“Scientists are close to building a quantum computer that can beat a conventional one”

Science 2016
Cat in Two Boxes
IBM: Superconducting Qubits and QX

**QX demo: $m$-qubit QFT, $m = 2$**

For each frequency $f < 2^m$ Hz:
1. Prepare each qubit $q_n$ in $(|0\rangle + e^{2\pi ift}|1\rangle)/\sqrt{2}$, $t = 1/2^{(m-n)}$
2. Perform QFT
3. Measure all $q_n$
4. Reverse the bit order (in principle this could be done with a series of SWAP gates prior to measurement)
5. Convert binary to decimal; should recover $f$

<table>
<thead>
<tr>
<th>Freq.</th>
<th>Step: 1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Hz:</td>
<td>$</td>
<td>0\rangle$</td>
<td>$H$</td>
<td>$U_1$</td>
<td>$U_1$</td>
</tr>
<tr>
<td>1 Hz:</td>
<td>$</td>
<td>1\rangle$</td>
<td>$H$</td>
<td>$U_1$</td>
<td>$U_1$</td>
</tr>
<tr>
<td>2 Hz:</td>
<td>$</td>
<td>2\rangle$</td>
<td>$H$</td>
<td>$U_1$</td>
<td>$U_1$</td>
</tr>
<tr>
<td>3 Hz:</td>
<td>(left as an exercise)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Oliver: Superconducting Qubits & 3D Integration
Pakin: Quantum Annealing

\[ \mathcal{H}(t) = -\sum_{i=0}^{N-2} \sum_{j=i+1}^{N-1} J_{i,j} \sigma_i^z \sigma_j^z - \sum_{i=0}^{N-1} h_i \sigma_i^z - \Gamma(t) \sum_{i=0}^{N-1} \sigma_i^x \]

- Longitudinal interactions
- Longitudinal field
- Transverse field

\[ \mathcal{H}_S(s) = \frac{\varepsilon(s)}{2} \left( \sum_{(i,j)} J_{i,j} \sigma_i^z \sigma_j^z + \sum_{(i)} h_i \sigma_i^z \right) - \frac{\Delta(s)}{2} \sum_{(i)} h_i \sigma_i^x + \mathcal{H}_I(s) \]

- in which \( \mathcal{H}_I(s) \) encapsulates the interaction with the environment
Alicea: Topological Quantum Computing

Designer non-Abelian anyon platforms: from Majorana to Fibonacci

Jason Alicea and Ady Stern
Shabani: Topological Qubits

There are a lot of ways to manipulate the internal and external states of atoms.

$10^6$ atomic qubits in $< 5 \text{ mm}^2$ or $< 0.5 \text{ mm}^3$
Strontium ion loading and trapping.

Multilayer stack of trap chip (not drawn to scale).

- Pad Ti/Au 20/450 nm
- Trap electrodes Nb 1,000 nm
- PECVD SiO₂ 1,000 nm
- Wiring Nb 500 nm
- PECVD SiO₂ 1,000 nm
- Ground Nb 500 nm
- Thermal SiO₂ 500 nm
- Si substrate 750 μm

*Nature Communications 7*, Article number: 13005 (2016)
Co-designing a scalable quantum computer with trapped atomic ions

Kenneth R Brown¹, Jungsang Kim²,³ and Christopher Monroe⁴

Figure 3. Advanced microfabricated ion traps. LEFT: High-optical access (HOA) trap from Sandia National Laboratories (Image courtesy of Duke University). RIGHT: Ball-grid array (BGA) trap from GTRI/Honeywell (Image courtesy of Honeywell).
Why Electron Spins?

$\sim 10^9$ Qubits

for full-scale Quantum Computer

Lyon: Spin Qubits
Forging Solid-State Qubit Design Principles in a Molecular Furnace

Michael J. Graham, Joseph M. Zadrozny, Majed S. Fataftah, and Danna E. Freedman

Figure 5. Periodic table with elements highlighted according to the natural abundance of zero-spin isotopes. Green: $\geq 90\%$ abundance, yellow: $\geq 80\%$ abundance, orange: $\geq 70\%$ abundance, and white: $< 70\%$ abundance.
Aspuru-Guzik: Quantum Simulation

https://quantum.nasa.gov/materials/2012-01-17-B3-Aspuru.pdf

Manucharyan: Simulation with Superconducting Qubits

http://online.kitp.ucsb.edu/online/synquant16/manucharyan/

The impurity: boundary sine-Gordon model

\[ H_{\text{imp}} = -E_3 \cos (\psi_n - \psi_s) \]

Corresponds to backscattering/tunneling in fermions picture

(see Kane & Fisher; Finkelstein & Oreg)

Simulation of Kondo impurities

Fast control knobs:
- Infrared cut-off (length)
- exchange anisotropy (impedance)
- magnetic field (charge/flux offsets)

Relevant theory:
- G. Ripoll et al. (2007)
- K. Le Hur et al. (2012)
- M. Giamarchi et al. (2012)

Relevant experiments:
- K. Lehner et al. (2008)
- O. Astafiev et al. (2010)
- A. Weiss et al. (2015)
- P. Forn Díaz et al. (2016)
Mosca: Broad Views of Quantum Computing

https://www.youtube.com/watch?v=vWP4LF2hz80

New paradigm brings new possibilities

Designing new materials, drugs, etc.  Optimizing  Sensing and measuring  Secure communication  What else???
Superconducting qubits:

Theory (S. Girvin)

Experiment (V. Manucharyan)

Working prototypes demonstrated at QS3:

IBM Quantum Experience (4 physical qubits)

D-Wave
Scott Pakin LANL
### Trapped Ions and neutral atoms

<table>
<thead>
<tr>
<th>Trapped Ions</th>
<th>Optical lattices: neutral atoms</th>
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<tbody>
<tr>
<td>Theoretical background and experiment</td>
<td>Davis Weiss</td>
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<tr>
<td>Demonstration of 5 physical qubits working</td>
<td></td>
</tr>
<tr>
<td>Chris Monroe</td>
<td></td>
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</tbody>
</table>

| Trapped ions, 3D integration | |
| J. Sage | |

Positive: large coherence times, higher temperatures than SC qubits
Identical qubits

month of trapped ion life time
not getting lost

seconds of qubit (trapped atom) life time
Functioning of a QC

IBM QX

A

Trapped Ions

B

Chris Monroe
published
28 March 2017

- Developing algorithms
- Communicating with the hardware
Spin Qubits

Putting many qubits together to build QC

Si-based: S. Lyons

Molecular magnets
Danna Freedman

only principle ideas
bad coherence times
quantum sensors possible

No working QC yet
Right now on the level of cool theoretical proposal

Basic theory of topological computation
J. Alicea

Topological Quantum Computing: Experiment
J. Shabani: topological qubits in 1000 years?

Not mentioned at QS3:
many experimental publications about zero-bias peak

Braiding not yet demonstrated
Materials point of view

• All functioning and close to functioning devices are based on well-known and industrially produced materials
  Si
  InAs, InGaAs, etc
  Al-based Josephson Junctions

• Molecular magnets: ideas (unrealistic?) about making qubits
  Quantum sensors

• New “quantum materials”, “materials by design”: interesting properties
  not used for QC