Introduction and Overview (Preskills Notes)

Quantum Error Correction

Fundamental Problem

Quantum States are fragile, especially when entangled

Classical Computation ? Dissipation helps

No dissipation ➡ Errors build up

Quantum Computation ➡

- Cannot tolerate dissipation
- Destroys superposition and entanglement

What to do ? Error Correction !

Classical Error Correction:

Simple example: Redundancy protects against bit flips

Encode:

0 → (000)

1 → (111)

Errors:

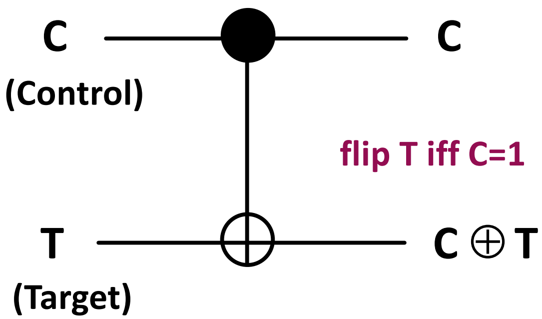
(000) → (100)

(111) → (011)

correct by majority vote

Introduction and Overview (Preskills Notes)

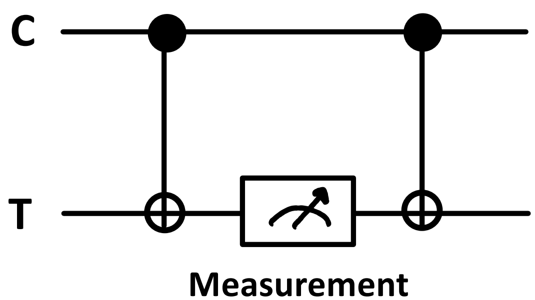
Controlled-NOT (CNOT)



Truth Table

C	T	C ⊕ T
0	0	0
0	1	1
1	0	1
1	1	0

Quantum Circuit for joint measurement



$\{|0\rangle, |1\rangle\}$

yields $C \oplus T$

Circuit maps logical basis states as

C	T
0	0
1	1
0	1
1	0

CNOT →

C	T
0	0
1	0
0	1
1	1

meas. T →

C	T
0	0
1	0
0	1
1	1

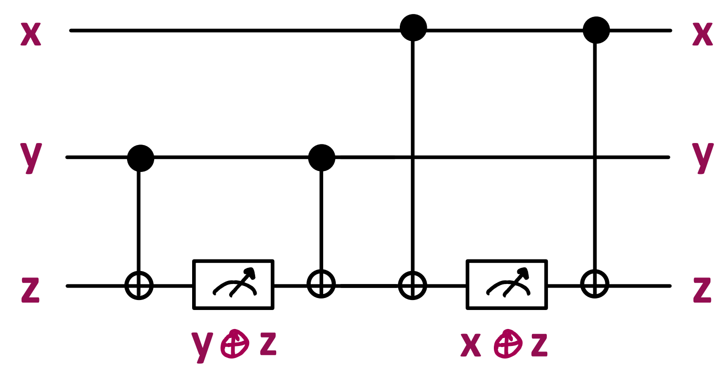
CNOT →

C	T
0	0
1	1
0	1
1	0

$T=0$ iff same

$T=1$ iff different

Full circuit to obtain Error Syndrome



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

Introduction and Overview (Preskills Notes)

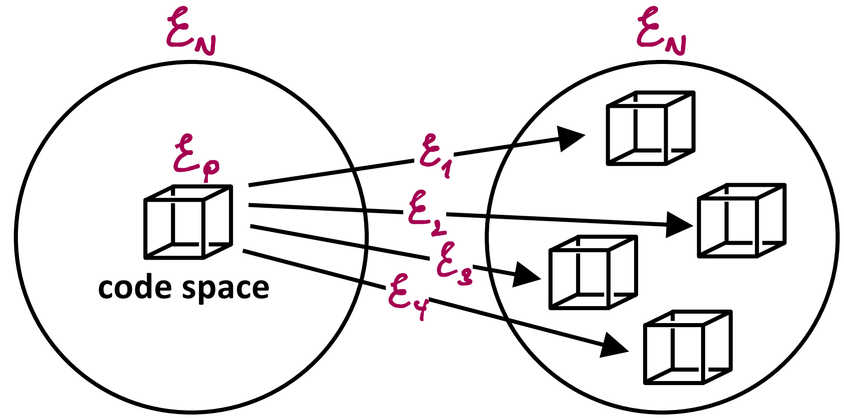
Shor's 9-bit code

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

General principle of error correction

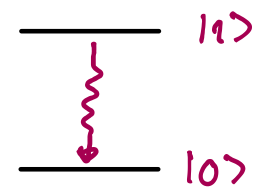
- ∗ Encode *p* logical qubits in *n* physical qubits.
- ∗ Valid Logical States form 2^p–dimensional subspace $\mathcal{E}_p$ (code space) in *n*-qubit (2^n–dimensional) Hilbert space $\mathcal{E}_N$
- ∗ Errors displace system into orthogonal (distinguishable) subspaces.

Geometric illustration



What about non-Unitary errors?

e. g., decay $|0\rangle \rightarrow |0\rangle$, $|1\rangle \rightarrow |0\rangle$



Problem: Errors not displaced into orthogonal subspaces

Solution: "Quantum jump codes", monitors the environment

Other kinds of errors?

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1. arXiv:quant-ph/9511003 [pdf, ps, other] quant-ph

Quantum Error Correction by Coding

Authors: I. L. Chuang, R. Laflamme

Abstract: ...cryptography and quantum computers has given hope to their imminent practical realization. An essential element at the heart of the application of these quantum systems is a **quantum error correction** scheme. We propose a new technique based on the use of coding in order to detect... ▽ More

Submitted 3 November, 1995; **originally announced** November 1995.

Comments: 11 pages RevTeX + 2 figures in postscript; Please see http://feynman.stanford.edu/qcomp/ for figures.

2. arXiv:quant-ph/9512032 [pdf, ps, other] quant-ph doi 10.1103/PhysRevA.54.1098

Good Quantum Error-Correcting Codes Exist

Authors: A. R. Calderbank, Peter W. Shor

Abstract: A **quantum**... ▽ More

Submitted 16 April, 1996; **v1** submitted 30 December, 1995; **originally announced** December 1995.

Comments: Latex, 23 pages, 1 figure. Revised April 1996 to give more intuition and an example. Submitted to Phys. Rev. A

Journal ref: Phys. Rev. A, Vol. 54, No. 2, pp. 1098-1106, 1996

3. arXiv:quant-ph/9601029 [pdf, ps, other] quant-ph doi 10.1098/rspa.1996.0136

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1. arXiv:2309.00225 [pdf] cond-mat.mes-hall quant-ph

Rapid single-shot parity spin readout in a silicon double quantum dot with fidelity exceeding 99 %

Authors: Kenta Takeda, Akito Noiri, Takashi Nakajima, Leon C. Camenzind, Takashi Kobayashi, Amir Sammak, Giordano Scappucci, Seigo Tarucha

Abstract: ...(with >99% fidelity) parity spin measurement in a silicon double quantum dot. These results represent a significant step forward toward implementing measurement-based **quantum error correction** in silicon. ▽ More

Submitted 31 August, 2023; **originally announced** September 2023.

2. arXiv:2308.16233 [pdf, other] quant-ph

Bounds on Autonomous Quantum Error Correction

Authors: Oles Shtanko, Yu-Jie Liu, Simon Lieu, Alexey V. Gorshkov, Victor V. Albert

Abstract: Autonomous quantum memories are a way to passively protect quantum information using engineered dissipation that creates an "always-on" decoder. We analyze Markovian autonomous decoders that can be implemented with a wide range of qubit and bosonic error-correcting codes, and derive several upper bounds and a lower bound on the logical error rate in terms of correction and noise rates. For many-b... ▽ More

Submitted 30 August, 2023; **originally announced** August 2023.

Comments: 51 pages, 8 figures, 1 table

Introduction and Overview (Preskills Notes)

Quantum Hardware

Physical Implementation is Extremely demanding !

Requirements

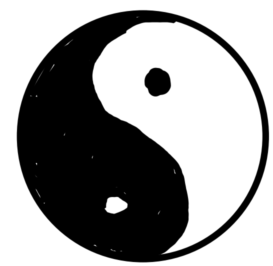
1. Storage: Quantum memory.
2. Gates: We put computation U_f together from 1 and 2-qubit operations.
3. Readout: Method to measure qubits.
4. Isolation: No coupling to environment to avoid decoherence & errors
5. Precision: Gates, readouts must be highly accurate

Inherent Contradictions

2. Gates vs **4. Isolation**

2. Gates ↑ coupling between qubits

4. Isolation ↑ no coupling to environment



To build a Quantum Computer

⇓

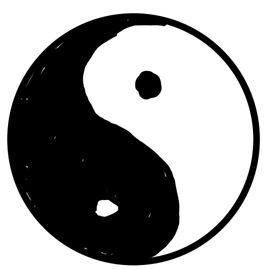
Choose, find or invent a system with acceptable tradeoffs

Introduction and Overview (Preskills Notes)

Inherent Contradictions

2. Gates vs **4. Isolation**

coupling between qubits — no coupling to environment



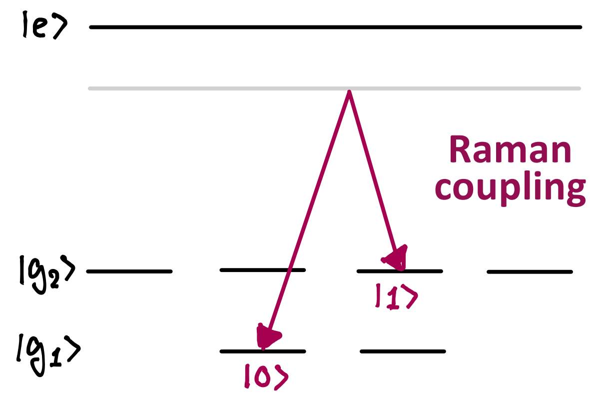
To build a Quantum Computer

Choose, find or invent a system with acceptable tradeoffs

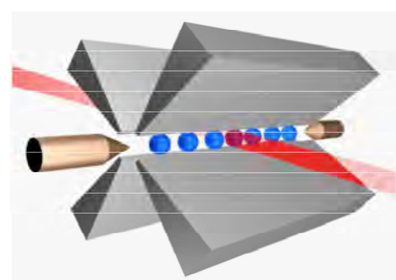
Ion Trap Quantum Computing

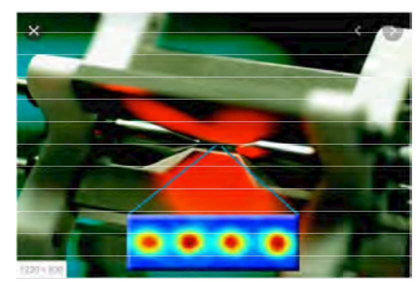
First to demonstrate a Quantum Gate

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



* Early design with a few ions in trap





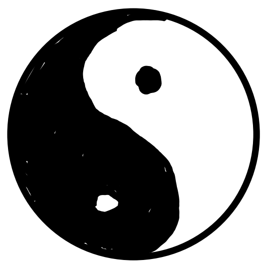
Introduction and Overview (Preskills Notes)

Inherent Contradictions

2. Gates vs **4. Isolation**

coupling between qubits ↑ (2. Gates)

no coupling to environment ↑ (4. Isolation)



To build a Quantum Computer

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Ion Trap Quantum Computing

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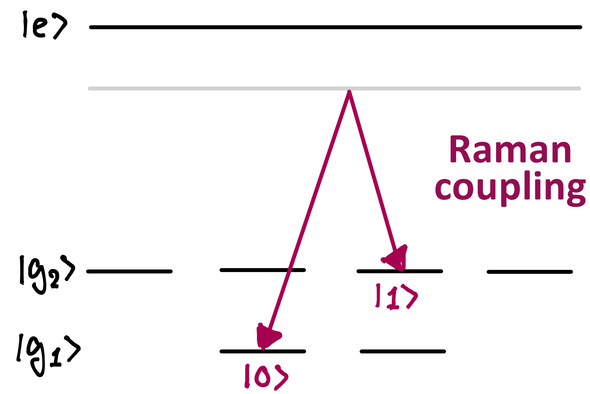
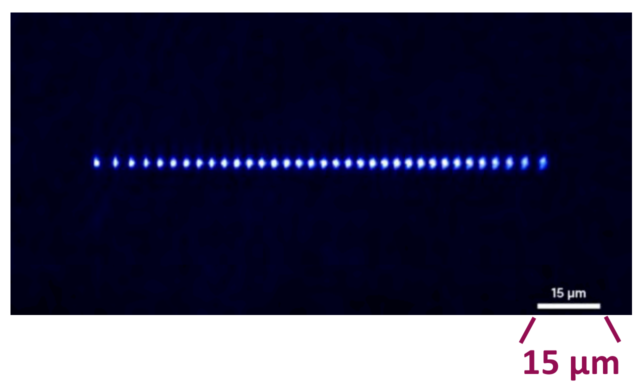


* Newer design with many ions in large trap



Introduction and Overview (Preskills Notes)

Ion Trap Quantum Computing

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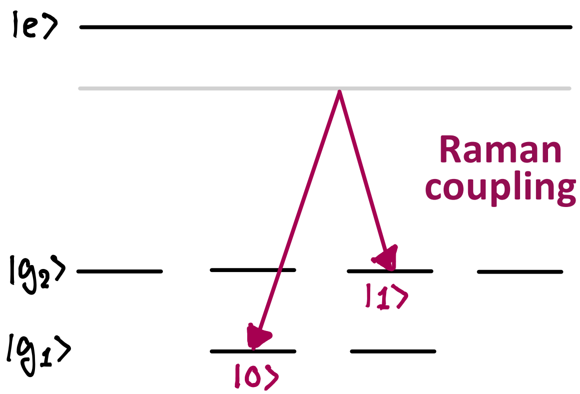

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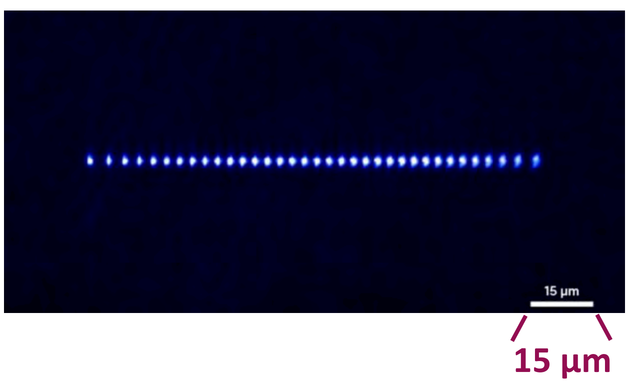
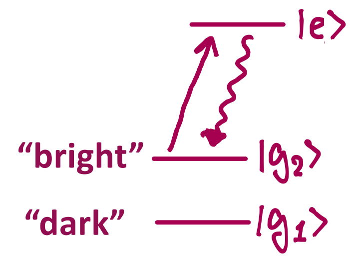


Requirements

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

Introduction and Overview (Preskills Notes)

Requirements

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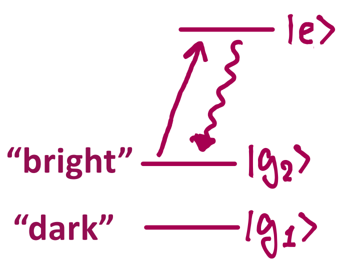

Cirac & Zoller: 5 laser pulses ⇨ CNOT gate between any 2 ions in linear array

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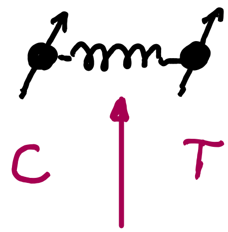
Use this example serves as conceptual template

2 – ion trap



center-of-mass mode
Is quantum bus

convention $(0 : \downarrow, 1 : \uparrow)$

CNOT input-output map:

$\vert\downarrow_C \downarrow_T\rangle \to \vert\downarrow_C \downarrow_T\rangle$ $\vert\downarrow_C \uparrow_T\rangle \to \vert\downarrow_C \uparrow_T\rangle$	$\vert\uparrow_C \downarrow_T\rangle \to \vert\uparrow_C \uparrow_T\rangle$ $\vert\uparrow_C \uparrow_T\rangle \to \vert\uparrow_C \downarrow_T\rangle$
does nothing	swaps $\vert\uparrow_C \downarrow_T\rangle$, $\vert\uparrow_C \uparrow_T\rangle$

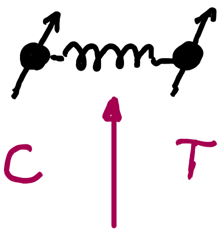
Notation for quantum states: $|n, \sigma_C^{(z)}, \sigma_T^{(z)}\rangle$

n: vibrational quantum number

$\sigma_C^{(z)}, \sigma_T^{(z)}$: spin states of C and T ions

Introduction and Overview (Preskills Notes)

2 – ion trap



center-of-mass mode
Is quantum bus

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CNOT input-output map:

$|\downarrow_C \downarrow_T\rangle \to |\downarrow_C \downarrow_T\rangle$

$|\downarrow_C \uparrow_T\rangle \to |\downarrow_C \uparrow_T\rangle$

does nothing

$|\uparrow_C \downarrow_T\rangle \to |\uparrow_C \uparrow_T\rangle$

$|\uparrow_C \uparrow_T\rangle \to |\uparrow_C \downarrow_T\rangle$

swaps $|\uparrow_C \downarrow_T\rangle, |\uparrow_C \uparrow_T\rangle$

Notation for quantum states: $|n, \sigma_C^{(z)}, \sigma_T^{(z)}\rangle$

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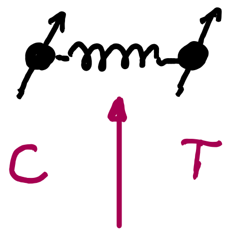
2 – ion trap

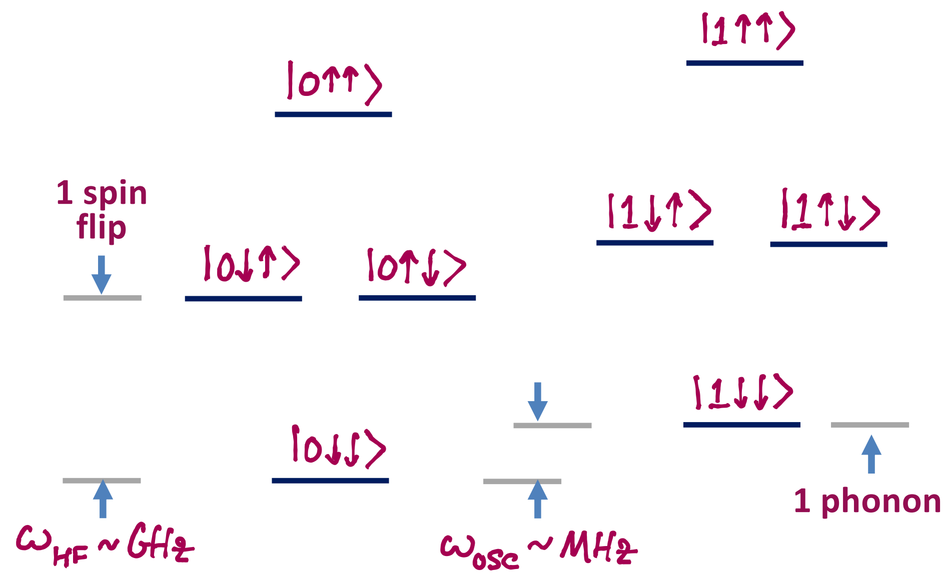


center-of-mass mode
Is quantum bus

convention

$(0 : \downarrow, 1 : \uparrow)$

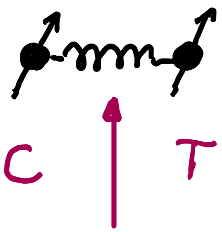
Energy Level diagram:



Notation: $|n, \sigma_C^{(z)}, \sigma_T^{(z)}\rangle$

Introduction and Overview (Preskills Notes)

2 – ion trap

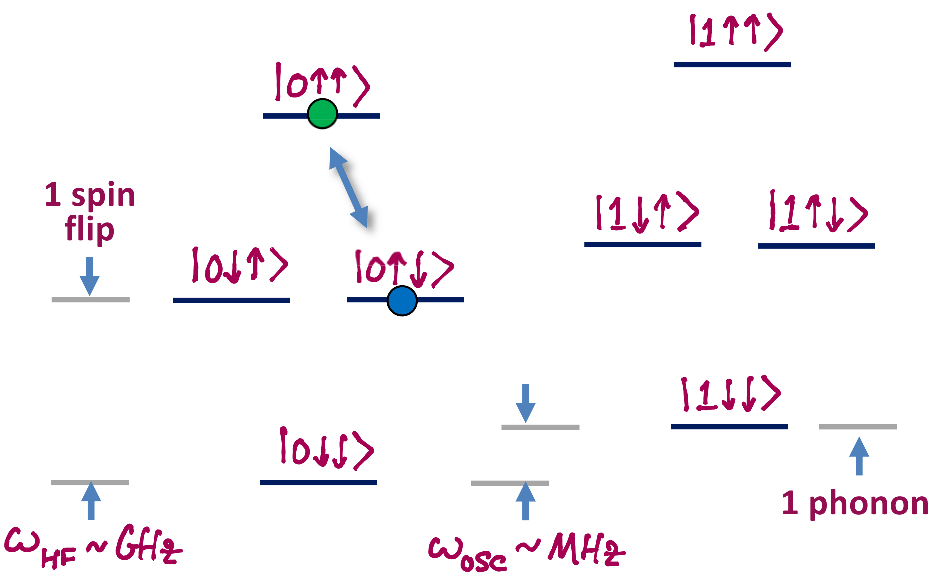


center-of-mass mode
Is quantum bus

convention

$(0 : \downarrow, 1 : \uparrow)$

Energy Level diagram:



Notation: $|n, \sigma_C^{(z)}, \sigma_T^{(z)}\rangle$

CNOT input-output map:

$|\downarrow_C \downarrow_T\rangle \rightarrow |\downarrow_C \downarrow_T\rangle$

$|\downarrow_C \uparrow_T\rangle \rightarrow |\downarrow_C \uparrow_T\rangle$

does nothing

$|\uparrow_C \downarrow_T\rangle \rightarrow |\uparrow_C \uparrow_T\rangle$

$|\uparrow_C \uparrow_T\rangle \rightarrow |\uparrow_C \downarrow_T\rangle$

swaps $|\uparrow_C \downarrow_T\rangle, |\uparrow_C \uparrow_T\rangle$

Do this and nothing else!

Laser pulse sequence:

(1) π pulse on C swaps $|0 \uparrow_C x_T\rangle \leftrightarrow |1 \downarrow_C x_T\rangle$

(2) π pulse on T swaps $|1 \downarrow_C \downarrow_T\rangle \leftrightarrow |1 \downarrow_C \uparrow_T\rangle$

(3) π pulse on C swaps $|0 \uparrow_C x_T\rangle \leftrightarrow |1 \downarrow_C x_T\rangle$

Performs CNOT Gate

Let us go through the process in detail !

- Clickthrough animantion follows -

Introduction and Overview (Preskills Notes)

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(1) π pulse on C swaps $|0 \uparrow_C x_T\rangle \leftrightarrow |1 \downarrow_C x_T\rangle$

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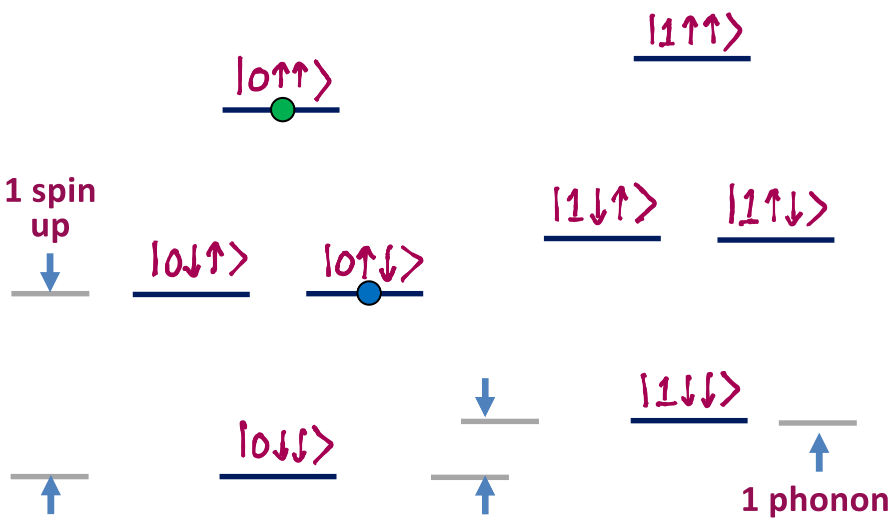

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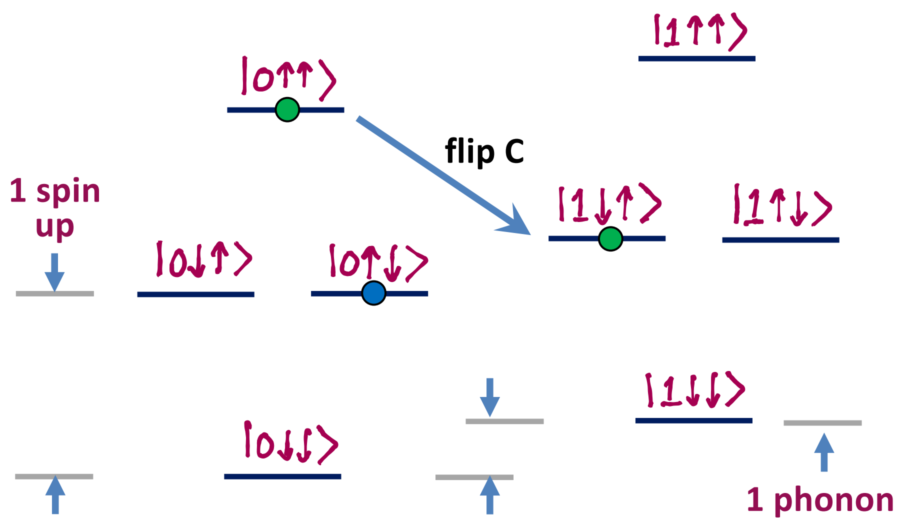

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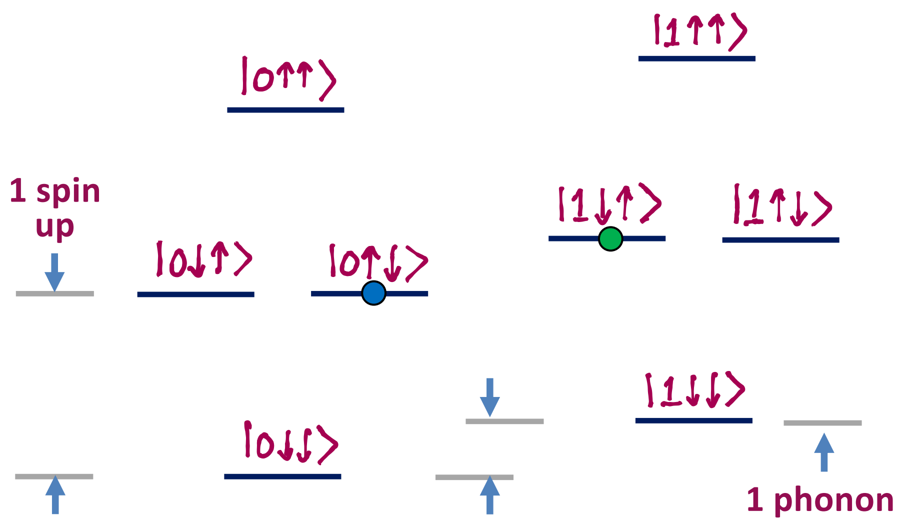

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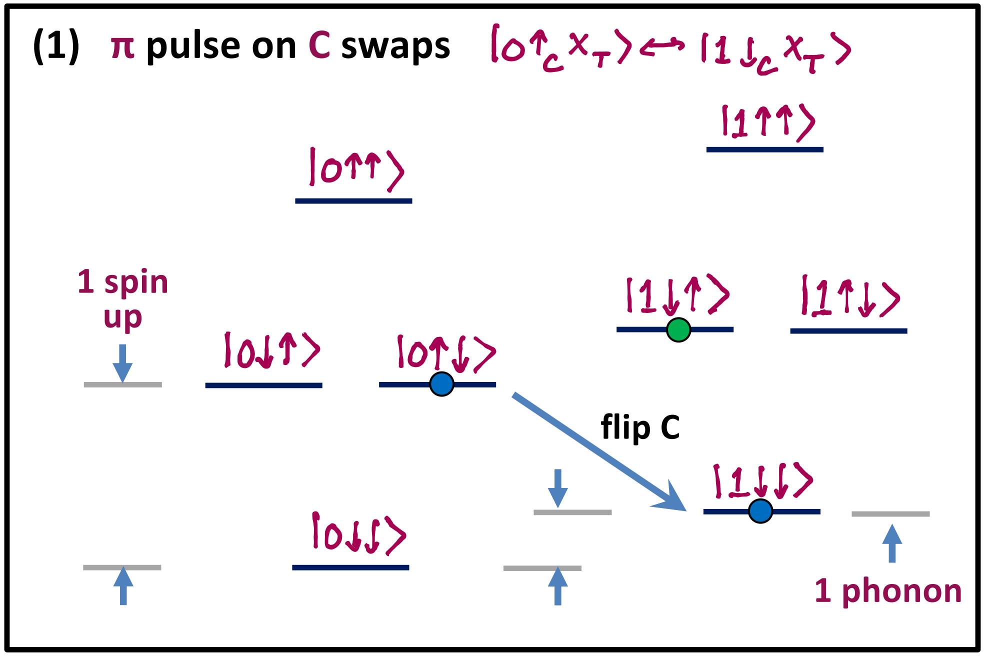

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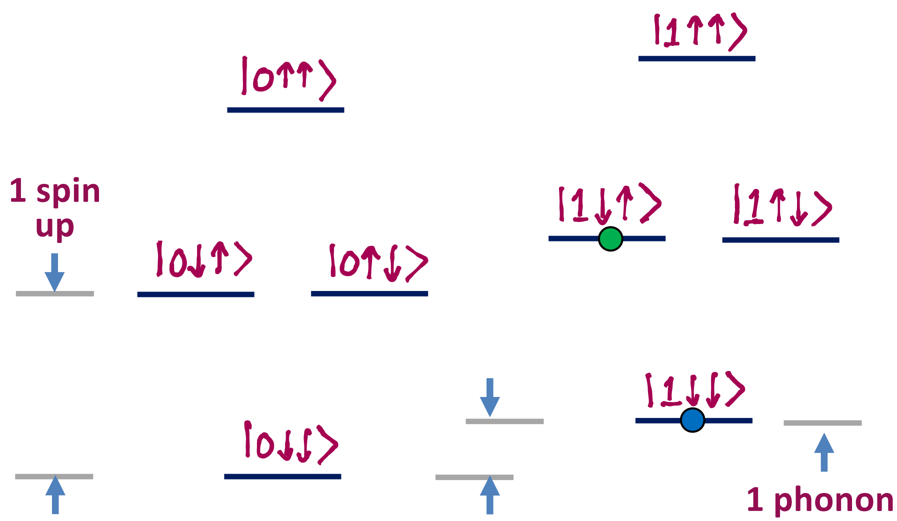

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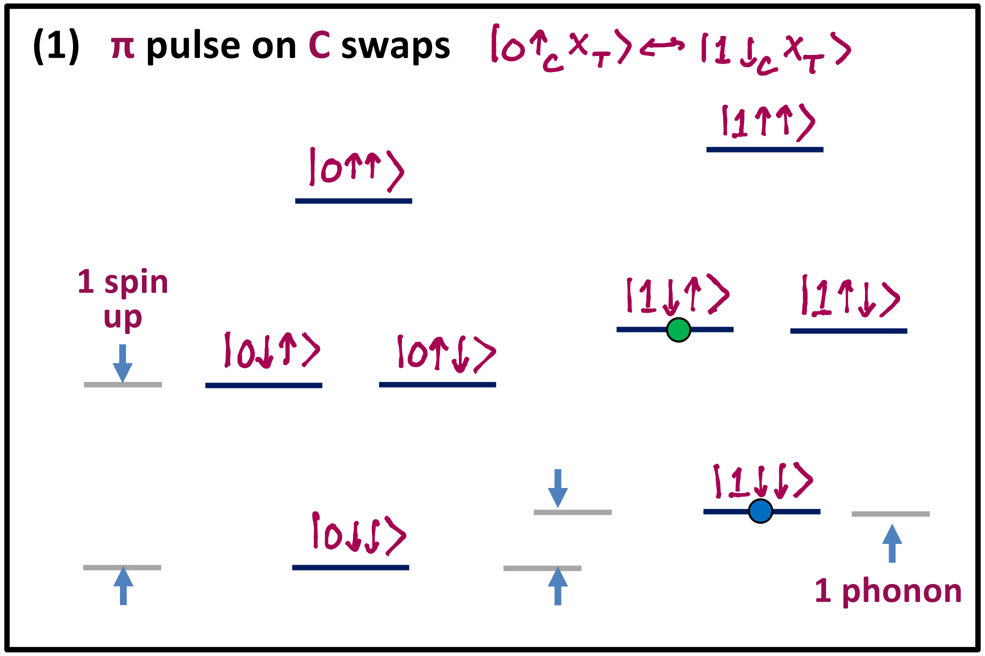

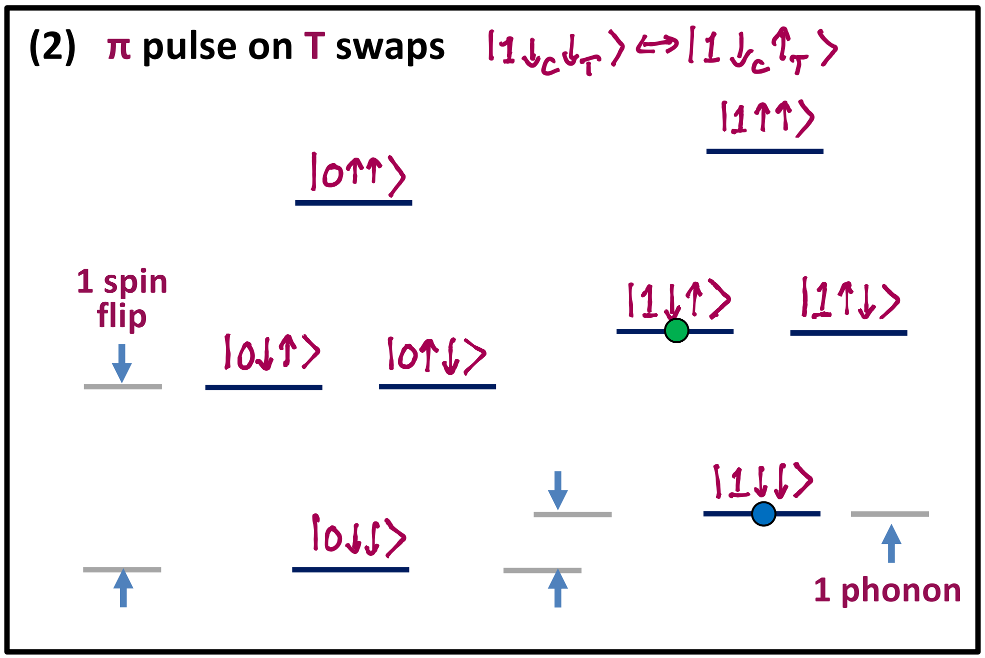

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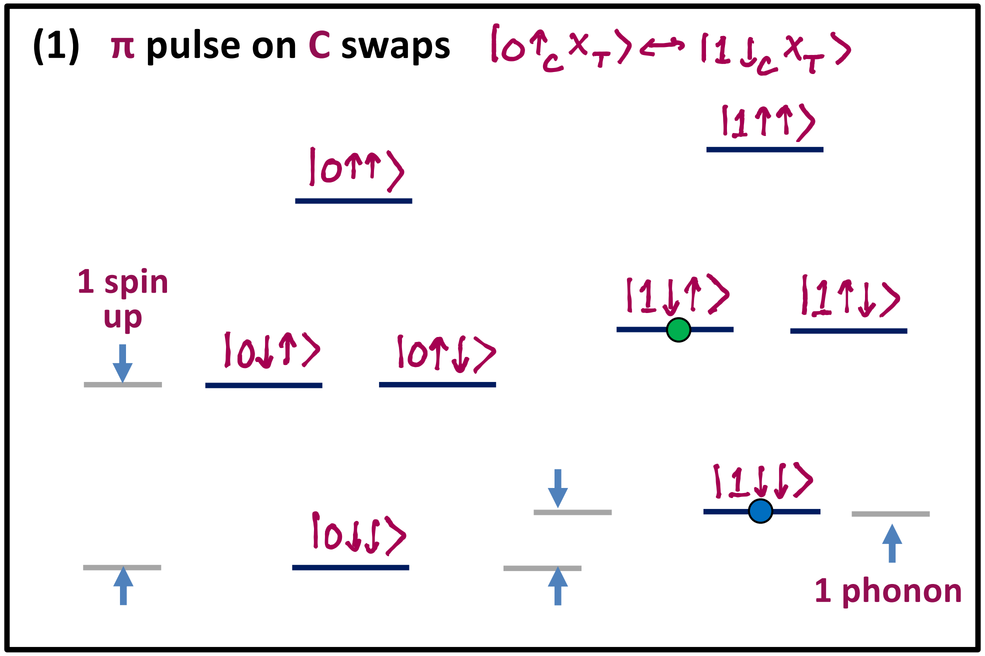

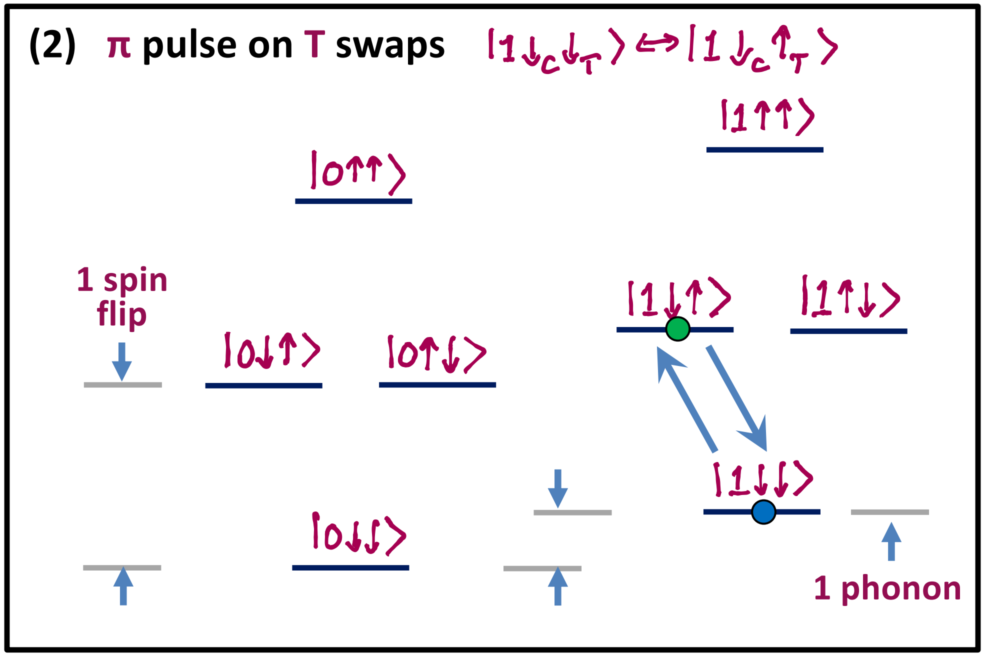

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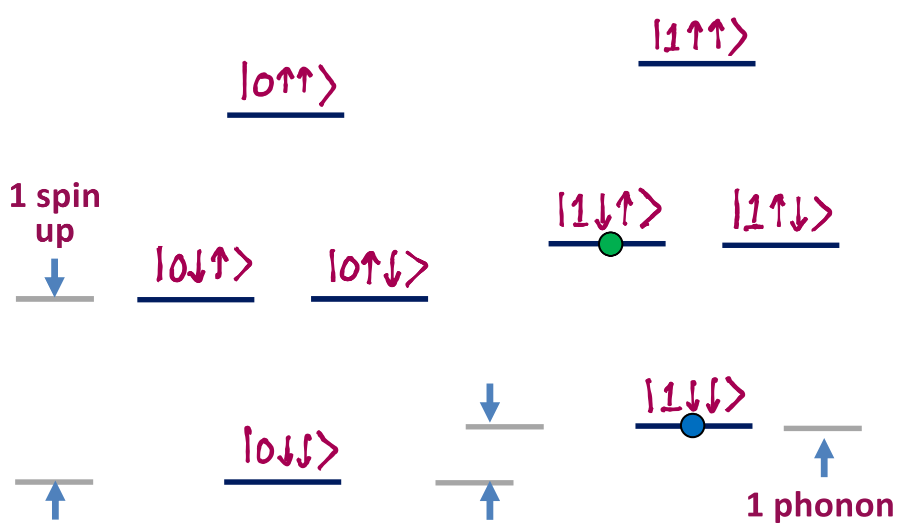
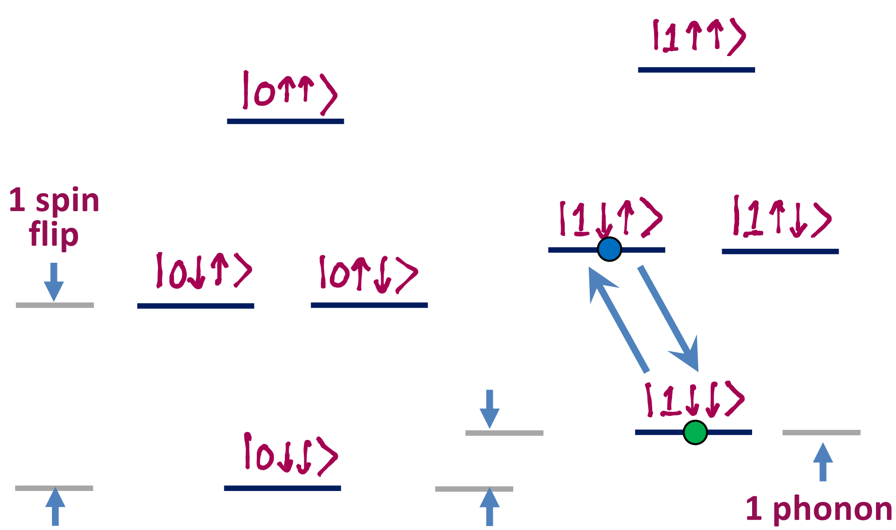


(2) π pulse on T swaps $|1\downarrow_C\downarrow_T\rangle \leftrightarrow |1\downarrow_C\uparrow_T\rangle$



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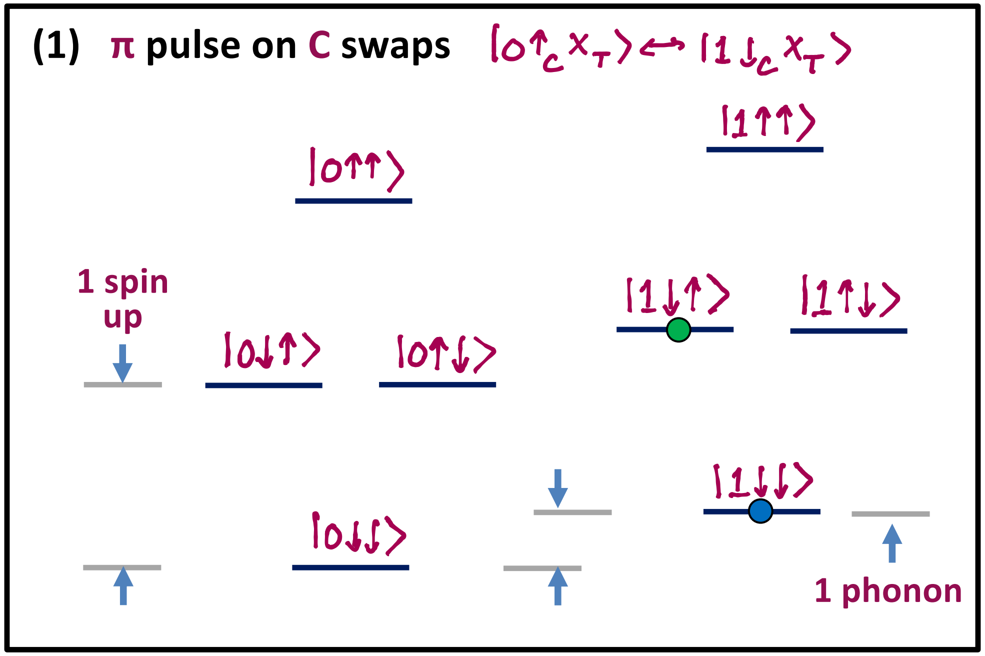

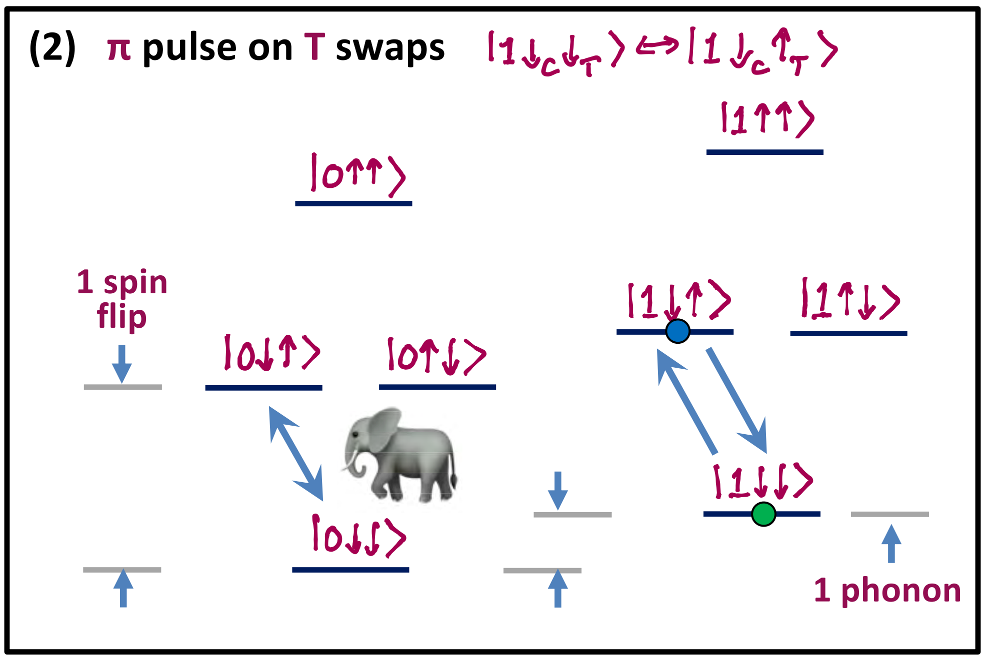

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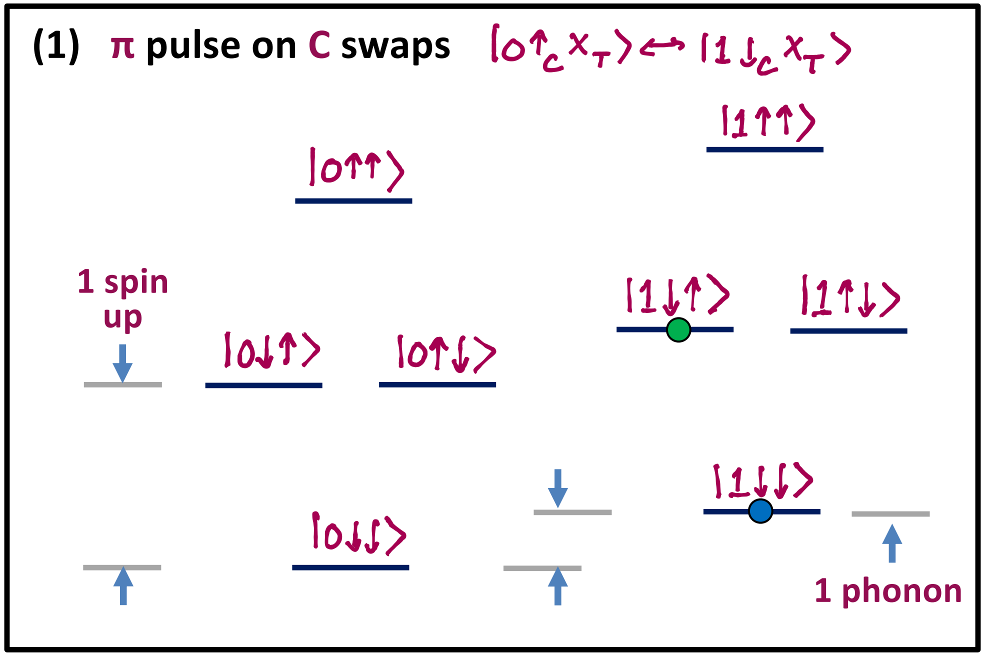
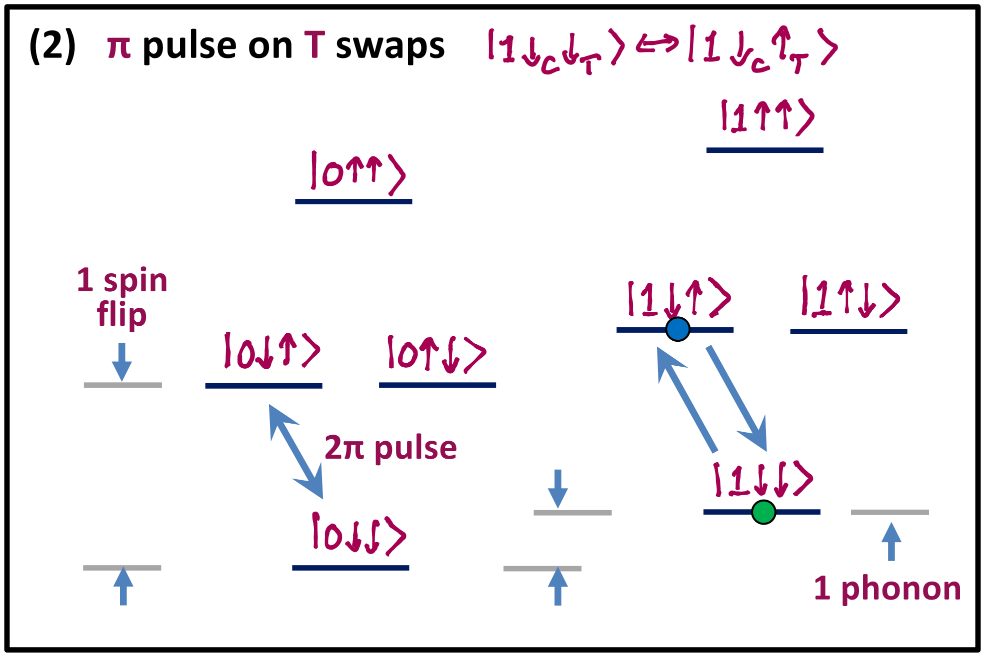
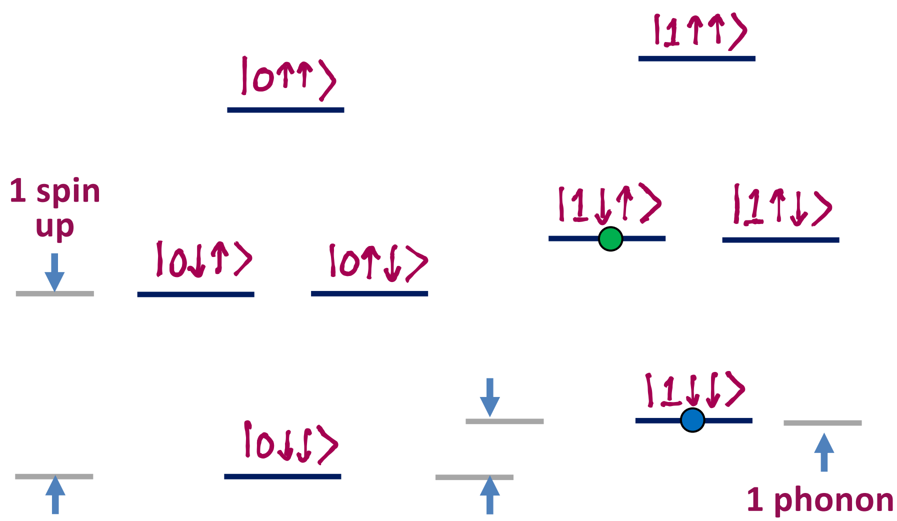


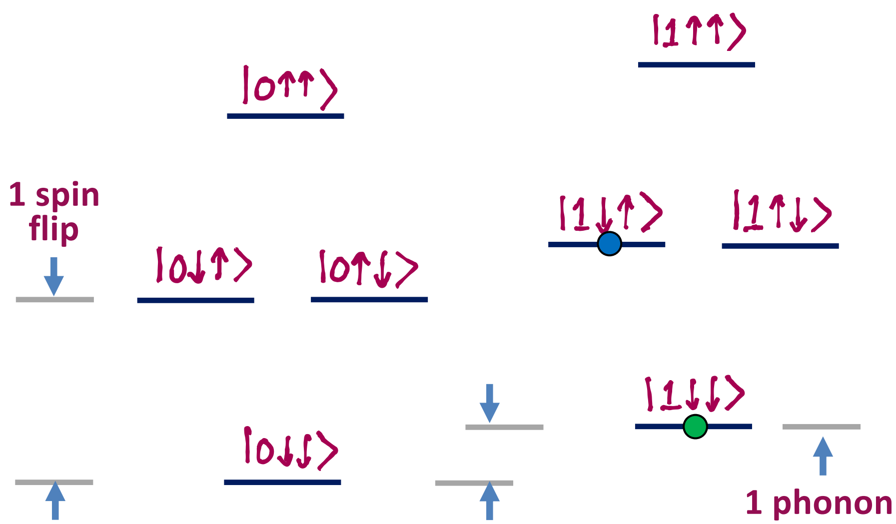


Introduction and Overview (Preskills Notes)

(1) π **pulse on C swaps** $|0\uparrow_C x_T\rangle \leftrightarrow |1\downarrow_C x_T\rangle$



(2) π **pulse on T swaps** $|1\downarrow_C\downarrow_T\rangle \leftrightarrow |1\downarrow_C\uparrow_T\rangle$



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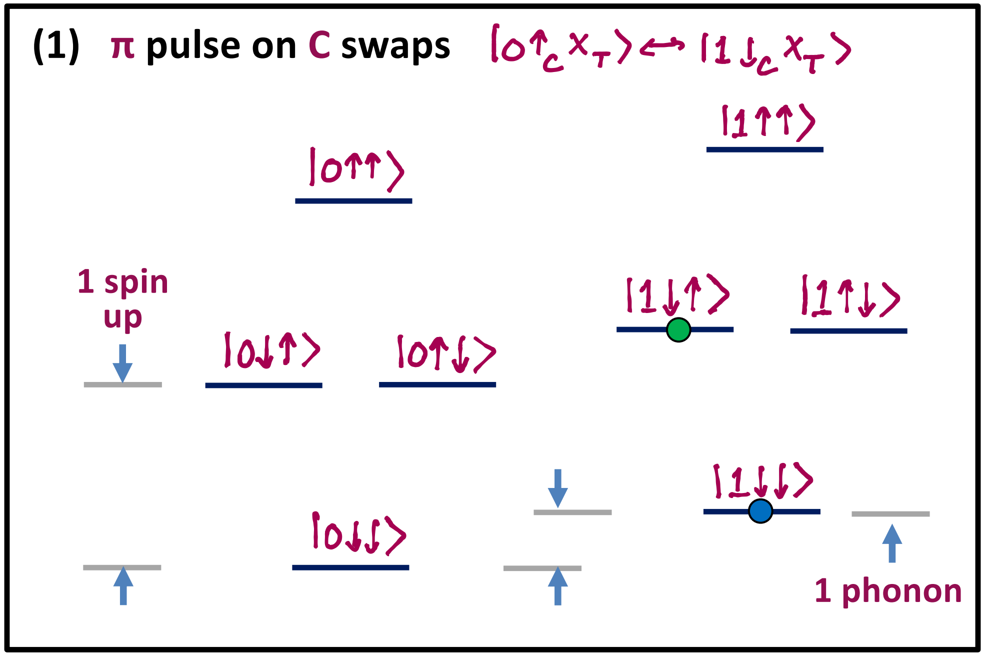
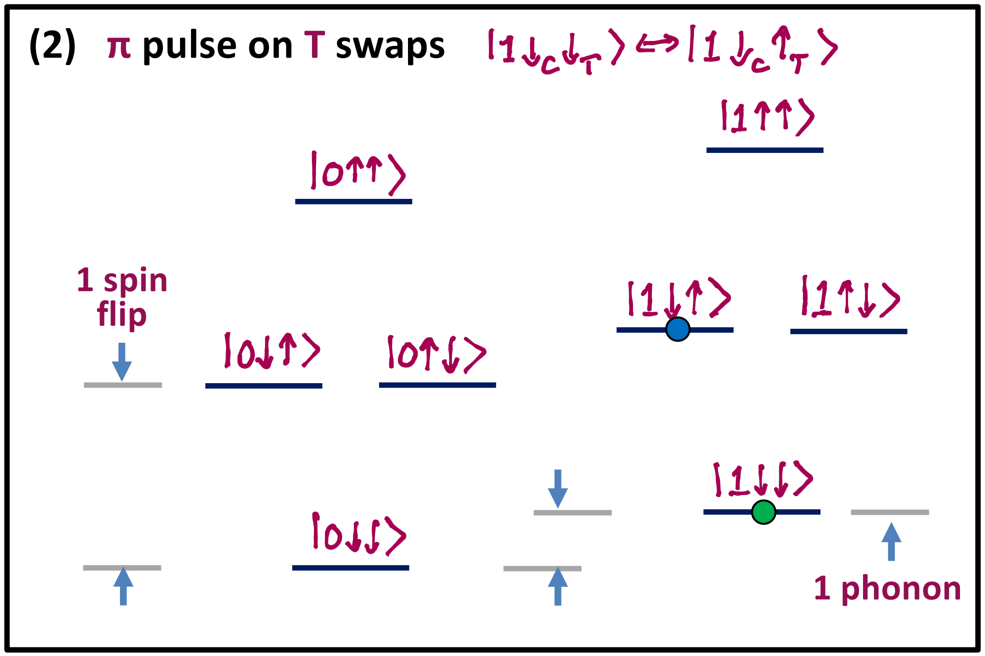
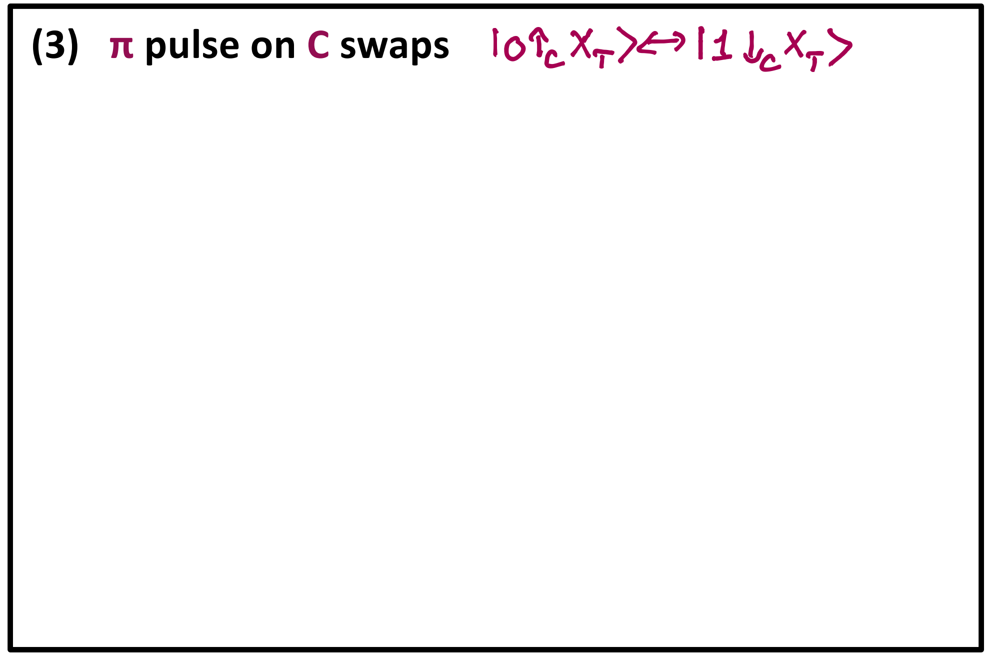
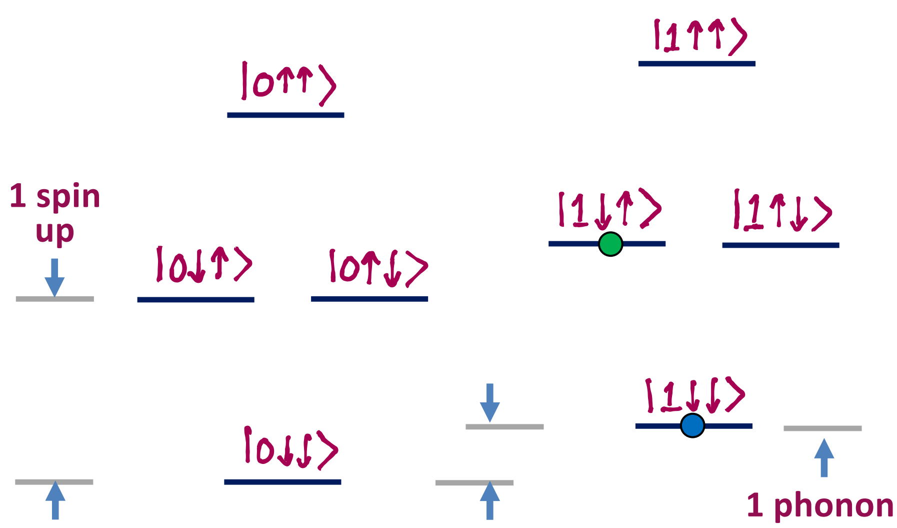




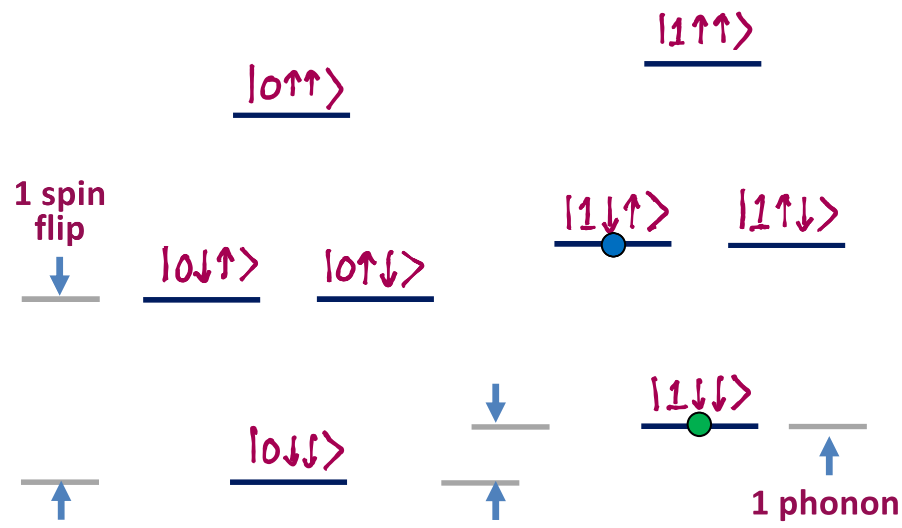


Introduction and Overview (Preskills Notes)

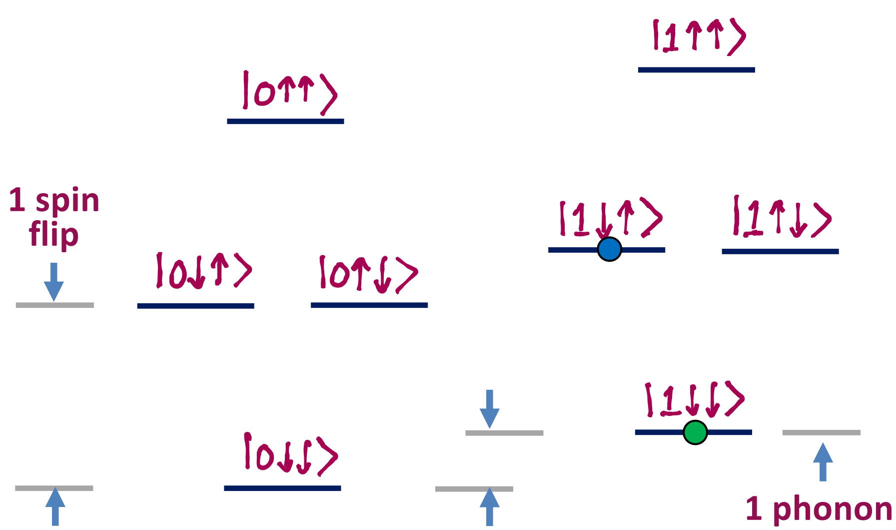
(1) π pulse on C swaps $|0\uparrow_C x_T\rangle \leftrightarrow |1\downarrow_C x_T\rangle$



(3) π pulse on C swaps $|0\uparrow_C X_T\rangle \leftrightarrow |1\downarrow_C X_T\rangle$



(2) π pulse on T swaps $|1\downarrow_C\downarrow_T\rangle \leftrightarrow |1\downarrow_C\uparrow_T\rangle$



Introduction and Overview (Preskills Notes)

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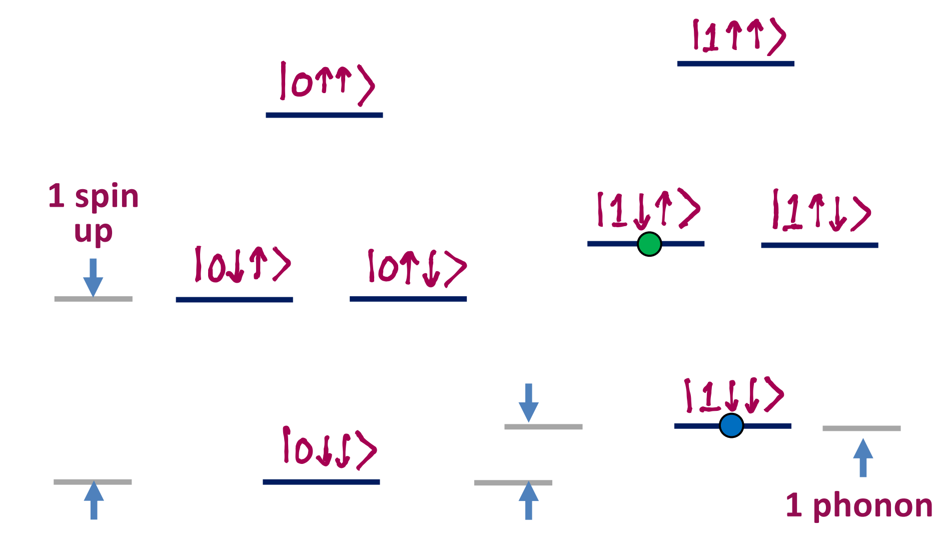

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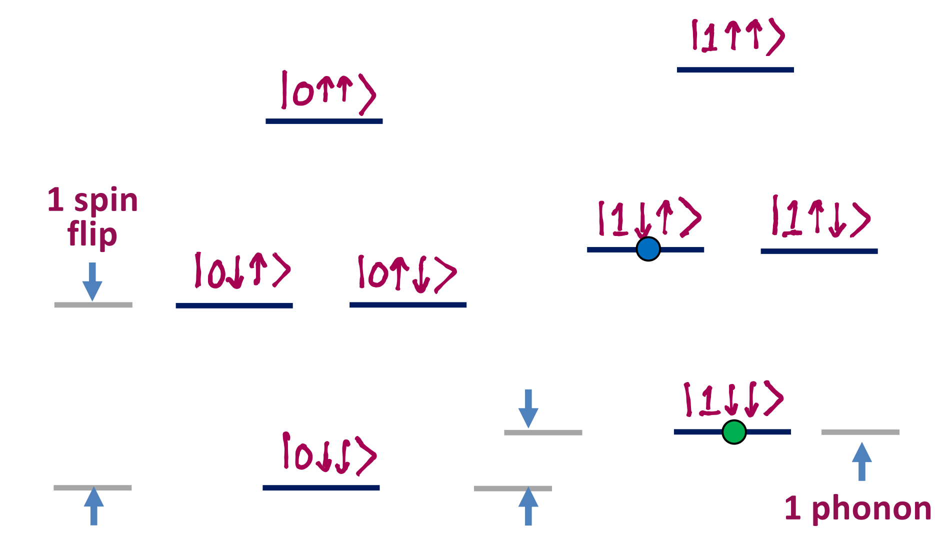
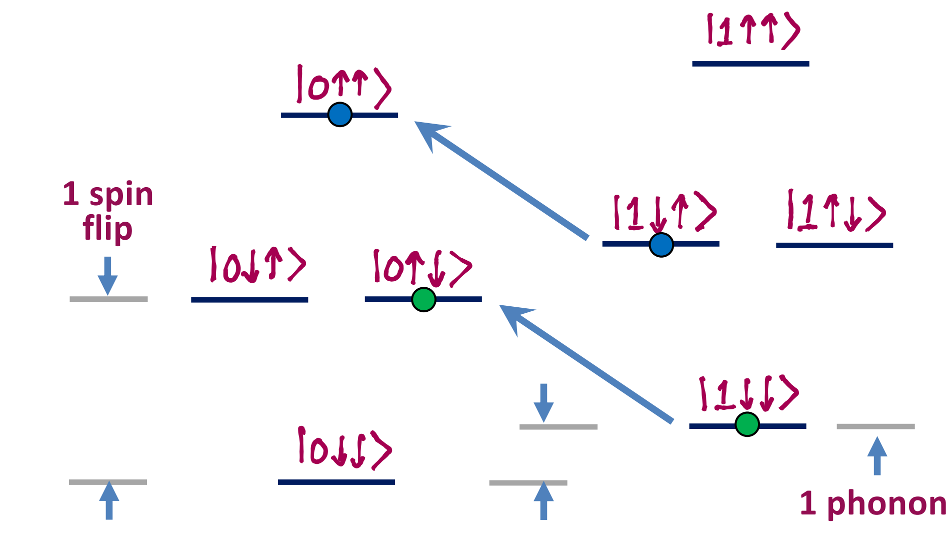


(3) π pulse on C swaps $|0\uparrow_C x_T\rangle \leftrightarrow |1\downarrow_C x_T\rangle$



Introduction and Overview (Preskills Notes)

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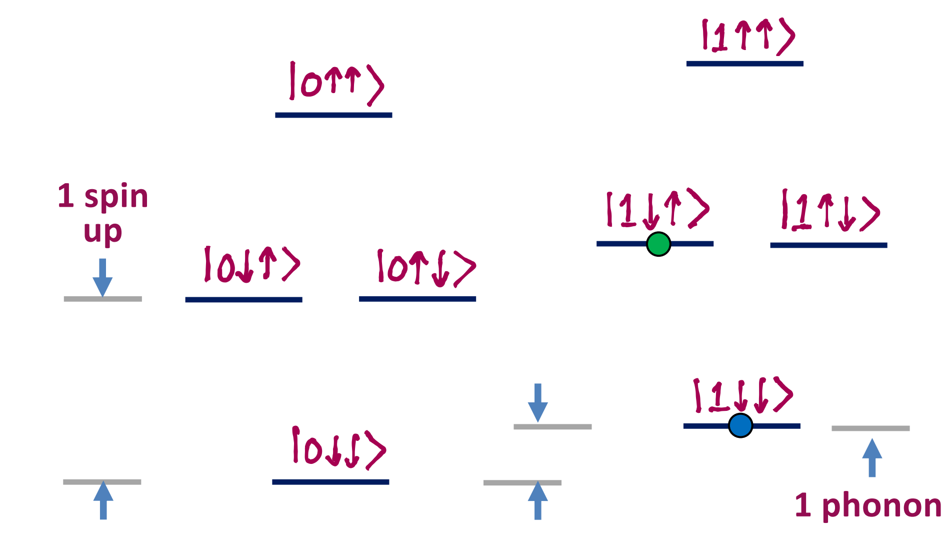

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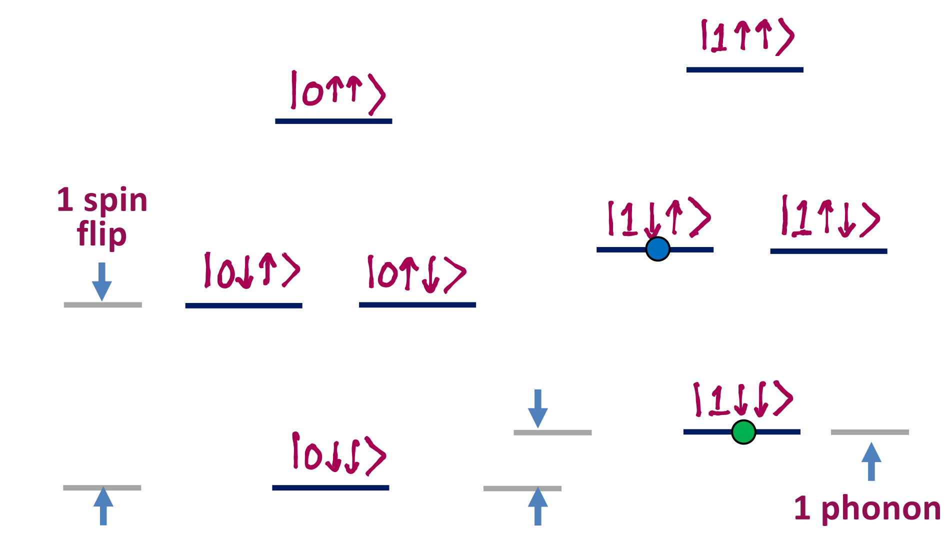
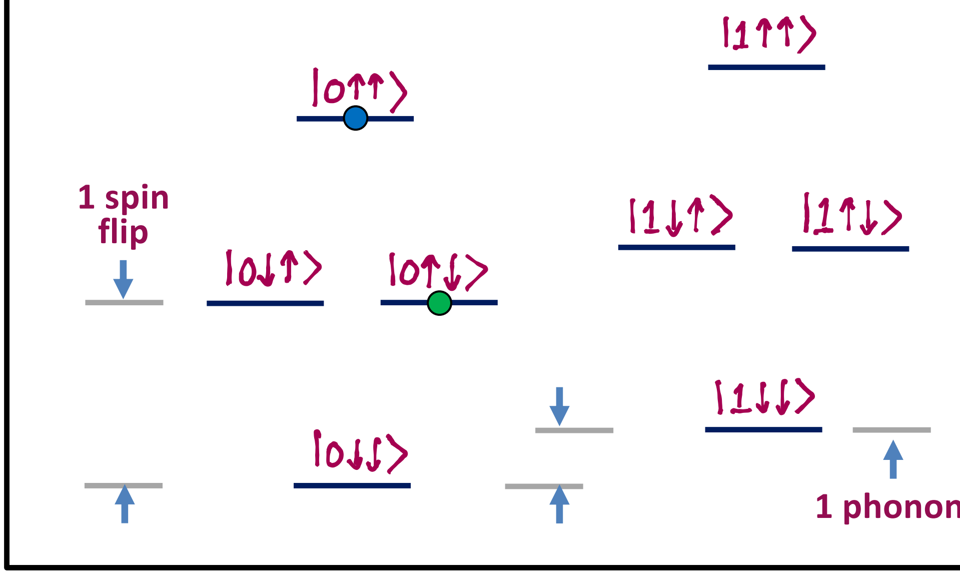


(3) π pulse on C swaps $|0 \uparrow_C X_T\rangle \leftrightarrow |1 \downarrow_C X_T\rangle$



Introduction and Overview (Preskills Notes)

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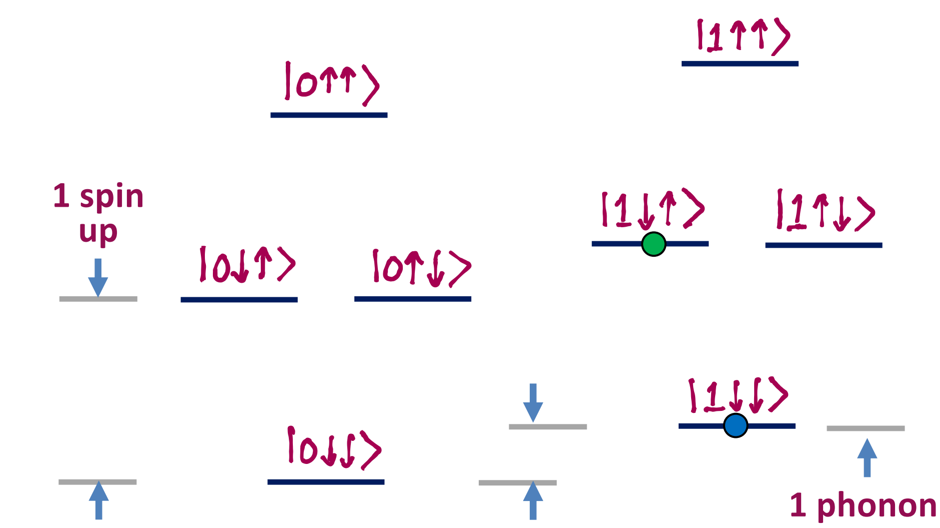

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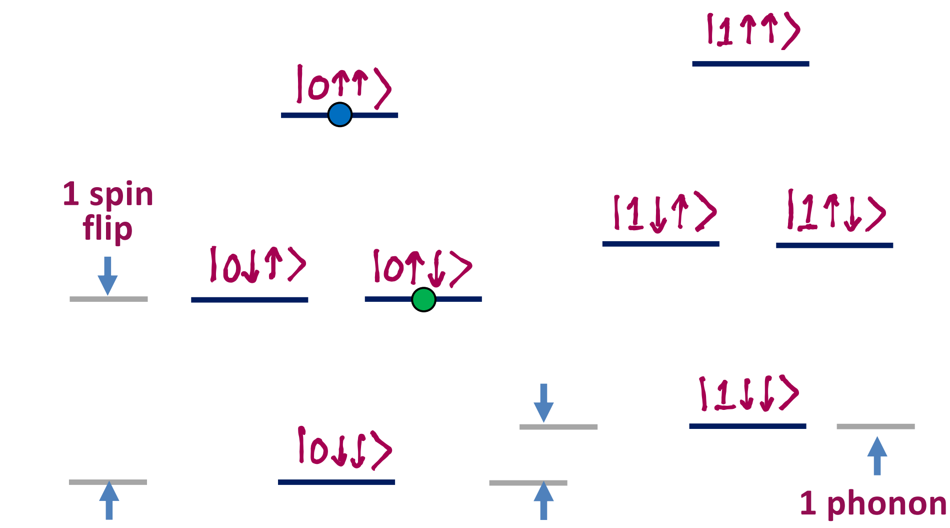

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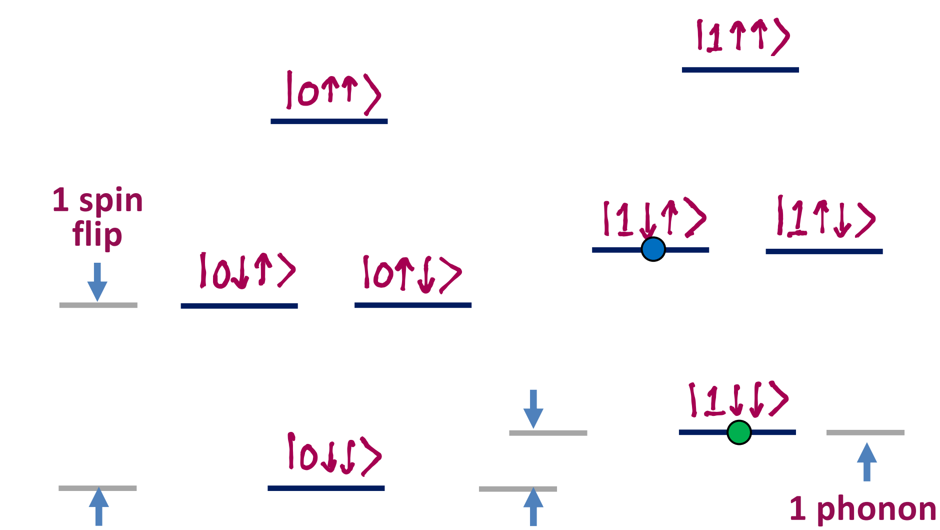
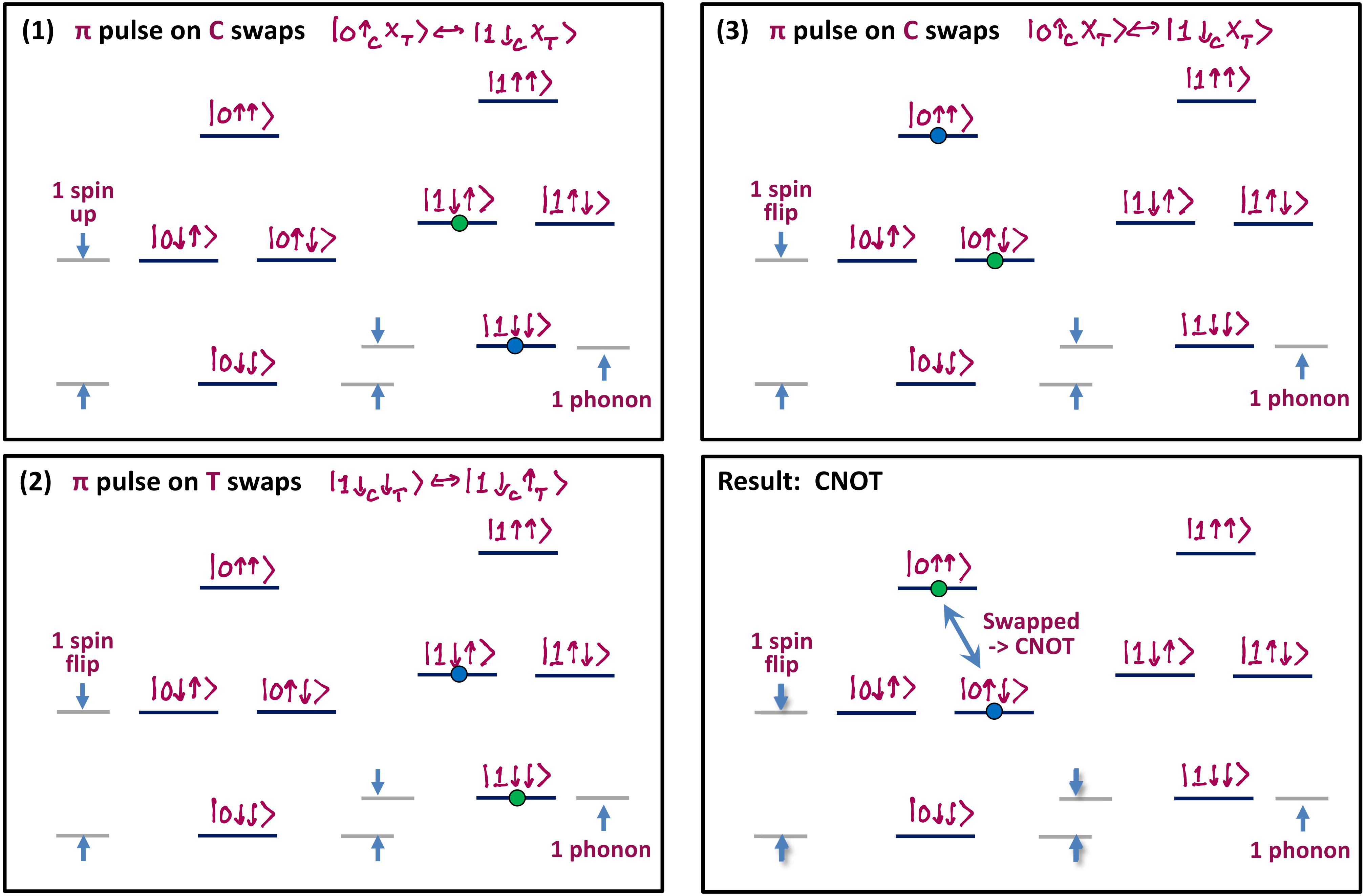
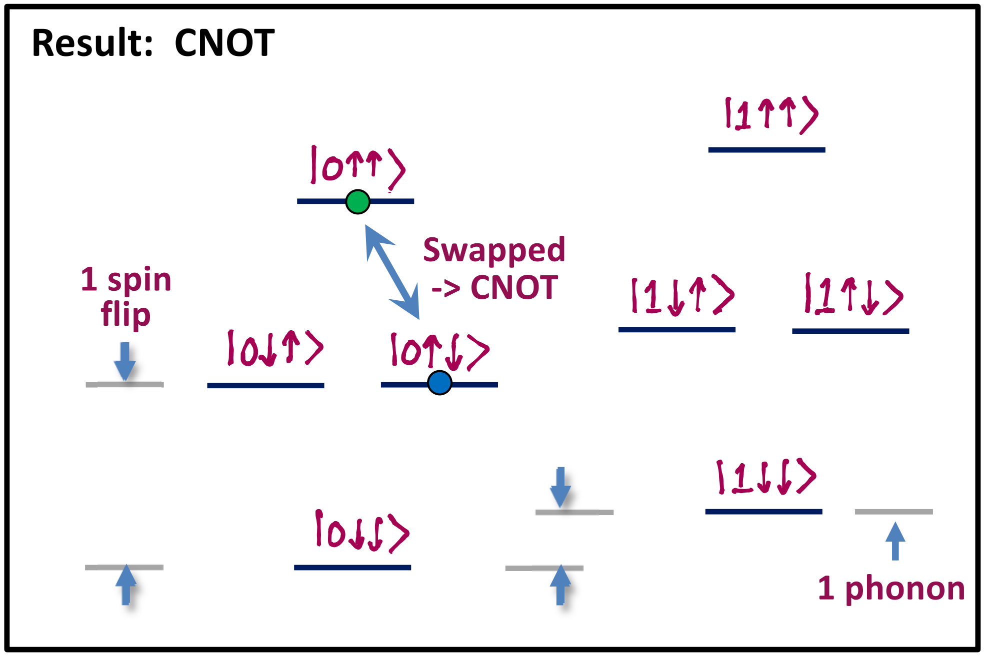


Result: CNOT

Introduction and Overview (Preskills Notes)



Introduction and Overview (Preskills Notes)



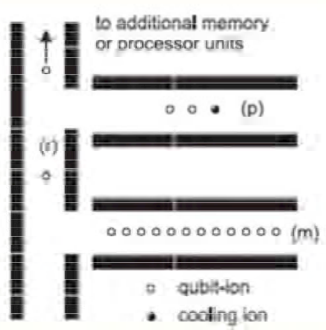
Note: The sequence (1) -> (2) -> (3) leaves the spin and vibrational degrees of freedom unentangled after the CNOT

Note: Todays Ion Trap QC experiments rely on much more sophisticated, accurate, and robust gate protocols. Examples: Molmer-Sorensen gate, Geometric gates, etc…

Introduction and Overview (Preskills Notes)

- Major challenges today – same as in 1998 !
- "Clock speed" set by vibrational freqs
  microfabricated traps do better
- More ions -> harder to cool motion, harder to individually address ions in linear trap.
- Scaling up to 1000's of ions is an enormous challenge

Scalable Ion Trap Quantum Processor – one vision



D. Kielpinski, C. Monroe, and D. J. Wineland, Nature 417, 709 (2002).

To appear in the 2005 International Symposium on Microarchitecture (MICRO-38)

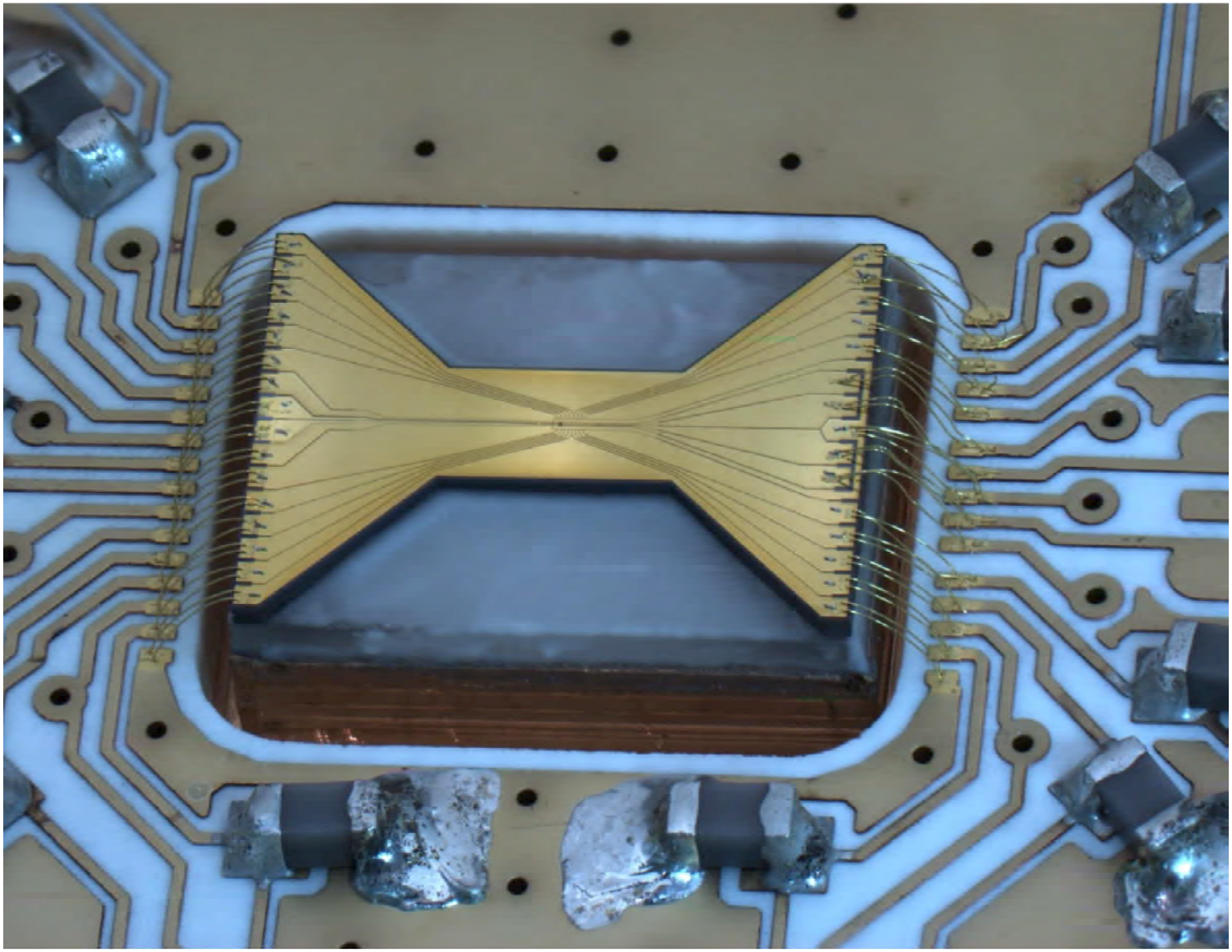
A Quantum Logic Array Microarchitecture: Scalable Quantum Data Movement and Computation

Tzvetan S. Metodi[1], Darshan D. Thaker[1], Andrew W. Cross[2]
Frederic T. Chong[3] and Isaac L. Chuang[2]

Operation	Time	$P_{current}$	$P_{expected}$
Single Gate	$1\mu s$	0.0001	10^{-8}
Double Gate	$10\mu s$	0.03	10^{-7}
Measure	$100\mu s$	0.01	10^{-8}
Movement	$10ns/\mu m$	$0.005/\mu m$	10^{-6}/cell
Split	$10\mu s$		
Cooling	$1\mu s$		
Memory time	10 – 100 sec		

Introduction and Overview (Preskills Notes)

NIST Group, Current as of 2023



Introduction and Overview (Preskills Notes)

Status: **Many important milestones achieved**

- ✱ **Entanglement of ≥ 20 ions (2018)**
- ✱ **Highest gate & readout fidelities, longest coherence times**
- ✱ **Error Correction, Fault Tolerance proof of principle demonstrations**
- ✱ **Complex algorithms on few ions, quantum simulations with ≥ 50**
- ✱ **Research groups in academia, National Labs, Industry**

Some leading groups

NIST	**Quantinuum**	**IonQ**
Sandia NL	**Duke U**	

Many, many others

Some links to get started

Amazon Braket (IonQ, other Technologies)
https://aws.amazon.com/braket/

Quantinuum (Ion Trap Quantum Computing
https://www.quantinuum.com

IonQ https://ionq.com

NIST https://www.nist.gov/pml/time-and-frequency-division/ion-storage

Challenge: Do a web search and look for the largest GHZ state made in the lab

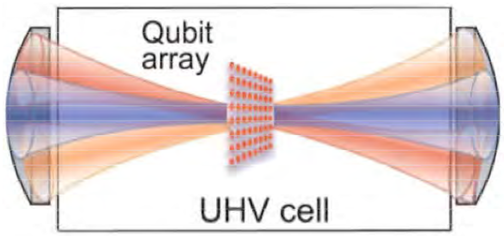
$$|GHZ\rangle = \frac{1}{\sqrt{N}}\left(|00\ldots00\rangle + |11\ldots11\rangle\right)$$

Note: What is the fidelity of the state ?

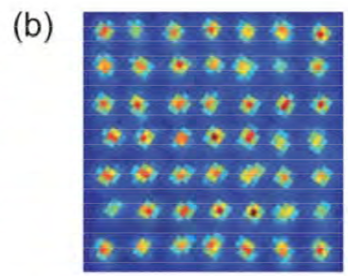
Introduction and Overview (Preskills Notes)

Neutral Atom based Quantum Processors

Optical tweezer array



Fluorescing atoms



- **Large numbers of non-interacting qubits, (≥ 100) trapped in 2D or 3D arrays.**
- **Qubits interact when excited into Rydberg states with large dipole moments**
- **Major advantage: Weak coupling to the environment when not doing gates**
  - ⇨ **excellent quantum memory**
- **Favorite platform for quantum simulation of quantum manybody physics**
- **BEC's in optical lattices as analog simulators of superconductivity, quantum magnetism and more**

End 09-11-2023