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Quantum Hardware

Applied Quantum Information

Spring 2022

Paraj Titum

Outline

- DiVincenzo’s Criteria
- Different Quantum Hardware
  - Atoms
  - Artificial Atoms
  - Photons

DiVincenzo’s Criteria

The conditions necessary for creating a Quantum Computer

1. A scalable physical system with well characterized qubit
2. The ability to initialize the state of the qubits to a simple fiducial state
3. Long relevant decoherence times
4. A "universal" set of quantum gates
5. A qubit-specific measurement capability

DiVincenzo, D. P., *Fortschritte der Physik*., **48** (9–11): 771–783(2000).
"The Physical Implementation of Quantum Computation"

A Survey of Quantum Hardware

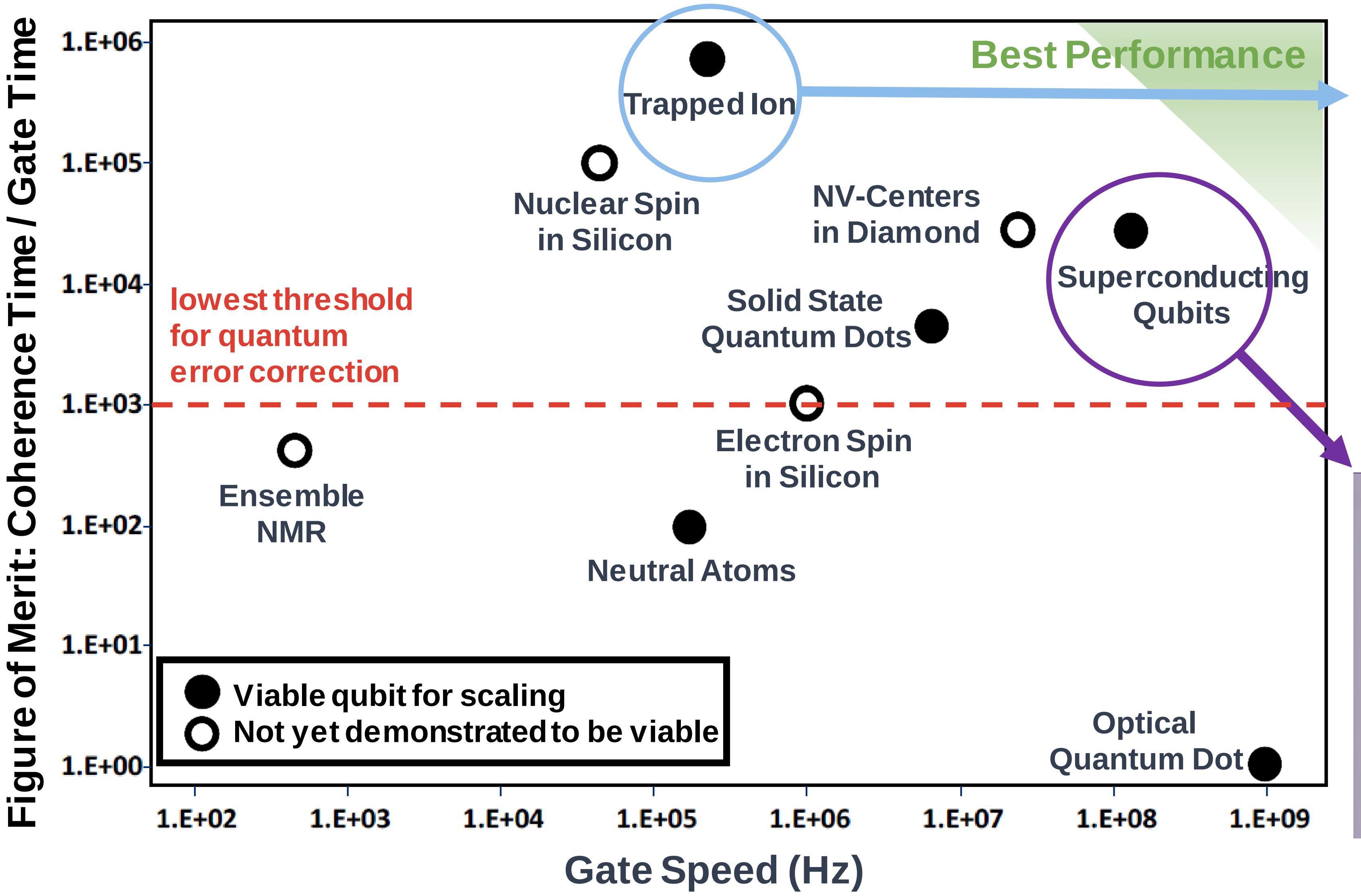
Atoms	Artificial Atoms	Photons
• Trapped Ions IONQ Honeywell • Rydberg atoms QuEra Computing Inc.	• Superconducting Qubits IBM Q rigetti Google • Spin Qubits • NMR systems • Solid-state spins	• Silicon Photonics PsiQuantum XANADU

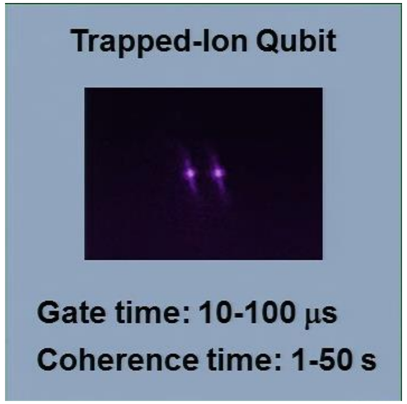
A Survey of Quantum Hardware

Atoms	Artificial Atoms	Photons
• Trapped Ions • Rydberg atoms	• Superconducting Qubits • Spin Qubits • NMR systems • Solid-state spins	• Silicon Photonics

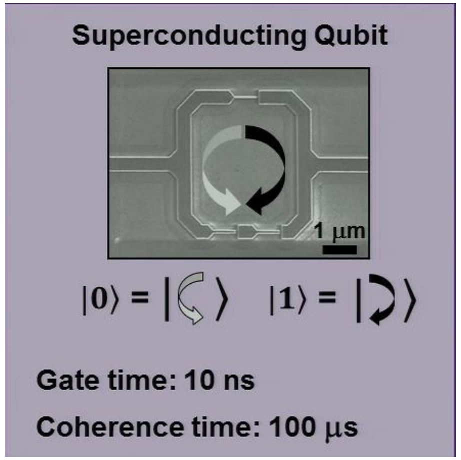
Figure of merits

$$\frac{\text{Coherence Time}}{\text{Gate Time}} \sim \text{\# Operations}$$



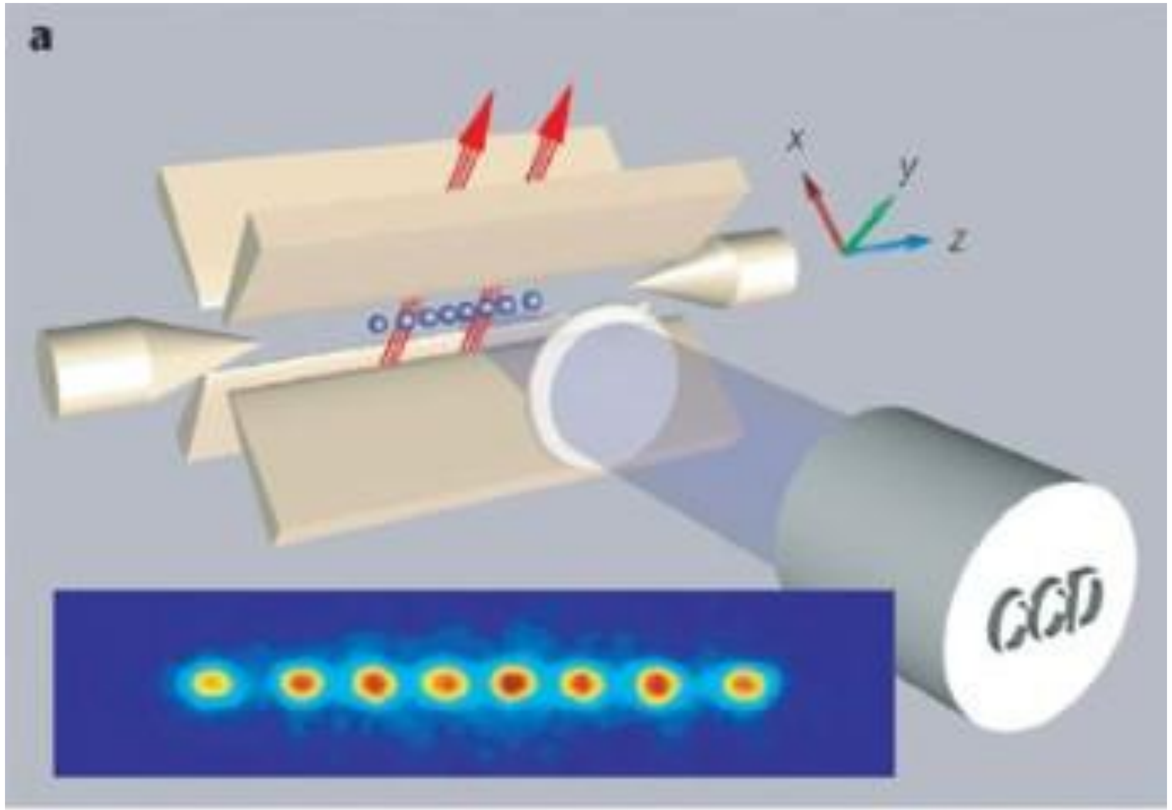


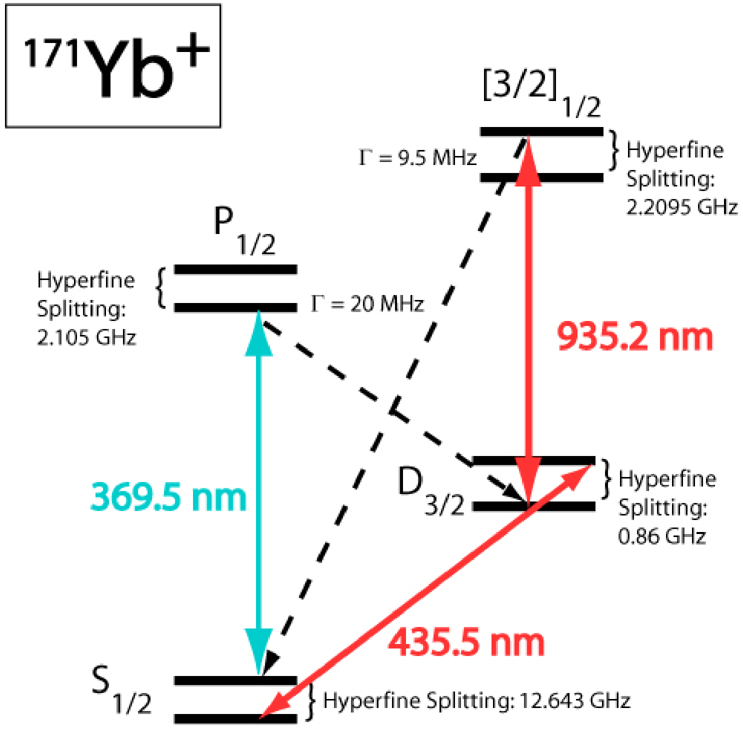
- Live long
- Slow



- Fast
- Live short

Atom-based Platforms
Trapped Ions: Setup

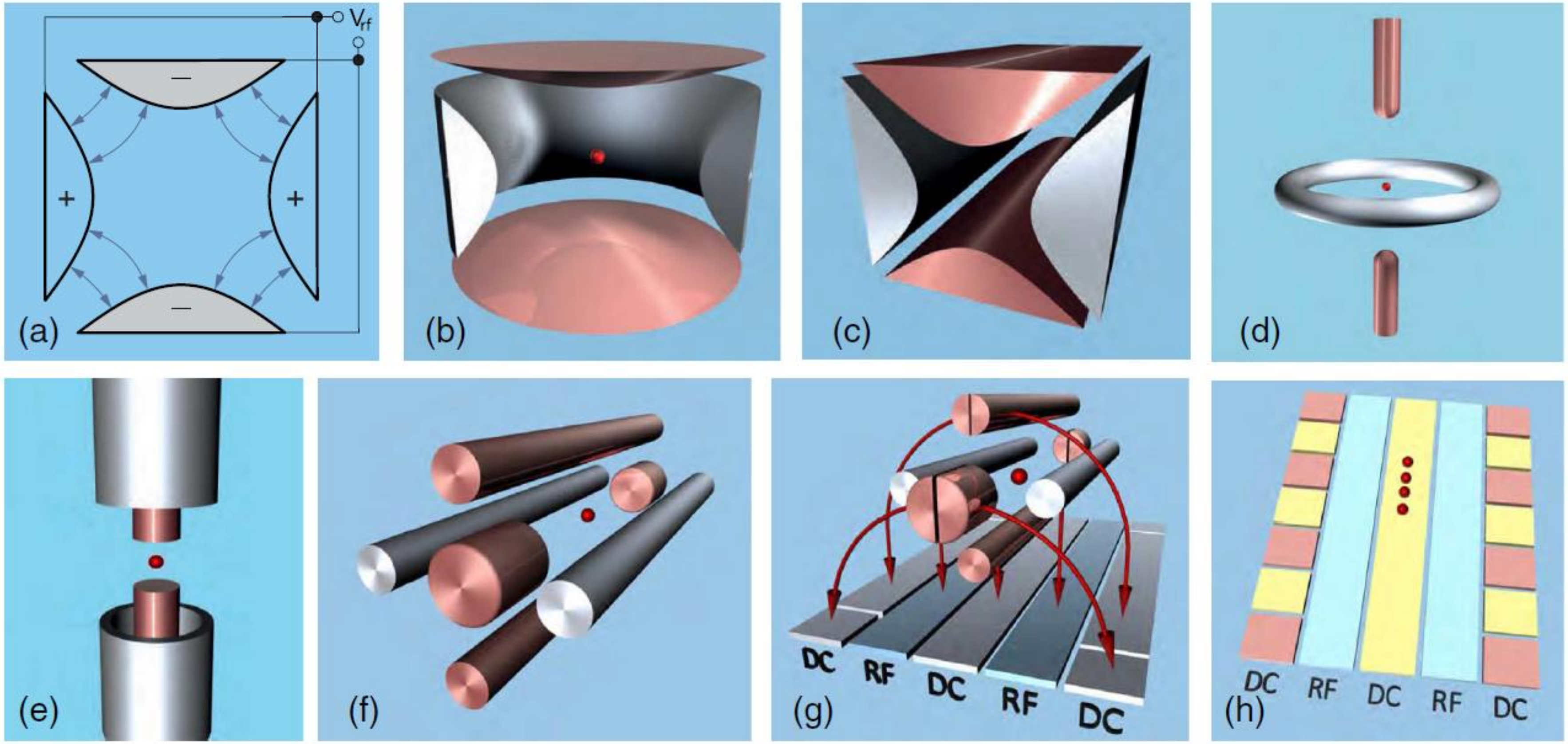




Blatt, Wineland, Nature 453,1008–1015 (2008)

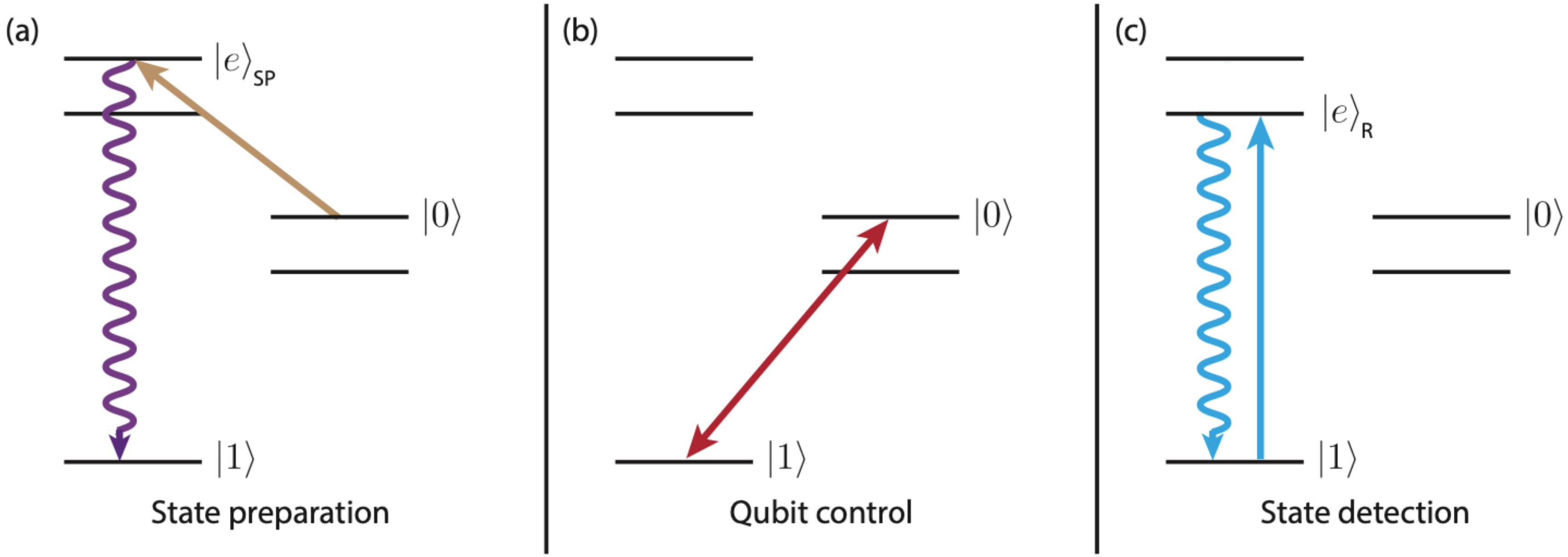
Trapped ions

Trapping Ions



Trapped ions

State-preparation, Gates, Measurement



Trapped Ions

Pros and Cons

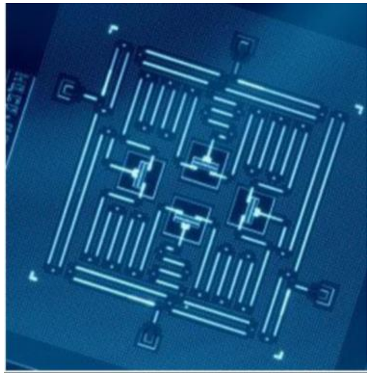
- Pros
  - Ions are identical
  - Long Coherence times

- Cons
  - Gates are slow

Artificial Atom based platforms

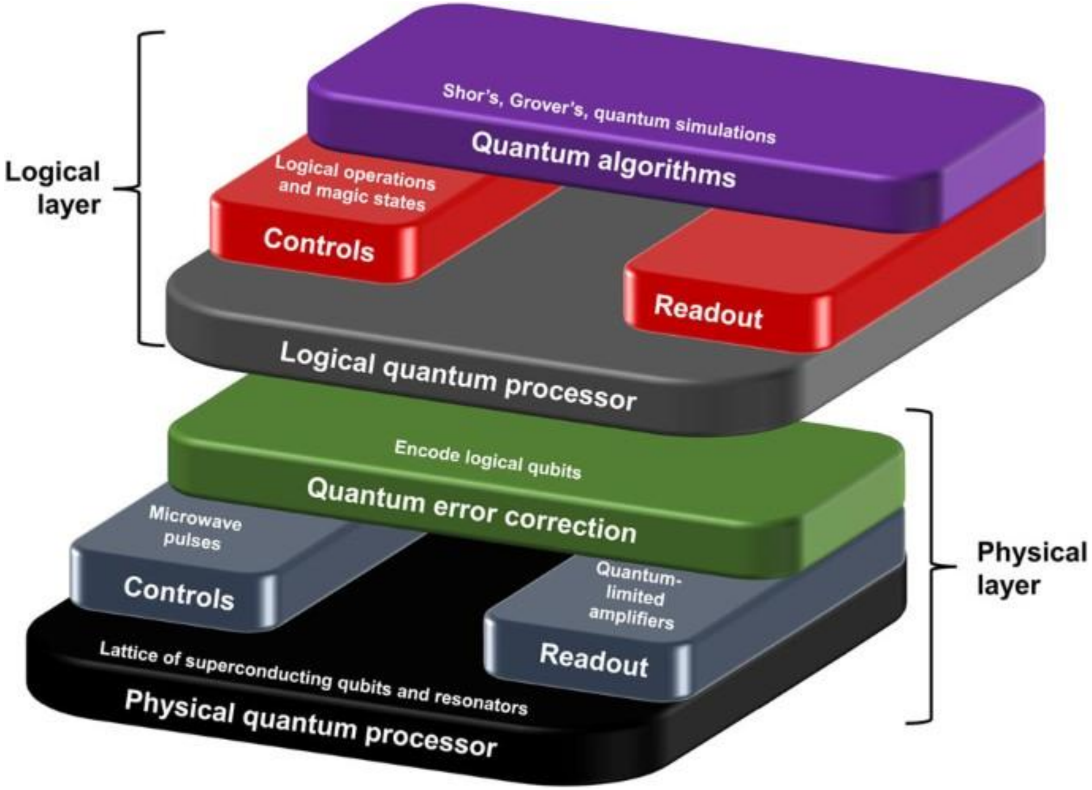
Superconducting qubits

Control Hardware



The Chip

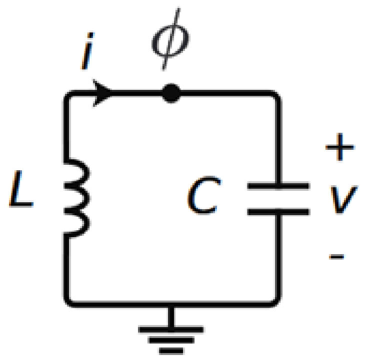
The Quantum Computing Software Stack



Superconducting Qubits

A Detour: QHO

LC circuit



$$H = \frac{1}{2}CV^2 + \frac{1}{2}LI^2 = \frac{Q^2}{2C} + \frac{\Phi^2}{2L} \qquad \left(\frac{Q}{C} = \dot{\Phi}\right)$$

Quantize: $[\hat{\Phi}, \hat{Q}] = i\hbar \quad \Big\downarrow \quad \left(\omega = \frac{1}{\sqrt{LC}}\right)$

$$\hat{H} = 4\,E_C\hat{n}^2 + \frac{1}{2}E_L\hat{\phi}^2 = \hbar\omega\left(a^\dagger a + \frac{1}{2}\right)$$

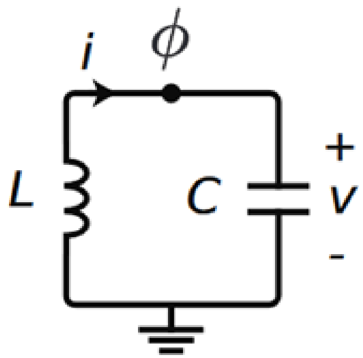
- (number of Cooper pairs) $n = Q/2e$
- (gauge invariant phase) $\phi = 2\pi\Phi/\Phi_0$
- (SC flux quanta) $\Phi_0 = h/2e$

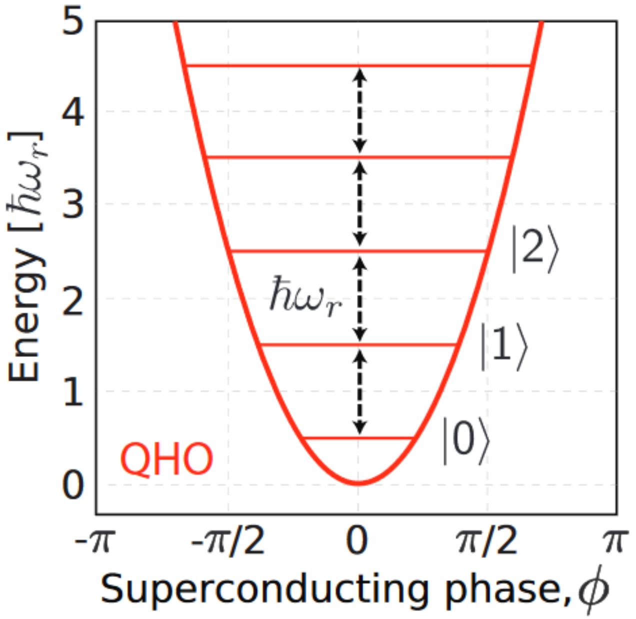
- (charging energy per electron) $E_C = e^2/2C$
- (inductive energy) $E_L = \left(\frac{\Phi_0}{2\pi}\right)^2/L$

Superconducting Qubits

A Detour: QHO

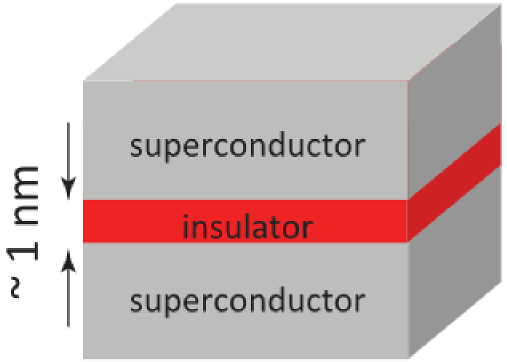
LC circuit





Superconducting Qubits

Josephson Junctions

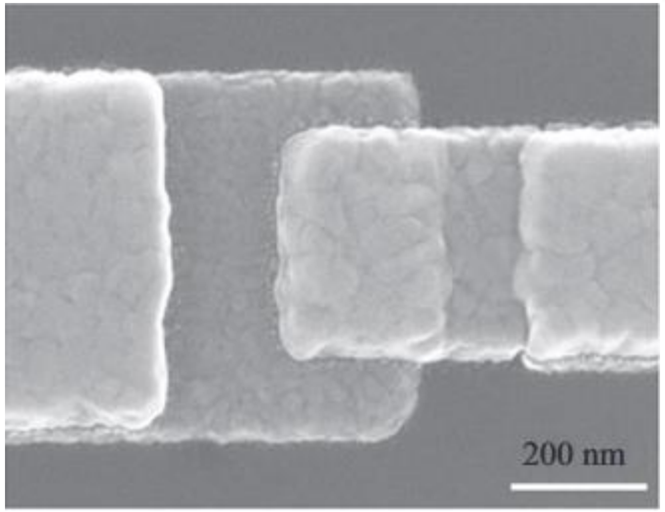


$$I = I_C \sin(\phi)$$

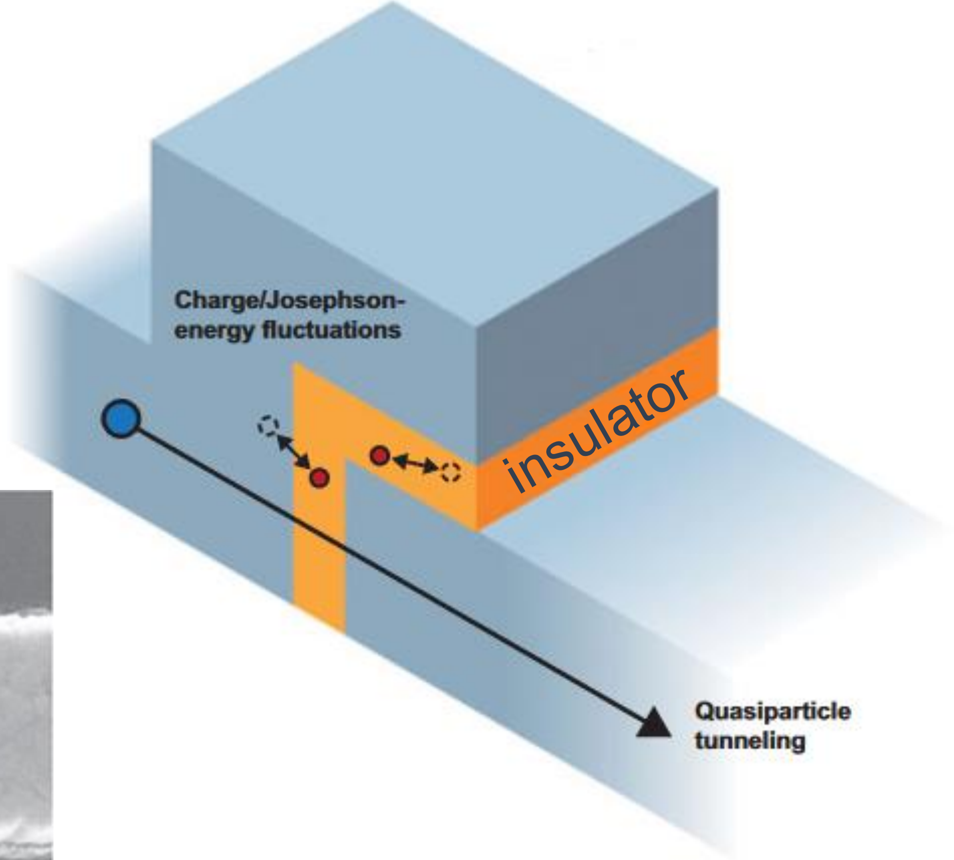
$$V = \frac{\hbar}{2e}\frac{d\phi}{dt}$$

Cooper pairs

Tunneling

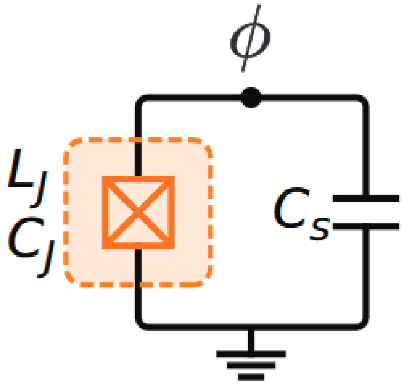


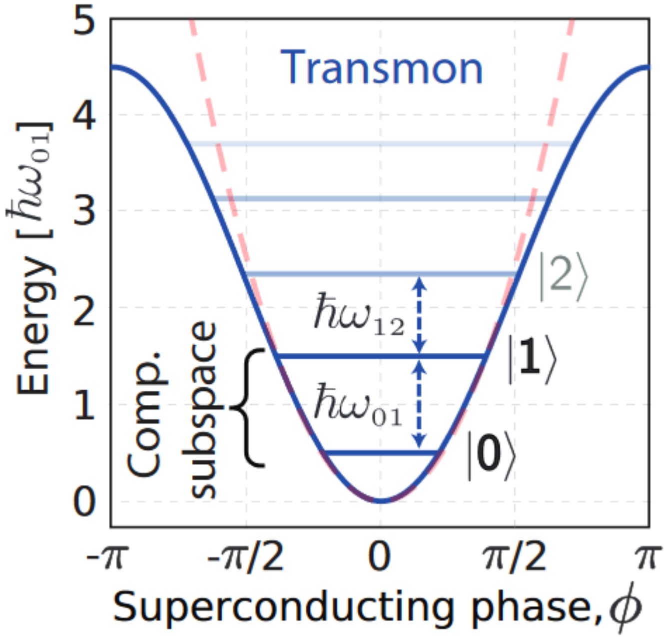
(SEM image)



*Al: SC transition at 1.26K

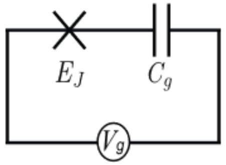
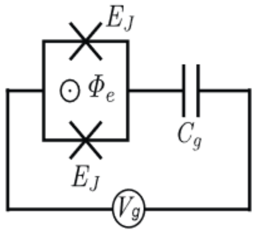
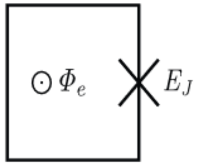
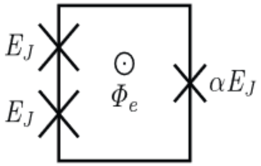
Superconducting Qubit
Transmon





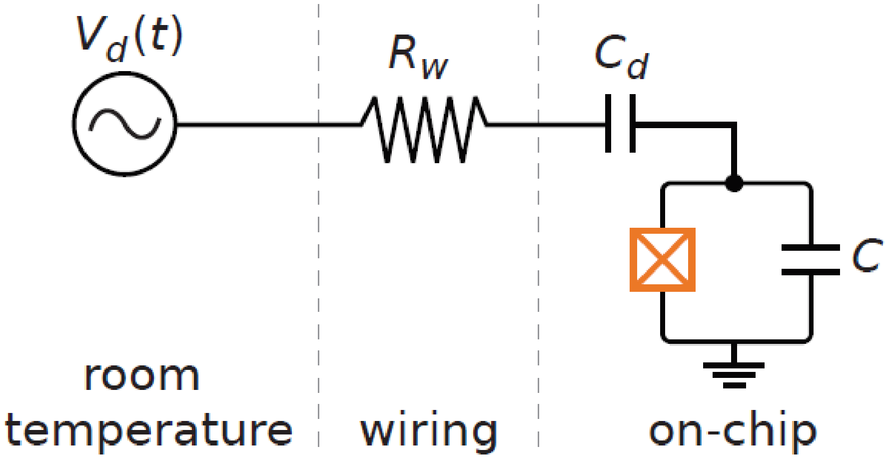
Superconducting Qubits

Different Qubits

	Circuit	Properties	Dominant noise
Charge qubit		$E_J/E_C < 1$ Controlled by V_g.	Charge fluctuations; mainly 1/f noise.
		$E_J/E_C < 1$ Controlled by both V_g and Φ_e.	
Flux qubit		$E_J/E_C > 1$ Controlled by Φ_e.	Flux fluctuations; mainly 1/f noise.
		$E_J/E_C > 1$ $0.5 < \alpha < 1$ Controlled by Φ_e.	

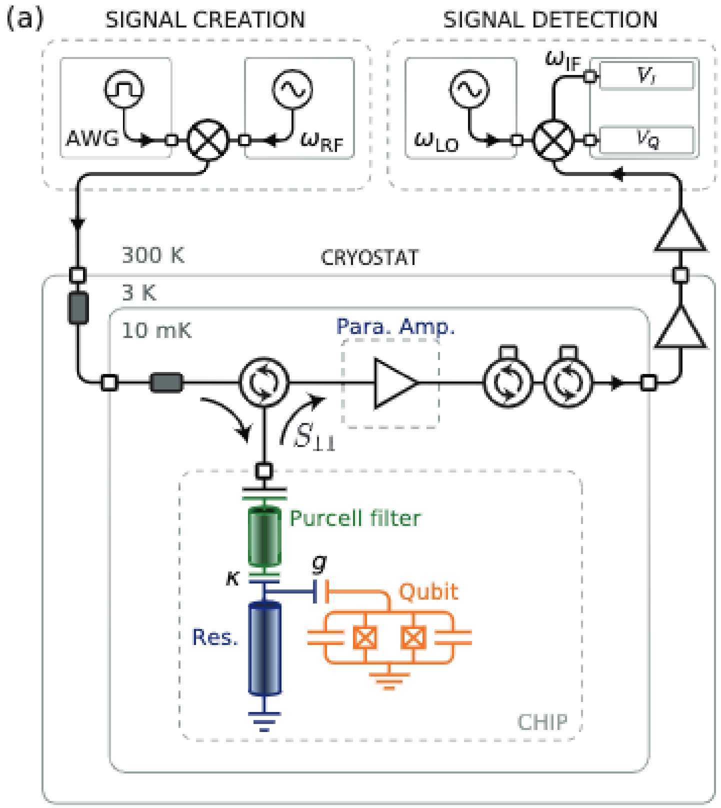
Superconducting Qubits

Single Qubit Gates



Superconducting Qubits

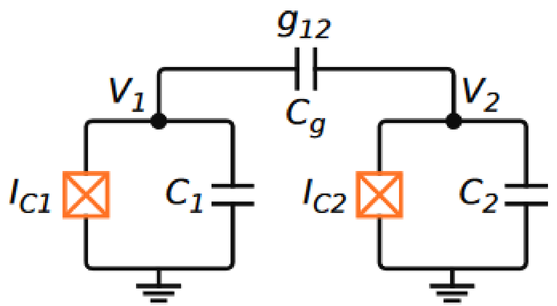
Readout



- Qubits are coupled to a resonator.
- The optical resonator is a cavity that stores photons in a particular frequency.
- The qubit coupling modifies the frequency of the resonator based on the state of a qubit
- The state of the qubit is measured from the shift in the resonator frequency.

Superconducting Qubits

Capacitive Coupling



$$H_{\text{int}} = C_g V_1 V_2$$

$$H = \sum_{i=1,2} \left[4E_{C,i} n_i^2 - E_{J,i} \cos\phi_i\right] + +4e^2 \frac{C_g}{C_1 C_2} n_1 n_2$$

$$H = \sum_{i=1,2} \frac{1}{2} \omega_i \sigma_{z,i} + g\sigma_{y,1}\sigma_{y,2}$$

Superconducting Qubits

Pros and Cons

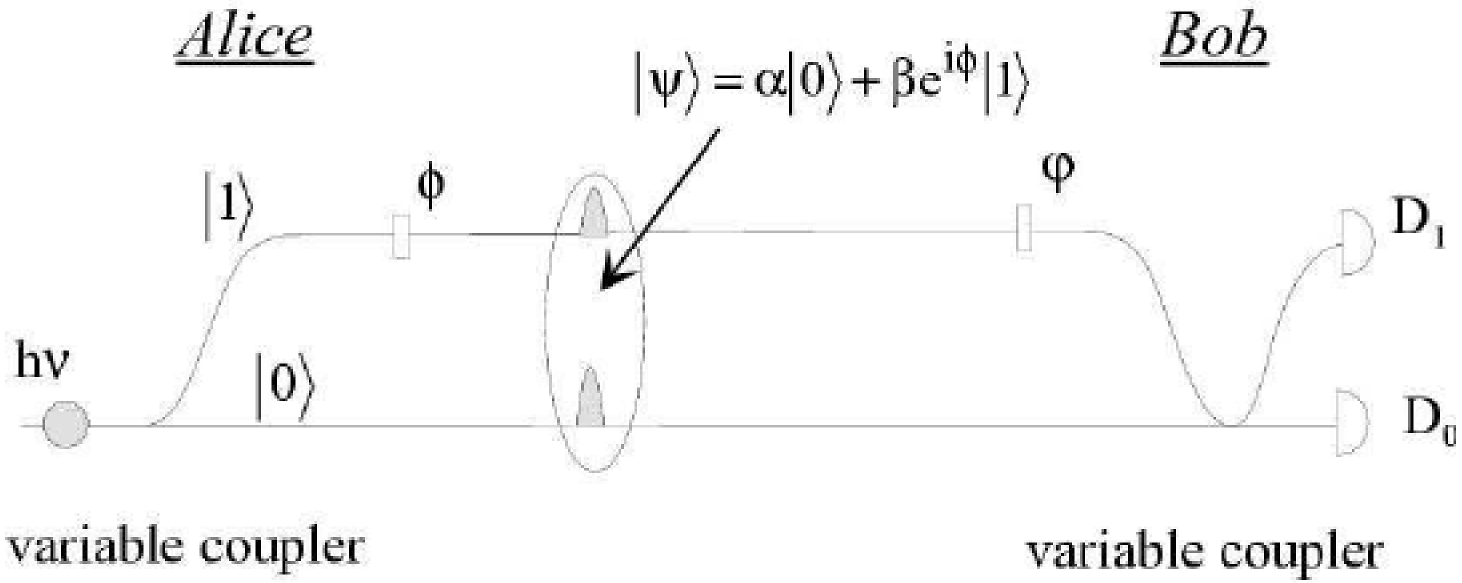
- Pros:
  - Fast gates
  - Rapidly improving coherence time
  - Fabrication processes are getting standardized

- Cons:
  - Qubits are not identical
  - Cross talk is a problem
  - correlated noise in prevalent
  - Superconducting

Photons

Photons as qubits

- Store a qubit in the two different degrees of freedom of photons:
  - Distinct polarization : |1> is a state with a particular polarization or right/left circularly polarized
  - Spatial modes: two spatially separated beams.
  - Time-bin encoding: Two different timings
- Measurement: Single photon detection

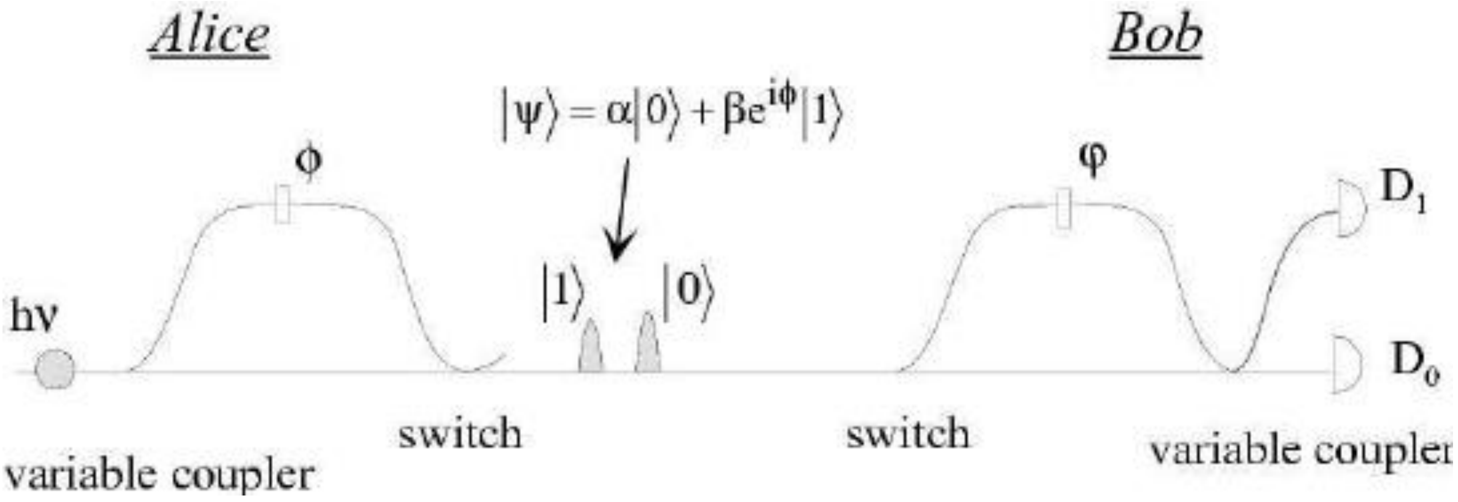


Spatial modes as qubits

Photons

Photons as qubits

- Store a qubit in the two different degrees of freedom of photons:
  - Distinct polarization : |1> is a state with a particular polarization or right/left circularly polarized
  - Spatial modes: two spatially separated beams.
  - Time-bin encoding: Two different timings. Measurement based on arrival times on detectors
- Measurement: Single photon detection



Temporal modes as qubits

Photons

Photons as qubits

- Store a qubit in the two different degrees of freedom of photons:
  - Distinct polarization : |1> is a state with a particular polarization or right/left circularly polarized
  - Spatial modes: two spatially separated beams.
  - Time-bin encoding: Two different timings. Measurement based on arrival times on detectors
- Measurement: Single photon detection
- Entangling photons: Non-linear media
- Pros and Cons
  - Pros: Single photons can be transmitted with low loss optical fibers, easy to do single qubit operations , Useful for quantum communication and cryptography
  - Cons: Hard to make photons interact, slow to generate single photons
- Measurement based quantum computing using linear optical elements.
  - Uses resource states, in combination with linear optical elements

Further Reading

- Trapped Ions
  - https://arxiv.org/abs/1904.04178
- Superconducting Qubits
  - https://arxiv.org/abs/1904.06560
- Photon-based qubits
  - Nielsen & Chuang Chapter 7.2

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