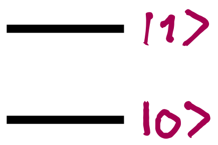
Introduction and Overview (Preskills Notes)

Quantum Complexity

Benioff, Feynman ⇨ **Simulating QM is hard**

Simulating Physics with computers (1982)

qubit



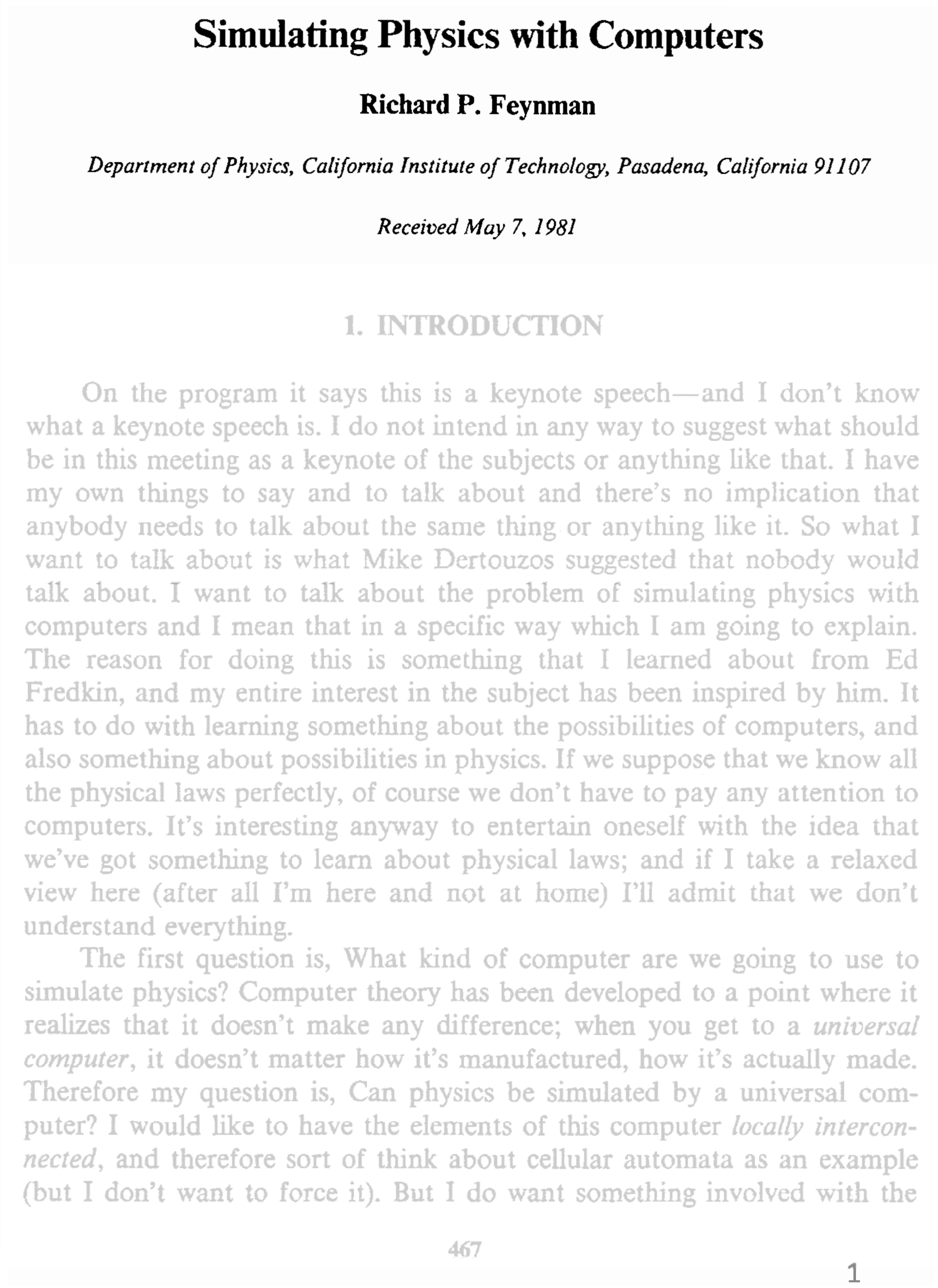
$|\psi\rangle = a|0\rangle + b|1\rangle$

N qubits ⇨ $\underbrace{|01101011\ldots010\rangle} = |x\rangle \in \mathcal{E}$

N bit integer = *X* : logical basis state

2^N - dimensional Hilbert Space

General State: $$\boxed{|\psi\rangle = \sum_{x=0}^{2^N-1} a_x |x\rangle}$$



Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

1. INTRODUCTION

On the program it says this is a keynote speech—and I don't know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have my own things to say and to talk about and there's no implication that anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with computers and I mean that in a specific way which I am going to explain. The reason for doing this is something that I learned about from Ed Fredkin, and my entire interest in the subject has been inspired by him. It has to do with learning something about the possibilities of computers, and also something about possibilities in physics. If we suppose that we know all the physical laws perfectly, of course we don't have to pay any attention to computers. It's interesting anyway to entertain oneself with the idea that we've got something to learn about physical laws; and if I take a relaxed view here (after all I'm here and not at home) I'll admit that we don't understand everything.

The first question is, What kind of computer are we going to use to simulate physics? Computer theory has been developed to a point where it realizes that it doesn't make any difference; when you get to a *universal computer*, it doesn't matter how it's manufactured, how it's actually made. Therefore my question is, Can physics be simulated by a universal computer? I would like to have the elements of this computer *locally interconnected*, and therefore sort of think about cellular automata as an example (but I don't want to force it). But I do want something involved with the

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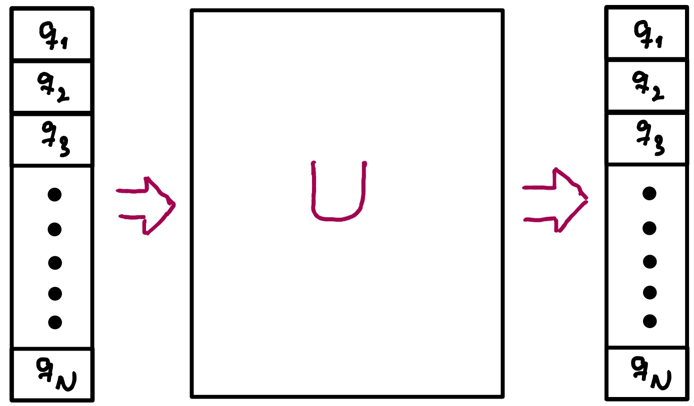
Introduction and Overview (Preskills Notes)

OK – Plausible QM can do more

Where does the QC's power come from?

Visualization of Computation



input

output

memory register

machine that does physical process of computation

memory register

Classical: Register is in one of the logical states $\underbrace{x = q_1 q_2 q_3 \ldots q_N}_{\text{binary \#}}$

Reversible transformation $U: x \to y$

Quantum: Register can be in any coherent superposition of logical states $|x\rangle$

Unitary transformation $U: |x\rangle \to |y\rangle$

Maps basis to basis $U: \{|x\rangle\} \to \{|y\rangle\}$

Quantum Parallelism

$$|\psi_{in}\rangle \to \sum_x a_x |x\rangle \to$$

$$\to |\psi_{out}\rangle = U|\psi_{in}\rangle = \sum_x a_x |y\rangle = \sum_x b_x |x\rangle$$

Machine processes 2^N inputs "in parallel" !

Beware: measurement collapses Q. Register into a single basis state at random

We get one random result out of 2^N

Introduction and Overview (Preskills Notes)

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Quantum Parallelism

Quantum Sampling Problem

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Quantum Algorithms look for global properties of functions – symmetry, periodicity, etc.

- ∗ Classical -> requires many function evaluations
- ∗ Quantum -> design U so measurement gives answer with high probability
- ∗ ∃ classes of problems (sampling problems) which are classically hard but quantum "easy"

Google "Quantum Supremacy"


Expert insight into current research

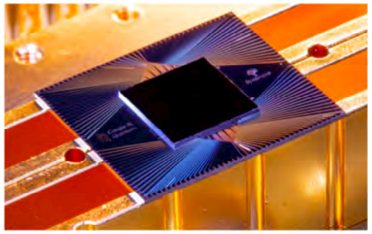
News & views

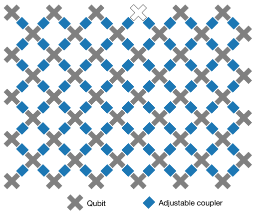
Quantum information

Quantum computing takes flight

William D. Oliver

A programmable quantum computer has been reported to outperform the most powerful conventional computers in a specific task – a milestone in computing comparable in importance to the Wright brothers' first flights. See p.505





Introduction and Overview (Preskills Notes)

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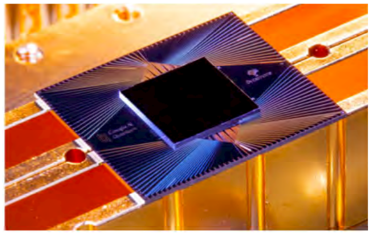
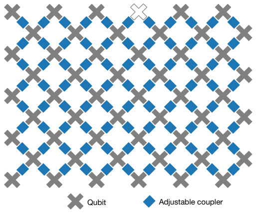
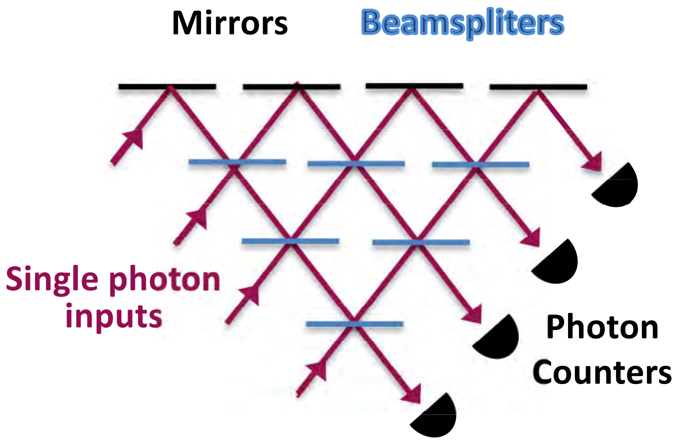


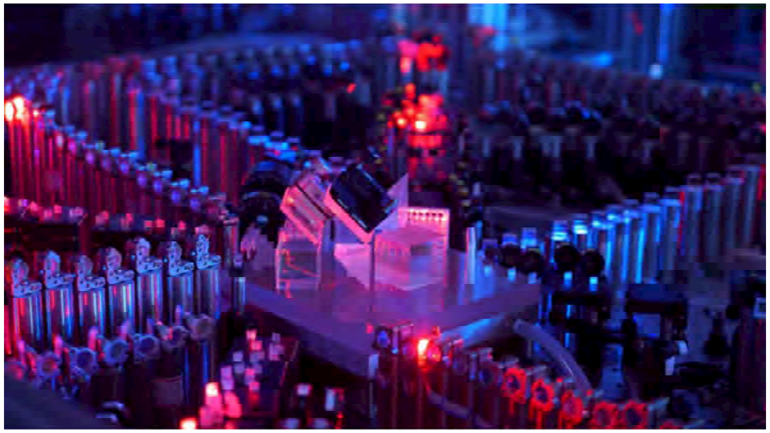


Boson Sampling

An example from Optics/Photonics

Setup



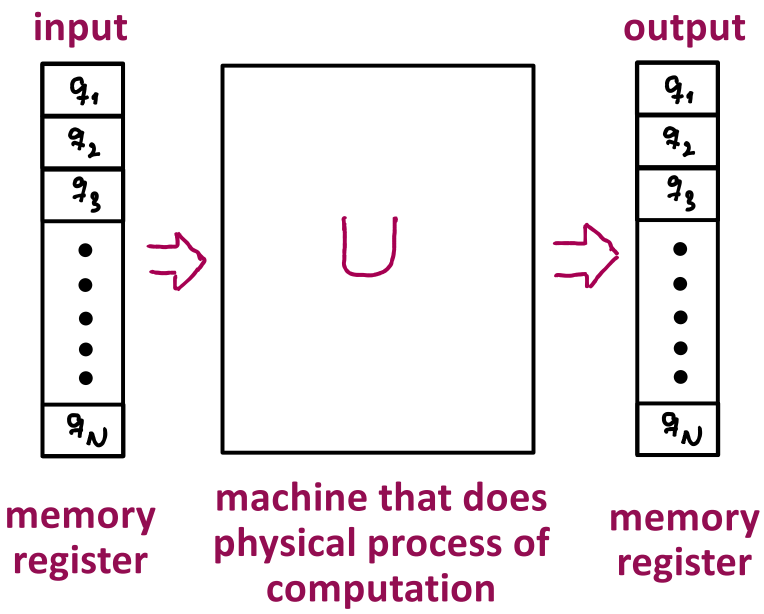


An optical quantum computer developed by a team of Chinese researchers including those from the University of Science and Technology of China. (courtesy of Han-Sen Zhong of the research group)

Introduction and Overview (Preskills Notes)

Back to Universal Computation

Visualization of Computation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machine that does physical process of computation

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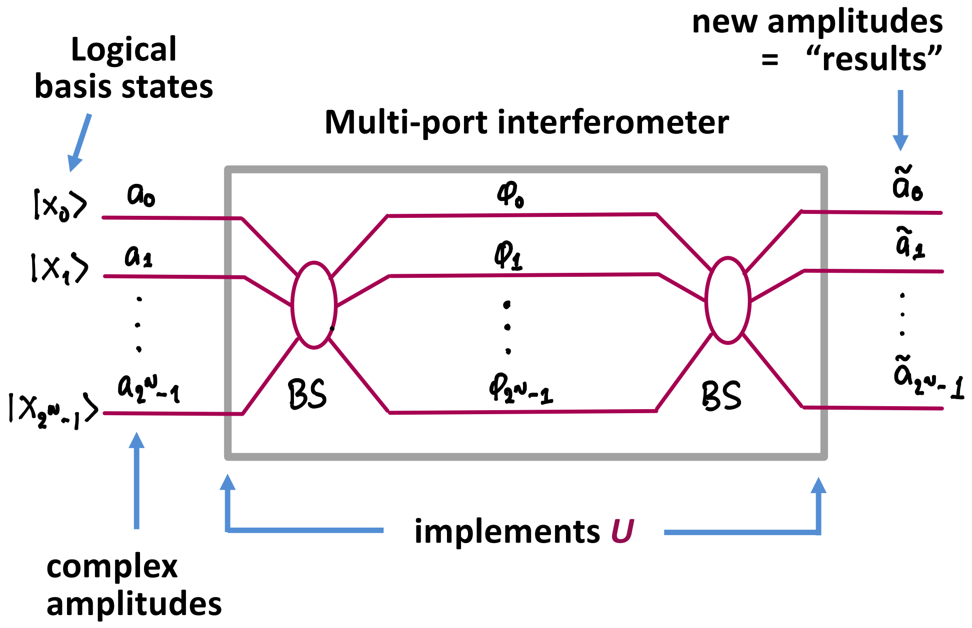
Classical: Register is in one of the logical states $\underbrace{x = q_1 q_2 q_3 \ldots q_N}_{\text{binary \#}}$

Reversible transformation $U: x \to y$

What might be inside the machine ?

Wave interference w/classical fields ?


Logical basis states

new amplitudes = "results"

Multi-port interferometer

implements *U*

complex amplitudes

Note: *N* - qubit register ⇨ 2^N "paths"

Beware of Resource Scaling !

End 08-28-2023

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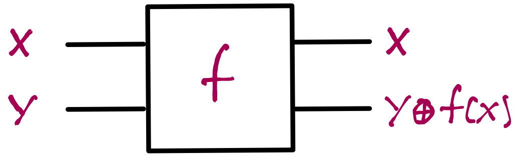
08-30-2023

Introduction and Overview (Preskills Notes)

Quantum Advantage

David Deutsch: Toy problem that shows Quantum Advantage

Oracle



(Black Box)

Is the function

constant $f(0)=f(1)$

balanced $f(0)\neq f(1)$

Classical Box: Need 2 queries $f(0)$ & $f(1)$

Introduction and Overview (Preskills Notes)

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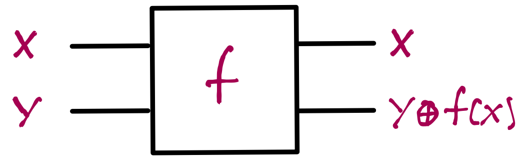

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Quantum Box: In 3 steps can show that

(1) $U_f : |x\rangle|y\rangle \rightarrow |x\rangle|y \oplus f(x)\rangle$

(2) $U_f : |x\rangle\frac{1}{\sqrt{2}}(|0\rangle-|1\rangle) \rightarrow |x\rangle\frac{1}{\sqrt{2}}(|f(x)\rangle-|1\oplus f(x)\rangle)$

$= |x\rangle\frac{1}{\sqrt{2}}(-1)^{f(x)}(|0\rangle-|1\rangle)$

(3) $U_f : \frac{1}{\sqrt{2}}(|0\rangle+|1\rangle)\frac{1}{\sqrt{2}}(|0\rangle-|1\rangle)$

$\rightarrow \frac{1}{2}\left((-1)^{f(0)}|0\rangle+(-1)^{f(1)}|1\rangle\right)(|0\rangle-|1\rangle)$

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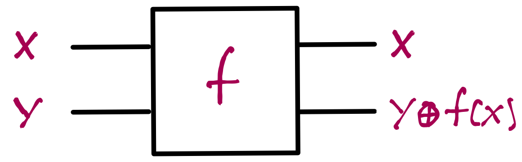

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Measure 1st qubit in basis $|\pm\rangle = \frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)$

$\rightarrow$ $|+\rangle$ if constant, $|-\rangle$ if balanced

Quantum Speedup: can solve w/1 query

Introduction and Overview (Preskills Notes)

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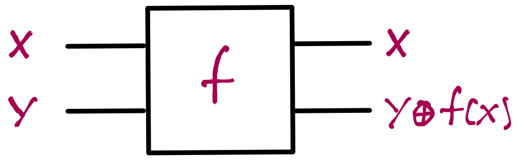

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Quantum Speedup: can solve w/1 query

Key aspect of Deutsch's algorithm:

We are looking for a global property of the function f

N bit binary number

Generally: $U_f: |x\rangle|0\rangle \rightarrow |x\rangle|f(x)\rangle$

Input $|\psi_{in}\rangle = \left[\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)\right]^{\otimes N}|0\rangle$

$$= \frac{1}{2^{N/2}}\sum_{x=0}^{2^N-1}|x\rangle|0\rangle$$

compute once

Output $|\psi_{out}\rangle = \frac{1}{2^{N/2}}\sum_{x=0}^{2^N-1}|x\rangle|f(x)\rangle$

Global properties encoded in state,
trick is to extract desired information

Introduction and Overview (Preskills Notes)

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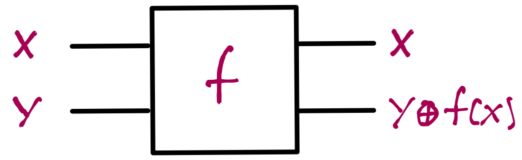

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Introduction and Overview (Preskills Notes)

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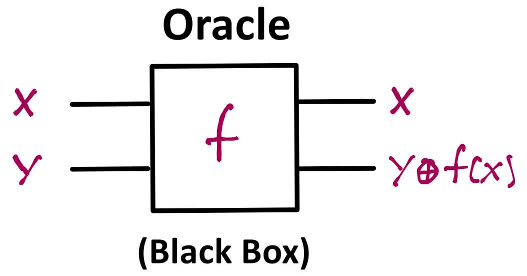

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Peter Shor: Period finding, QFT, Factoring

Introduction and Overview (Preskills Notes)

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Peter Shor: Period finding, QFT, Factoring

Next: Will this work with real-world Quantum Hardware ?

Faulty gates, decoherence !

Begin
09-01-2022

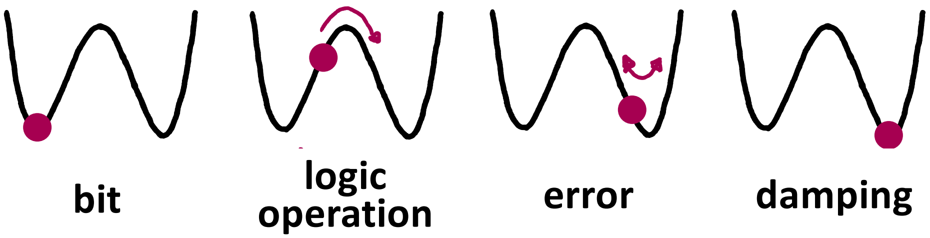
Introduction and Overview (Preskills Notes)

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:
$0 \to (000)$
$1 \to (111)$

Errors:
$(000) \to (100)$
$(111) \to (011)$
correct by majority vote

Introduction and Overview (Preskills Notes)

Quantum Computation ➡

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Von Neumann:

- ✱ A classical computer w/faulty components can work, given enough redundancy
- ✱ Classical error correction is well developed and highly sophisticated…

✱ Quantum Errors

1) Bit Flip $|0\rangle \to |1\rangle$, $|1\rangle \to |0\rangle$, phase flip $|0\rangle \to |0\rangle$, $|1\rangle \to -|1\rangle$

2) Small errors $a|0\rangle + b|1\rangle$ a, b can change by ε errors accumulate

3) Measurement disturbs ➡ collapse of quantum states

4) No cloning ➡ Cannot protect by making copies

Introduction and Overview (Preskills Notes)

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Example: Peter Shor's code for bit flip error when P(error) << 1

Encode: $|0\rangle \to |\bar{0}\rangle \equiv |000\rangle$, $|1\rangle \to |\bar{1}\rangle \equiv |111\rangle$ (3 bit code)

⇩

$$a|0\rangle + b|1\rangle \to a|000\rangle + b|111\rangle$$

Single-qubit measurement ⇨ collapse of state, destroys info, no majority voting !

Collective 2-qubit measurement:

- for $|x,y,z\rangle$ measure $y \oplus z$, $x \oplus z$ (never measure individual bits)
- if $|000\rangle$, $|111\rangle$ these observables $= 0$
- if one bit-flip, at least one observable $= 1$
- easy to check that $(y \oplus z, x \oplus z) =$ binary address of qubit flip

$|000\rangle \to |010\rangle$ $(1,0) =$ 2nd bit

Introduction and Overview (Preskills Notes)

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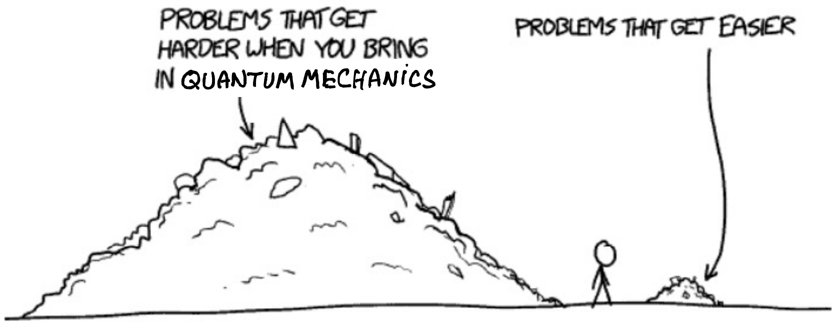
Small errors: $|000\rangle \rightarrow |000\rangle + \varepsilon|001\rangle$

$|111\rangle \rightarrow |111\rangle + \varepsilon|110\rangle$

Quantum mechanics to the rescue !

- mostly no error detected
  - ⇨ collapse into $|000\rangle$ resp. $|111\rangle$
- sometime error detected
  - ⇨ collapse into $|001\rangle$ resp. $|110\rangle$
  - ⇨ full bit flip, correct as such



Source: xkcd.com

Introduction and Overview (Preskills Notes)

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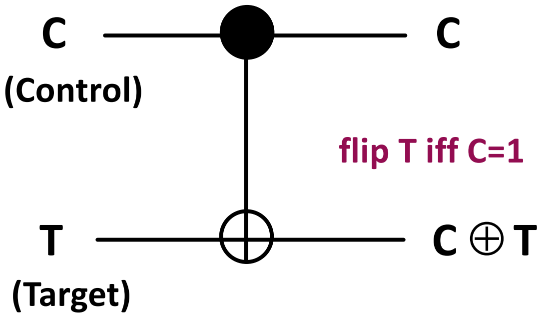
How to implement ?

Quantum circuit + single qubit measurement

Quantum Gates – work on superpositions, and entangled states

Introduction and Overview (Preskills Notes)

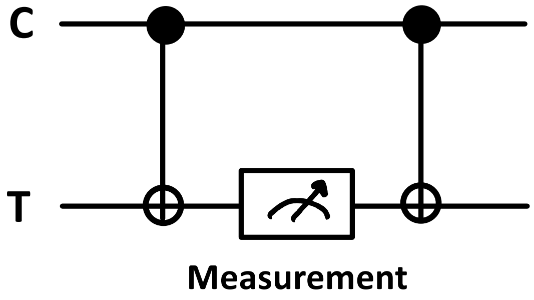
Controlled-NOT (CNOT)



Truth Table

C	T	C ⊕ T
0	0	0
0	1	1
1	0	1
1	1	0

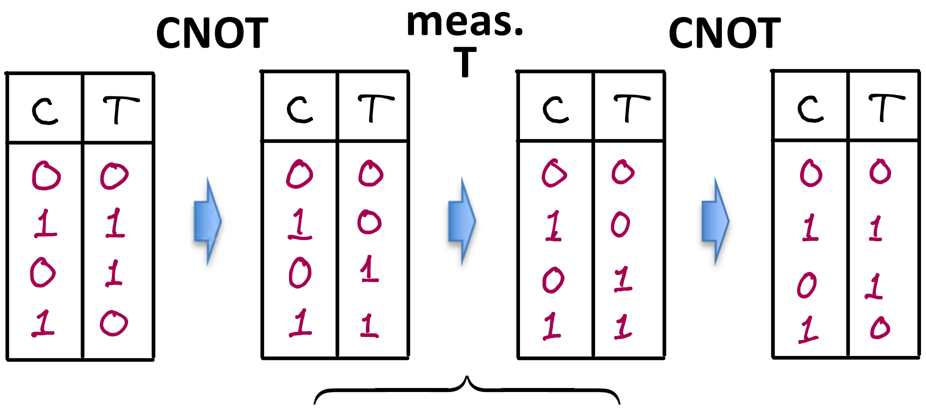
Quantum Circuit for joint measurement



Measurement in $\{|0\rangle, |1\rangle\}$ basis

yields $C \oplus T$

Circuit maps logical basis states as



C	T
0	0
1	1
0	1
1	0

C	T
0	0
1	0
0	1
1	1

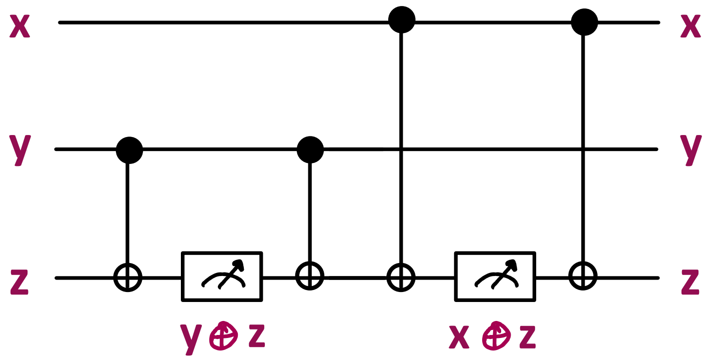
C	T
0	0
1	0
0	1
1	1

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 = $(y \oplus z, x \oplus z)$

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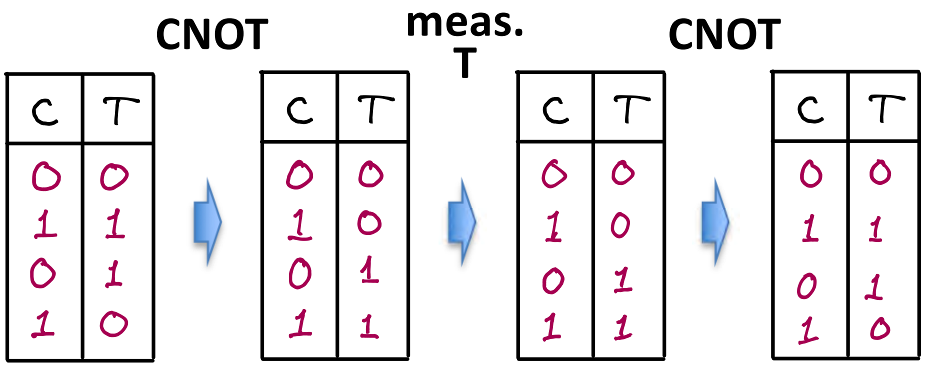
Introduction and Overview (Preskills Notes)

Begin
09-06-2023

Circuit maps logical basis states as



C	T
0	0
1	1
0	1
1	0

C	T
0	0
1	0
0	1
1	1

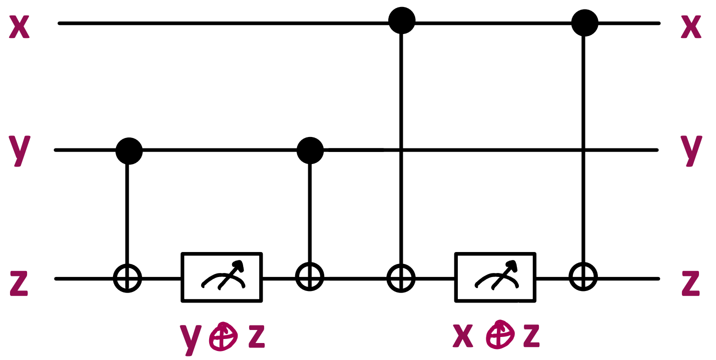
C	T
0	0
1	0
0	1
1	1

C	T
0	0
1	1
0	1
1	0

$T=0$ iff same

$T=1$ iff different

Full circuit to obtain Error Syndrome



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

End 09-01-2023

Quantum Phase Error

$|0\rangle \to |0\rangle$

$|1\rangle \to -|1\rangle$

Encoding

$$|0\rangle \to |\bar{0}\rangle = \frac{1}{2^{3/2}} \overset{x'}{(|0\rangle+|1\rangle)}\overset{y'}{(|0\rangle+|1\rangle)}\overset{z'}{(|0\rangle+|1\rangle)}$$

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

Relabel

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

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

Measure in basis $\{|0'\rangle, |1'\rangle\} \to y'\oplus z', x'\oplus z'$

Error Syndrome

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

Introduction and Overview (Preskills Notes)

Quantum Phase Error

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

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Shor's 9-bit code

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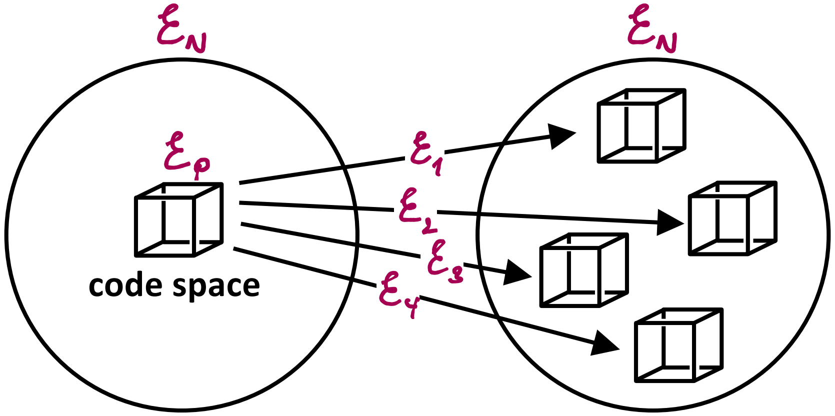
- ✱ Errors displace system into orthogonal (distinguishable) subspaces.

Geometric illustration

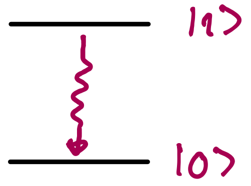


What about non-Unitary errors ?

e. g., decay

$|0\rangle \to |0\rangle$

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



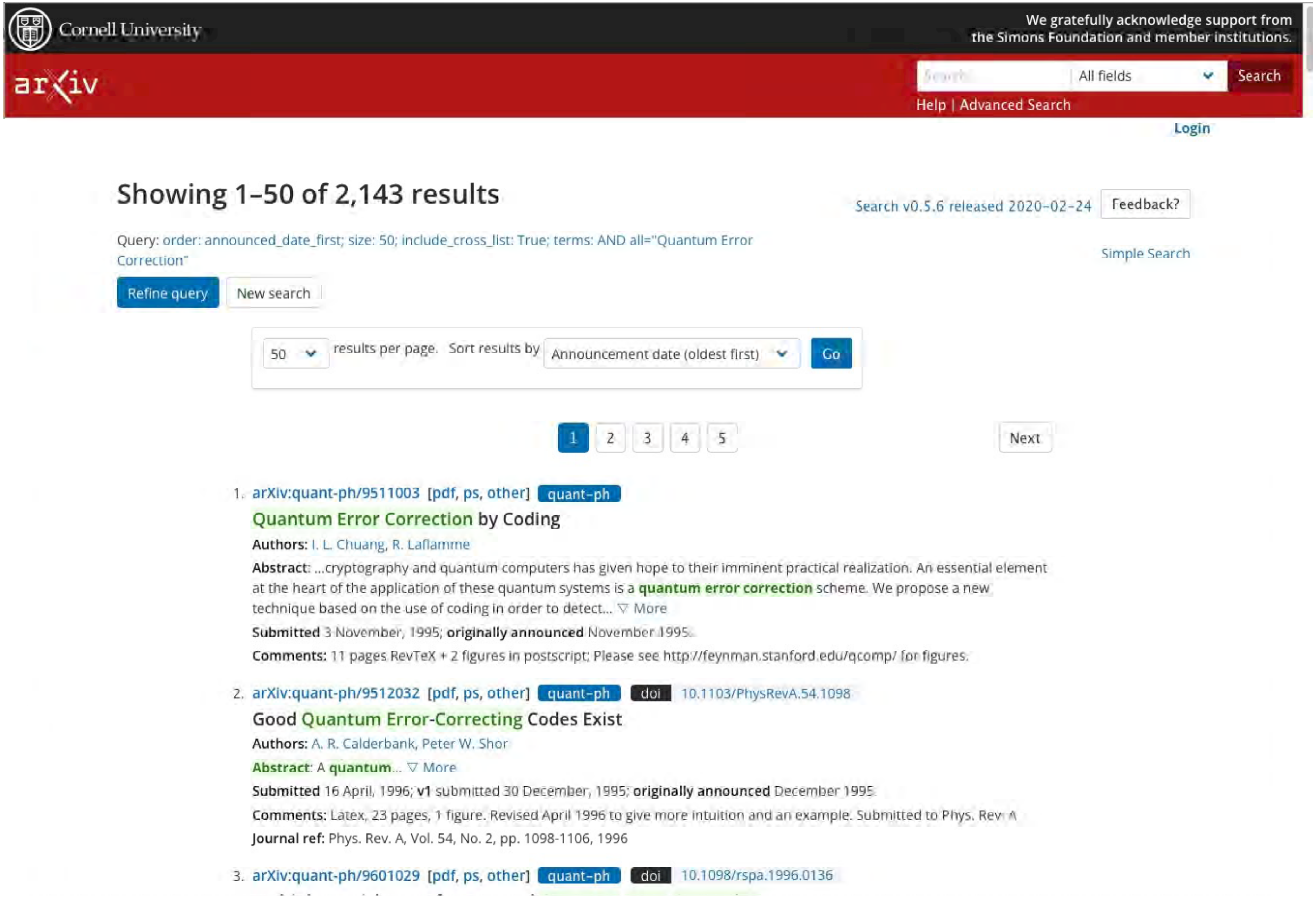
Problem: Errors not displaced into orthogonal subspaces

Solution: "Quantum jump codes", monitors the environment

Other kinds of errors ?

Introduction and Overview (Preskills Notes)

Catnip for Theoretical Physicists & Computer Scientists



Showing 1–50 of 2,143 results

Query: order: announced_date_first; size: 50; include_cross_list: True; terms: AND all="Quantum Error Correction"

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

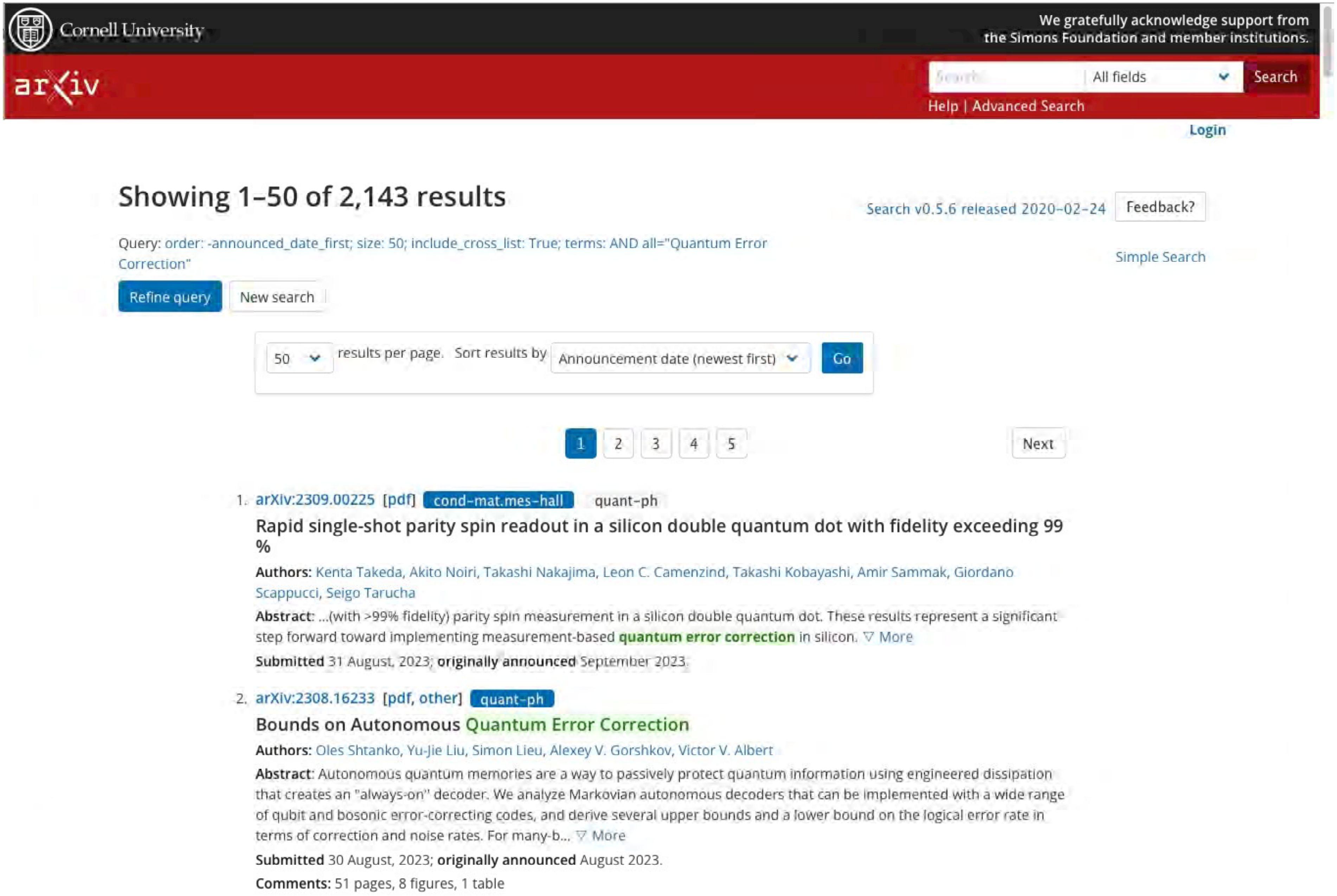
   Submitted 16 April, 1996; **v1** submitted 30 December, 1995; **originally announced** December 1995.

   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

Catnip for Theoretical Physicists & Computer Scientists



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

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

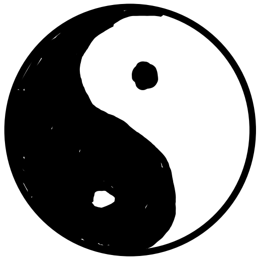
1. Storage: Quantum memory.
2. Gates: We put computation U_f together from 1 and 2-qubit operations.
3. Readout: Method to measure qubits.
4. Isolation: No coupling to environment to avoid decoherence & errors
5. Precision: Gates, readouts must be highly accurate

Inherent Contradictions

2. Gates vs **4. Isolation**

coupling between qubits ↑ (2. Gates)

no coupling to environment ↑ (4. Isolation)



To build a Quantum Computer

↓

Choose, find or invent a system
with acceptable tradeoffs

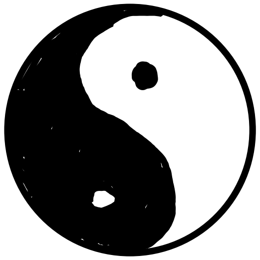
Introduction and Overview (Preskills Notes)

Inherent Contradictions

2. Gates vs **4. Isolation**

↑ coupling between qubits

↑ no coupling to environment



To build a Quantum Computer

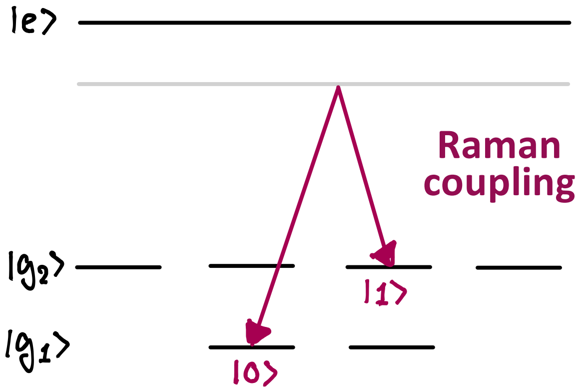
↓

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 large trap

Introduction and Overview (Preskills Notes)

Ion Trap Quantum Computing

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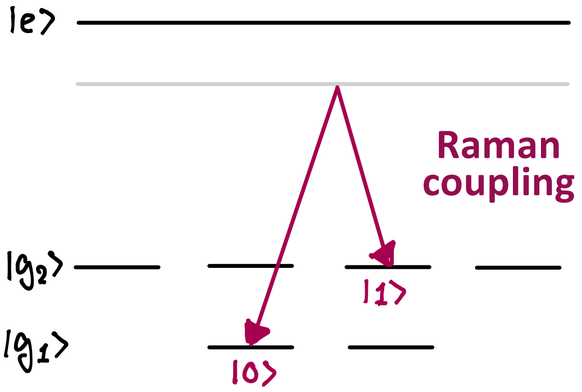
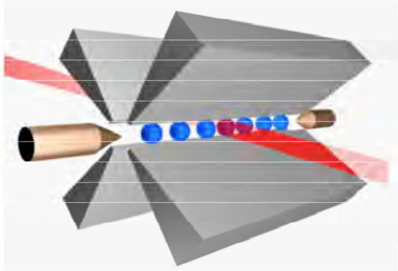
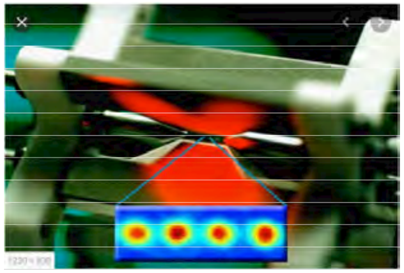


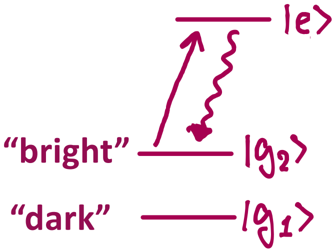
- Early design with a few ions in large trap





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

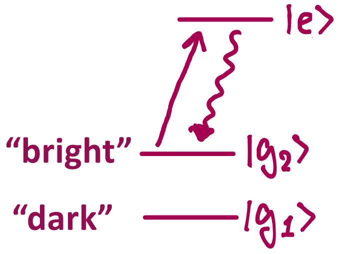
Wineland: 3 laser pulses enough for CNOT

Use this example serves as conceptual template

Introduction and Overview (Preskills Notes)

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

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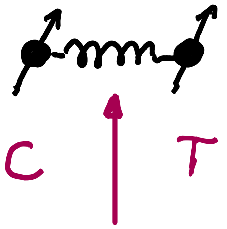
Use this example serves as conceptual template

2 – ion trap



center-of-mass mode
Is quantum bus

convention

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

CNOT input-output map:

$\lvert\downarrow_C \downarrow_T\rangle \rightarrow \lvert\downarrow_C \downarrow_T\rangle$	$\lvert\uparrow_C \downarrow_T\rangle \rightarrow \lvert\uparrow_C \uparrow_T\rangle$
$\lvert\downarrow_C \uparrow_T\rangle \rightarrow \lvert\downarrow_C \uparrow_T\rangle$	$\lvert\uparrow_C \uparrow_T\rangle \rightarrow \lvert\uparrow_C \downarrow_T\rangle$
does nothing	swaps $\lvert\uparrow_C \downarrow_T\rangle, \lvert\uparrow_C \uparrow_T\rangle$

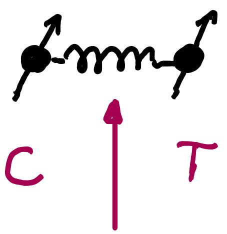
Notation for quantum states: $|n, \sigma_C^{(z)}, \sigma_T^{(z)}\rangle$

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



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

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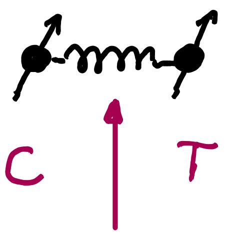

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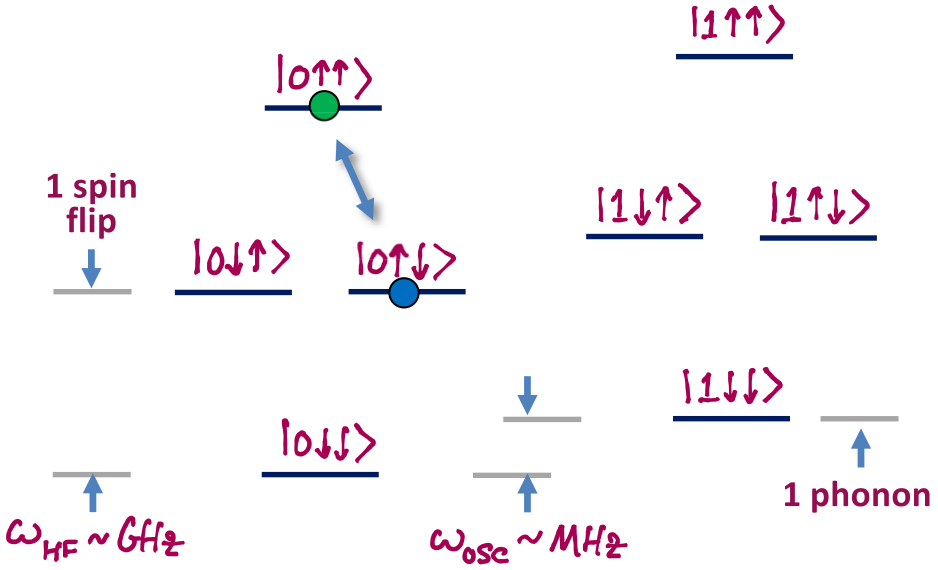
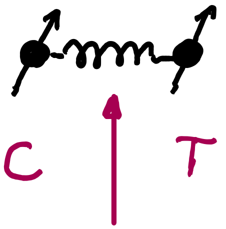
Energy Level diagram:



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

Introduction and Overview (Preskills Notes)

2 – ion trap



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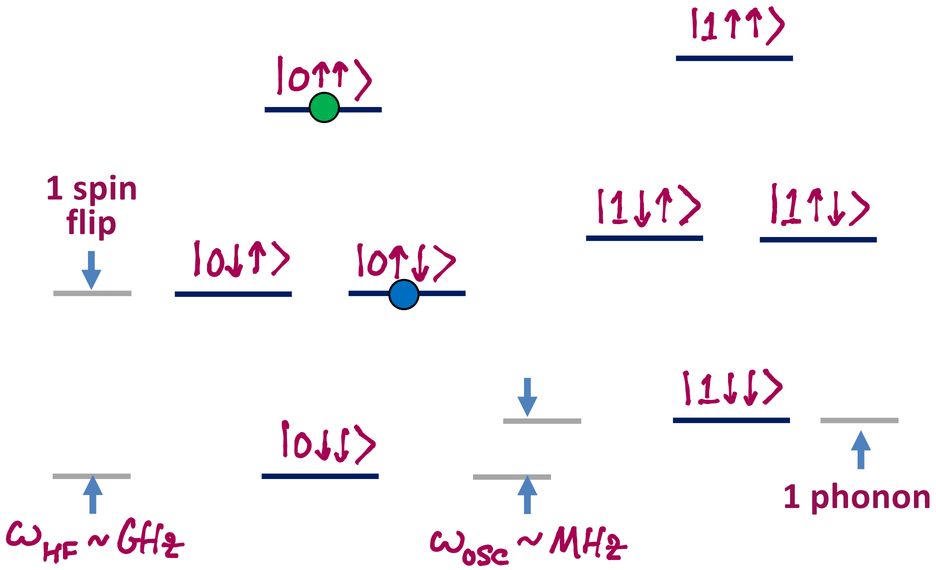

Notation: $|n, \sigma_C^{(z)}, \sigma_T^{(z)}\rangle$

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 !

(Note: Clickthrough Panels)

End
09-06-2023

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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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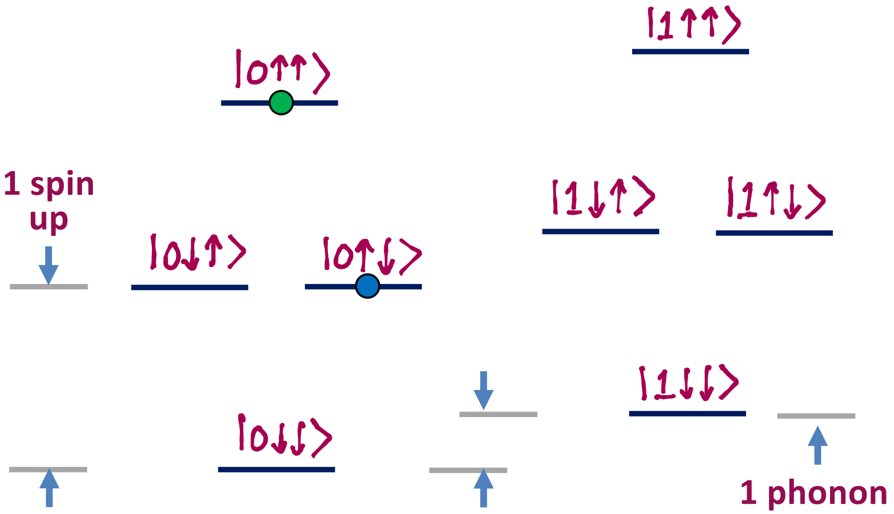

Introduction and Overview (Preskills Notes)

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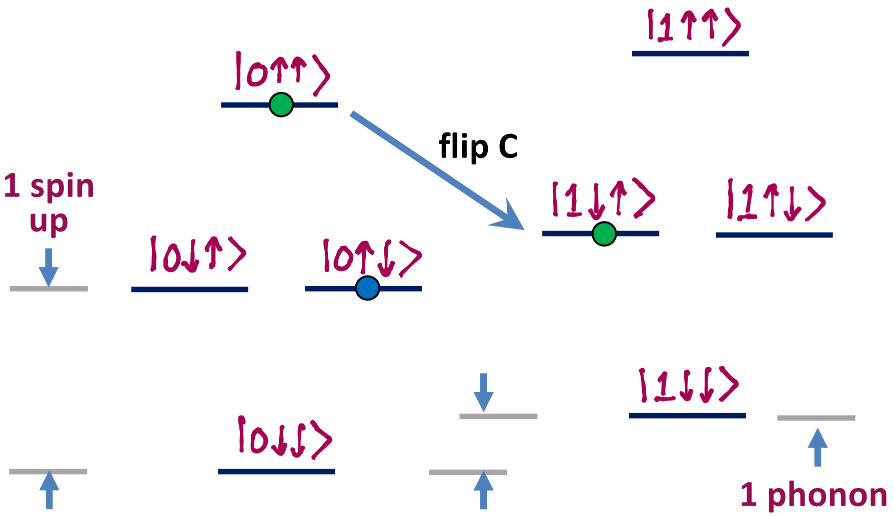

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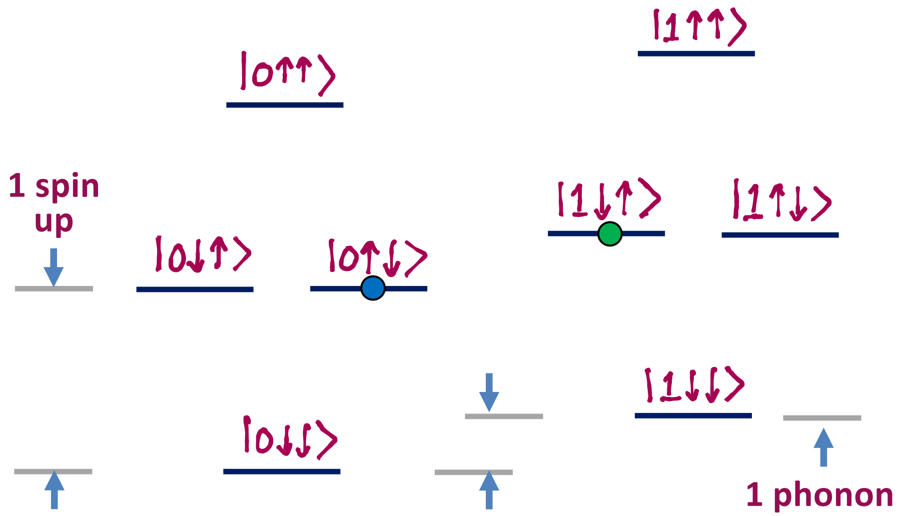

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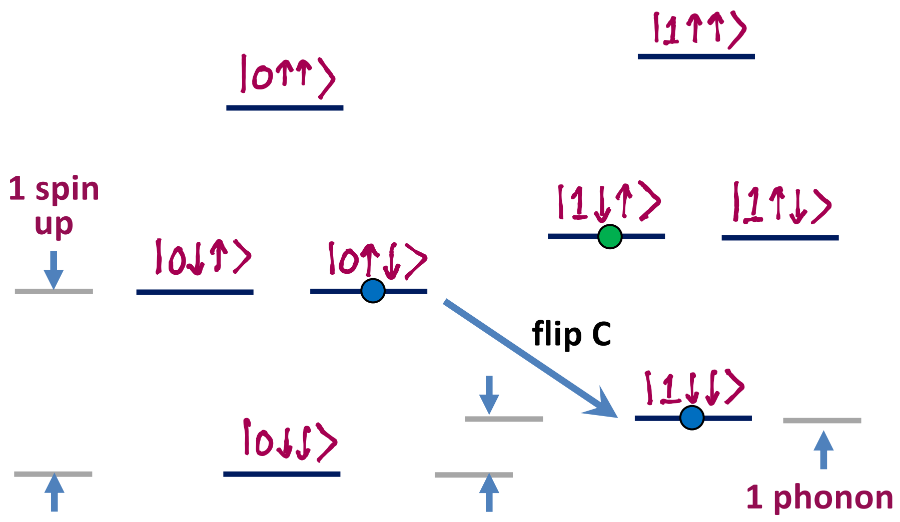

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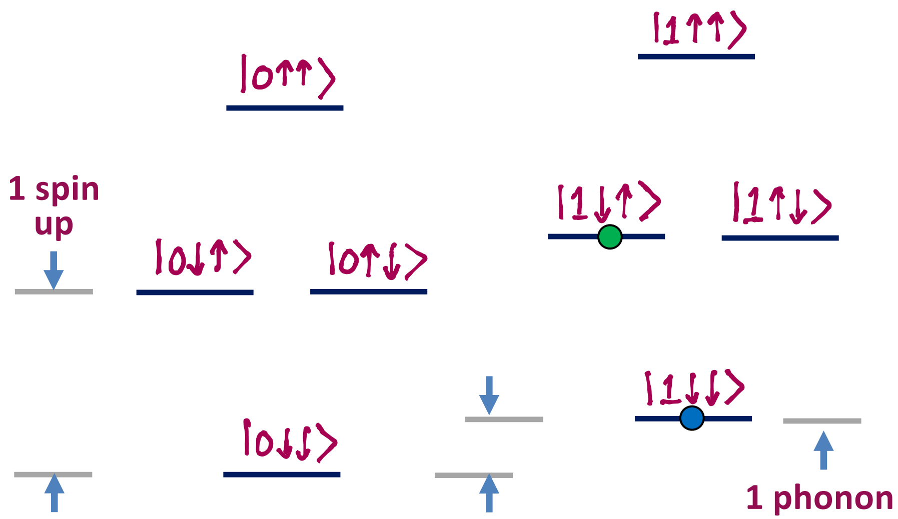

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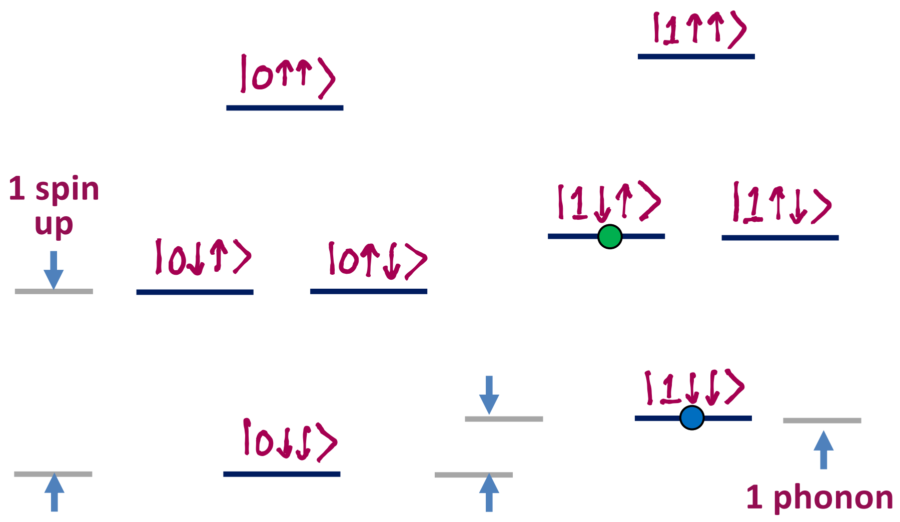
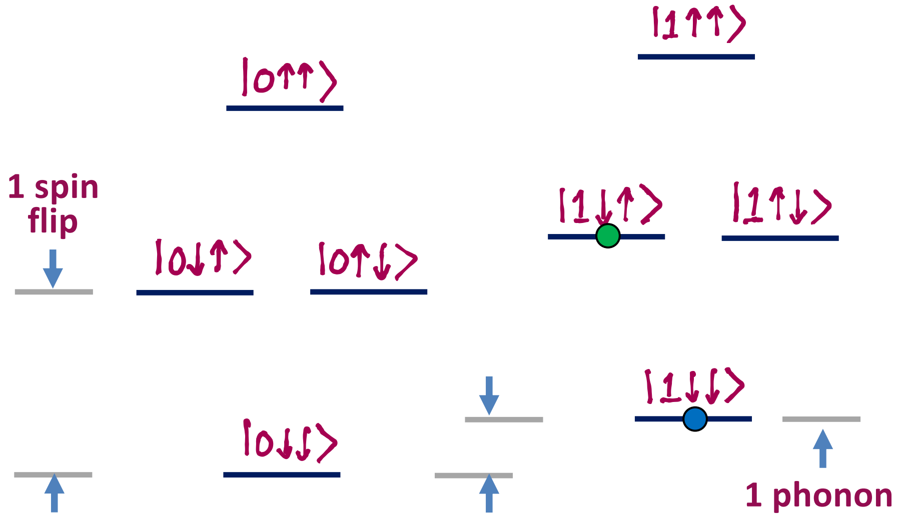


(2) π pulse on T swaps $|1\downarrow_C\downarrow_T\rangle \leftrightarrow |1\downarrow_C\uparrow_T\rangle$



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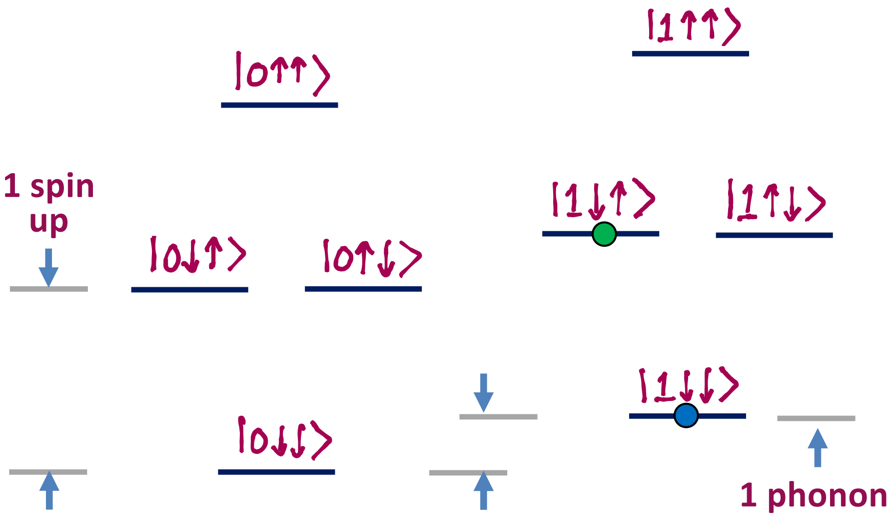

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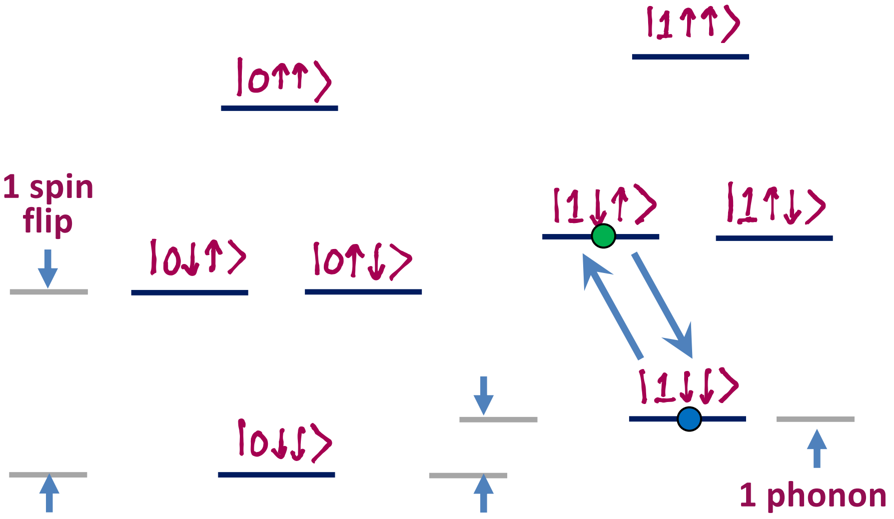

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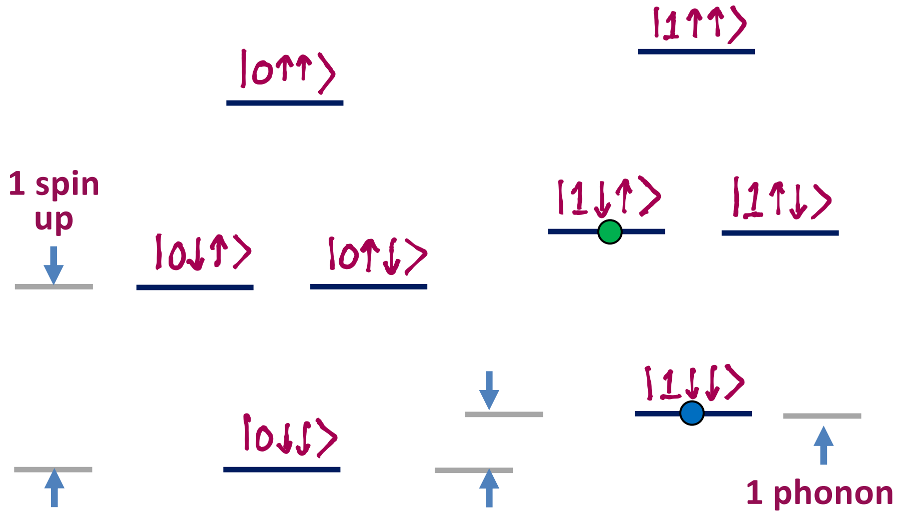

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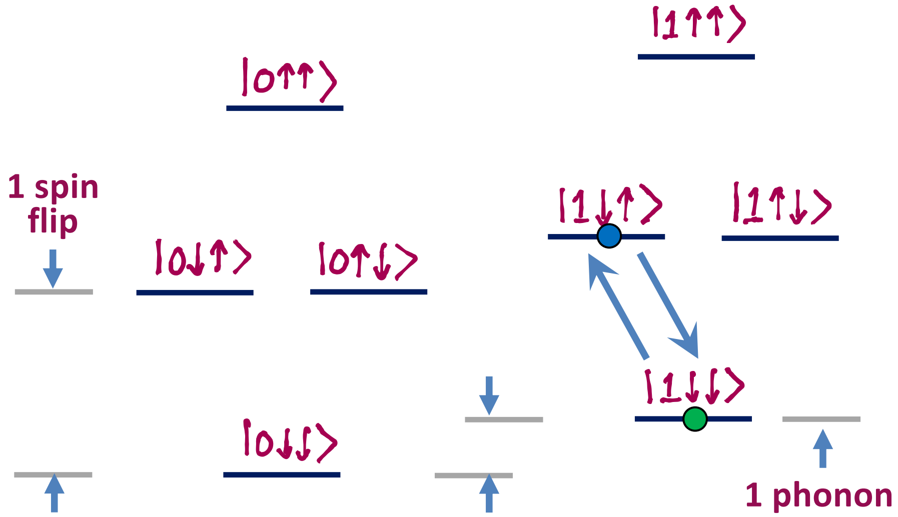

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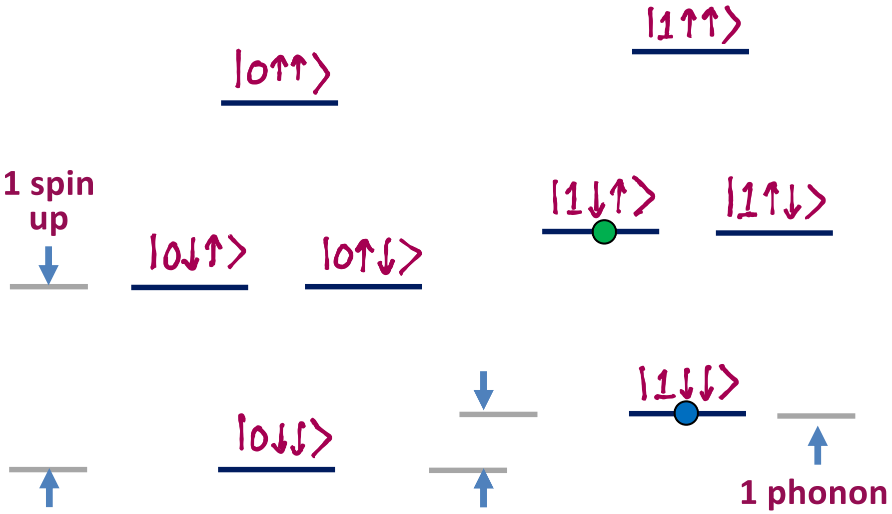

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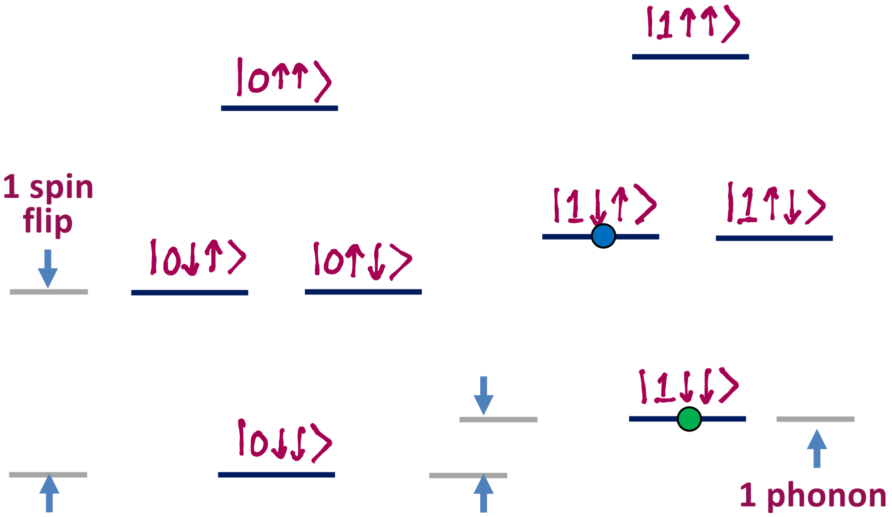

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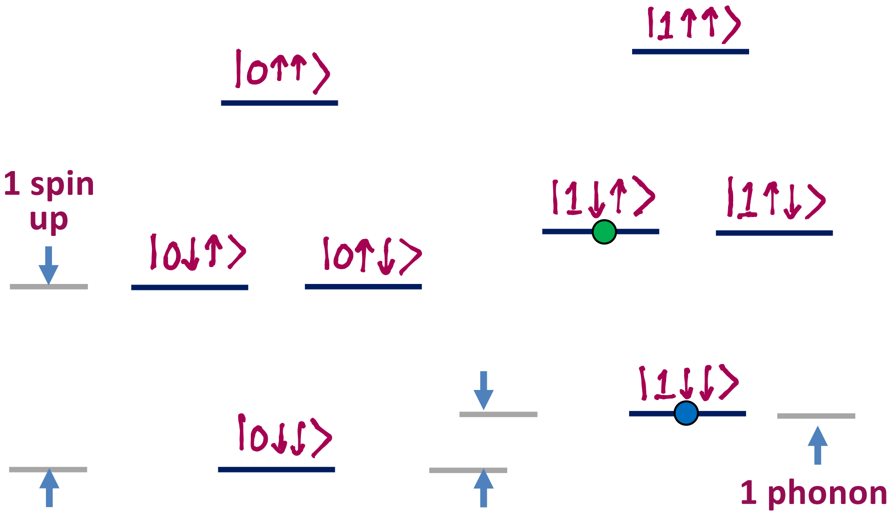
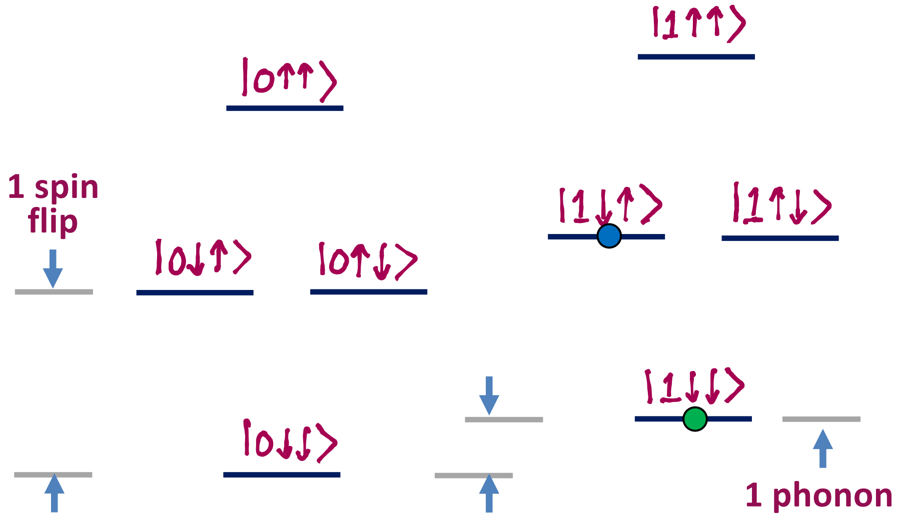


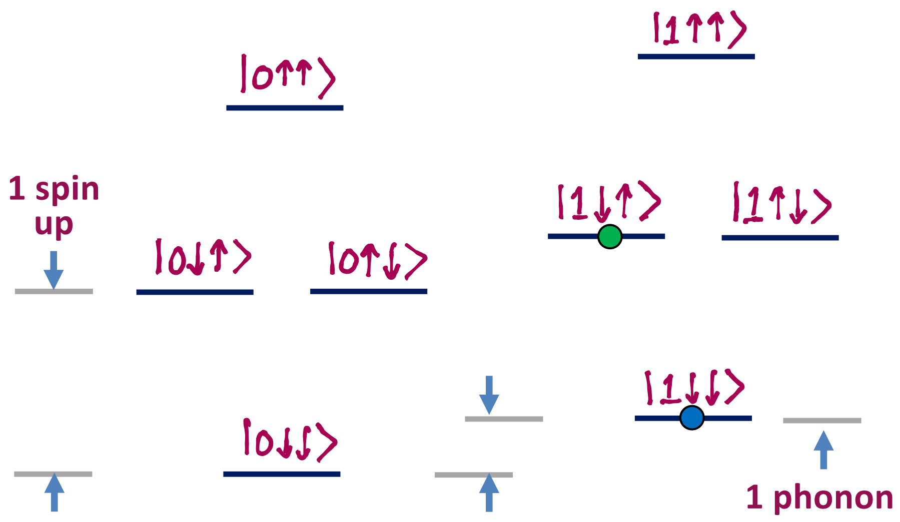
(2) π pulse on **T** swaps $|1\downarrow_C\downarrow_T\rangle \leftrightarrow |1\downarrow_C\uparrow_T\rangle$



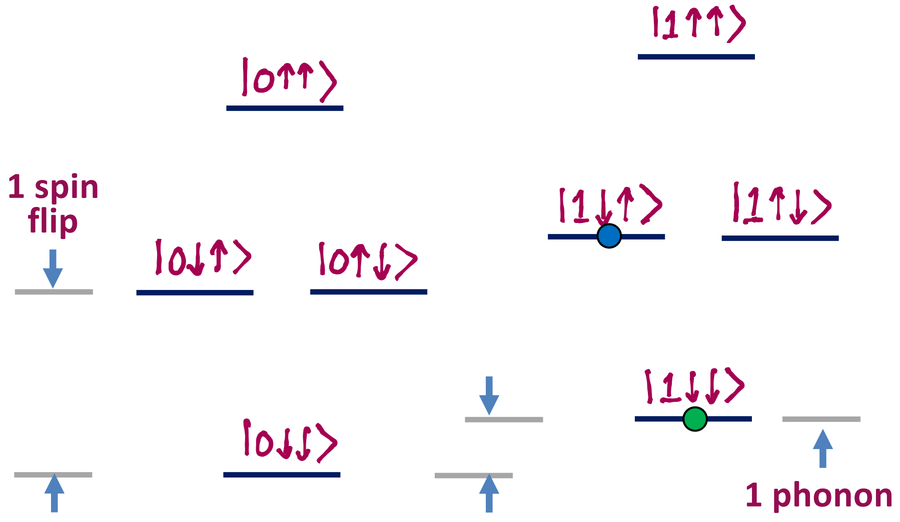
(3) π pulse on **C** swaps $|0\uparrow_C X_T\rangle \leftrightarrow |1\downarrow_C X_T\rangle$

Introduction and Overview (Preskills Notes)

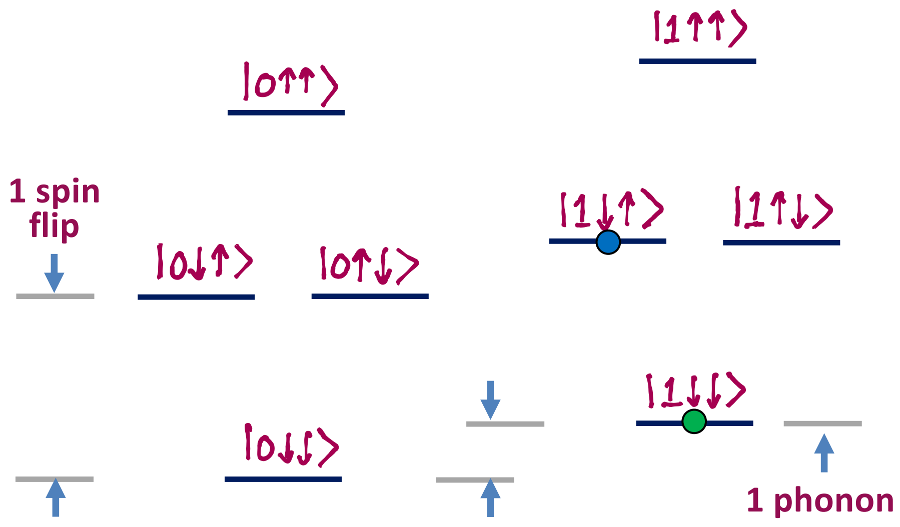
(1) π pulse on C swaps $|0\uparrow_C x_T\rangle \leftrightarrow |1\downarrow_C x_T\rangle$



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



(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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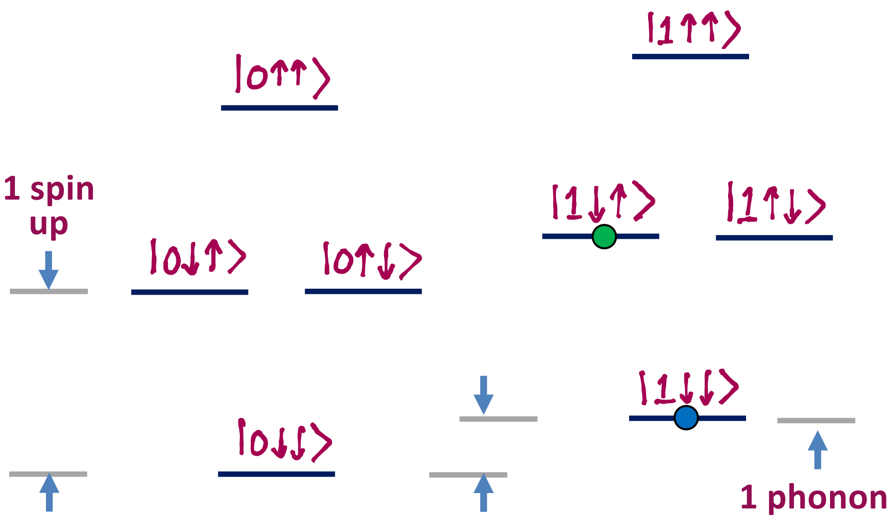

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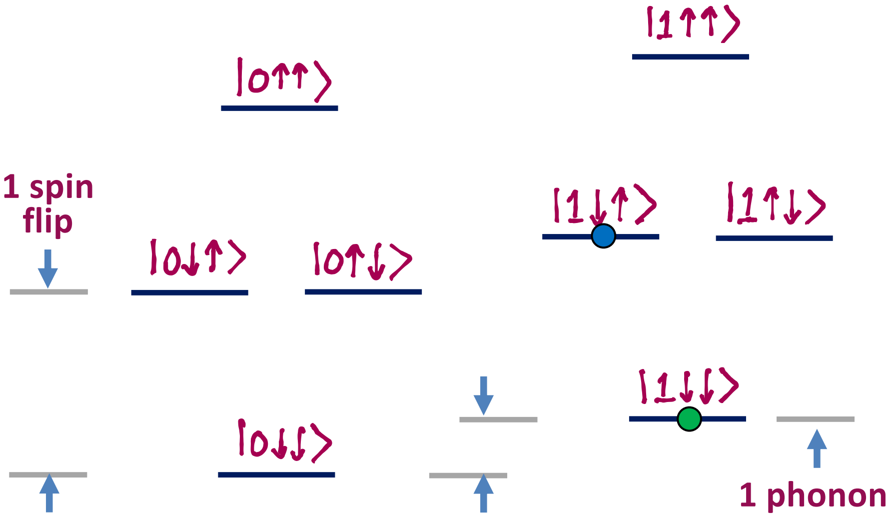

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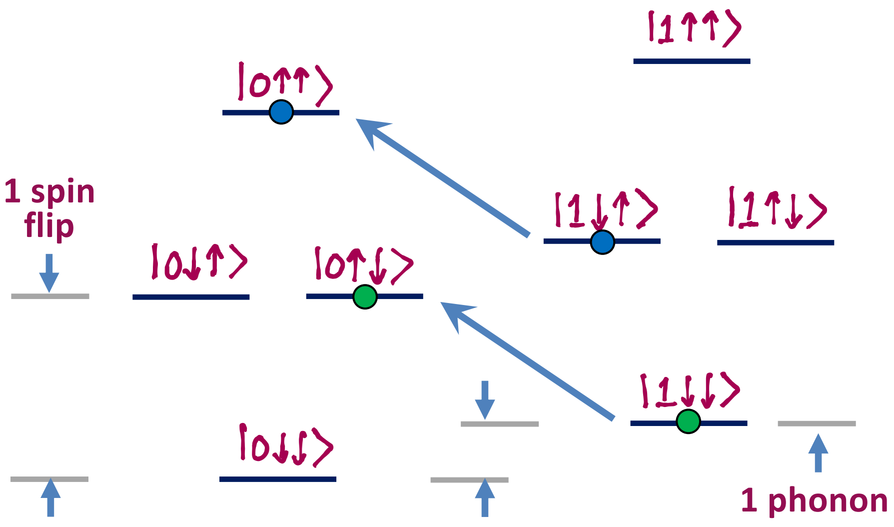

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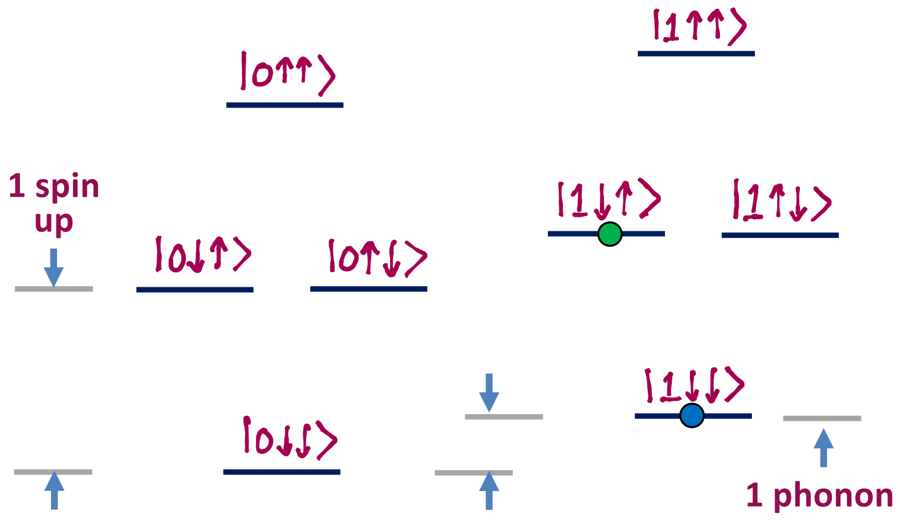

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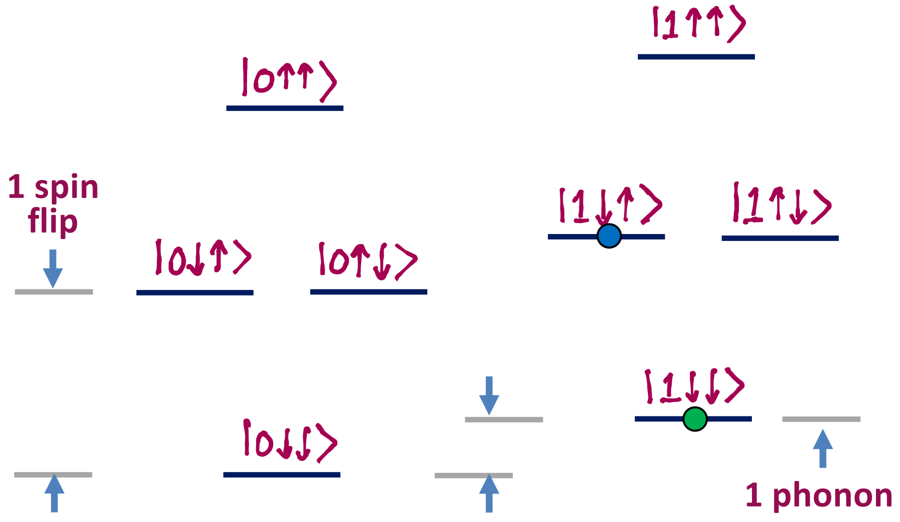

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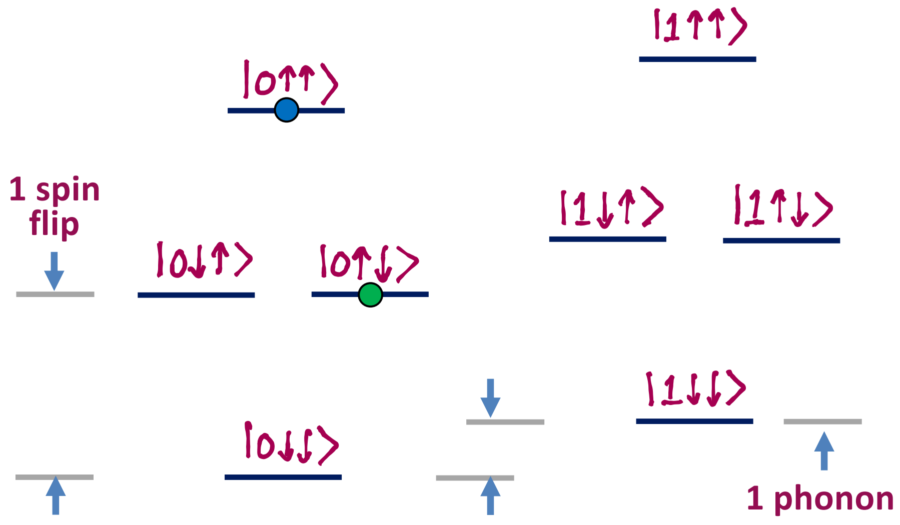

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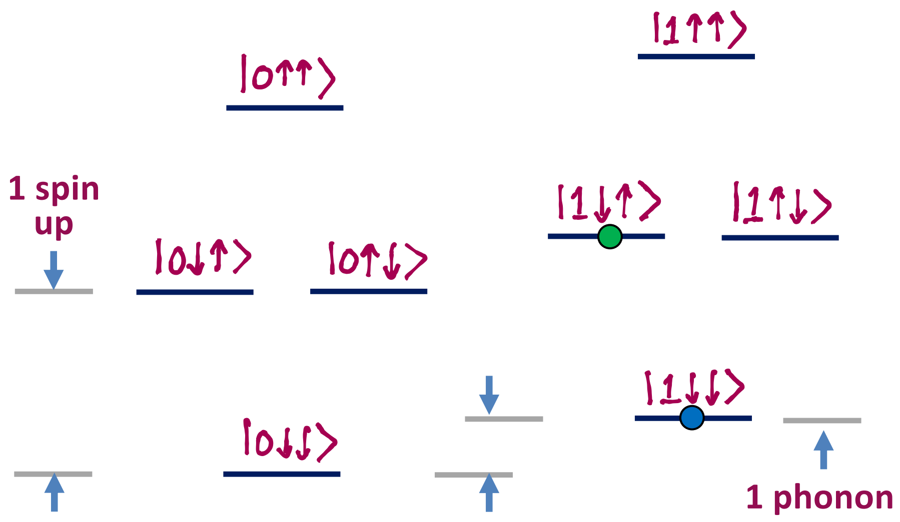

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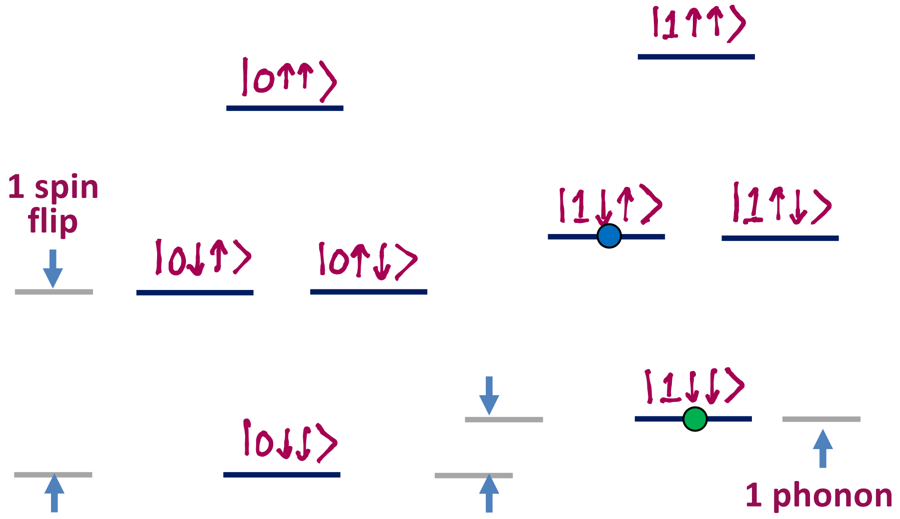

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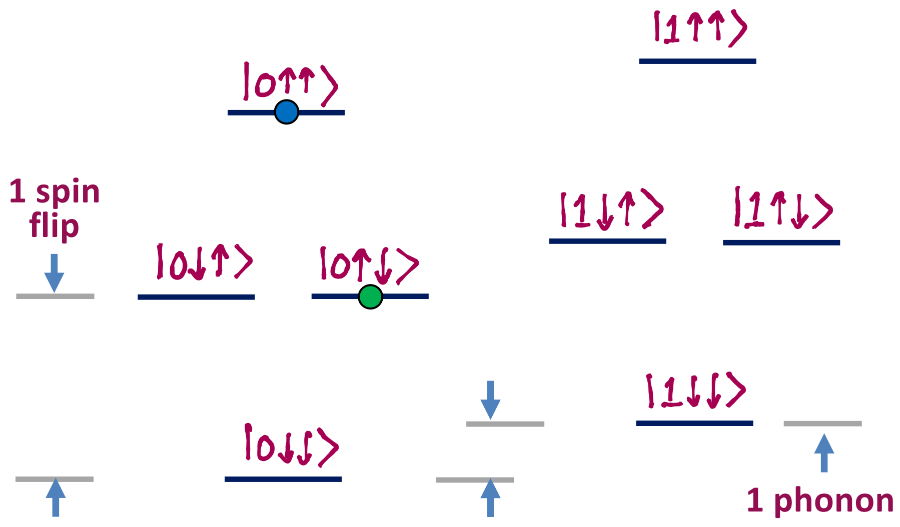

Result: CNOT

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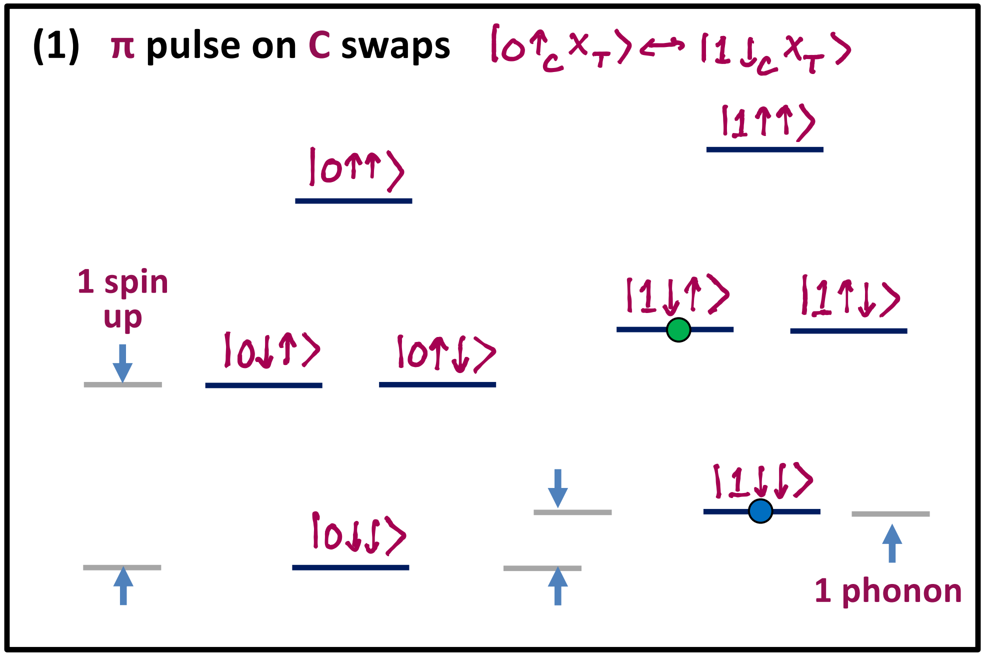

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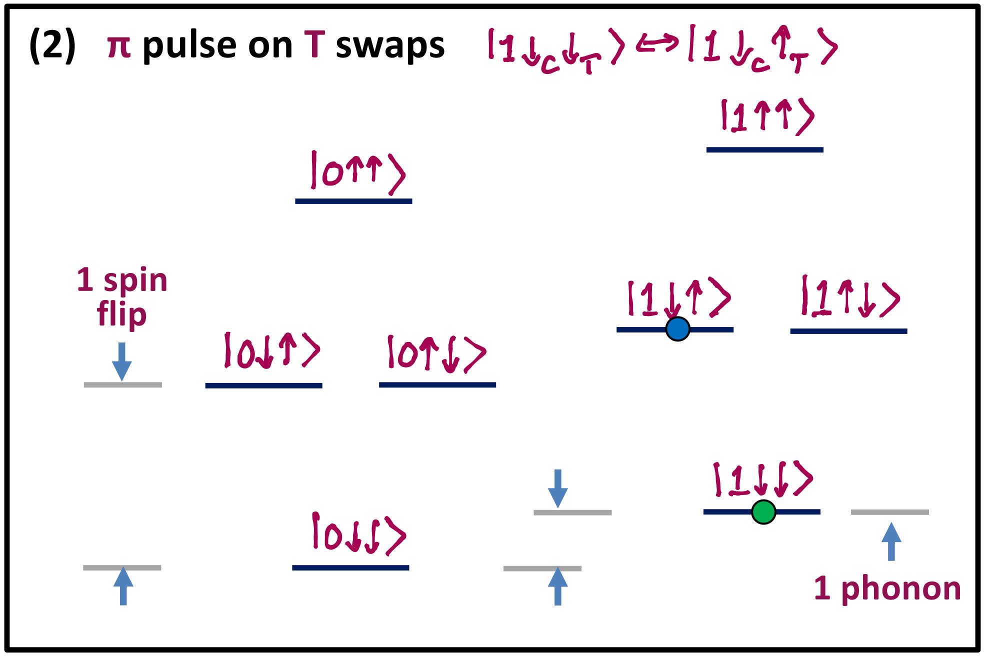

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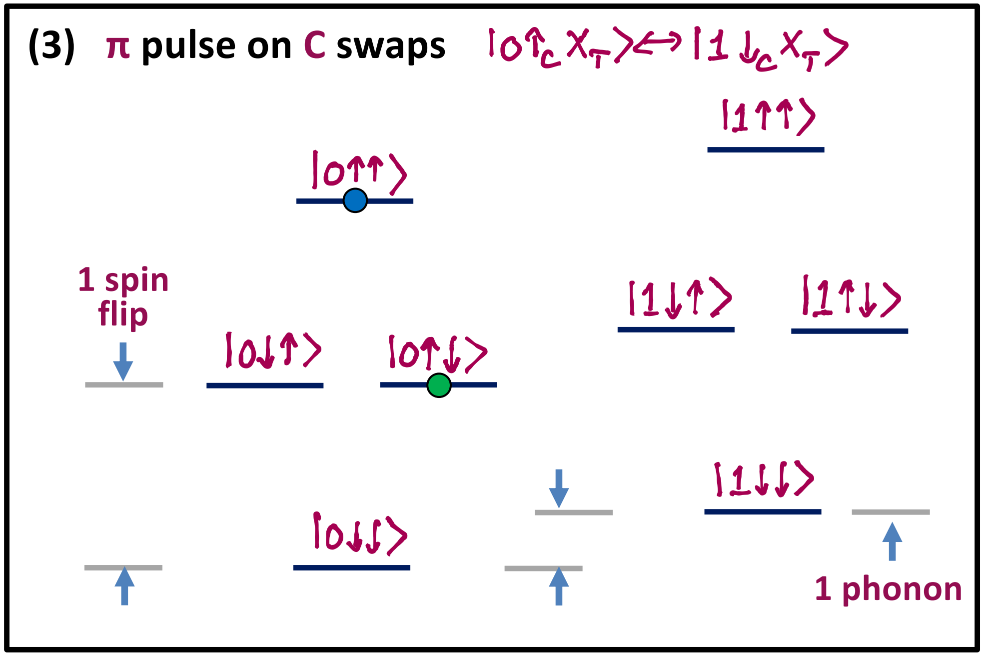

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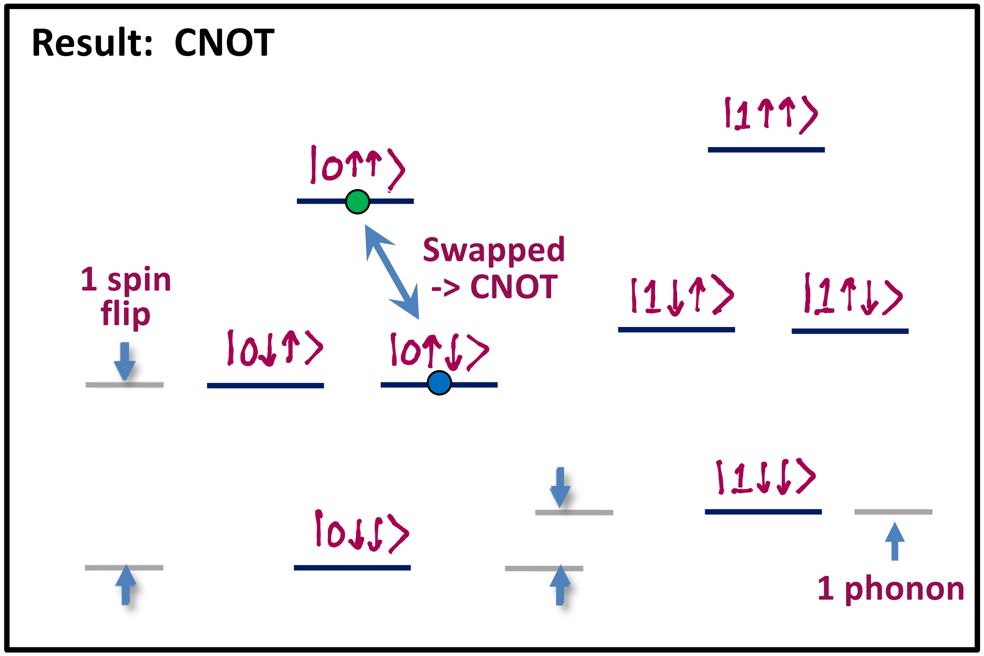

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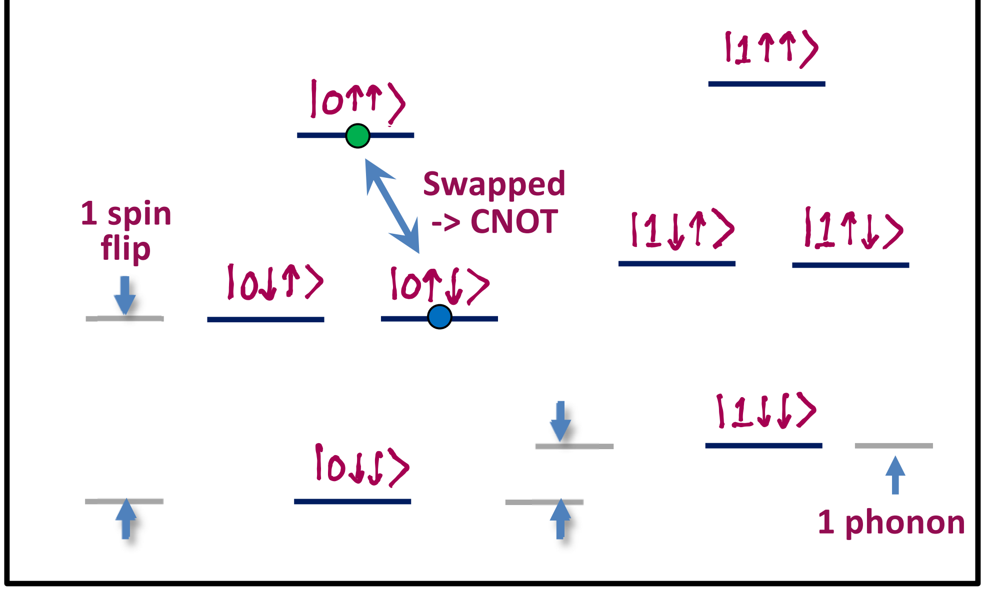

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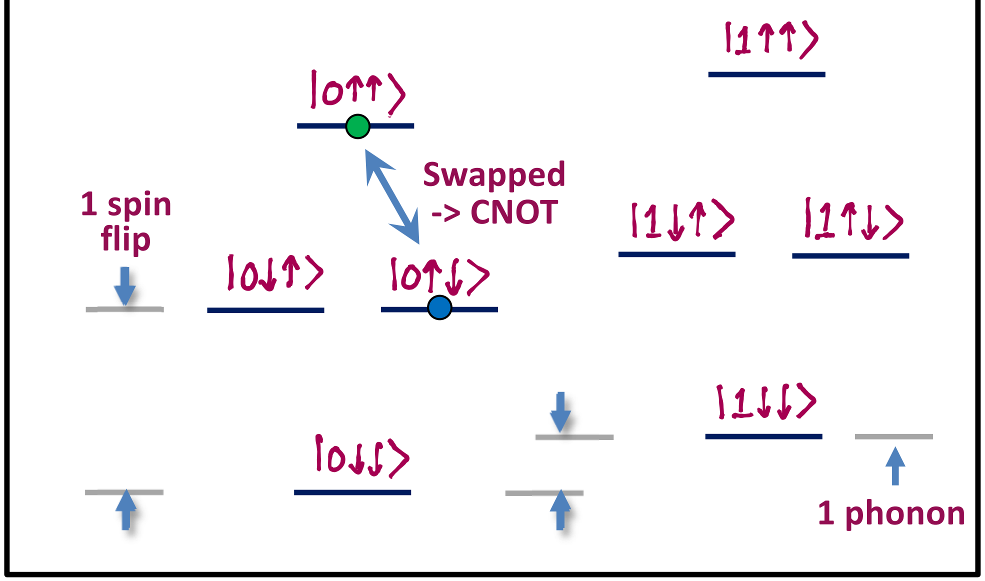
Result: CNOT



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

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	Innsbruck	Quantinuum
Sandia NL	Duke U	IonQ

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

Innsbrück
https://www.uibk.ac.at/th-physik/qic-group/