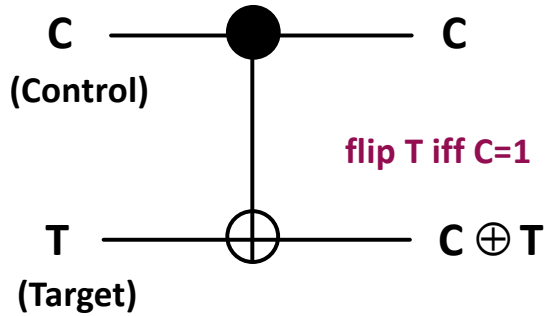


Introduction and Overview (Preskills Notes)

9-03-2024

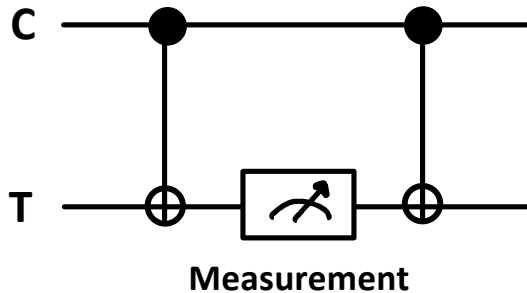
Controlled-NOT (CNOT)

Truth Table



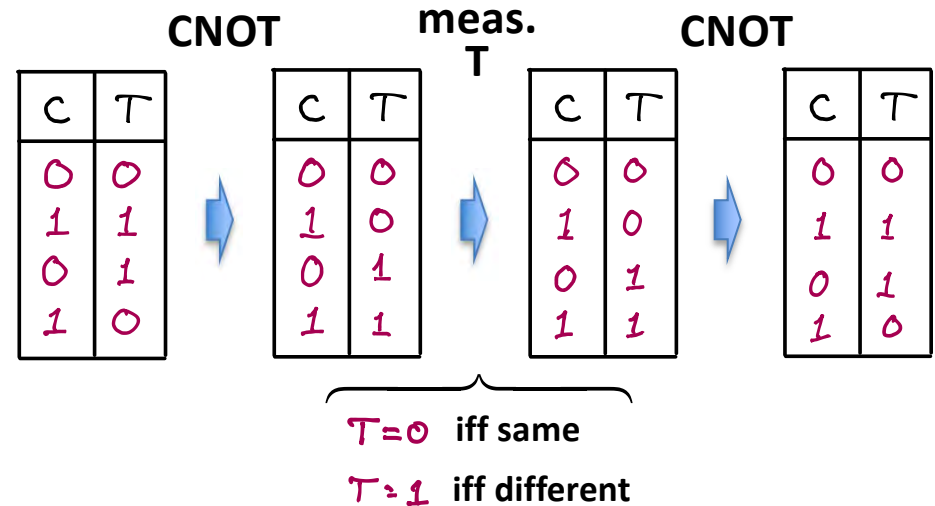
C	T	$C \oplus T$
0	0	0
0	1	1
1	0	1
1	1	0

Quantum Circuit for joint measurement

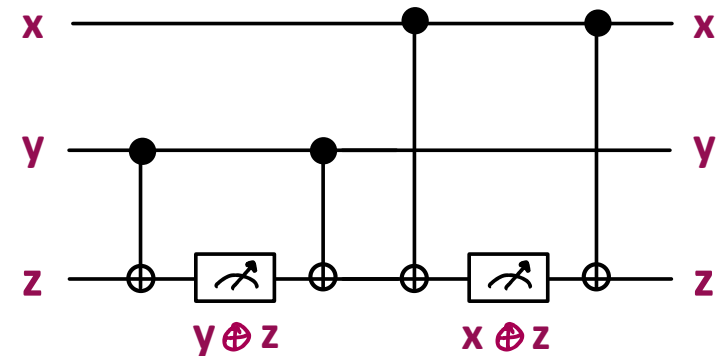


Measurement in $\{|0\rangle, |1\rangle\}$ basis yields $C \oplus T$

Circuit maps logical basis states as



Full circuit to obtain Error Syndrome

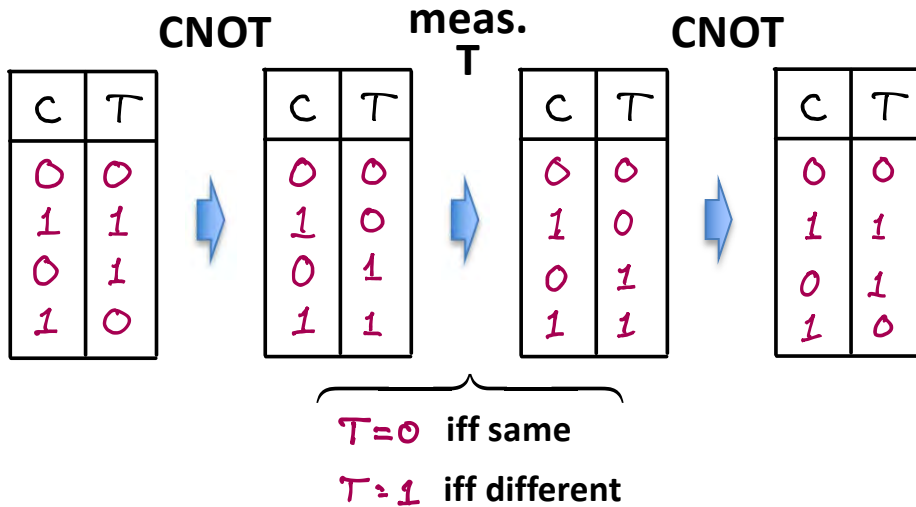


* iff qubit flip, binary address = $(y \oplus z, x \oplus z)$

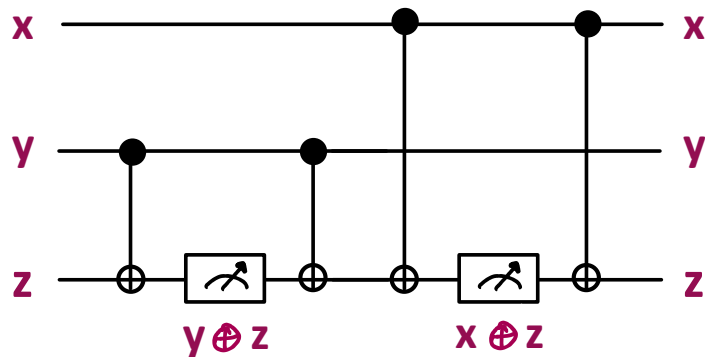
Introduction and Overview (Preskills Notes)

9-05-2024

Circuit maps logical basis states as



Full circuit to obtain Error Syndrome



* iif qubit flip, binary address = $(y \oplus z, x \oplus z)$

Quantum Phase Error

$$|0\rangle \rightarrow |0\rangle$$

$$|1\rangle \rightarrow -|1\rangle$$

Encoding

$$|0\rangle \rightarrow |\bar{0}\rangle = \frac{1}{2^{3/2}} (|0\rangle + |1\rangle)(|0\rangle + |1\rangle)(|0\rangle + |1\rangle)$$

$$|1\rangle \rightarrow |\bar{1}\rangle = \frac{1}{2^{3/2}} (|0\rangle - |1\rangle)(|0\rangle - |1\rangle)(|0\rangle - |1\rangle)$$

Relabel

$$\frac{1}{\sqrt{2}} (|0\rangle + |1\rangle) = |0'\rangle$$

$$\frac{1}{\sqrt{2}} (|0\rangle - |1\rangle) = |1'\rangle$$

Measure in basis

$$\{|0'\rangle, |1'\rangle\} \rightarrow y' \oplus z', x' \oplus z'$$

Error Syndrome

* Iff phase error, binary address = $(y' \oplus z', x' \oplus z')$

* Analogous to bit-flip code, just in different basis

Quantum Phase Error

$$\begin{aligned} |0\rangle &\rightarrow |0\rangle \\ |1\rangle &\rightarrow -|1\rangle \end{aligned}$$

Encoding

$$\begin{aligned} |0\rangle &\rightarrow |\bar{0}\rangle = \frac{1}{2^{3/2}} (|0\rangle + |1\rangle) (|0\rangle + |1\rangle) (|0\rangle + |1\rangle) \\ |1\rangle &\rightarrow |\bar{1}\rangle = \frac{1}{2^{3/2}} (|0\rangle - |1\rangle) (|0\rangle - |1\rangle) (|0\rangle - |1\rangle) \end{aligned}$$

Relabel

$$\begin{aligned} \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle) &= |0'\rangle \\ \frac{1}{\sqrt{2}} (|0\rangle - |1\rangle) &= |1'\rangle \end{aligned}$$

Measure in basis

$$\{|0'\rangle, |1'\rangle\} \rightarrow y' \oplus z', x' \oplus z'$$

Error Syndrome

- * Iff phase error, binary address = $(y' \oplus z', x' \oplus z')$
- * Analogous to bit-flip code, just in different basis

Shor's 9-bit code

- * Combines flip/phase error correction
- * Corrects one flip or phase error

General principle of error correction

- * Encode p logical qubits in n physical qubits.
- * Valid Logical States form 2^p -dimensional subspace \mathcal{E}_p (code space) in n -qubit (2^n -dimensional) Hilbert space \mathcal{E}_n
- * Errors displace system into orthogonal (distinguishable) subspaces.

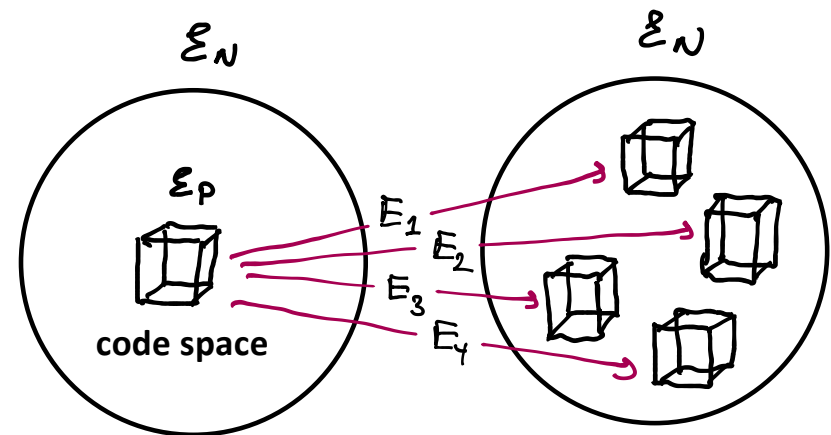
Shor's 9-bit code

- * Combines flip/phase error correction
- * Corrects one flip or phase error

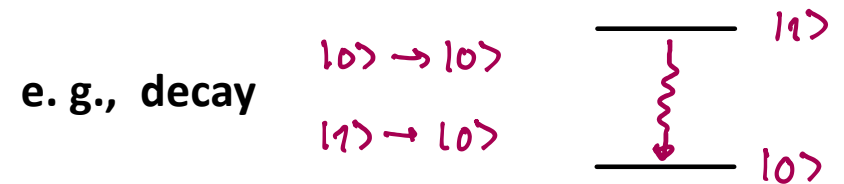
General principle of error correction

- * Encode p logical qubits in n physical qubits.
- * Valid Logical States form 2^p -dimensional subspace \mathcal{E}_p (code space) in n -qubit (2^n -dimensional) Hilbert space \mathcal{E}_n
- * Errors displace system into orthogonal (distinguishable) subspaces.

Geometric illustration



What about non-Unitary errors?



- Problem: Errors not displaced into orthogonal subspaces
- Solution: "Quantum jump codes", monitors the environment

Other kinds of errors?

Introduction and Overview (Preskills Notes)

9-05-2024

Catnip for Theoretical Physicists & Computer Scientists

The screenshot shows the arXiv search results page for the query "quantum error correction". The page displays 3451-3479 of 3,479 results. The search bar contains the query "quantum error correction" and the search button is labeled "Search". The page is set to show 50 results per page, sorted by "Announcement date (newest first)". The current page is 70, with navigation buttons for "Previous" and "1" through "70".

Showing 3451–3479 of 3,479 results for all: quantum error correction

quantum error correction All fields Search

Show abstracts Hide abstracts

50 results per page. Sort results by Announcement date (newest first) Go

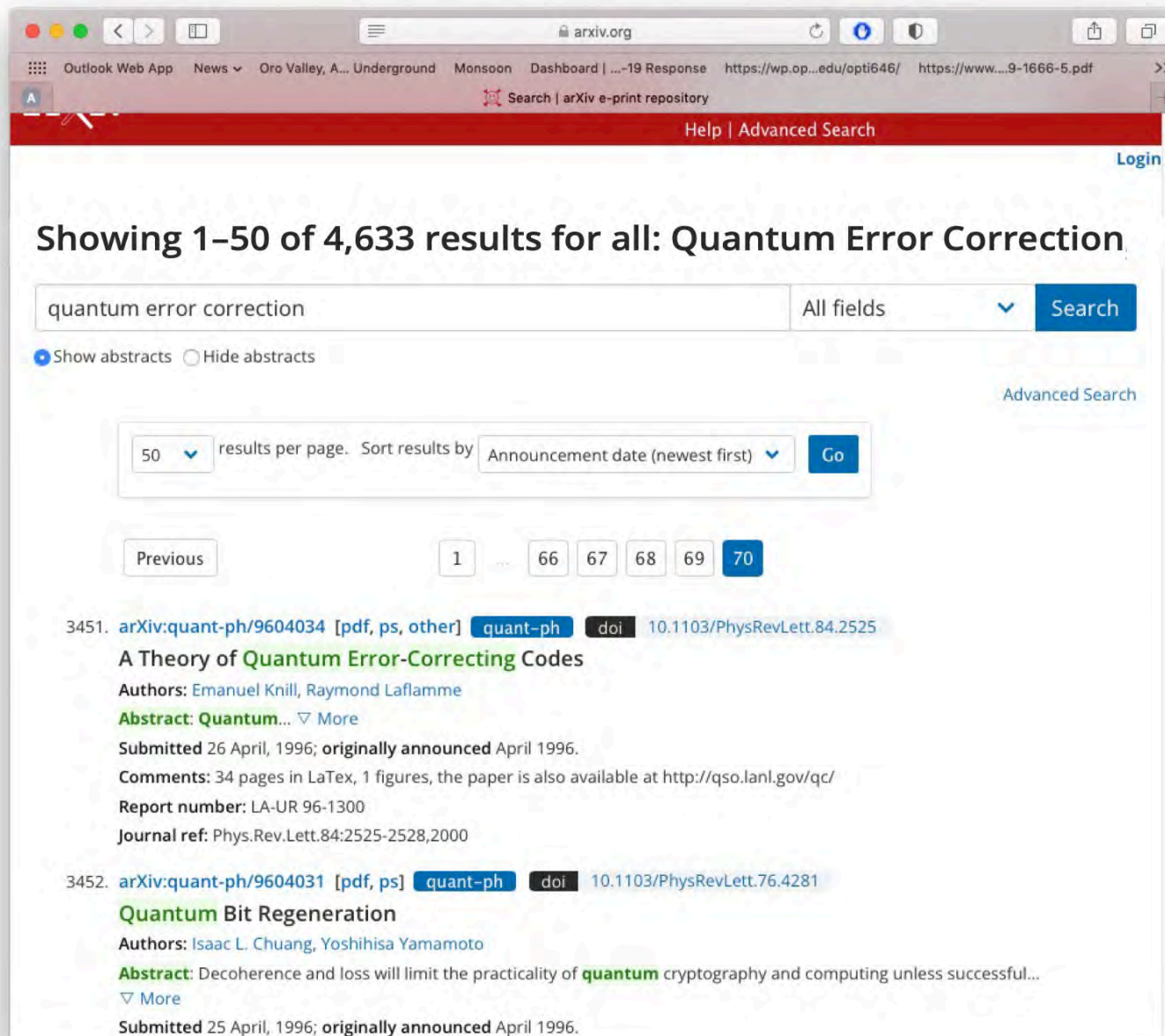
Previous 1 66 67 68 69 70

3451. [arXiv:quant-ph/9604034](#) [pdf, ps, other] [quant-ph](#) [doi](#) 10.1103/PhysRevLett.84.2525
A Theory of Quantum Error-Correcting Codes
Authors: Emanuel Knill, Raymond Laflamme
Abstract: Quantum... [More](#)
Submitted 26 April, 1996; originally announced April 1996.
Comments: 34 pages in LaTeX, 1 figures, the paper is also available at <http://qso.lanl.gov/qc/>
Report number: LA-UR 96-1300
Journal ref: Phys.Rev.Lett.84:2525-2528,2000

3452. [arXiv:quant-ph/9604031](#) [pdf, ps] [quant-ph](#) [doi](#) 10.1103/PhysRevLett.76.4281
Quantum Bit Regeneration
Authors: Isaac L. Chuang, Yoshihisa Yamamoto
Abstract: Decoherence and loss will limit the practicality of quantum cryptography and computing unless successful...
[More](#)
Submitted 25 April, 1996; originally announced April 1996.

Introduction and Overview (Preskills Notes)

Catnip for Theoretical Physicists & Computer Scientists



The screenshot shows the arXiv search results page for the query "quantum error correction". The page displays 4,633 results, with the first 50 shown. The search results are sorted by "Announcement date (newest first)". The first two results are highlighted:

- 3451. [arXiv:quant-ph/9604034](https://arxiv.org/abs/quant-ph/9604034) [pdf, ps, other] [quant-ph](#) [doi](#) 10.1103/PhysRevLett.84.2525
A Theory of Quantum Error-Correcting Codes
Authors: Emanuel Knill, Raymond Laflamme
Abstract: Quantum... [More](#)
Submitted 26 April, 1996; originally announced April 1996.
Comments: 34 pages in LaTeX, 1 figures, the paper is also available at <http://qso.lanl.gov/qc/>
Report number: LA-UR 96-1300
Journal ref: Phys.Rev.Lett.84:2525-2528,2000
- 3452. [arXiv:quant-ph/9604031](https://arxiv.org/abs/quant-ph/9604031) [pdf, ps] [quant-ph](#) [doi](#) 10.1103/PhysRevLett.76.4281
Quantum Bit Regeneration
Authors: Isaac L. Chuang, Yoshihisa Yamamoto
Abstract: Decoherence and loss will limit the practicality of quantum cryptography and computing unless successful...
[More](#)
Submitted 25 April, 1996; originally announced April 1996.

Quantum Hardware

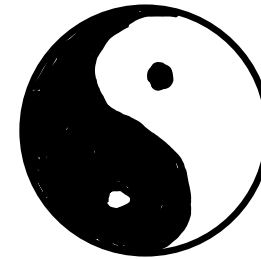
Physical Implementation is
Extremely demanding !

Requirements

1. Storage: Quantum memory.
2. Gates: We put computation U_f together from 1 and 2-qubit operations.
3. Readout: Method to measure qubits.
4. Isolation: No coupling to environment to avoid decoherence & errors
5. Precision: Gates, readouts must be highly accurate

Inherent Contradictions

2. Gates **vs** 4. Isolation
- ↑ ↑
- coupling between qubits no coupling to environment



To build a Quantum Computer:

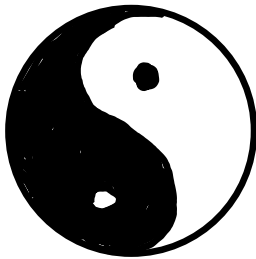
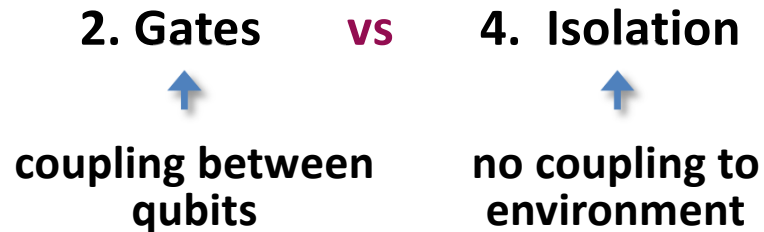
Choose, find or invent a system with acceptable tradeoffs.

6. Error Correction must not create more errors than it corrects.



7. Thresholds for Error Correction and Fault Tolerance

Inherent Contradictions



To build a Quantum Computer:

Choose, find or invent a system with acceptable tradeoffs.

6. Error Correction must not create more errors than it corrects.

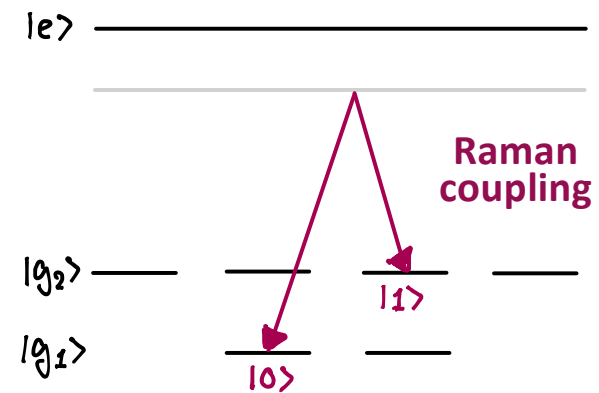


7. Thresholds for Error Correction and Fault Tolerance

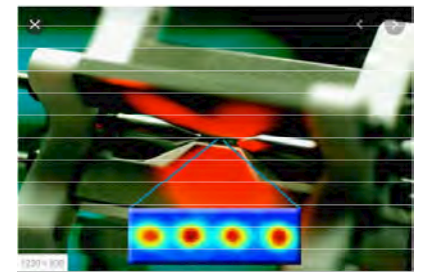
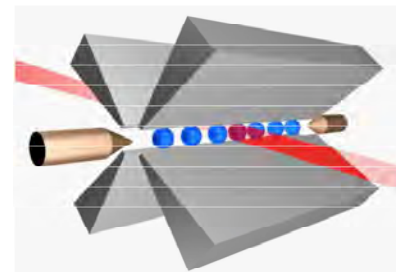
Ion Trap Quantum Computing

First to demonstrate a Quantum Gate

- * Qubit is encoded in the electronic ground state of an atomic ion



- * Early design with a few ions in large trap

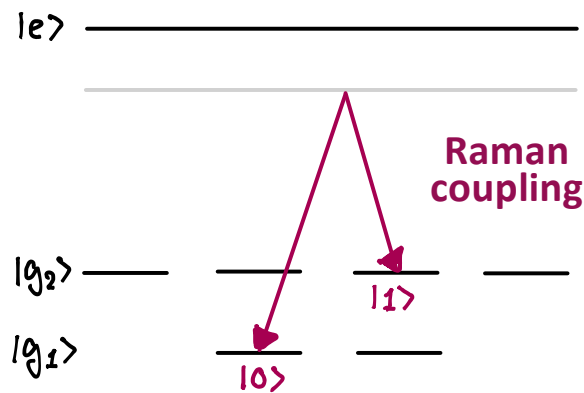


Introduction and Overview (Preskills Notes)

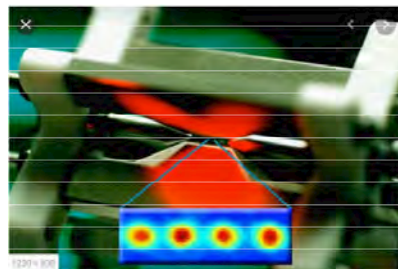
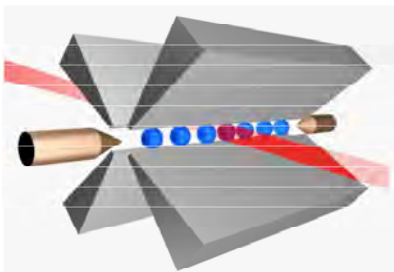
Ion Trap Quantum Computing

First to demonstrate a Quantum Gate

- * Qubit is encoded in the electronic ground state of an atomic ion



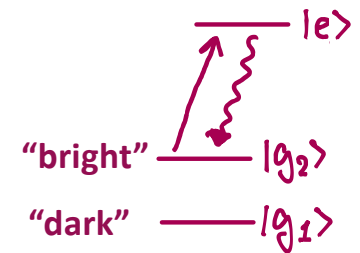
- * Early design with a few ions in large trap



Requirements

1. Storage: 10s-100s coherence time
2. Gates: Use collective vibrations as "quantum bus"

3. Readout: Fluorescence



Cirac & Zoller: 5 laser pulses

CNOT gate between any 2 ions in linear array

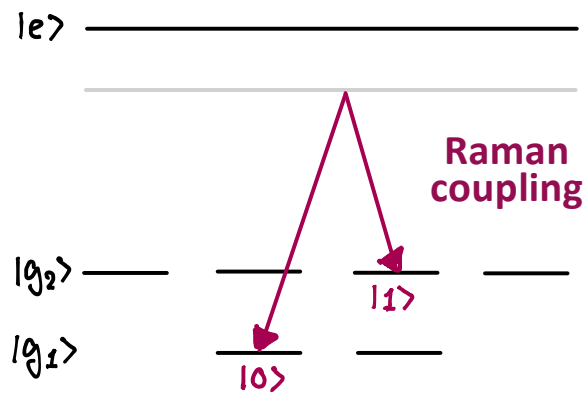
Wineland: 3 laser pulses enough for CNOT

Use this example serves as conceptual template

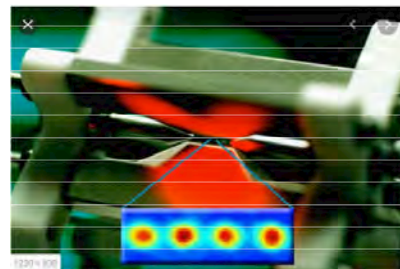
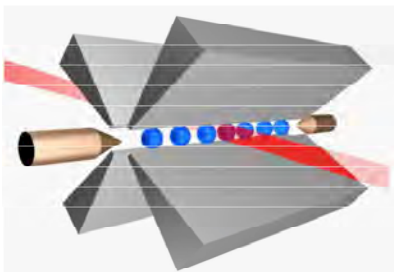
Ion Trap Quantum Computing

First to demonstrate a Quantum Gate

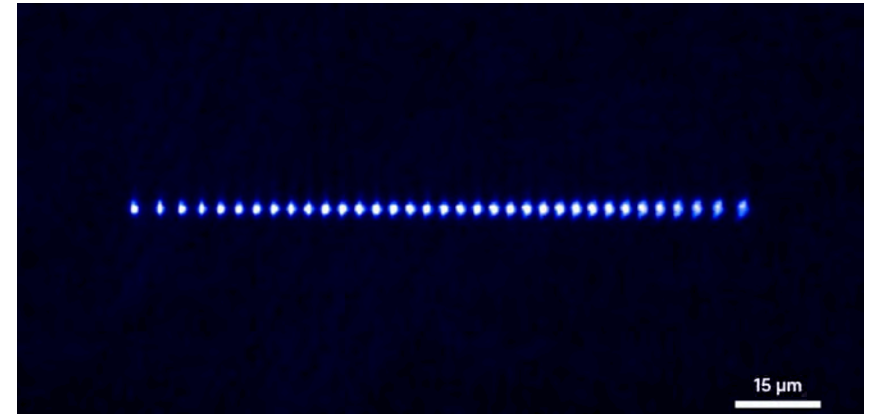
- * Qubit is encoded in the electronic ground state of an atomic ion



- * Early design with a few ions in large trap



- * Scaling up in Linear Ion Traps



- * Limitations

