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

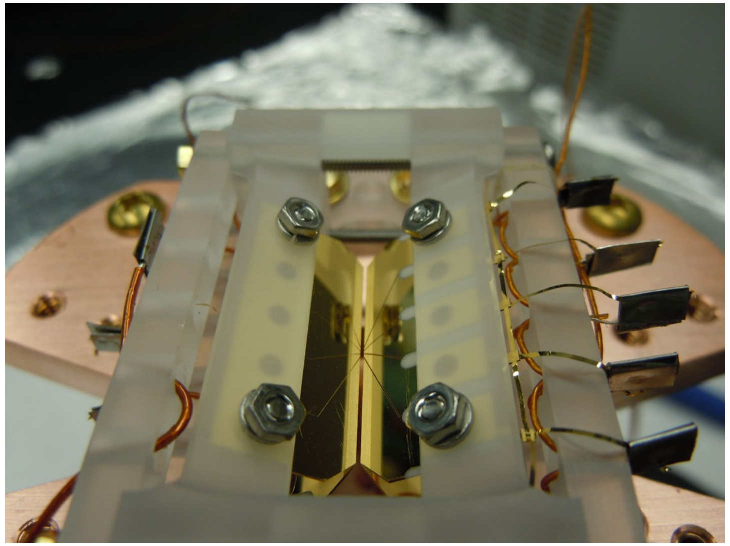


Image Credit: P. Hess
University of Maryland

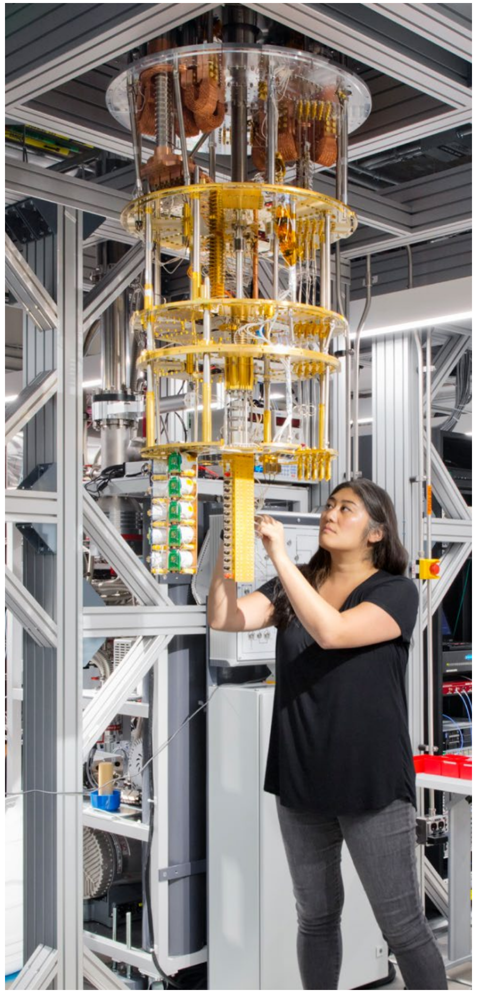
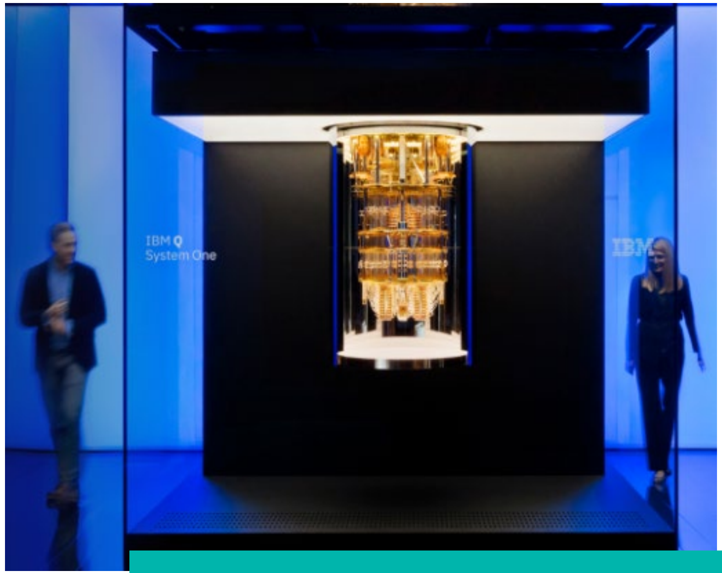


Image Credit: IBM

Quantum Hardware Companies and Start-Ups

IBM Quantum

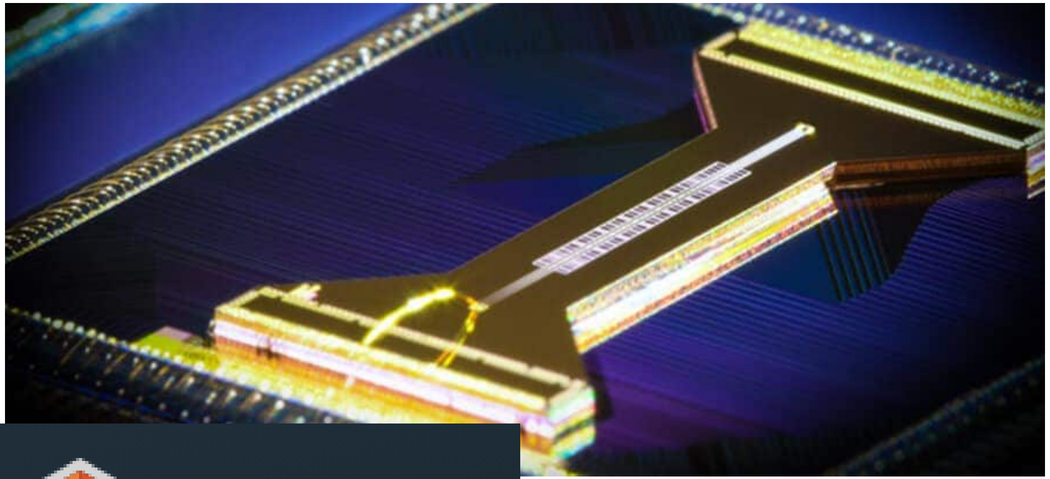


Rigetti Computing

Berkeley, CA & Fremont, CA

Google Research

Honeywell Quantum Solutions



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/

2) Superconducting Qubits (IBM)

- https://www.ibm.com/quantum-computing/what-is-quantum-computing/
  - Jump down to "How do they work". Or YouTube Video (11:00 – 13:40)

3) Trapped Atomic Ion Qubits (IONQ)

- https://ionq.com/technology

Photonic Quantum Computing

Conventional
Fiber Optics

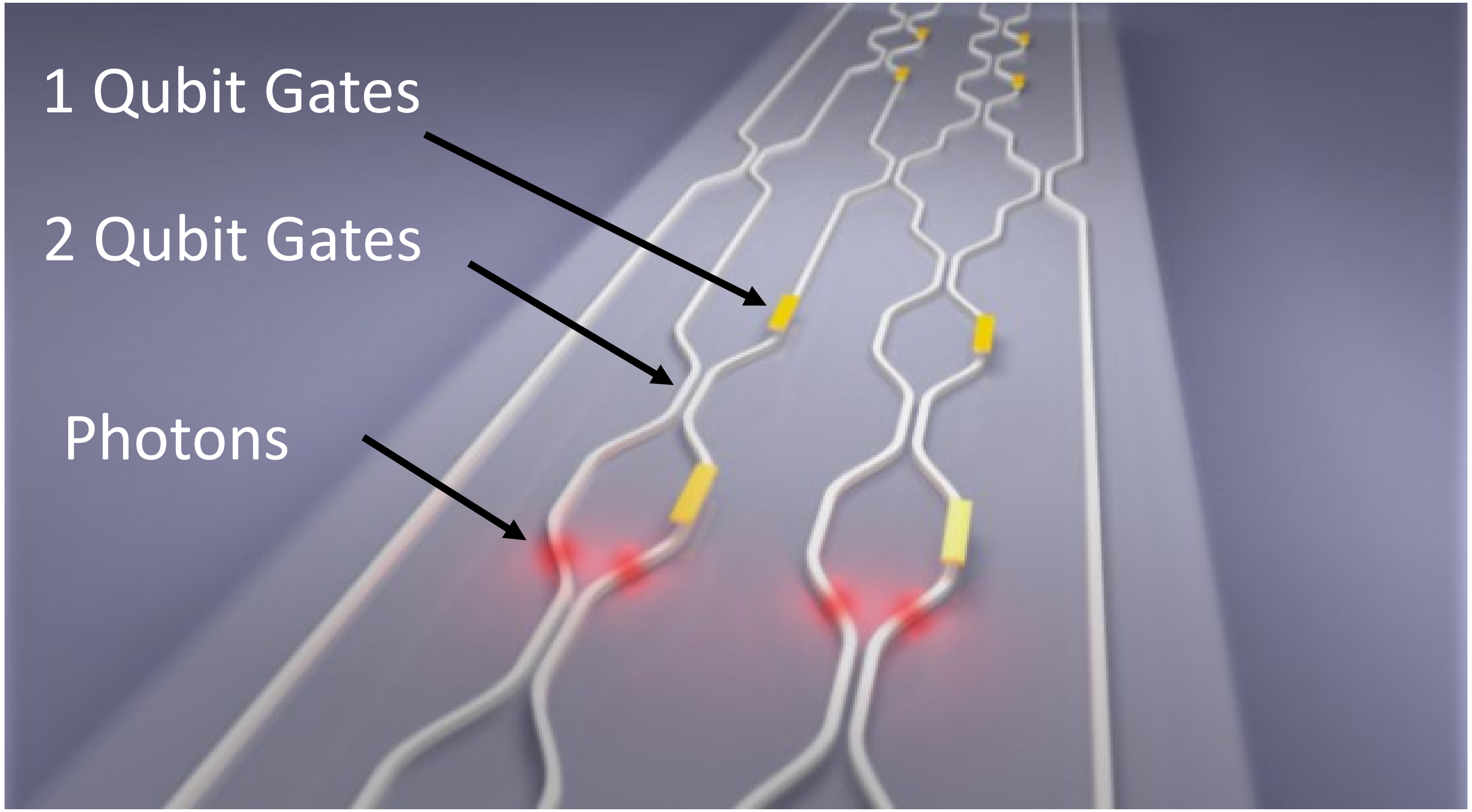
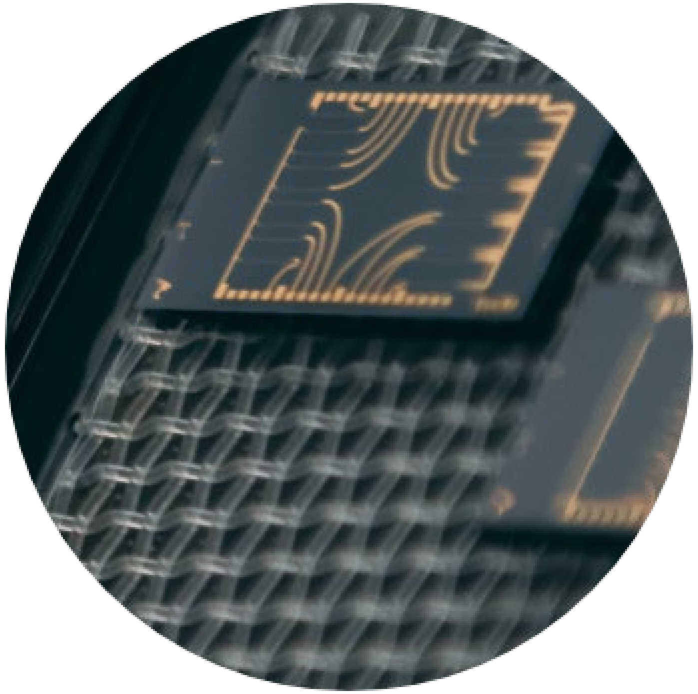


Image Credit: University of Bristol's Centre for Quantum Photonics

Xandau Photonic Chips



Processor Chip

Fiber Optics Routed
In and Out

“Chip Socket”

Superconducting Qubits: IBM

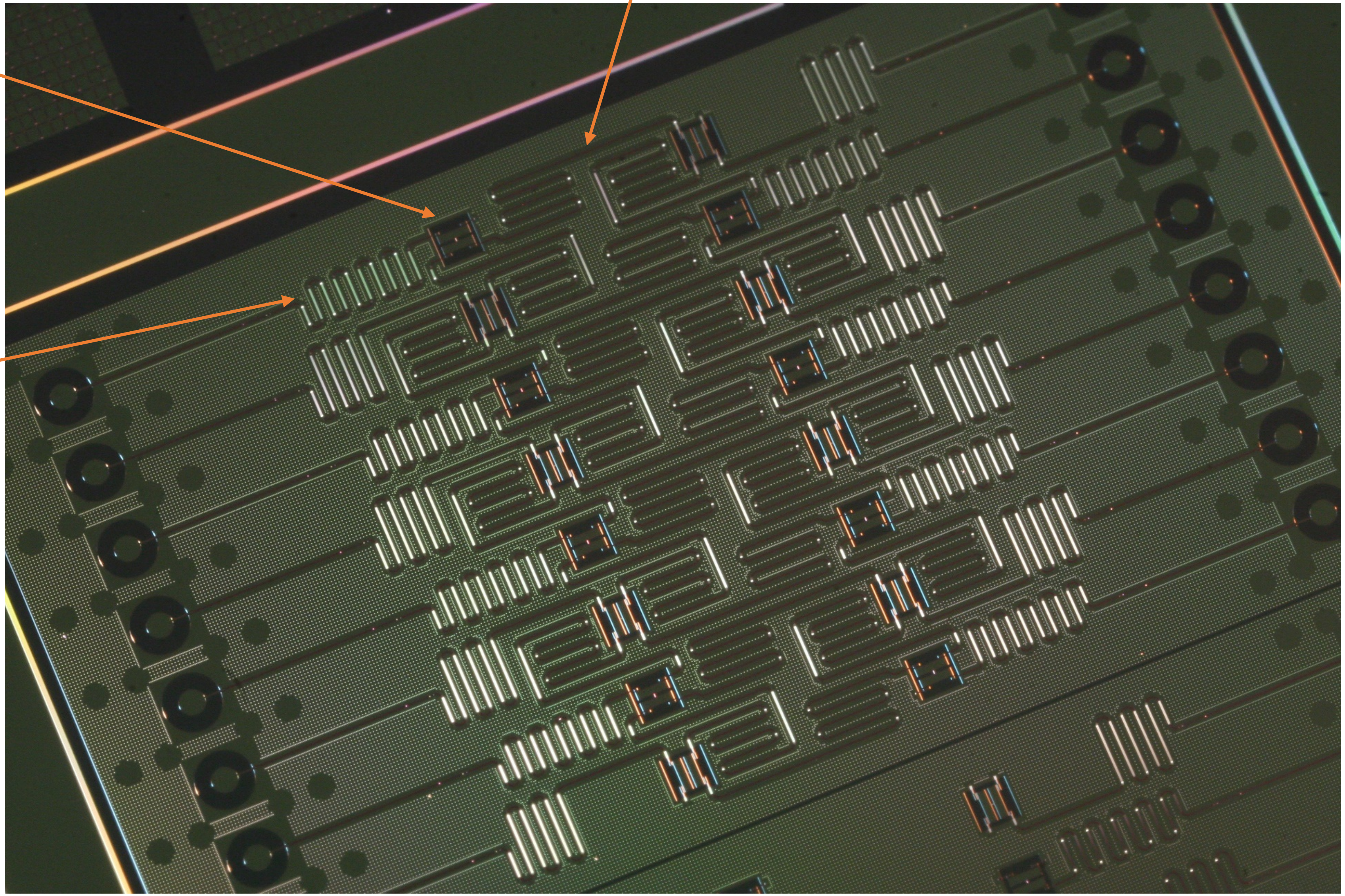
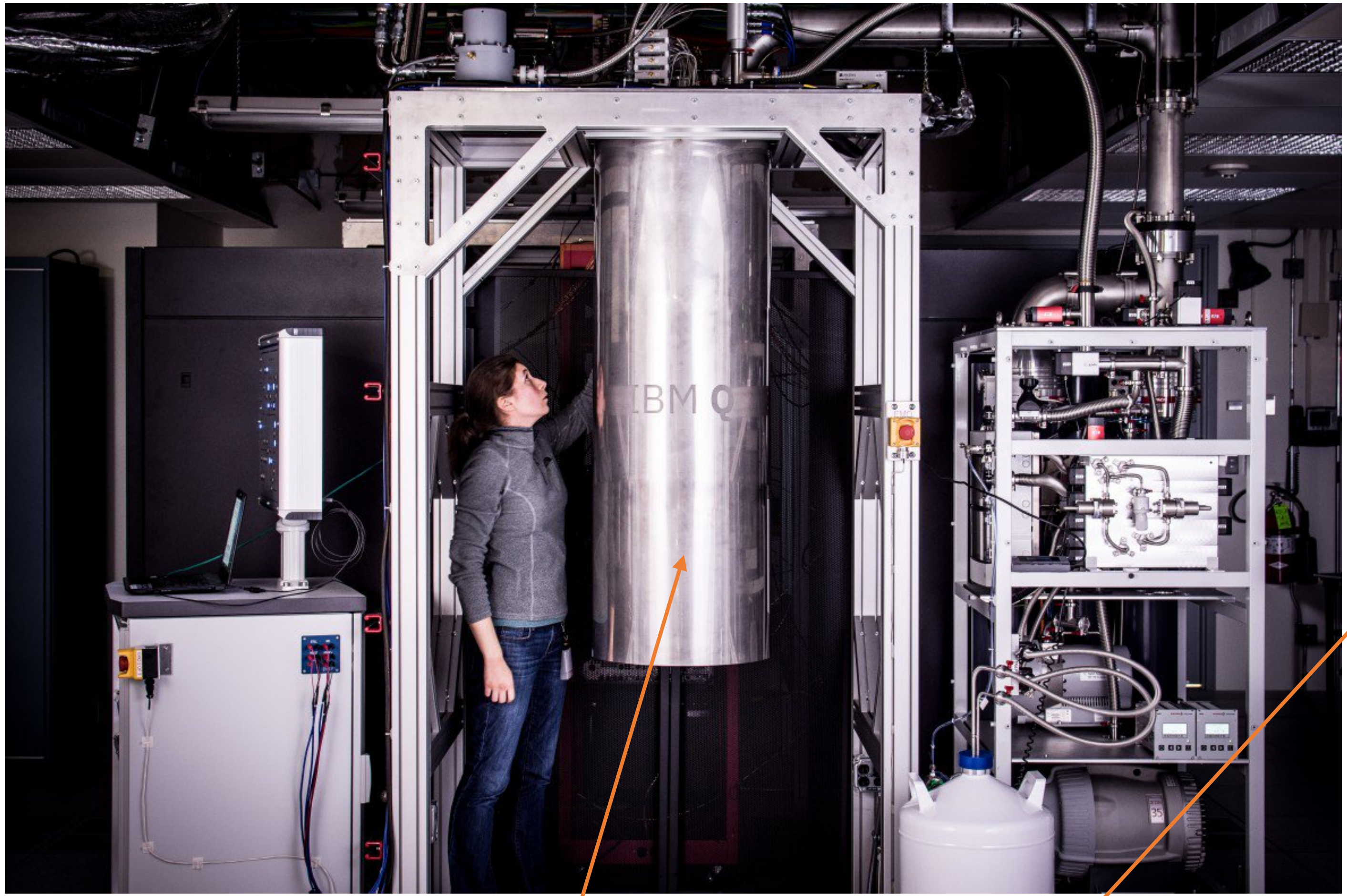


Photo Credit: MIT Tech Review

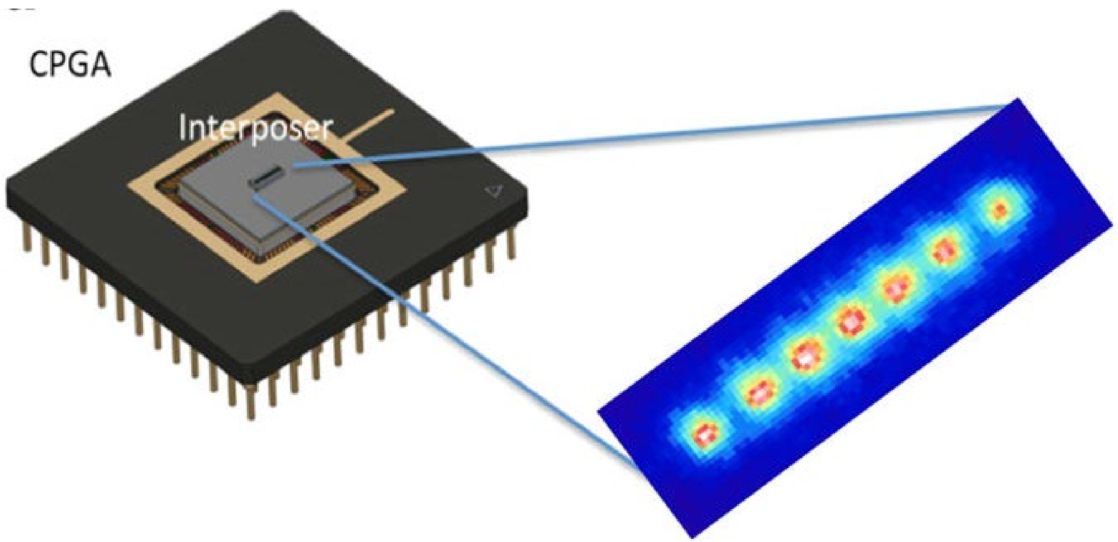
Superconducting Qubits: IBM



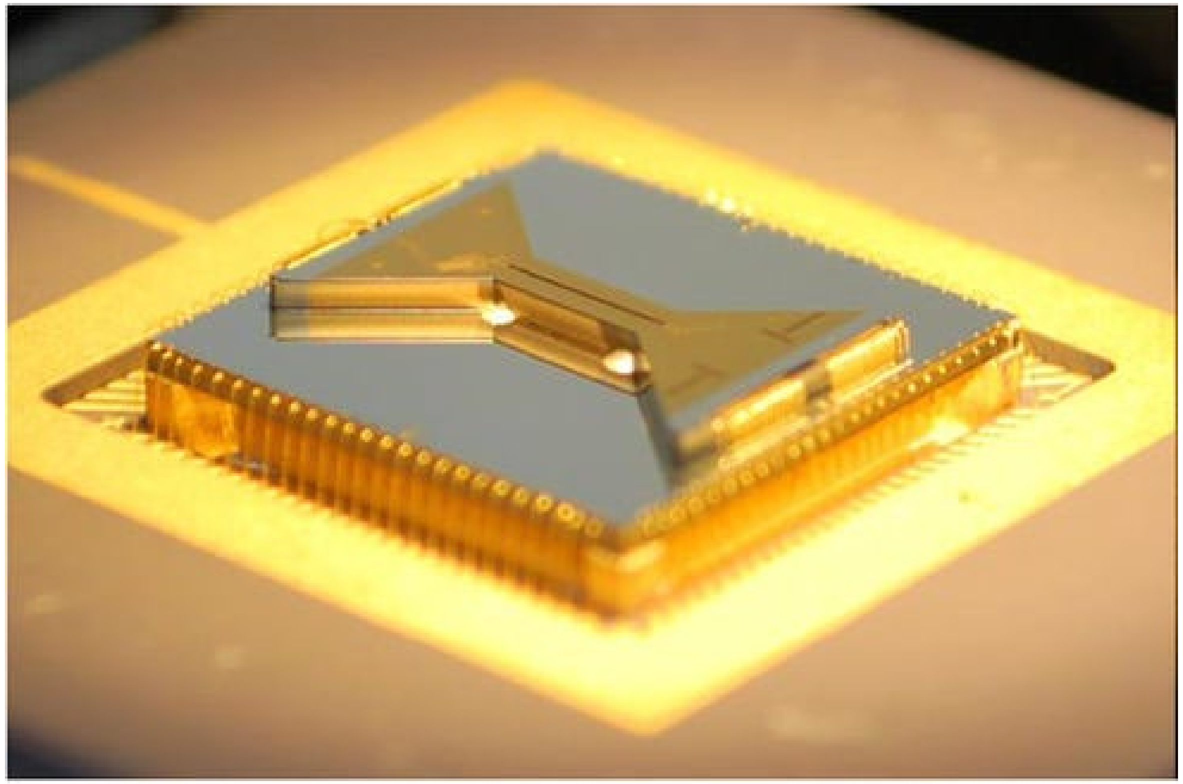
Dilution Refrigerator (T < 1 K inside)

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

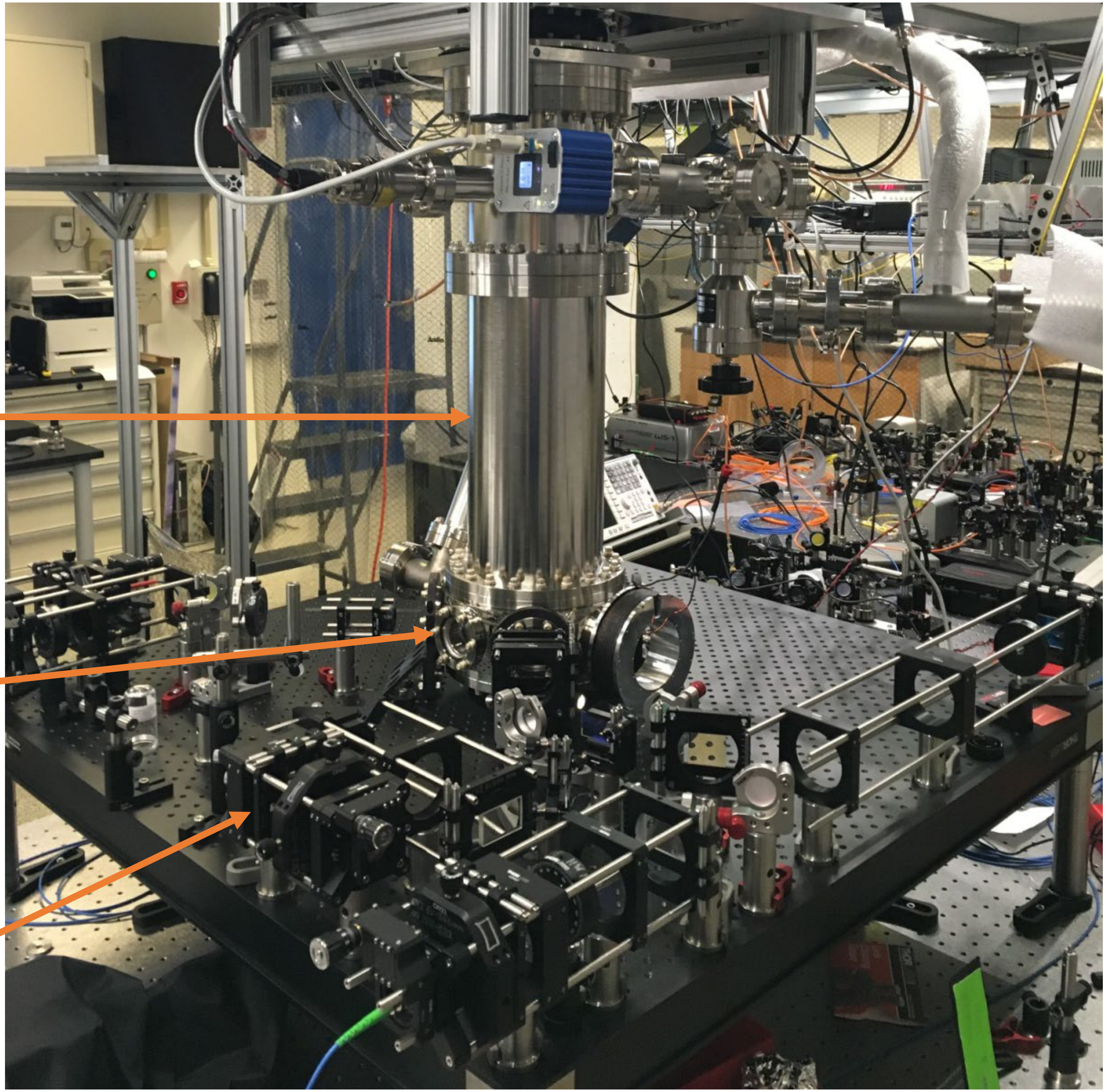
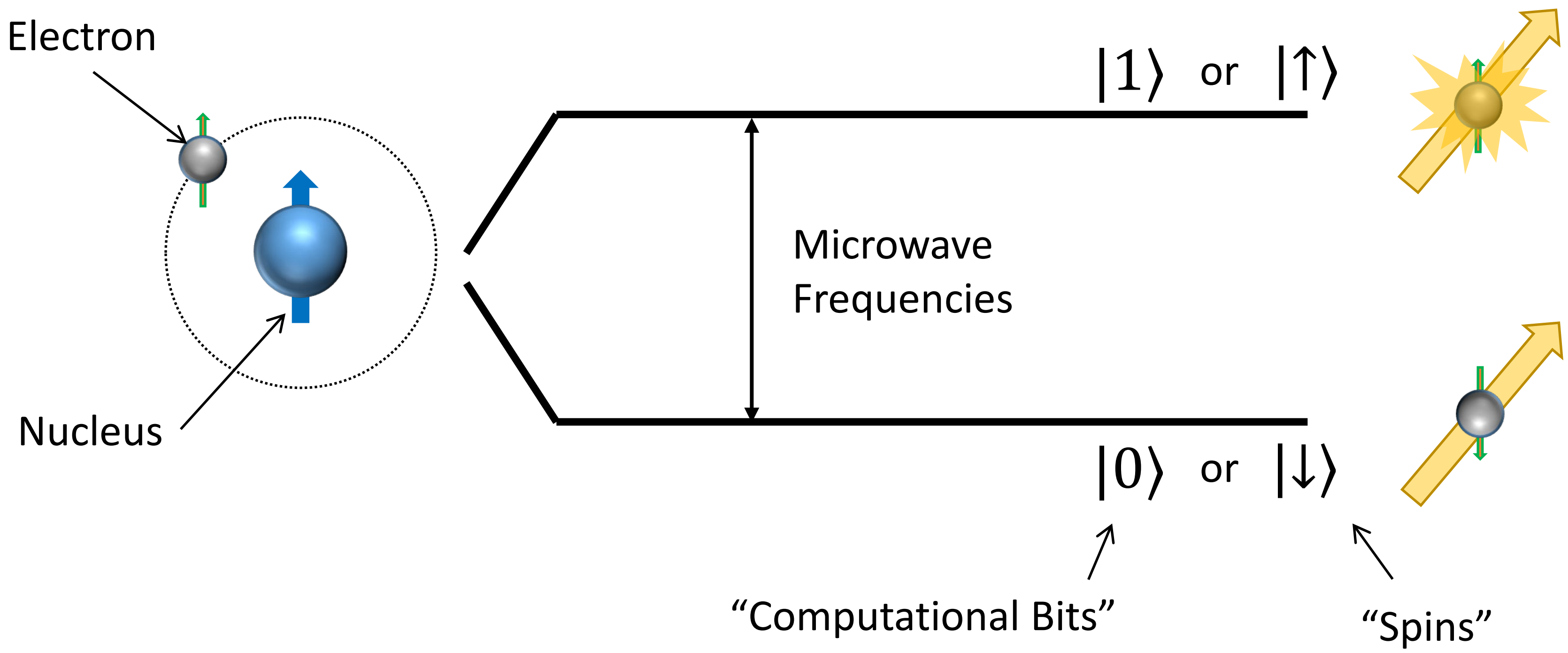
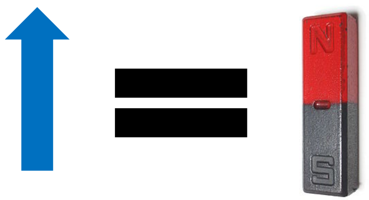


Image Credit: *P. Hess*

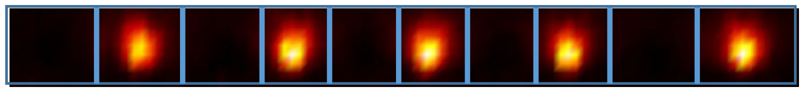
Trapped Ion Qubits



“The Hyperfine Interaction”
Interacting Bar Magnets



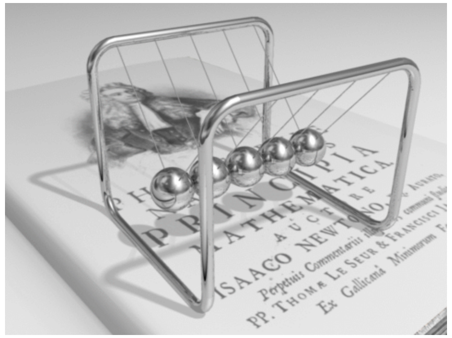
A trapped ion quantum state measurement



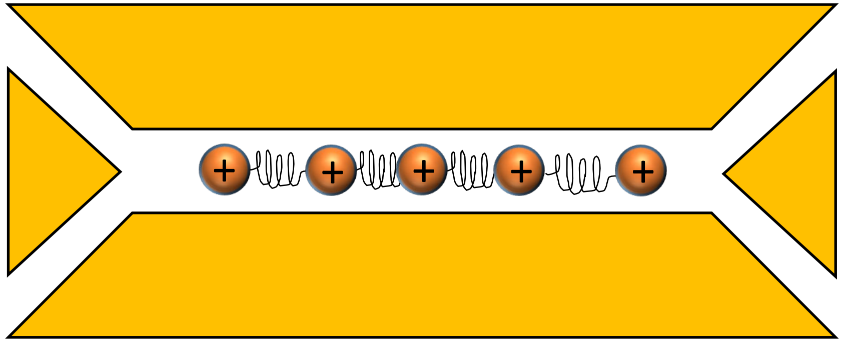
$|0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\rangle$

Linear Chains of Ions

Artist's Rendition of a Trapped Ion Quantum Computer



Newton's Cradle



Trapped Ion Motional Modes

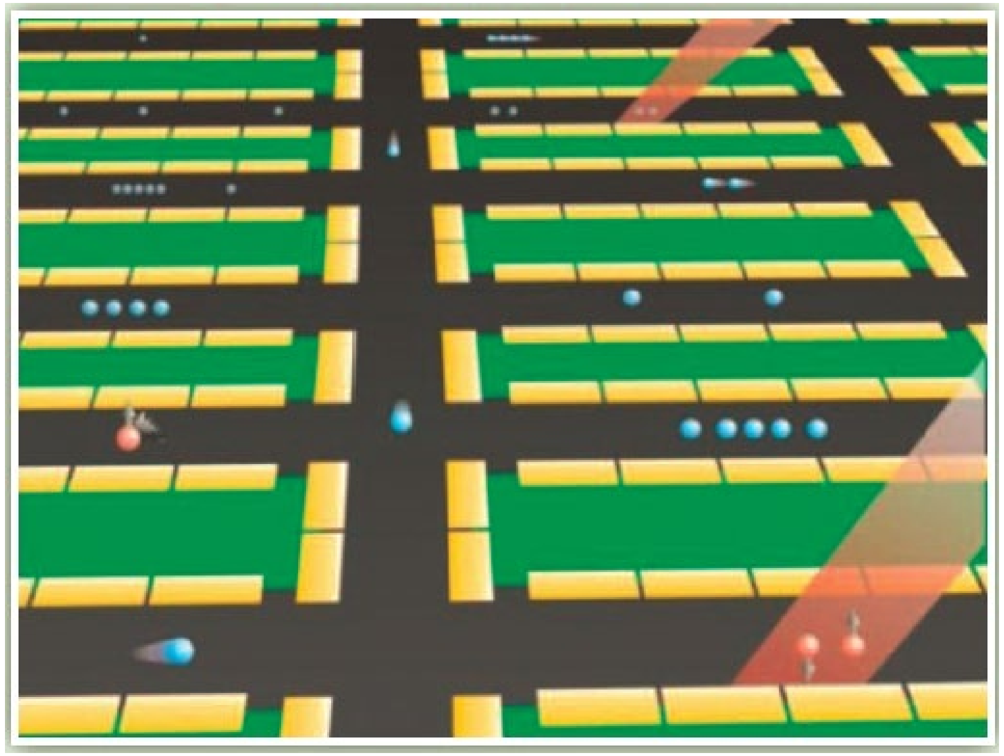
Center of Mass $\omega_{com} = \omega_a$

Breathing $\omega_{brth} = \sqrt{3}\,\omega_a$

Photo Credit: Scientific American

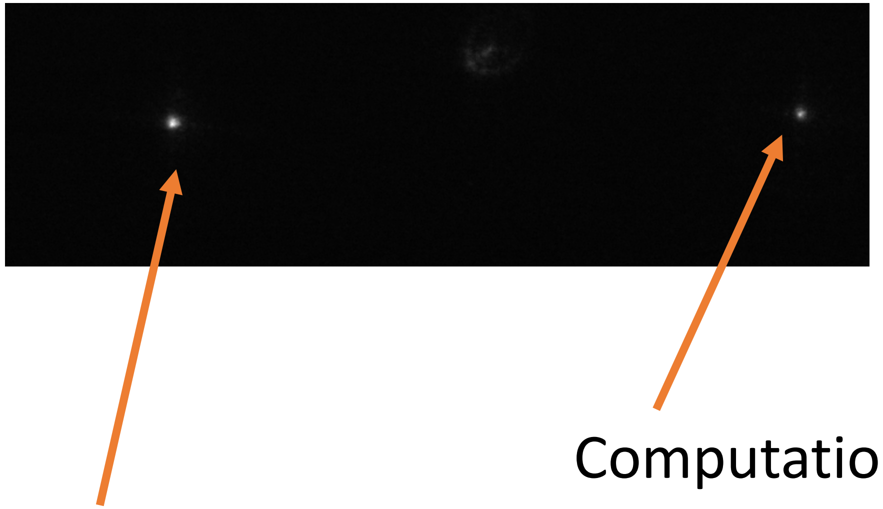
A Moveable Qubit

“Quantum CCD” Ion QI Processor



- NIST Ion Storage group

Shuttling in a surface trap



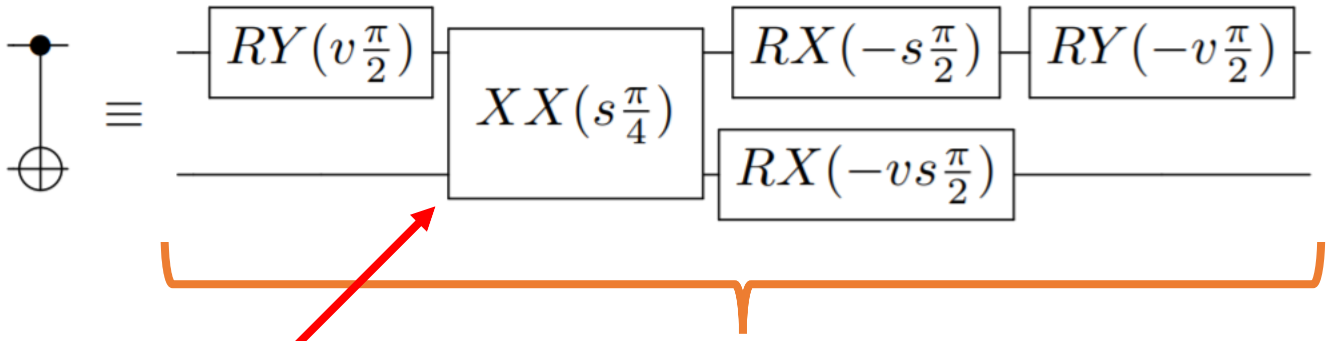
- GTRI QS group

Now being implemented by Honeywell Quantum Solutions

Compiling for Quantum Hardware

CNOT

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



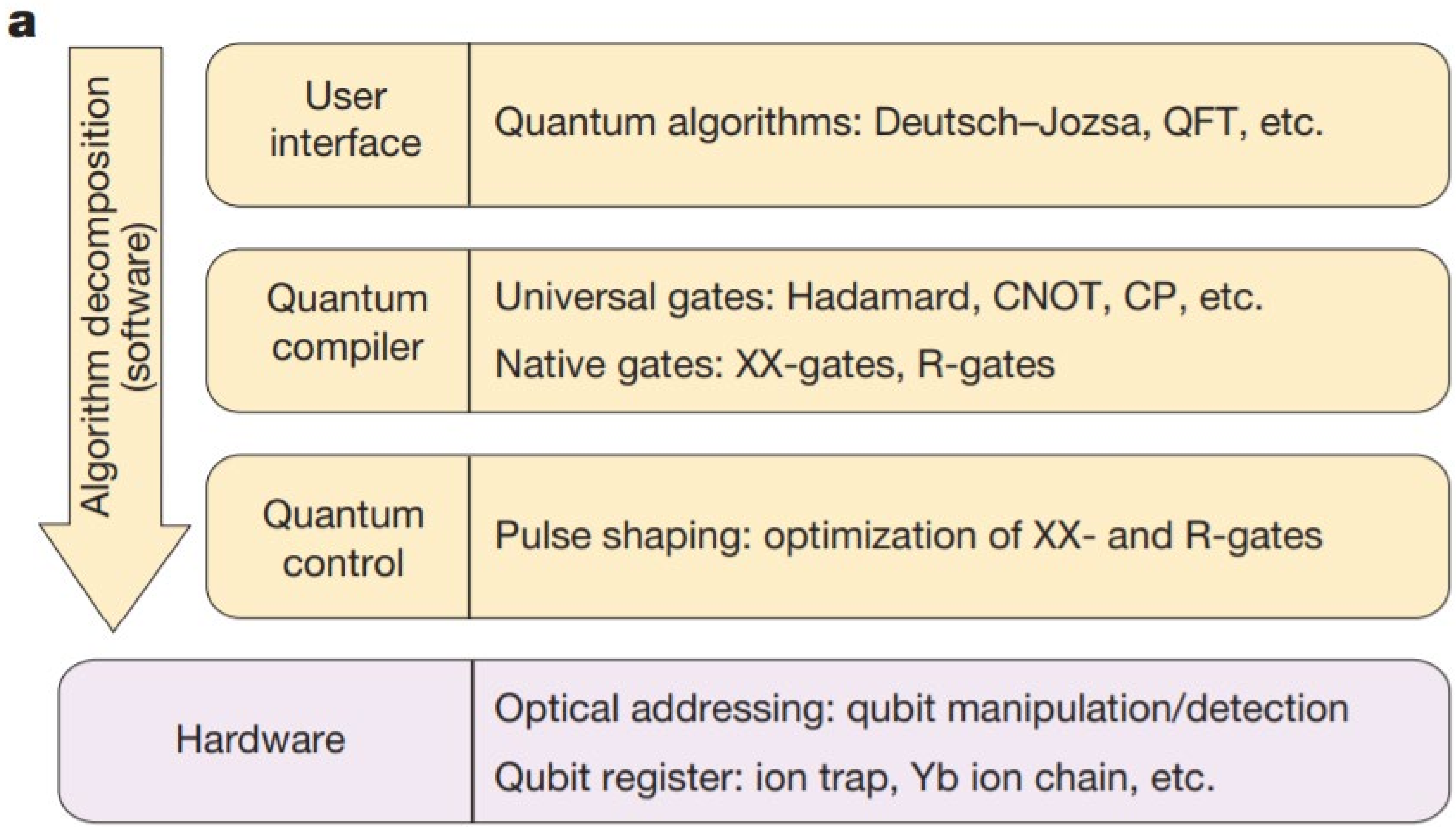
Native Trapped Ion Gates

Ising (XX) Entangling Gate

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

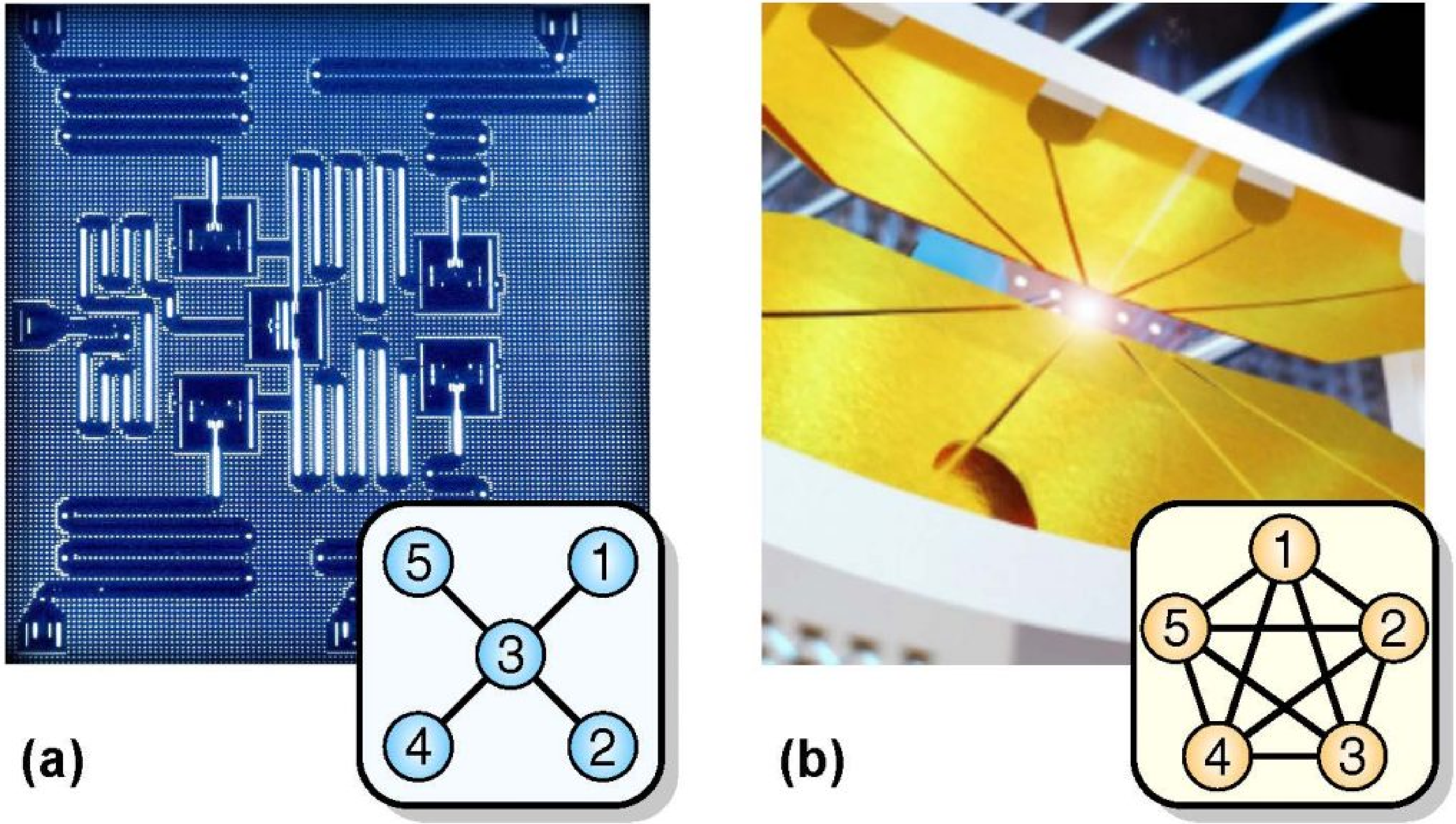
Basic circuit compilation techniques for an ion-trap quantum machine, D. Maslov New J. Phys. 19, 023035 (2017)

Controlling a quantum computer



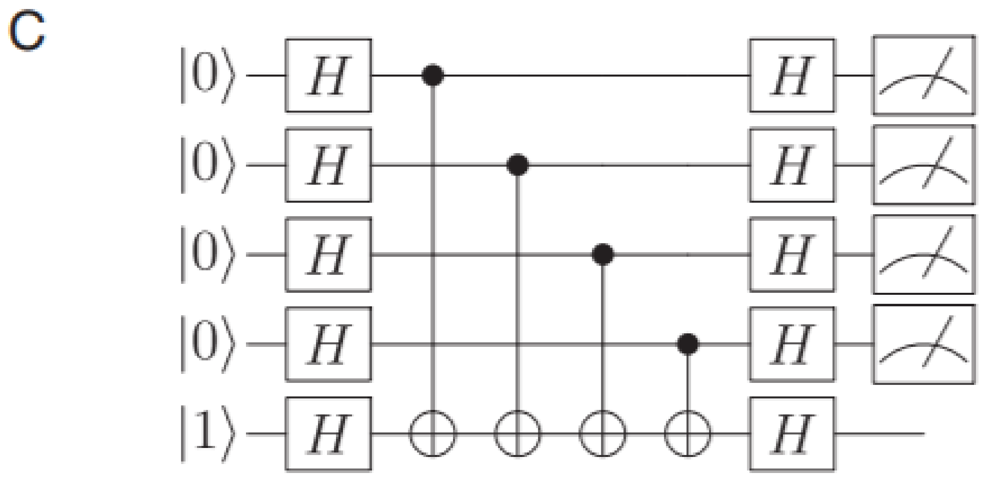
Demonstration of a small programmable quantum computer with atomic qubits. S. Debnath et al., Nature 536, 63 (2016).

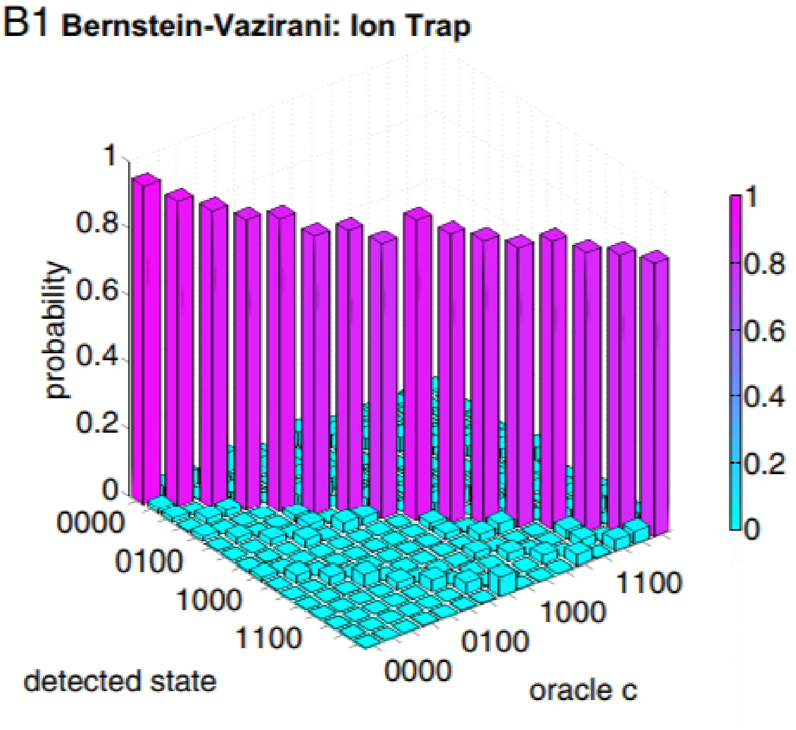
Wiring Matters:
Superconductors vs. Trapped Ions

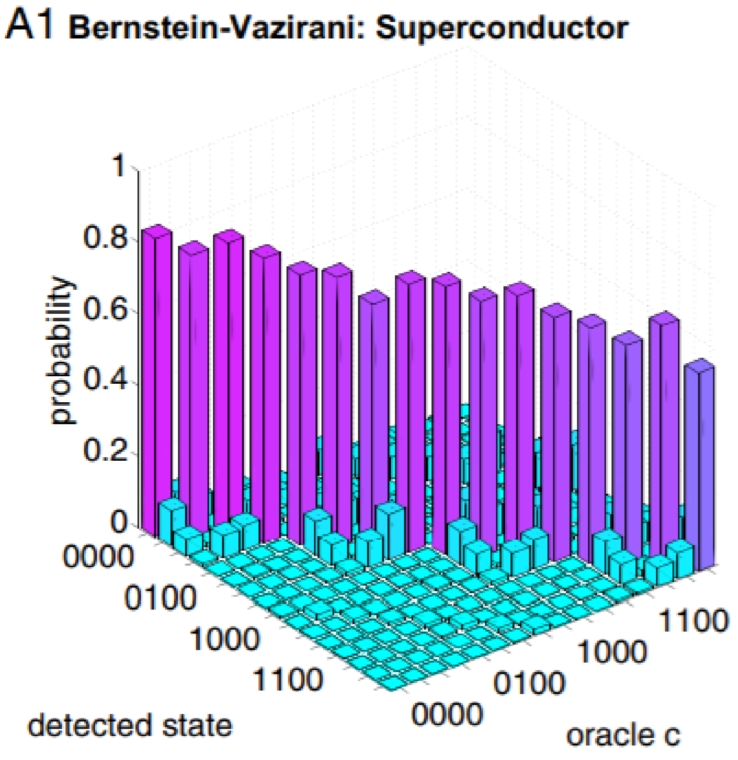


[Experimental Comparison of Two Quantum Computing Architectures](),” N. M. Linke, et. al. [Proceedings of the National Academies of Science 114, 13 (2017).]()

Example: Bernstein-Vazarani Algorithm







Experimental Comparison of Two Quantum Computing Architectures," N. M. Linke, et. al. PNAS 114, 13 (2017).