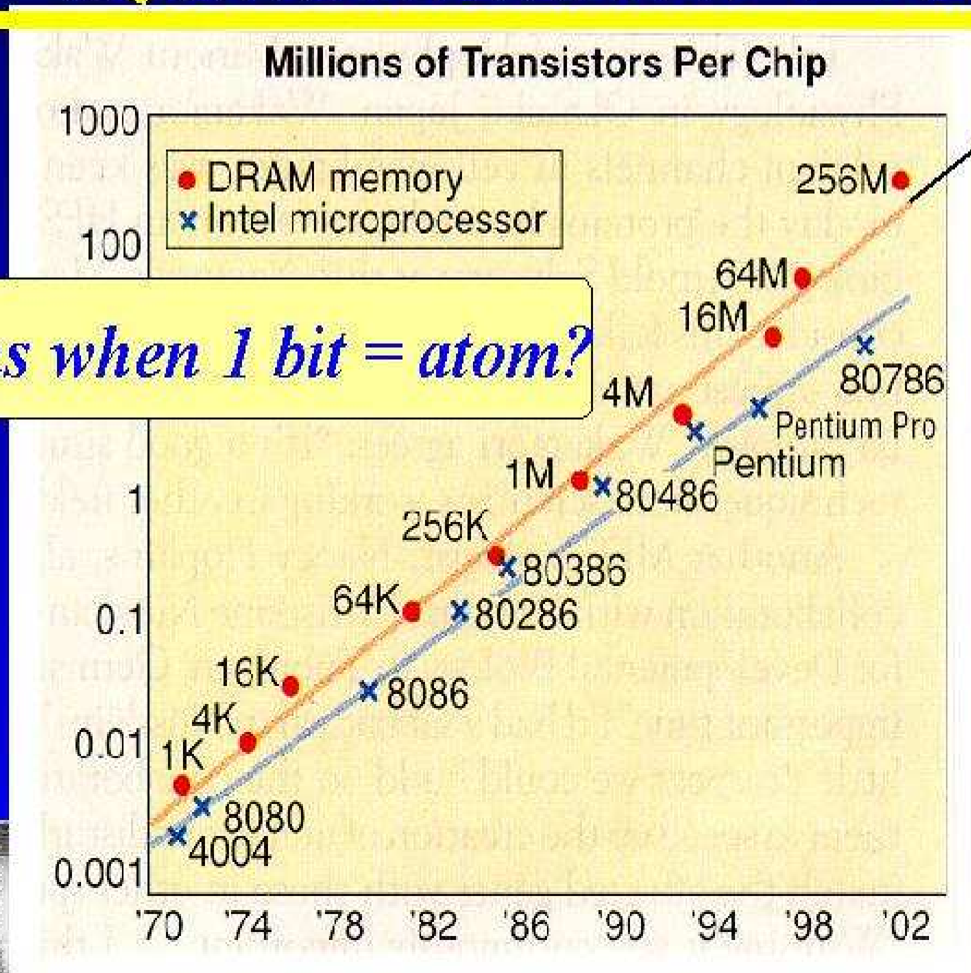
AND



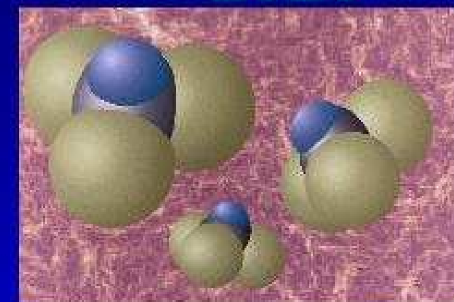
In	Out
00	0
01	0
10	0
11	1

The Quantum Limit

What happens when 1 bit = atom?

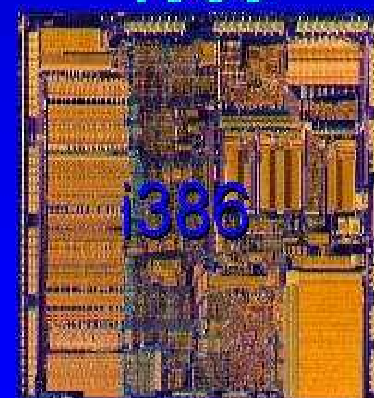


2020



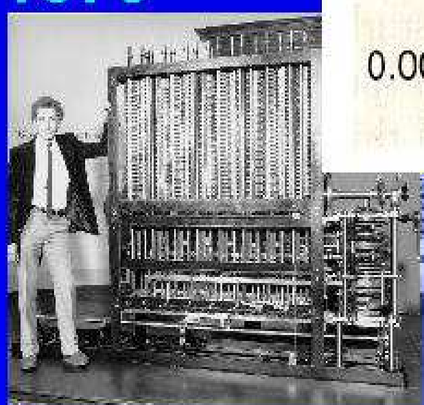
1 nanometer

1986



1 micrometer

1879



1 inch

Quantum Computation?

1. Classical computers can be reversible

   n bit computation = permutation on 2^n states

2. Quantum computation: replace

   bits → two level quantum systems

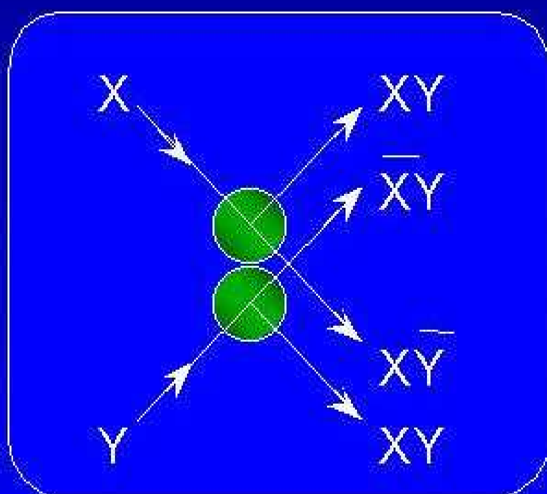
   permutations → unitary transformations

Facts:
- Quantum computation subsumes classical
- Certain problems can be solved faster with QC
- 2, 3, and 5 "qubit" QC's have been experimentally realized

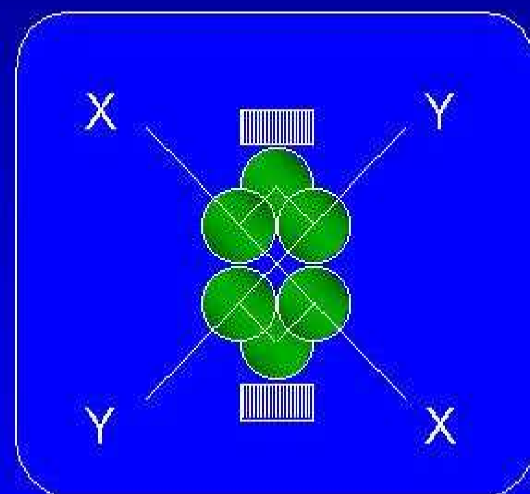
Computation is Reversible!

(Bennett 1973; Feynman 1982)

Billiard ball collisions may be used to build logic gates



Interaction Gate

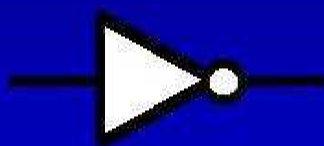


Crossover

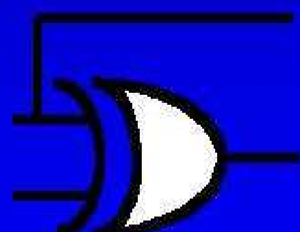
- Newton's laws are microscopically reversible
- Energy dissipation required *only* for stability

Classical ➡ Quantum

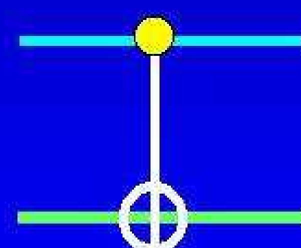
- States: **0,1** $|0\rangle, |1\rangle$
- Gates:



$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

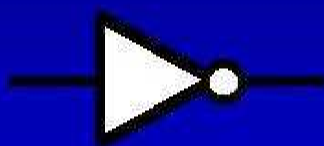
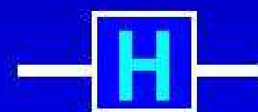


In	Out
00	00
01	01
10	11
11	10



$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Classical ➡ Quantum

- **States:** **0,1** $|0\rangle, |1\rangle$
- **Gates:**   $\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
- **Hadamard:**  

$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$

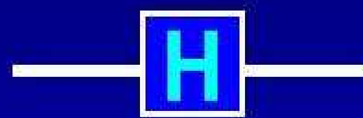
$$F = ma$$

$$i\hbar \frac{d}{dt}|\psi\rangle = H|\psi\rangle$$

Newton's laws **Schrodinger's Eq.**

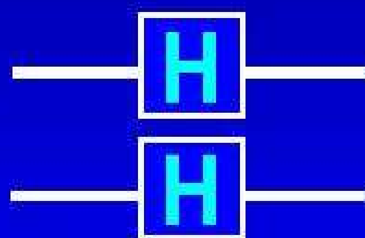
Quantum Parallelism

$|0\rangle$

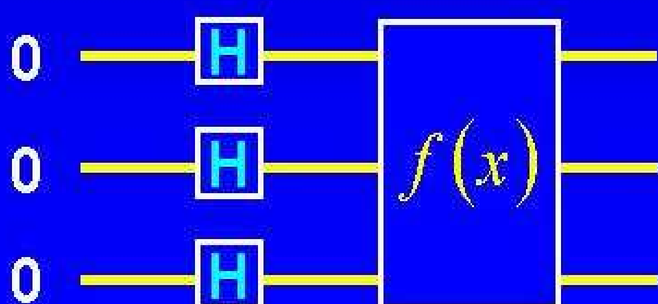


$\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$

$|00\rangle$



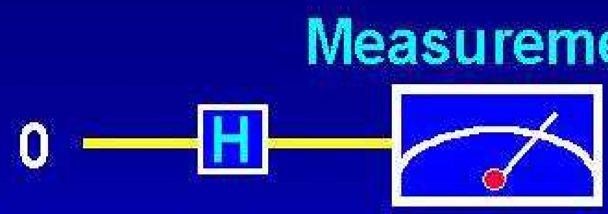
$$\frac{|00\rangle + |01\rangle + |10\rangle + |11\rangle}{\sqrt{4}}$$



f(000) + f(001) + f(010) + … + f(111)

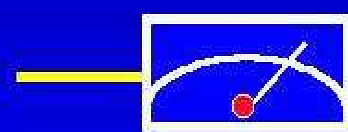
Exponential resource?

Quantum Parallelism



→ 0 / 1 with 50 % probability

$f(000) + f(001) + f(010) + \ldots + f(111)$



→ $f(000)$ or $f(001)$ or $f(010)$ or … or $f(111)$

each with probability 1/8

Superpositions collapse on measurement.

Theoretical Promise

ULTRAFAST COMPUTATION

(Shor, Grover, 1994-1996)

Factoring Integers

- N = pq
- L digits numbers
- Given N, what is p and q?

$O(e^{L^{(1/3)}})$ → $O(L^3)$

10 billion years (400 digits) → **3 years**

Searching Databases

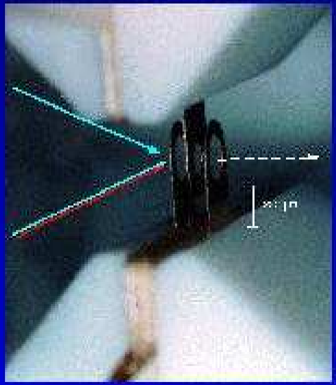
- Unordered list of N items
- Find an item: how many queries?

$O(N)$ → $O(\sqrt{N})$

1 Month → **27 minutes**

Experimental Challenge

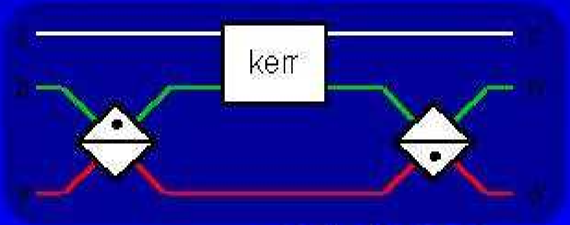
- Quantum systems typically have short lifetimes
- External control of quantum dynamics is difficult



NIST, IBM, LANL, Oxford

Ion Trap

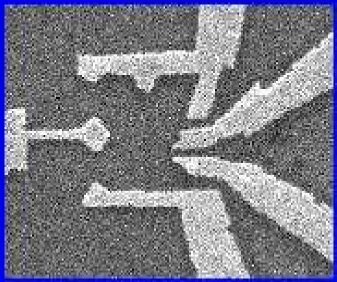
- Single electromagnetically trapped Be^{+} ion cooled to below 1 nano Kelvin



Nonlinear Optics

- Single photons incident on a single atom falling through a cavity with 99.999% reflectivity mirrors

Caltech, Ecol. Poly., Innsbruck



UCSB, Harvard

Quantum Dots

- Confined electrons in artificial atom

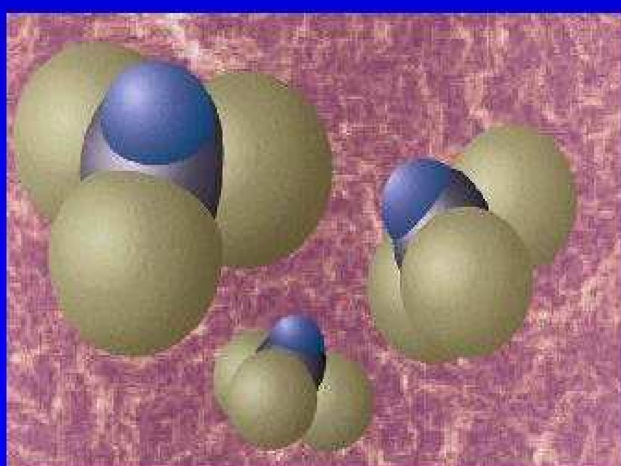
Bulk Spin-Resonance Quantum Computation

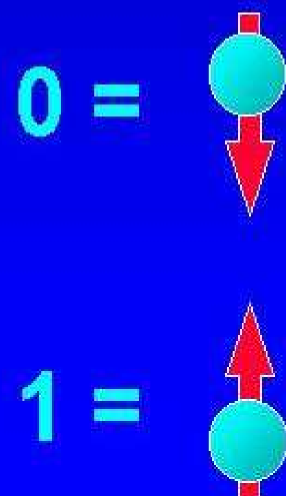
(Gershenfeld and Chuang, Science 275, p.350, 1997
Cory, Fahmy, and Havel, PNAS 94, p.1634, 1997)

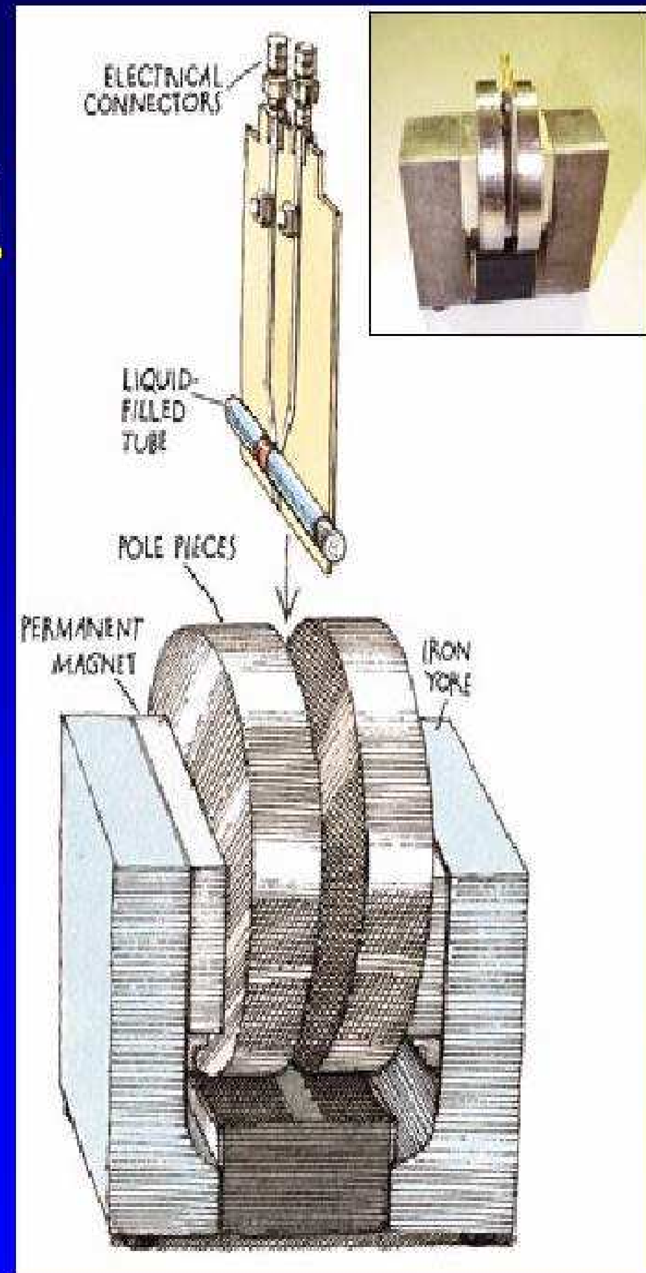
Information (qubits) = Nuclear spins

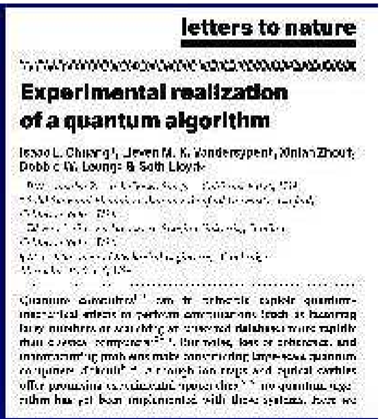
Interactions = Chemical bonds

Circuits = Electromagnetic field pulses








letters to nature

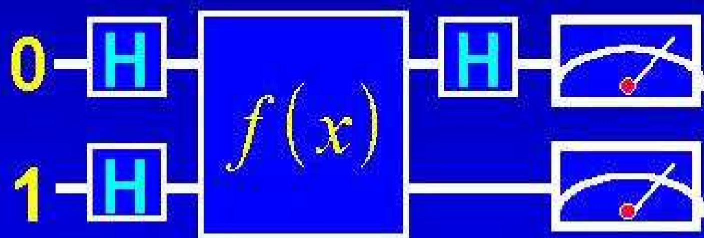
Experimental realization of a quantum algorithm

Isaac L. Chuang, Lieven M. K. Vandersypen, Xinlan Zhou, Debbie W. Leung & Seth Lloyd

First Implementation: Quantum Algorithm

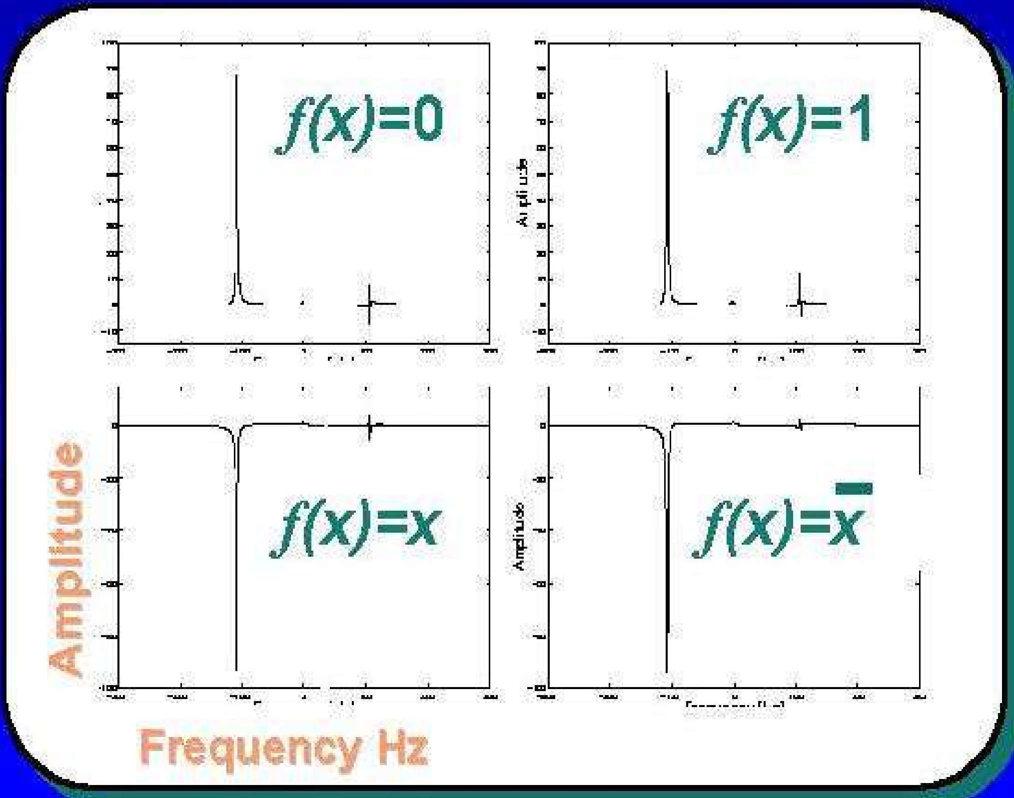
(Chuang, Vandersypen, Zhou, Leung, and Lloyd, Nature, May 14, 1998)

- Given $f(x)$: Calculate $f(0) + f(1)$ (*ONE* function evaluation)



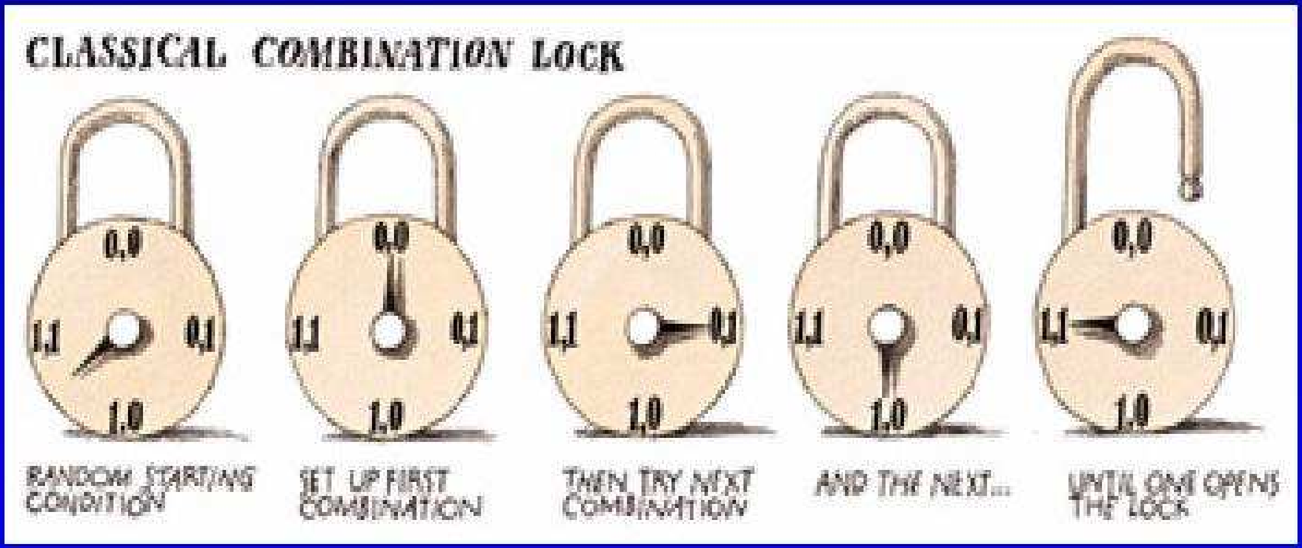
$f(0)+f(1) = 1$

$f(0)+f(1) = 0$



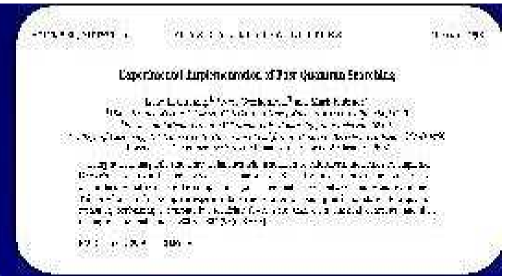
Demonstration of Fast Quantum Search

(Grover, 28th ACM Symposium on Theory of Computation, 1996)

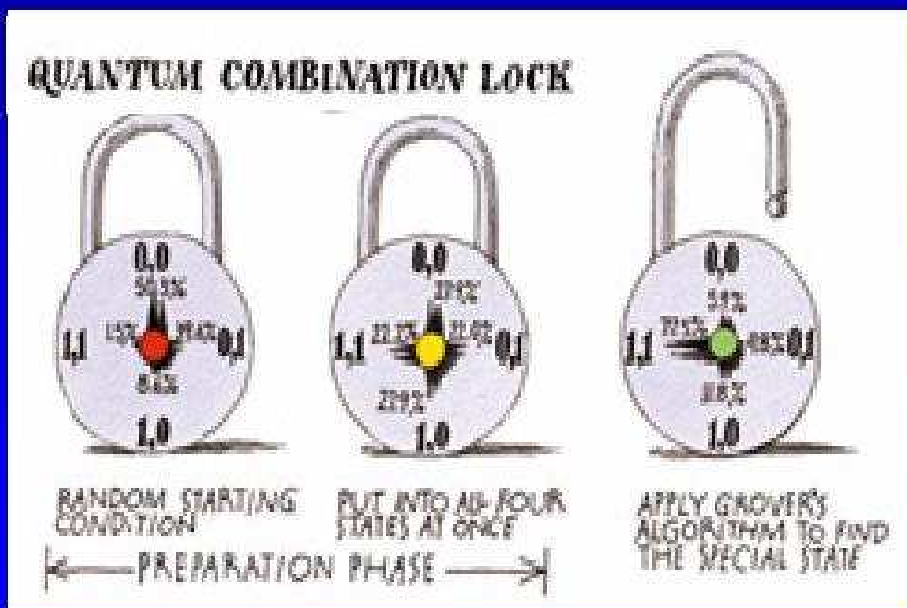


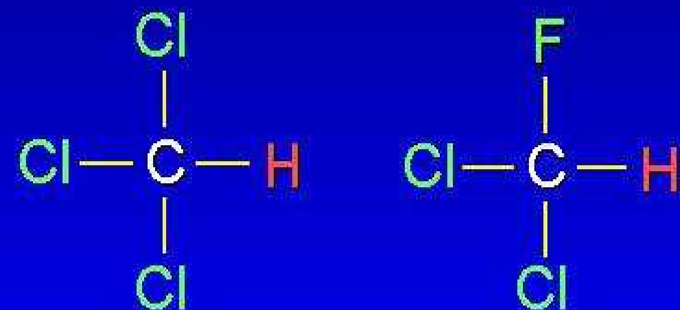
Classical search: # trials = $\frac{1+2+3+3}{4} = 2.25$

Demonstration of Fast Quantum Search



(Chuang, Gershenfeld, and Kubinec, PRL 80 p. 3408, 1998; Jones, Mosca, and Hansen, Nature 393, p. 344, 1998; Vandersypen, et. Al., APL 76, p646, Jan. 2000)





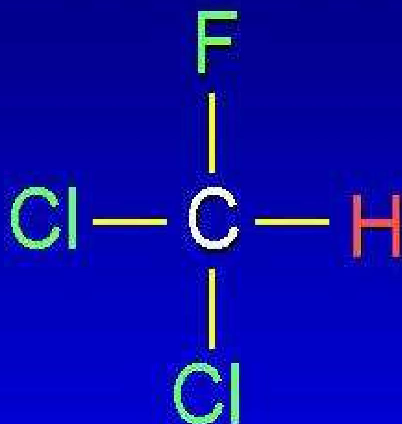
2 qubits 3 qubits

- ~250 Q. logic gates!

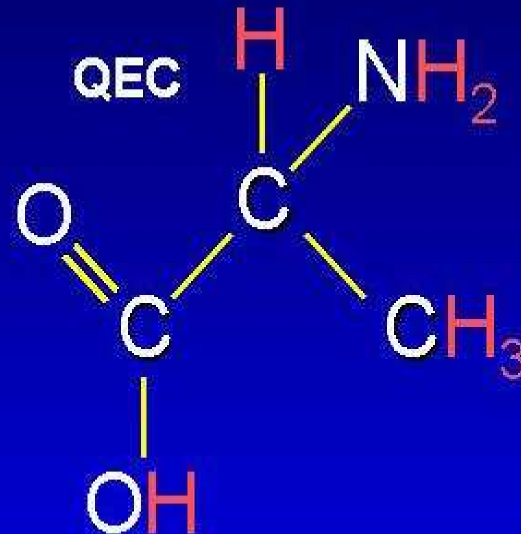
Quantum search: ONE trial $O(N) \Rightarrow O(\sqrt{N})$

NMRQC Molecules

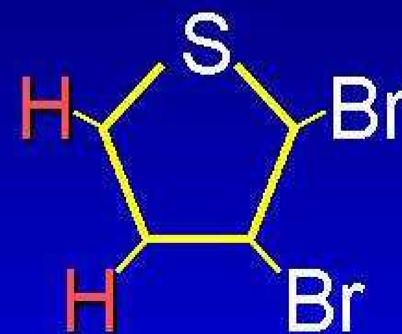
Fast Grover Search



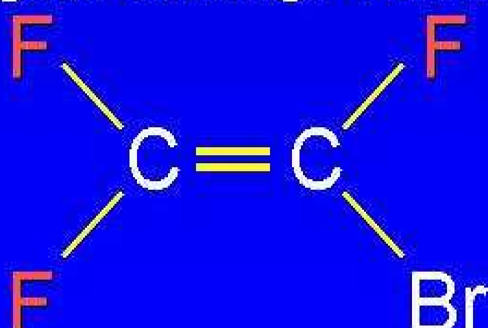
QEC



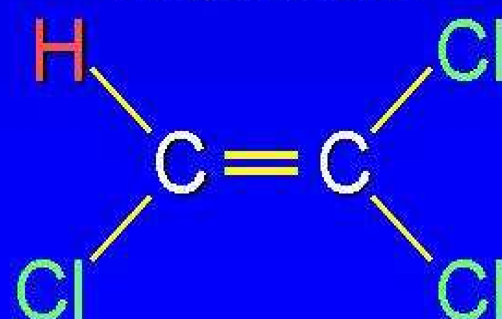
Simple H.O.



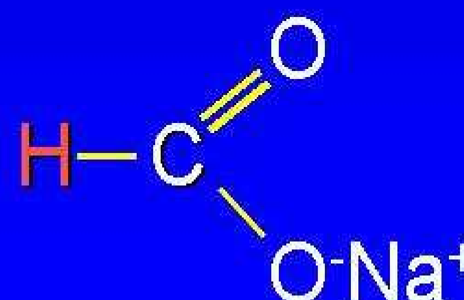
Logical labeling / Grover



Teleportation



Q. Error Correction



A 5-qubit Problem

- Given a permutation $\pi(y)$:

  Calculate r such that $\pi^r(y) = y$

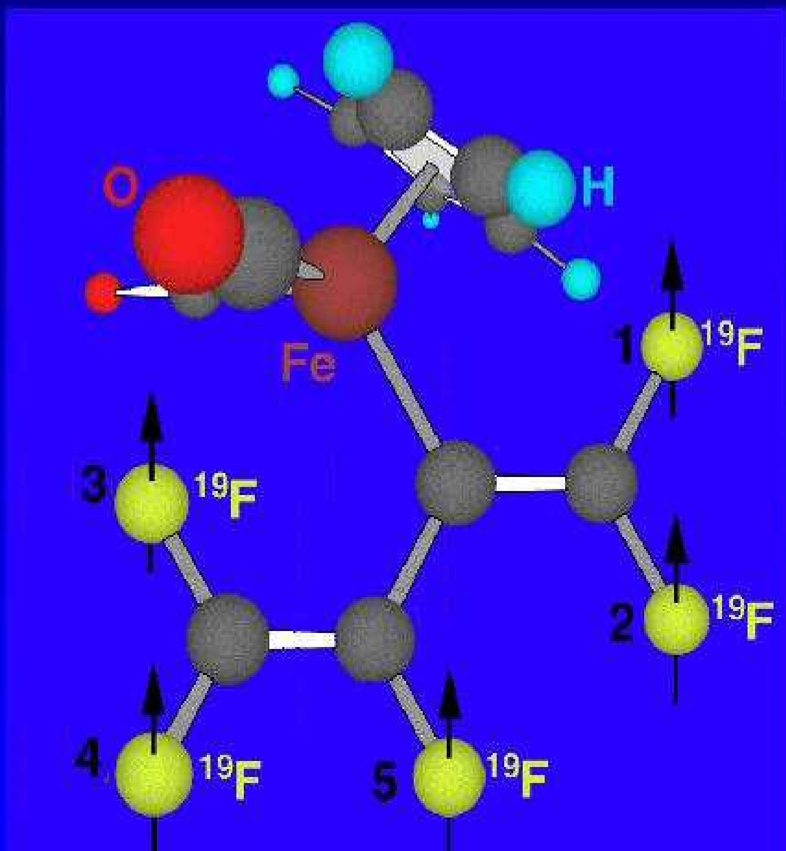
- This problem is *hard*! If $y \in \{0,1\}^n$

  then $O(2^n)$ trials are required, classically.

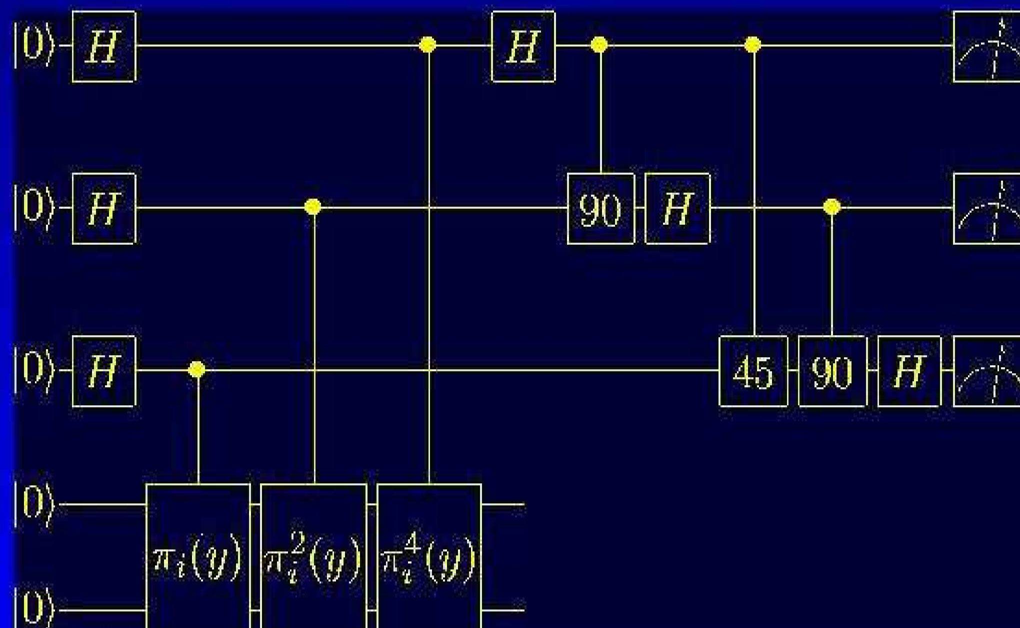
- ***Quantum:*** $O(n)$ ***trials***

5 qubit 215 Hz Q. Processor

(Vandersypen, Steffen, Breyta Yannoni, Cleve, and Chuang, 2000)



- The Molecule

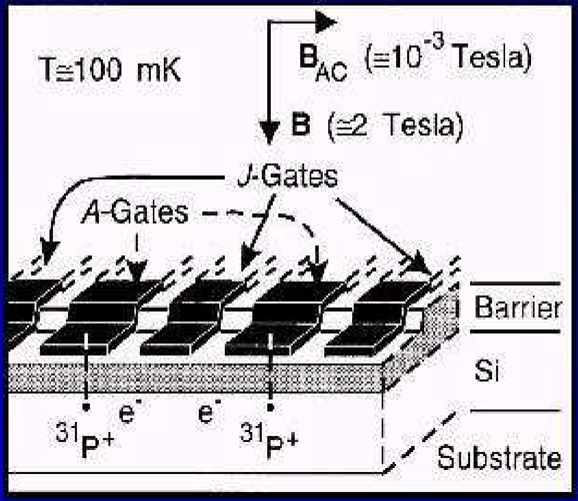


- Quantum Circuit

T_2 > 0.3 sec ; ~ 200 gates

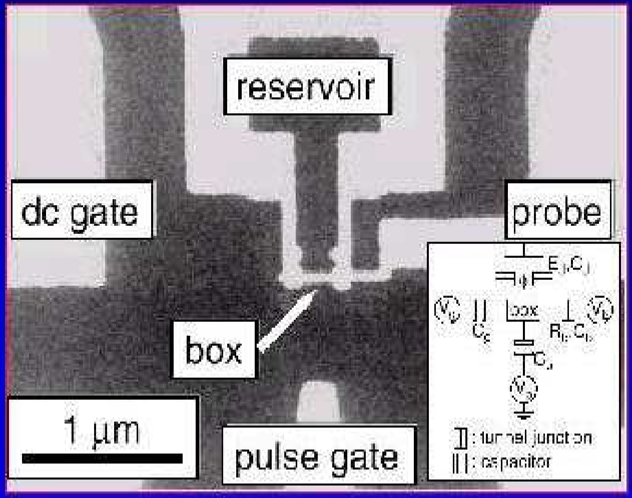
Solid State Spin QC?

- Nuclear spins of ^{31}P in Si
  (Kane, Nature 393, p133, 1998)

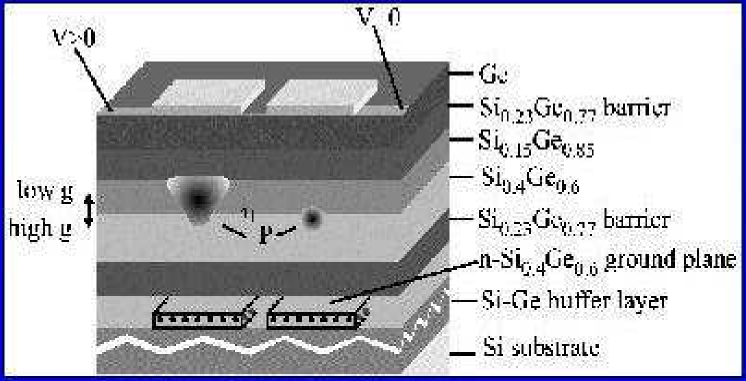


- Cooper pairs with Josephson Junctions

(Nakamura, Nature 398, p. 786, 1999)



- Electron spins with SiGe FET's
  (Yablonovitch, quant-ph 9905096)



Status: Concept, No Prototypes

Summary

- Quantum computation and quantum information:
  - New ways to view the physical world around us, in terms of algorithms and information processing
  - How do physical systems represent and process information?