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

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Classical Computers

Difference Engine (1879)
The Quantum Limit

What happens when 1 bit = atom?

1879
1 inch

1986
1 micrometer

2020
1 nanometer
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

- Newton’s laws are microscopically reversible
- Energy dissipation required only for stability
Classical $\rightarrow$ Quantum

- **States:** 0, 1
- **Gates:**

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Classical $\rightarrow$ Quantum

- States: $0, 1$
- Gates:
- Hadamard:

\[ F = ma \]

\[ |0\rangle, |1\rangle \]

\[ \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \]

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

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

Newton’s laws  Schrödinger’s Eq.
Quantum Parallelism

| 0 ⟩ → | H ⟩ → \frac{1}{\sqrt{2}} | 0 ⟩ + \frac{1}{\sqrt{2}} | 1 ⟩

| 00 ⟩ → | H ⟩ → \frac{1}{\sqrt{4}} (| 00 ⟩ + | 01 ⟩ + | 10 ⟩ + | 11 ⟩)

f(000) + f(001) + f(010) + ... + f(111)

Exponential resource?
Quantum Parallelism

Measurement

\[ f(000) + f(001) + f(010) + \ldots + f(111) \]

\[ f(000) \text{ or } f(001) \text{ or } f(010) \text{ or } \ldots \text{ or } f(111) \]

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 \( q \)?

\( O(e^{L^{1/3}}) \) \( \rightarrow \) \( O(L^3) \)
10 billion years
400 digits
3 years

Searching Databases
- Unordered list of \( N \) items
- Find an item: how many queries?

\( O(N) \) \( \rightarrow \) \( O(\sqrt{N}) \)
1 Month
27 minutes
Experimental Challenge

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

**Ion Trap**
- Single electromagnetically trapped $\text{Be}^+$ 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

**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
First Implementation: Quantum Algorithm


• 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: \[ \# \text{ trials} = \frac{1+2+3+3}{4} = 2.25 \]
Demonstration of Fast Quantum Search


Quantum combination lock

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 $^{31}\text{P}$ 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?