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Architectures and Approaches in Scaling the Trapped-Ion Quantum Computer

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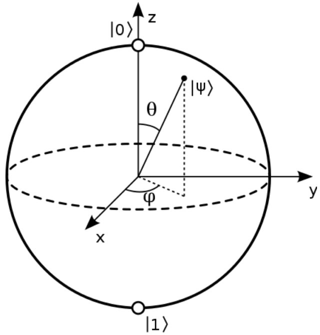
Why compute with qubits?



Quantum Rules

1. Superposition $|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$
2. Coherence
3. Entanglement $|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$

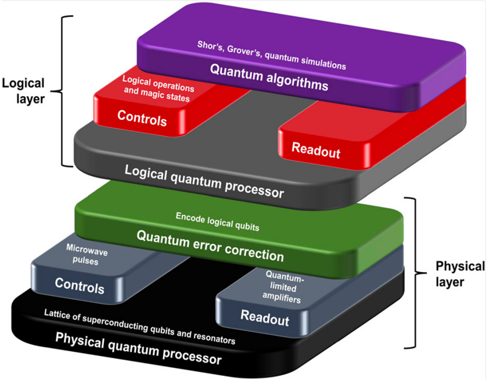
Quantum parallel processing on 2^N inputs

Example: $N = 3$

$$\begin{aligned}|\psi\rangle =& a_0|000\rangle + a_1|001\rangle + a_2|010\rangle + a_3|011\rangle\\ &+ a_4|100\rangle + a_5|101\rangle + a_6|110\rangle + a_7|111\rangle\end{aligned}$$

$N = 300$ qubits: more information than particles in the universe!

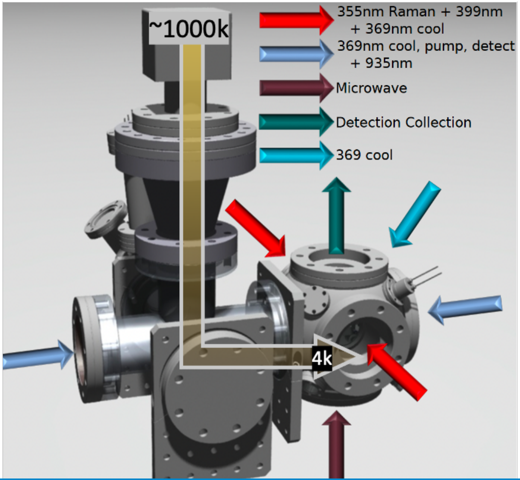
How to build a Quantum Computer?

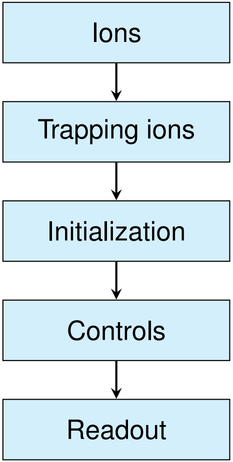


DiVincenzo Criteria

1. A **scalable** physical system with well characterized qubits;
2. The ability to initialize the qubits;
3. Long relevant coherence times;
4. A ‘universal’ set of quantum gates;
5. A qubit-specific measurement capability.

Trapped-Ion Quantum Computer Architecture

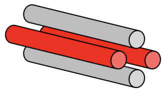




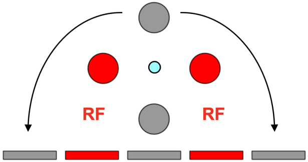
Ion Traps[1]

- **Penning trap:** static electric and magnetic field
- **Paul trap:** static and oscillating electric fields
  - Linear trap
  - Surface-electrode trap

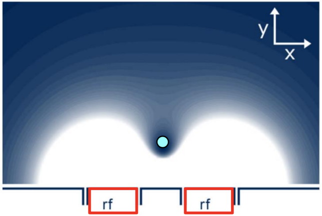
3D Paul trap



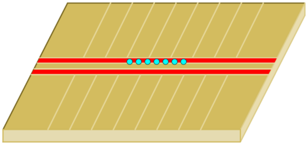
Unfolding 3D to 2D



Ion trapped in electric field null



Ions confined within cylinder along trap axis

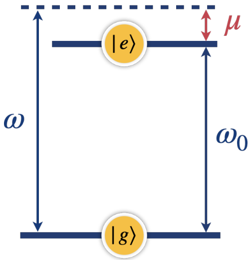


DC electrodes shuttle ions along trap axis

[1] Image source: MIT Lincoln Laboratory

The Basic Hamiltonian

The interaction between a two-level ion and a single-mode light.



$$\hat{H}_{int} = \frac{\hbar}{2}\Omega\left(|e\rangle\langle g| + |g\rangle\langle e|\right)\left[e^{i(kx-\omega t+\phi)} + e^{-i(kx-\omega t+\phi)}\right]$$

1. Trans to Interaction picture
2. $kx = kx_0(\hat{a}^\dagger + \hat{a}) = \eta(\hat{a}^\dagger + \hat{a})$
3. Rotational wave approximation (RWA)
4. Lamb-Dicke limit $\eta = k\sqrt{\hbar/(2m\omega_\mathrm{m})} \ll 1$

$$\hat{H} = \frac{\hbar}{2}\Omega\hat{\sigma}_+\left[1 + i\eta\left(\hat{a}^\dagger e^{i\omega_m t} + \hat{a}e^{-i\omega_m t}\right)\right]e^{i(\phi-\mu t)} + h.c.$$

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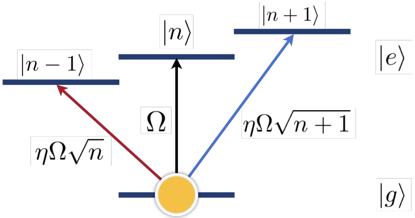
Transitions

$$
\begin{aligned}
\hat{H} =& \frac{\hbar}{2}\Omega\left(\hat{\sigma}_+ \mathrm{e}^{i\phi} + \hat{\sigma}_- \mathrm{e}^{-i\phi}\right) && \Rightarrow \hat{H}_{car} \\
&+ i\eta\frac{\hbar}{2}\Omega\left[\hat{\sigma}_+ \hat{a}^\dagger \mathrm{e}^{i\phi}\mathrm{e}^{-i(\mu-\omega_m)t} + \hat{\sigma}_- \hat{a}\mathrm{e}^{-i\phi}\mathrm{e}^{i(\mu-\omega_m)t}\right] && \Rightarrow \hat{H}_{bsb} \\
&+ i\eta\frac{\hbar}{2}\Omega\left[\hat{\sigma}_+ \hat{a}\mathrm{e}^{i\phi}\mathrm{e}^{-i(\mu+\omega_m)t} - \hat{\sigma}_- \hat{a}^\dagger\mathrm{e}^{-i\phi}\mathrm{e}^{i(\mu+\omega_m)t}\right] && \Rightarrow \hat{H}_{rsb}
\end{aligned}
$$

- **Carrier transition** $(\mu = 0)$
  $|g\rangle\,|n\rangle \leftrightarrow |e\rangle\,|n\rangle$
- **Blue sideband transition** $(\mu = \omega_m + \delta)$
  $|g\rangle\,|n\rangle \leftrightarrow |e\rangle\,|n+1\rangle$
- **Red sideband transition** $(\mu = -\omega_m - \delta)$
  $|g\rangle\,|n\rangle \leftrightarrow |e\rangle\,|n-1\rangle$



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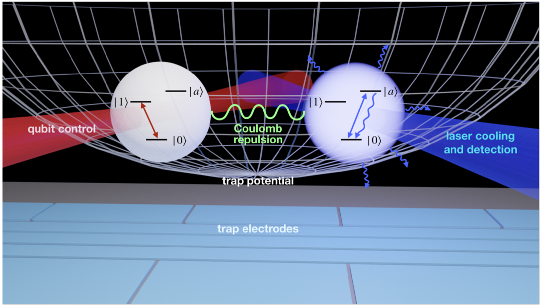
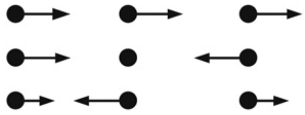
More Ions

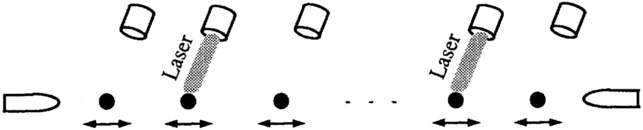




When N oscillators are coupled, N different canonical modes are obtained, which correspond to **phonons** of N **different frequencies**.

$$\hat{H} = \underbrace{\boxed{\frac{\hbar}{2}\sum_{j=1}^{N}\Omega_j\hat{\sigma}_+^j e^{i(\phi_j-\mu_j t)}}}_{\text{internal state}} \underbrace{\boxed{\sum_{k=1}^{N}\left[1 + i\eta_{j,k}\left(\hat{a}_k^\dagger e^{i\omega_k t} + \hat{a}_k e^{-i\omega_k t}\right)\right]}}_{\text{phonon state (ion vibration)}} + h.c.$$

The Cirac-Zoller Gate[2]



- Based on **red** sideband transition $|g\rangle|1\rangle \leftrightarrow |e\rangle|0\rangle$
- Laser frequency
  $\omega = \omega_0 - \omega_m$

1. Apply a π-pulse on ion A
2. Apply a 2π-pulse on ion B
3. Apply a π-pulse on ion A again

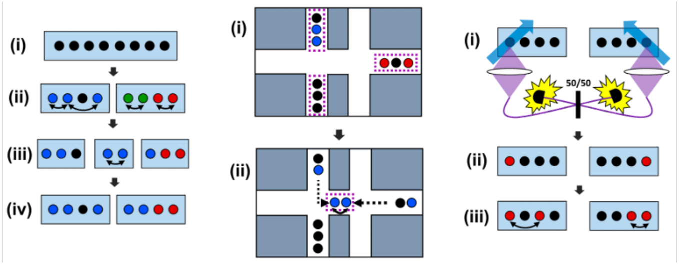
$$
\begin{array}{ccccccc}
 & (1) & & (2) & & (3) & \\
|gg0\rangle & \rightarrow & |gg0\rangle & \rightarrow & |gg0\rangle & \rightarrow & |gg0\rangle \\
|ge0\rangle & \rightarrow & |ge0\rangle & \rightarrow & |ge0\rangle & \rightarrow & |ge0\rangle \\
|eg0\rangle & \rightarrow & -i\,|gg1\rangle & \rightarrow & i\,|gg1\rangle & \rightarrow & |eg0\rangle \\
|ee0\rangle & \rightarrow & -i\,|ge1\rangle & \rightarrow & -i\,|ge1\rangle & \rightarrow & -\,|ee0\rangle
\end{array}
$$

$$|\pm\rangle = (|g\rangle \pm |e\rangle)/\sqrt{2} \quad \Rightarrow \quad \begin{cases} |g\rangle|\pm\rangle \rightarrow |g\rangle|\pm\rangle \\ |e\rangle|\pm\rangle \rightarrow |e\rangle|\mp\rangle \end{cases} \quad \Rightarrow$$ **Controlled-Z Gate!**

[2]Cirac and Zoller 1995

Approaches to Scaling Trapped Ions[3]

1. Linear arrays
2. Two dimensional arrays
3. Remote entanglement



[3] Image source: Bruzewicz et al. 2019

Linear Arrays[4]

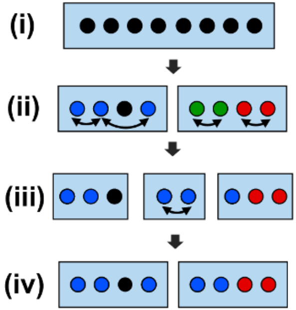
Problem: may prove more difficult as the chain size grows.

1. weak coupling to the ion motion
2. an increased susceptibility

Modularity!

Strategy:

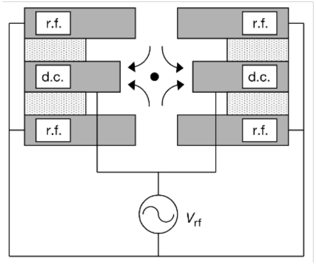
1. Splitting the chain into smaller modules;
2. Reconfiguring the modules allows for high-fidelity entangling gates between ions in different modules;
3. Upon completion, the modules can revert to their original state.

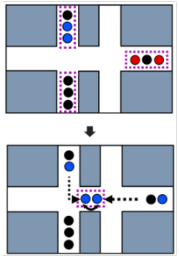


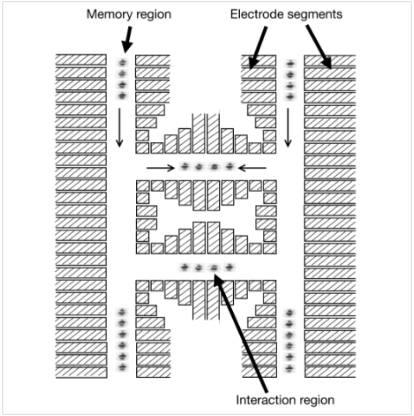
[4] Bruzewicz et al. 2019

Two Dimensional Arrays - QCCD (Quantum Charge-Coupled Device)[5]

Ion transport is typically much faster than a two-ion gate or a reordering operation.







[5]Kielpinski, Monroe and Wineland 2002

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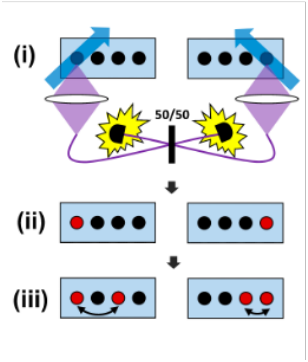
Remote Entanglement - Photonic Interconnect

1. Ions within each module initially exist in an **unentangled** state.
2. A dedicated “communication ion” in each module is excited by a laser, resulting in the emission of photons **entangled** with the internal ion state.
3. There is a probability that these photons reach the 50/50 beam splitter and **interfere**.
4. Simultaneous detection of photons by single-photon detectors heralds **entanglement** between communication ions.



Summary

1. Overview
   - Why compute with qubits?
   - How to build a Quantum Computer?
2. Quantum Computing with Trapped Ions
   - Ion Traps
   - The Basic Hamiltonian
   - Quantum Gates
3. Approaches to Scaling Trapped Ions
   - Linear Arrays
   - Two Dimensional Arrays
   - Remote Entanglement

Thanks for Listening!