Quantum Computing: Hardware Implementations

Guest Lecturer: Prof. Paul Hess

CSCI 0333 – Spring 2021
5/18/21

Agenda:
- What elements does our quantum hardware need?
- Compare three competing technologies
- Discuss details of trapped ion technology
Quantum Hardware Companies and Start-Ups

IBM | Quantum

Rigetti Computing
Berkeley, CA & Fremont, CA

Honeywell Quantum Solutions

Google Research

IONQ

AQT
Market Research: Hardware comparison

- Review the “how it works” page from one of these quantum hardware companies
- See if you can identify what the **qubit** is for each platform, how they are connected, and how they are measured.
- What is one additional question you have about the technology?

1) Photonic Qubits (Xanadu)
   - [https://www.xanadu.ai/hardware/](https://www.xanadu.ai/hardware/)

2) Superconducting Qubits (IBM)
     - Jump down to “How do they work”. Or [YouTube Video](https://www.youtube.com/watch?v=dQw4w9WgXcQ) (11:00 – 13:40)

3) Trapped Atomic Ion Qubits (IONQ)
   - [https://ionq.com/technology](https://ionq.com/technology)
Photonic Quantum Computing

Conventional Fiber Optics

1 Qubit Gates
2 Qubit Gates
Photons

Image Credit: University of Bristol’s Centre for Quantum Photonics
Xandau Photonic Chips

Processor Chip

“Chip Socket”

Fiber Optics Routed In and Out
Superconducting Qubits: IBM

Dilution Refrigerator (T < 1 K inside)

Photo Credit: MIT Tech Review
Ion Trap Hardware

Levitated Ion String

“High Optical Access”: HOA 2 Trap
Sandia National Labs
Ion Trap Hardware

- Ultra-high Vacuum Chamber
- Windows
- Optics for delivering laser light

Image Credit: P. Hess
Trapped Ion Qubits

“The Hyperfine Interaction”
Interacting Bar Magnets

“A trapped ion quantum state measurement

\[ |0\rangle \quad \text{or} \quad |\downarrow\rangle \]

\[ |1\rangle \quad \text{or} \quad |\uparrow\rangle \]

Microwave Frequencies

“Computational Bits”
“Spins”
Linear Chains of Ions

Trapped Ion Motional Modes

- Center of Mass: $\omega_{com} = \omega_a$
- Breathing: $\omega_{brth} = \sqrt{3} \omega_a$

Newton’s Cradle

Artist’s Rendition of a Trapped Ion Quantum Computer

Photo Credit: Scientific American
A Moveable Qubit

“Quantum CCD” Ion QI Processor

- NIST Ion Storage group

Shuttling in a surface trap

Loading Zone

Computation Zone

- GTRI QS group

Now being implemented by Honeywell Quantum Solutions
Compiling for Quantum Hardware

CNOT

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

Ising (XX) Entangling Gate

\[
XX(\chi) = \begin{pmatrix}
\cos(\chi) & 0 & 0 & -i \sin(\chi) \\
0 & \cos(\chi) & -i \sin(\chi) & 0 \\
0 & -i \sin(\chi) & \cos(\chi) & 0 \\
-i \sin(\chi) & 0 & 0 & \cos(\chi)
\end{pmatrix}
\]

Native Trapped Ion Gates

Controlling a quantum computer

<table>
<thead>
<tr>
<th>Algorithm decomposition (software)</th>
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<td>User interface</td>
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<td>Quantum algorithms: Deutsch–Jozsa, QFT, etc.</td>
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<tr>
<td>Quantum compiler</td>
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<td>Universal gates: Hadamard, CNOT, CP, etc.</td>
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<td>Native gates: XX-gates, R-gates</td>
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<td>Quantum control</td>
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<td>Pulse shaping: optimization of XX- and R-gates</td>
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<td>Hardware</td>
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<td>Optical addressing: qubit manipulation/detection</td>
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<td>Qubit register: ion trap, Yb ion chain, etc.</td>
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Wiring Matters: Superconductors vs. Trapped Ions

Example: Bernstein-Vazarani Algorithm