Quantum computing…
…with single atoms and single photons

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

Dr. Josiah Sinclair, UW-Madison Colloquium, May 1 , 2026

Google Image Search: Madison, WI

Research Interests

- Is quantum theory the correct and best description of nature; do we live in a quantum world?
- What are the fundamental physical limits of computation, communication, and measurement in a quantum universe?
- Best way I know how to make progress on these questions is to build quantum computers.

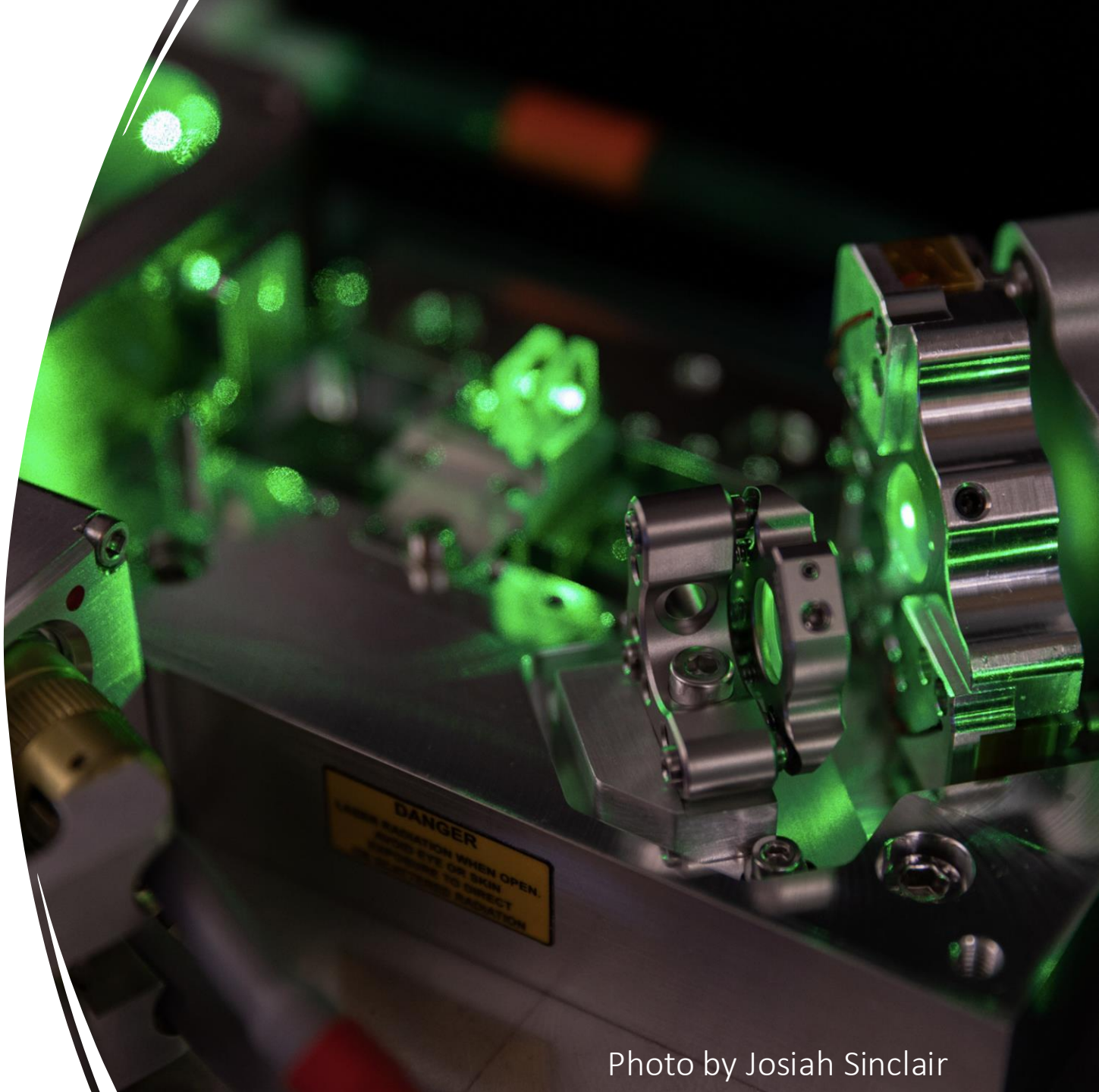


Photo by Josiah Sinclair

Talk Outline

- Quantum computing
- With single atoms
- With single photons

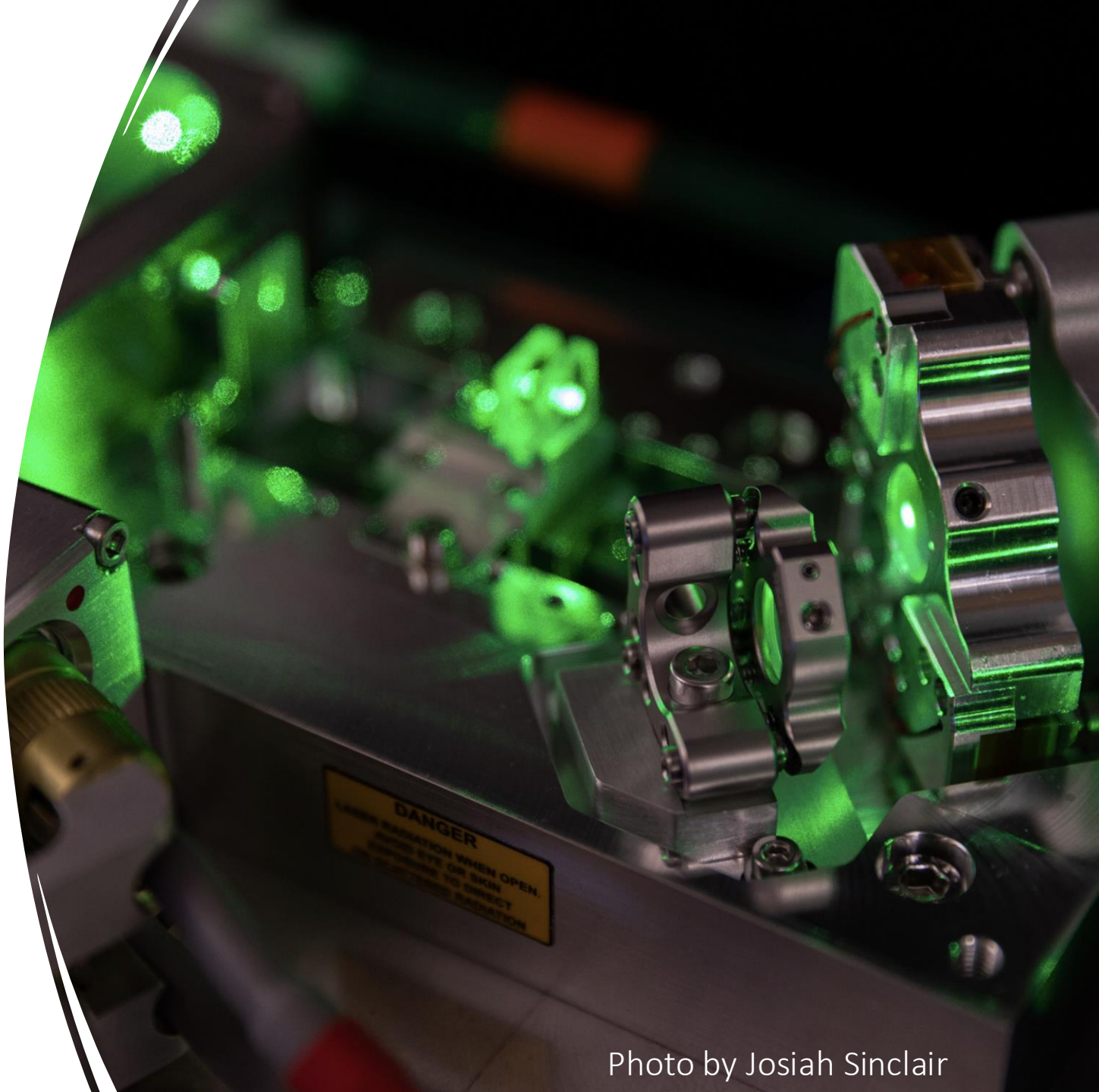
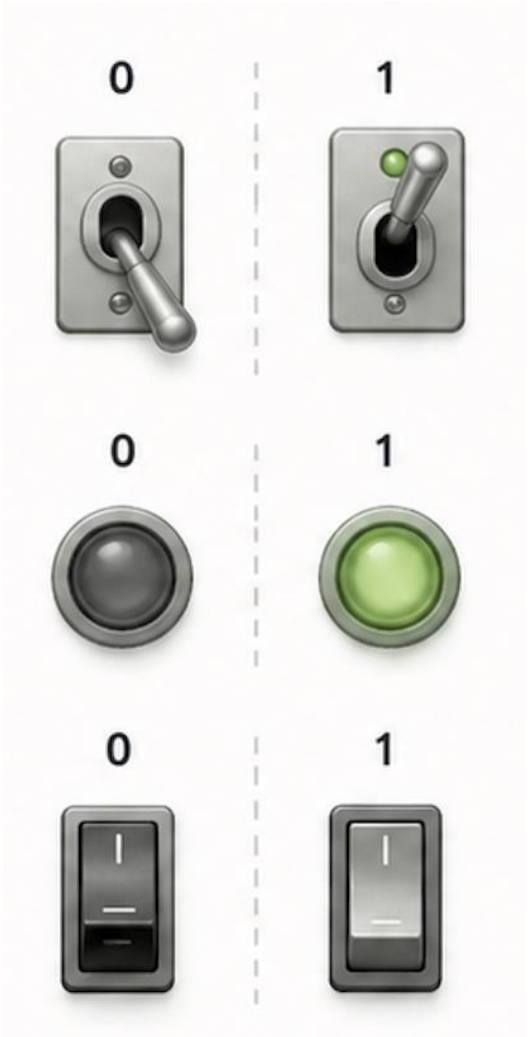
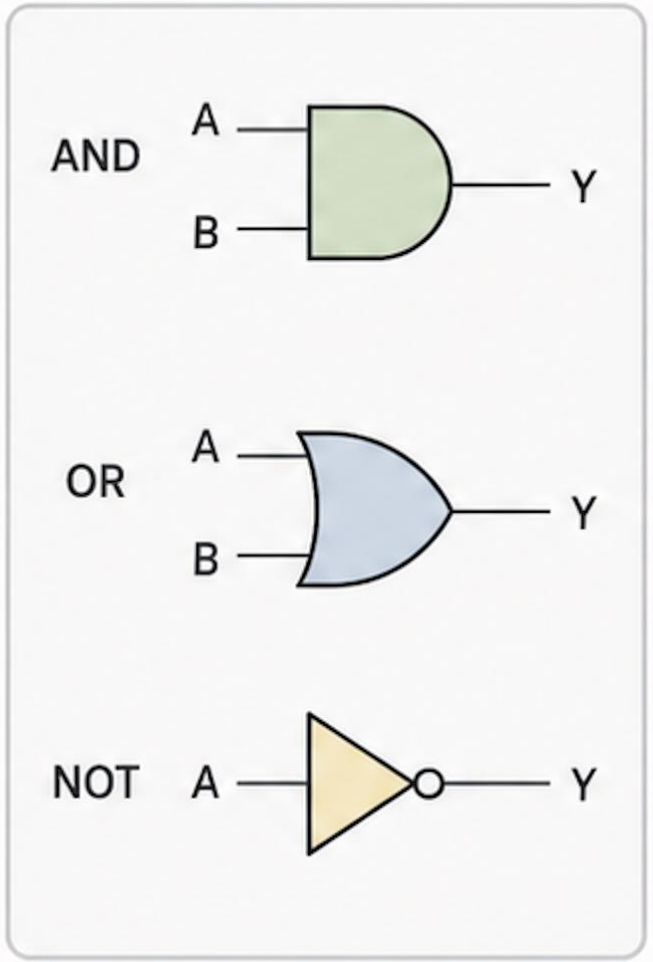


Photo by Josiah Sinclair

What is a computer?

- A physical device with the following two capabilities:
- A way to store information in physical states.
- A way to manipulate the information to implement logical operations.





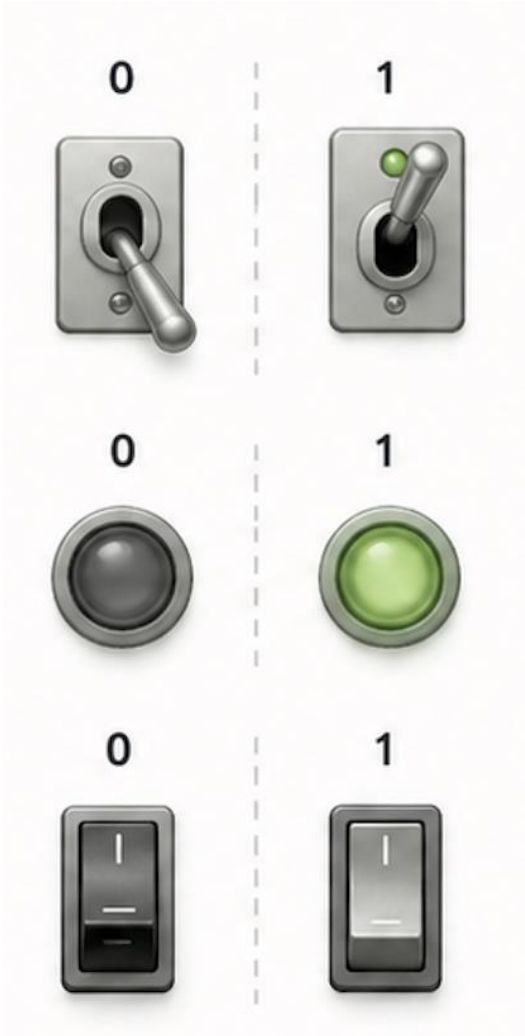
What is a computer?

- A way to store information in physical states.

1	0	1	1	0	1	0	1

- Bit (binary digit) is the elementary unit of information.

- A bit of information can be stored in any system with only two states.



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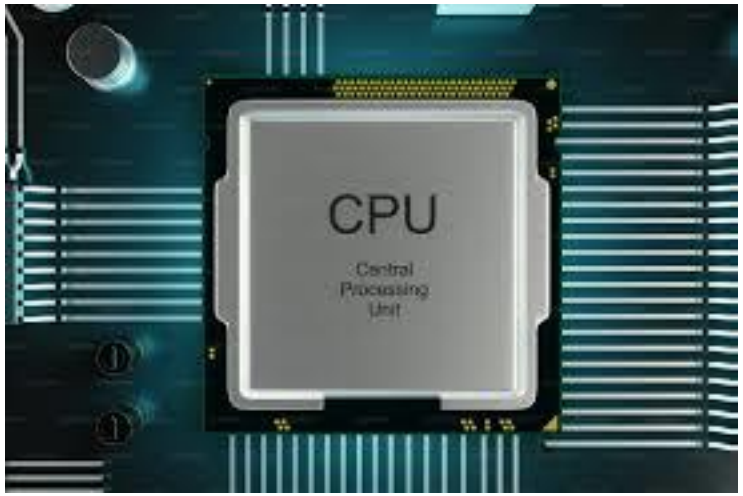
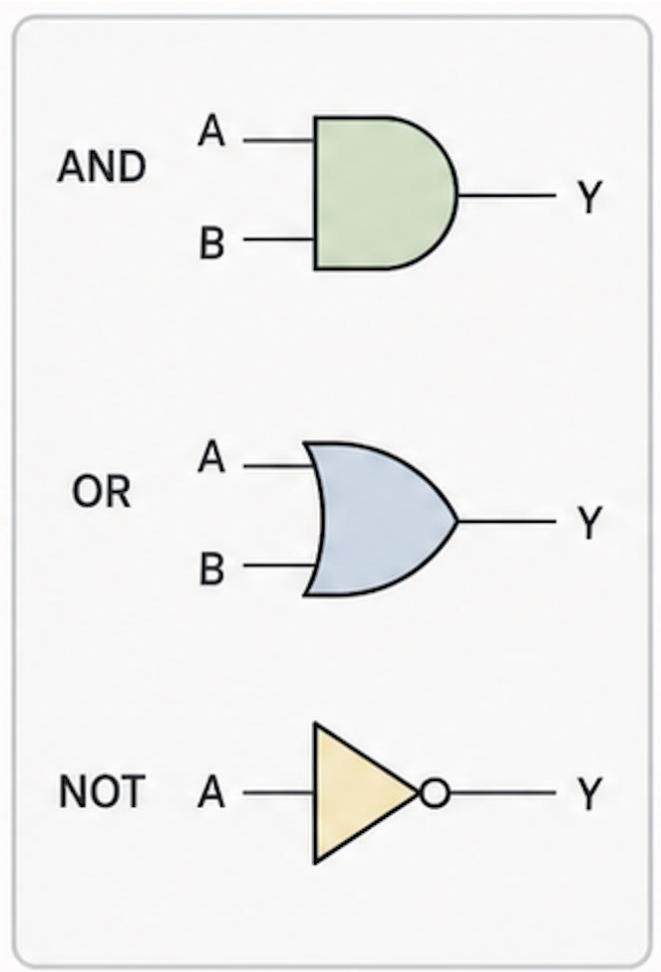




A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

AND Truth Table

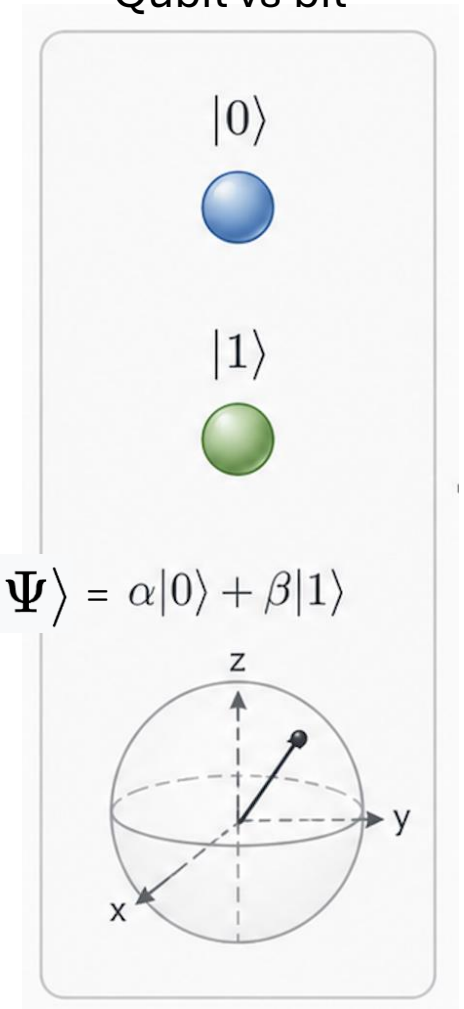
A	Y
0	1
1	0

NOT Truth Table

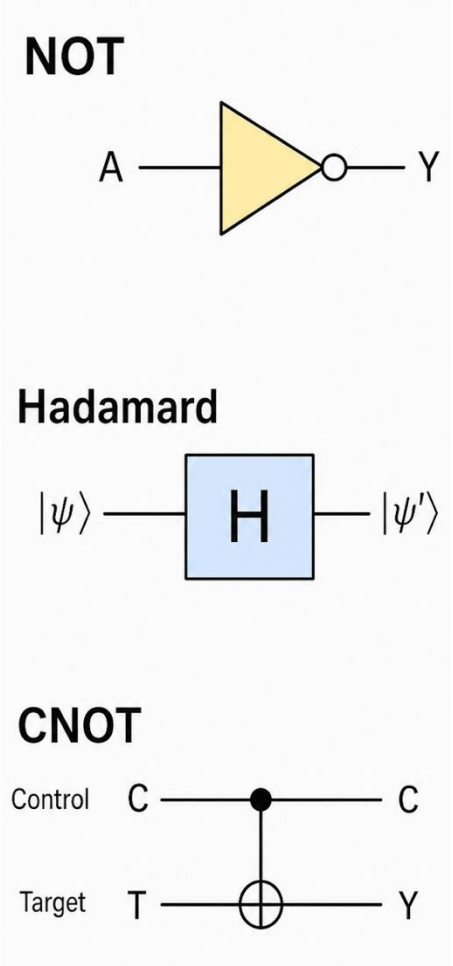
What is a quantum computer?

- A physical device with the following two capabilities:
- A way to store quantum information in physical states
- A way to manipulate quantum information in physical states to implement quantum logic

Qubit vs bit

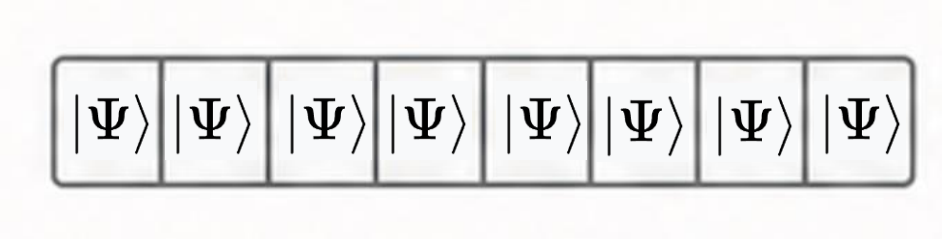


Quantum vs. Classical Gates



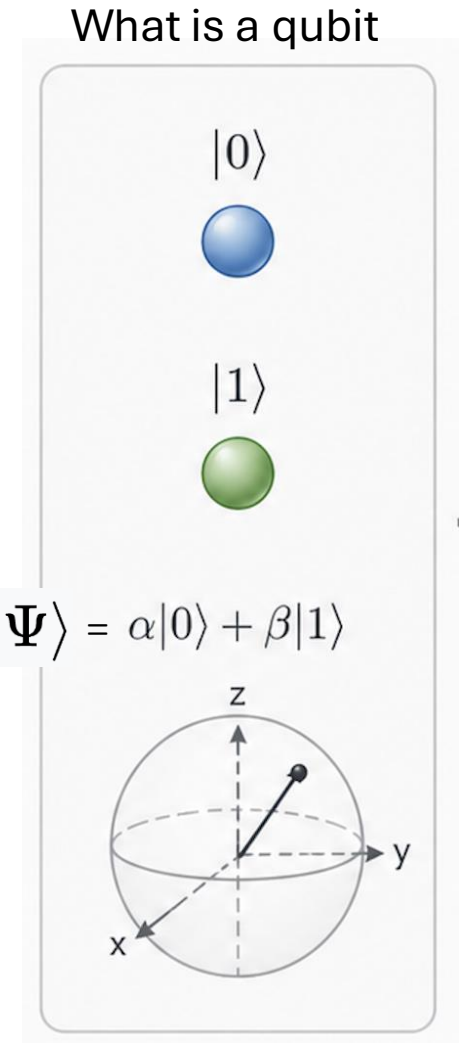
What is a quantum computer?

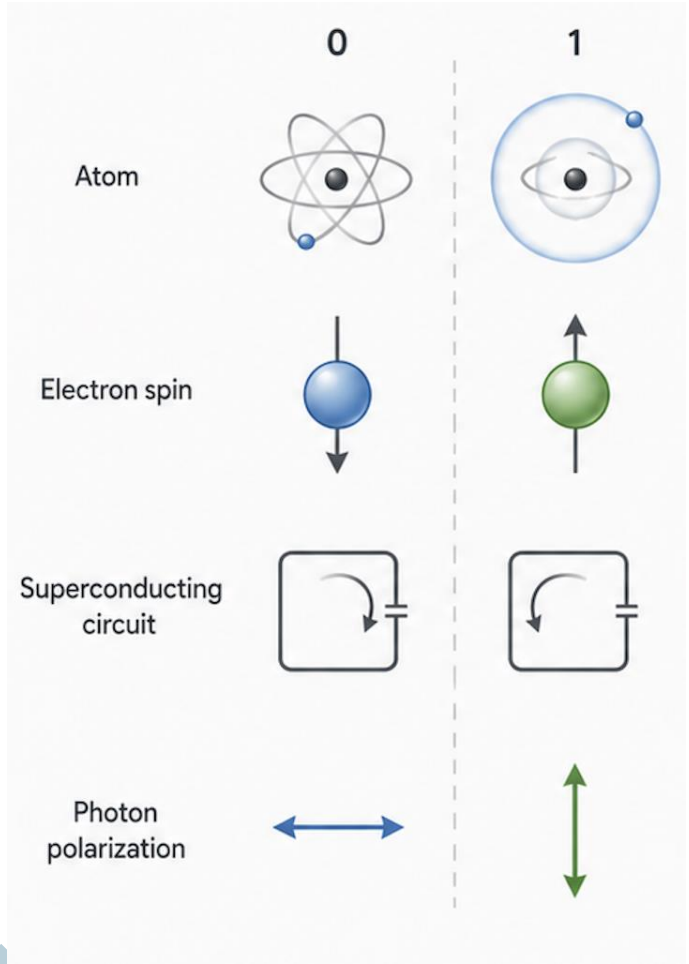
- A way to store quantum information in physical states



- A qubit is the elementary unit of quantum information.

- A qubit can be stored in any two-state quantum system.





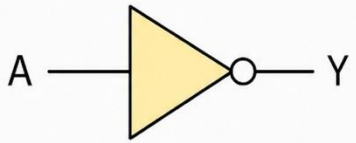
What is a quantum computer?

- A way to manipulate quantum information in physical states to implement quantum logic
- Quantum gates are reversible, unlike AND or OR.
- Hadamard gate creates quantum superposition!

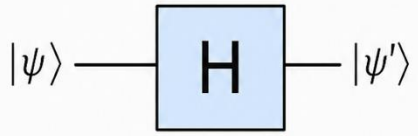
HADAMARD Gate Truth Table

Input State		Output State
$\|0\rangle$	$\rightarrow$	$\frac{\|0\rangle + \|1\rangle}{\sqrt{2}}$
$\|1\rangle$	$\rightarrow$	$\frac{\|0\rangle - \|1\rangle}{\sqrt{2}}$

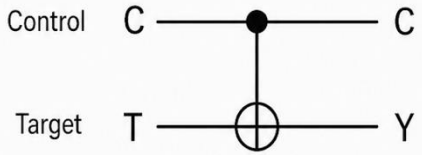
NOT



Hadamard



CNOT



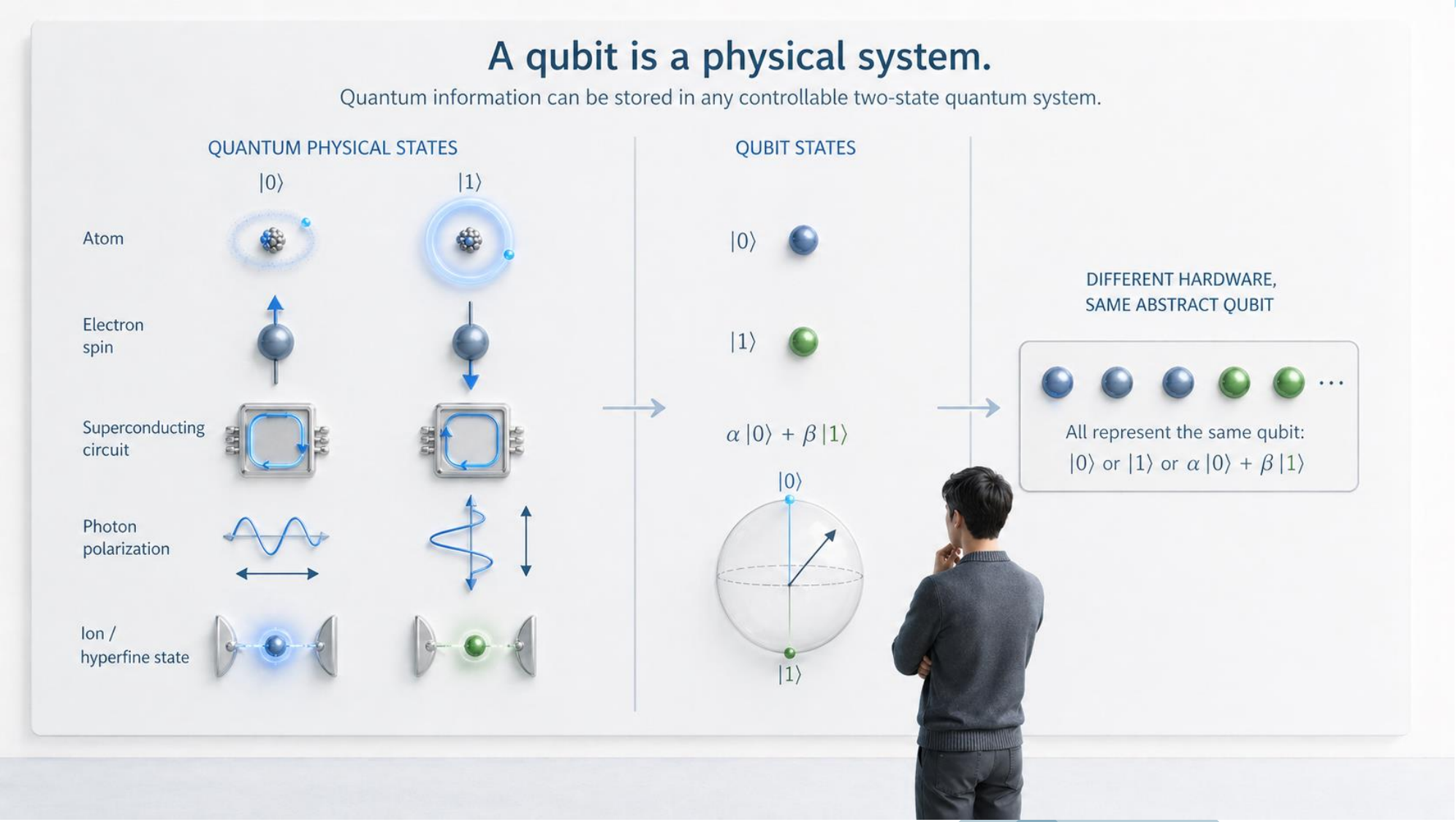
NOT Truth Table

Input State		Output State
$\|0\rangle$	$\rightarrow$	$\|1\rangle$
$\|1\rangle$	$\rightarrow$	$\|0\rangle$

CONTROL-NOT Truth Table

Input State (Control, Target)		Output State (Control, Target)
$\|00\rangle$	$\rightarrow$	$\|00\rangle$
$\|01\rangle$	$\rightarrow$	$\|01\rangle$
$\|10\rangle$	$\rightarrow$	$\|11\rangle$
$\|11\rangle$	$\rightarrow$	$\|10\rangle$

What is a quantum computer?



Neutral-Atom Quantum Computing

- A relatively recent entry to the race.

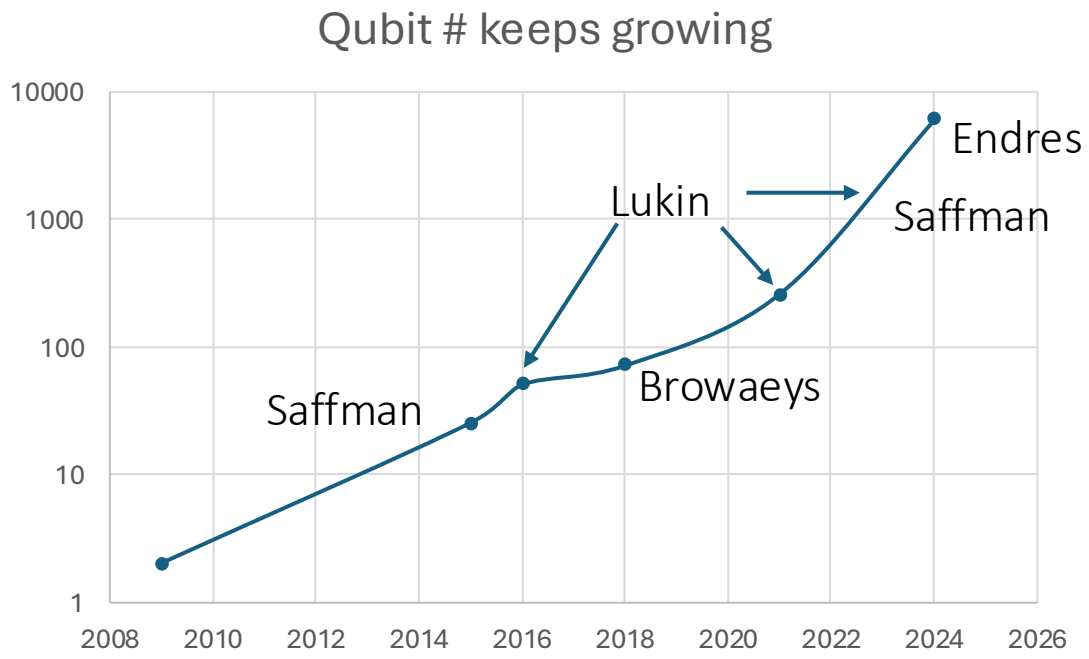
Bluvstein 2022

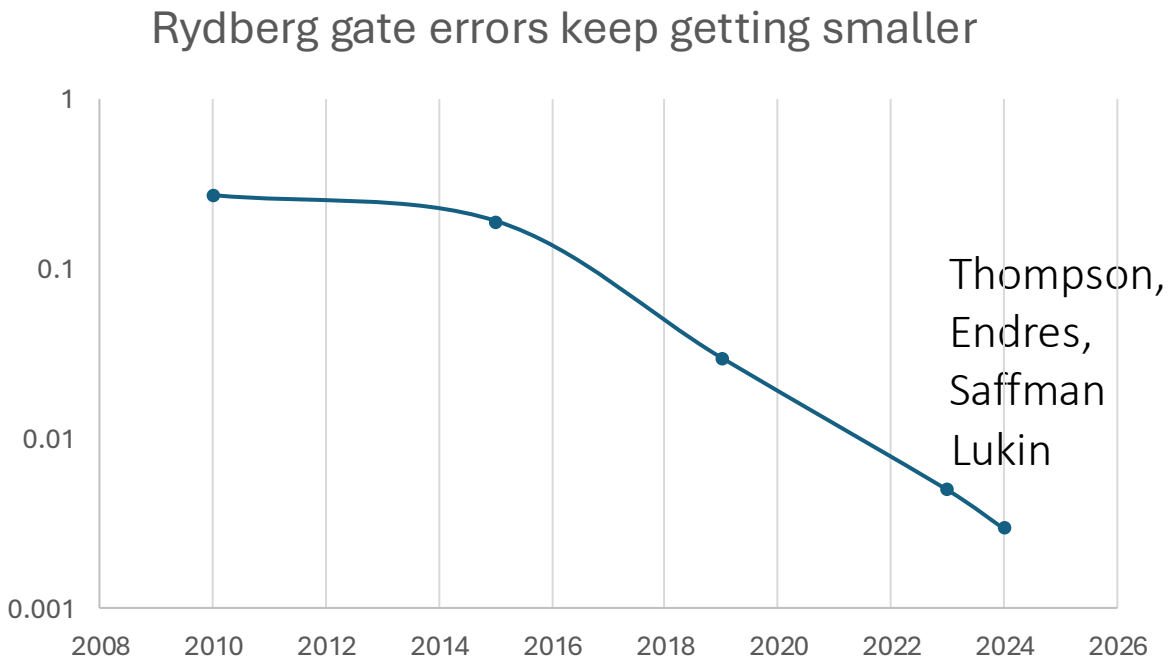
- Now a strong contender in the race to build utility-scale quantum computers.

https://www.economist.com/science-and-technology/**2015**/06/20/a-little-bit-better

Cartoon from 2015, so notice a conspicuous absence…

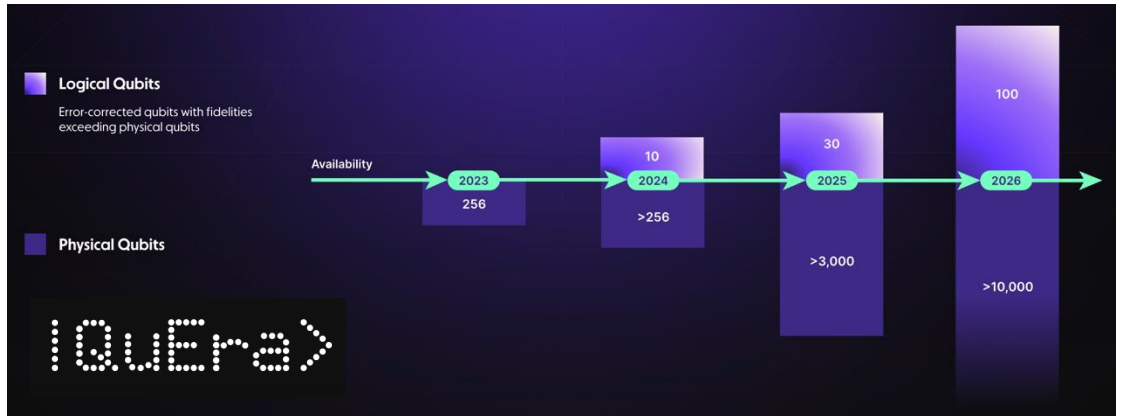
Neutral-Atom Quantum Computing

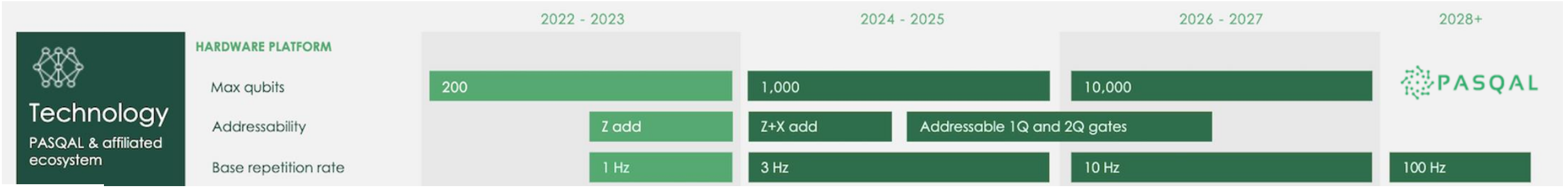




Neutral-Atom Quantum Computing

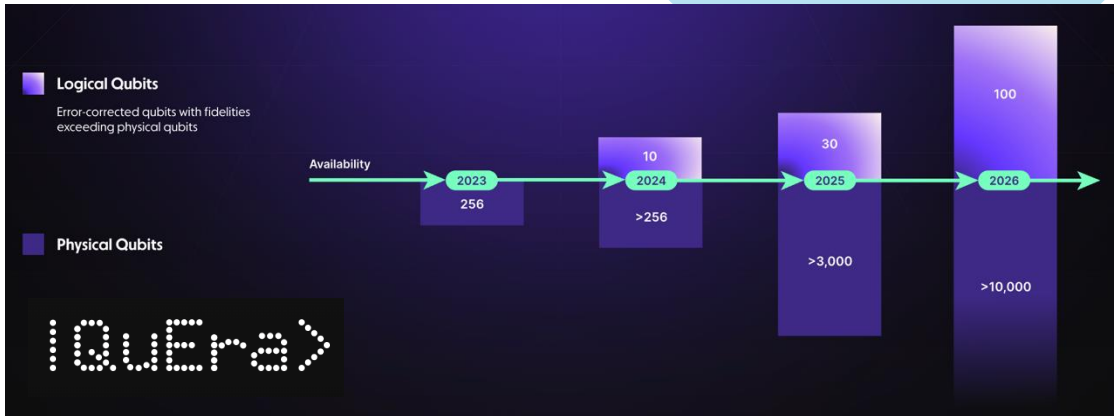
- What will the next 10 years hold?
- How to scale beyond where the roadmaps end?

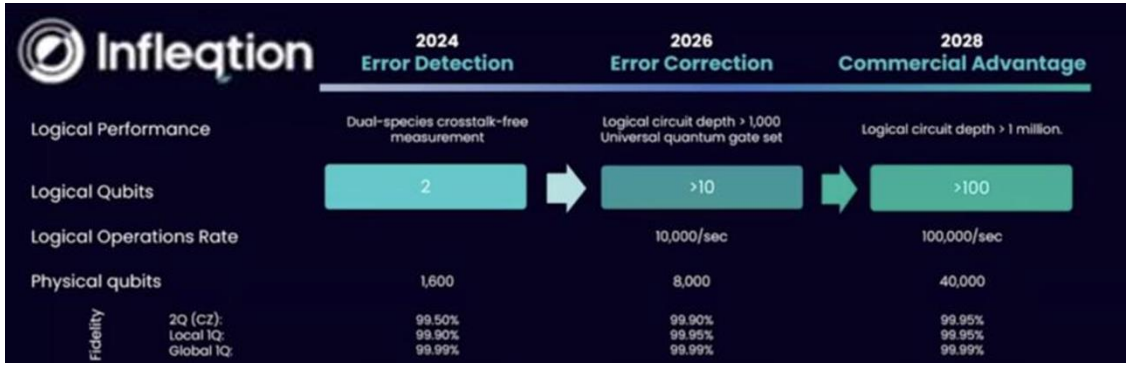


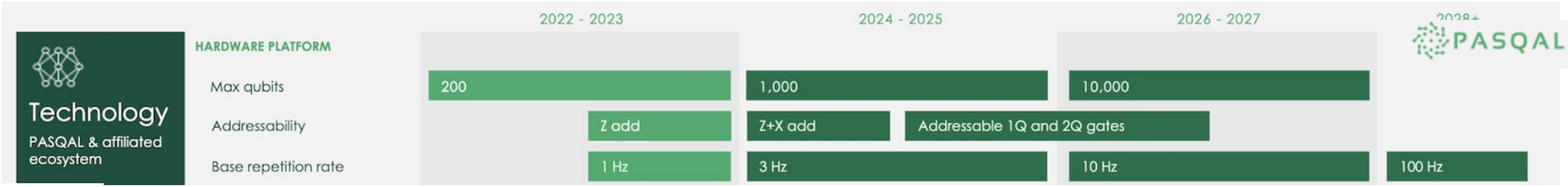


Neutral-Atom Quantum Computing

- Aggressive roadmaps promising
  - 100 logical qubits
  - 10,000 physical qubits
  - in the next few years!







Introduction to Atom Arrays

- Start from a cold (stationary) cloud of 10-100 million atoms
- A great starting point—unlimited supply of identical quantum systems.
- Cool, trap, and manipulate with light!

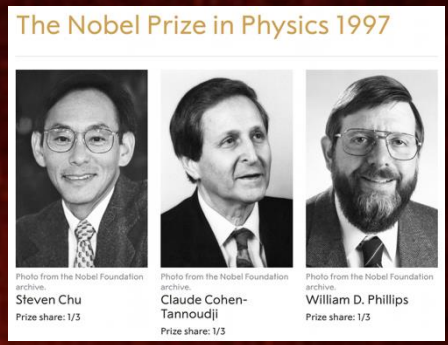
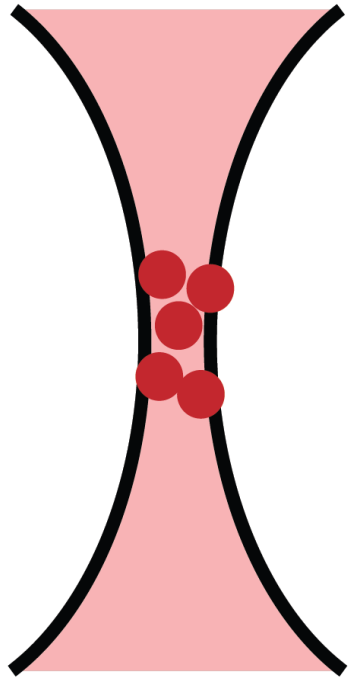


Photo by Josiah Sinclair

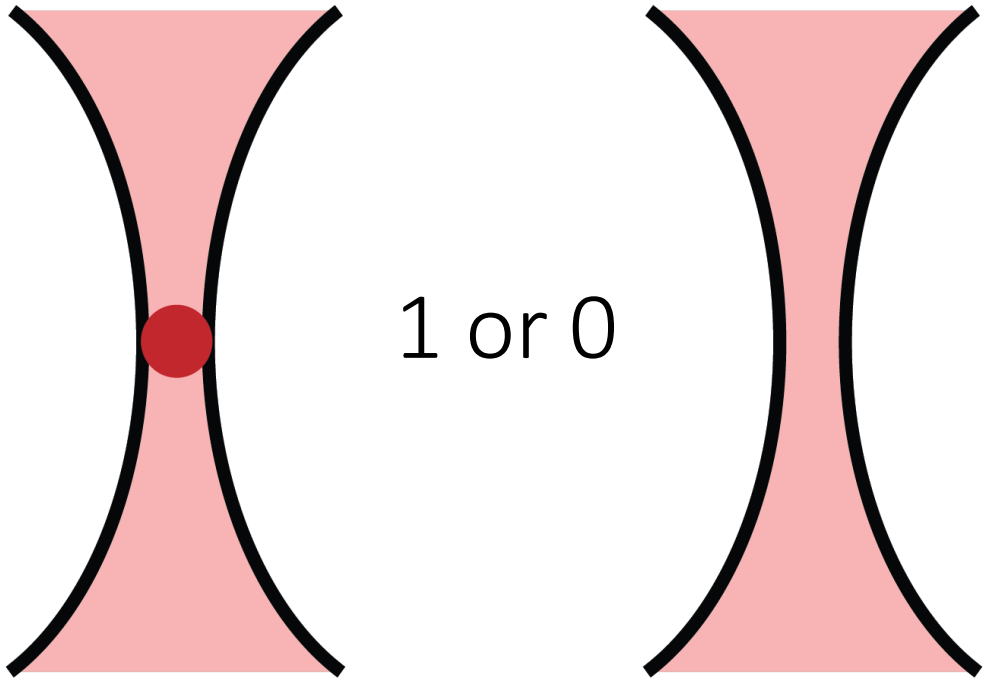
Introduction to Atom Arrays

- Start from a cold (stationary) cloud of 10-100 million atoms
- A focused optical beam traps many atoms.



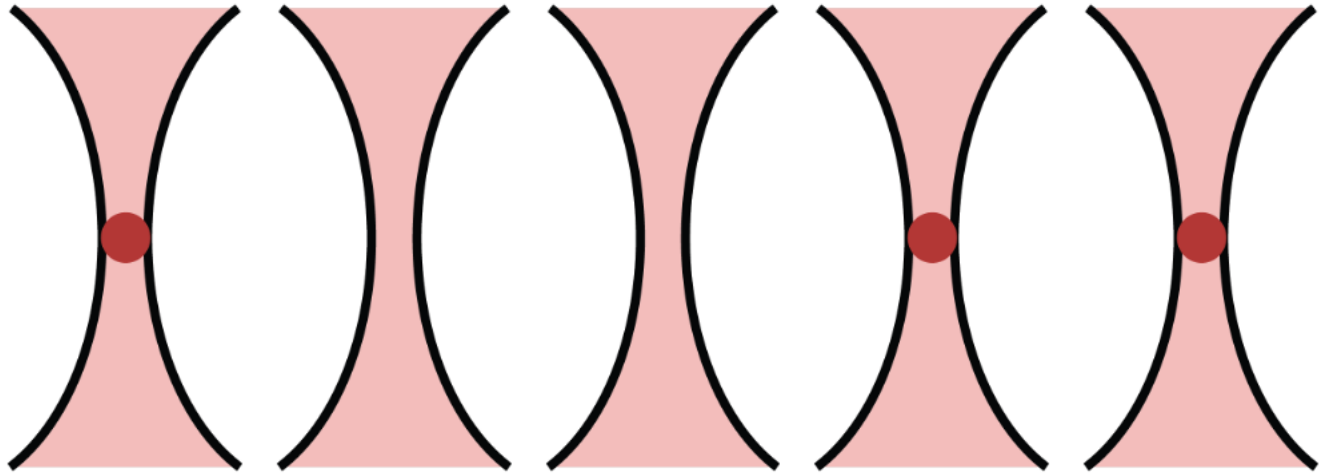
Introduction to Atom Arrays

- Start from a cold (stationary) cloud of 10-100 million atoms
- A focused optical beam traps many atoms.
- Atoms collide and leave in pairs, leaving 0 or 1 atoms
- First observed in 2001 [Graingier].



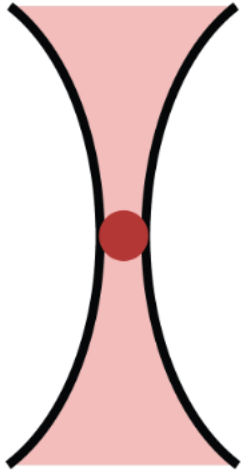
Introduction to Atom Arrays

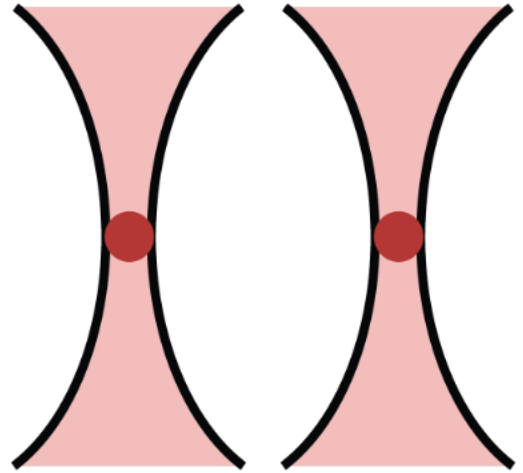
- Start from a cold (stationary) cloud of 10-100 million atoms
- An array of traps results in a partially filled array of atoms



Introduction to Atom Arrays

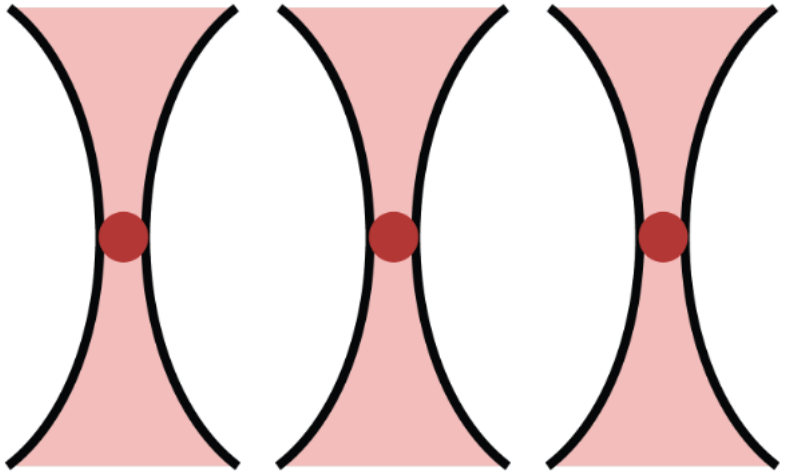
- Start from a cold (stationary) cloud of 10-100 million atoms
- An array of traps results in a partially filled array of atoms
- Empty traps are turned off





Introduction to Atom Arrays

- Start from a cold (stationary) cloud of 10-100 million atoms
- An array of traps results in a partially filled array of atoms
- Traps are rearranged to to produce a filled array



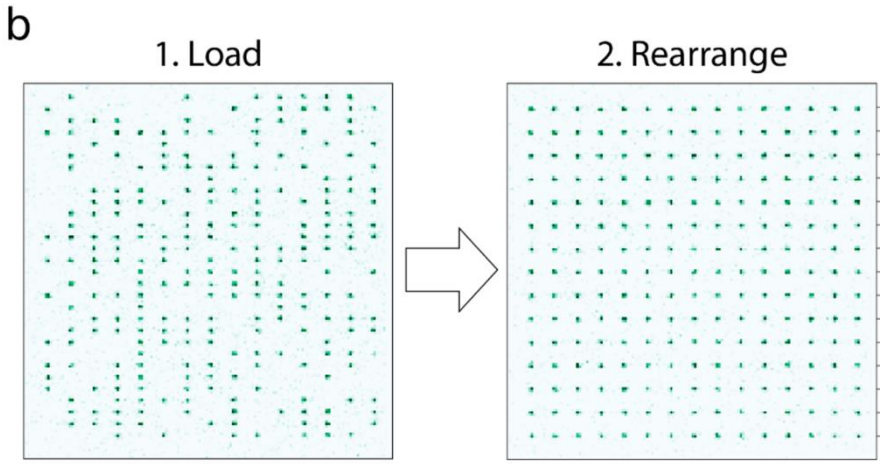
Lukin, Browaeys, Ahn

Defect-free arrays of atoms

- Sorting demonstrated in 1D

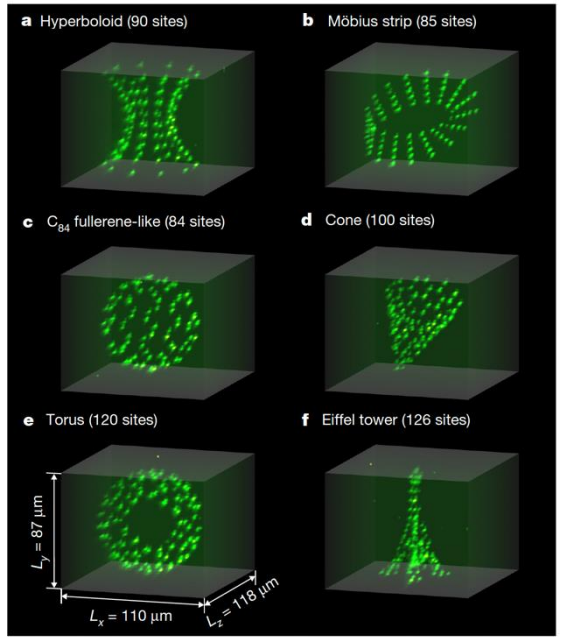
Lukin 2016

- And 2D



Lukin 2021

- And even 3D



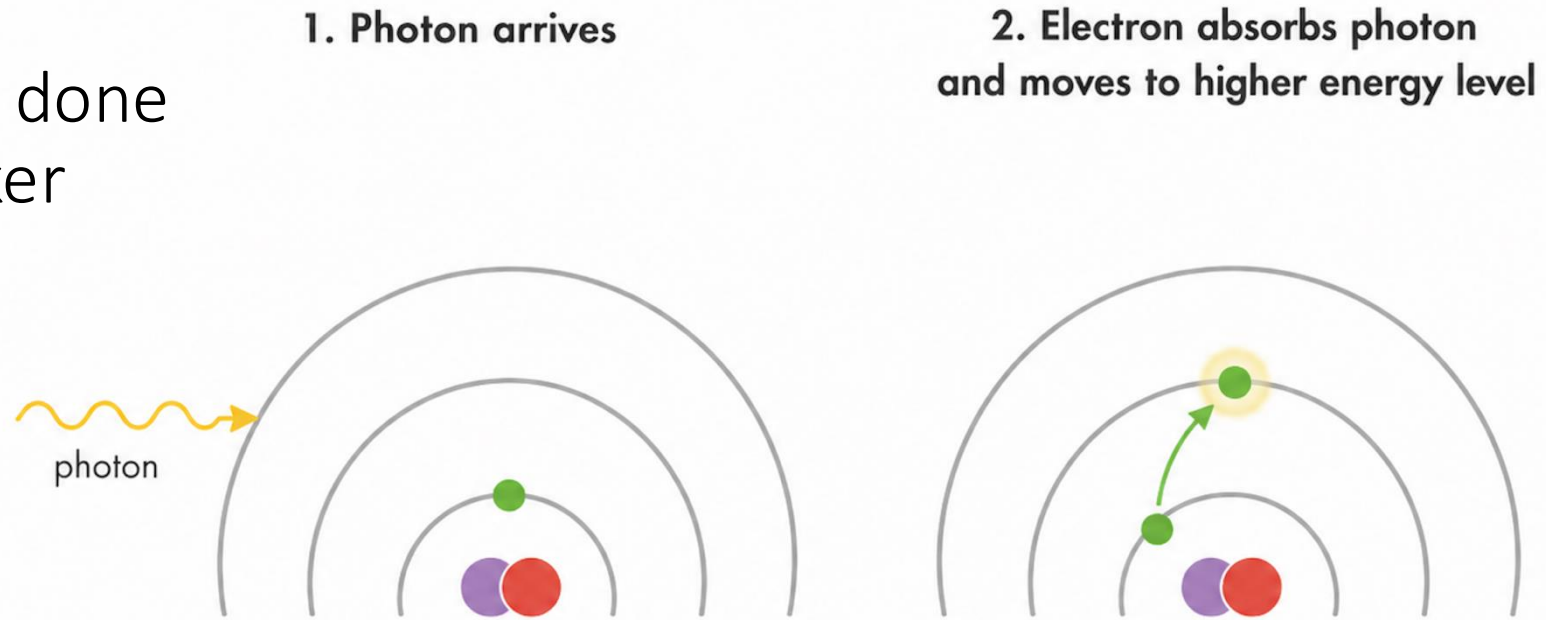
Browaeys (2018)

Atom Array as Quantum Memory

- Store a quantum bit (qubit) in each atom.
- Manipulate the qubit by using lasers to drive transitions in the atom.
- Pioneering experiments done here by Saffman & Walker groups circa 2006.

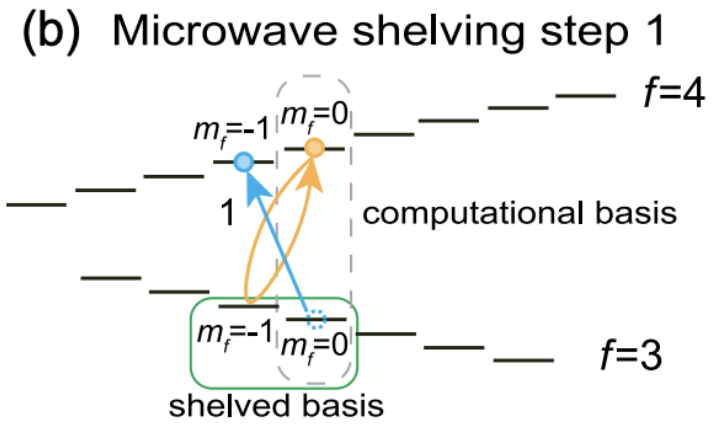

Mark Saffman

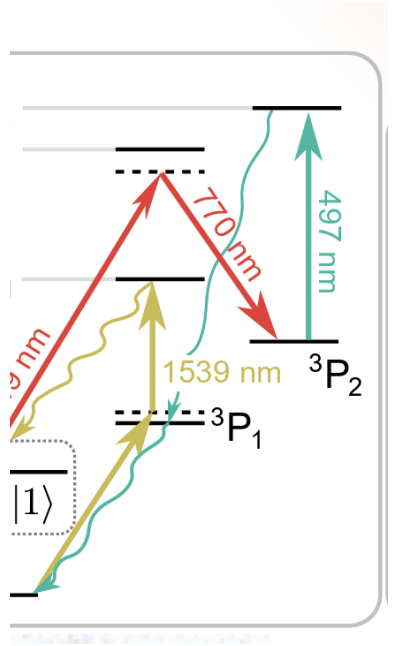

Thad Walker



State preparation in neutral atom arrays

- Choose qu
- Use optica
  Raman to
  in qubit su
- Now have
  |0000000.

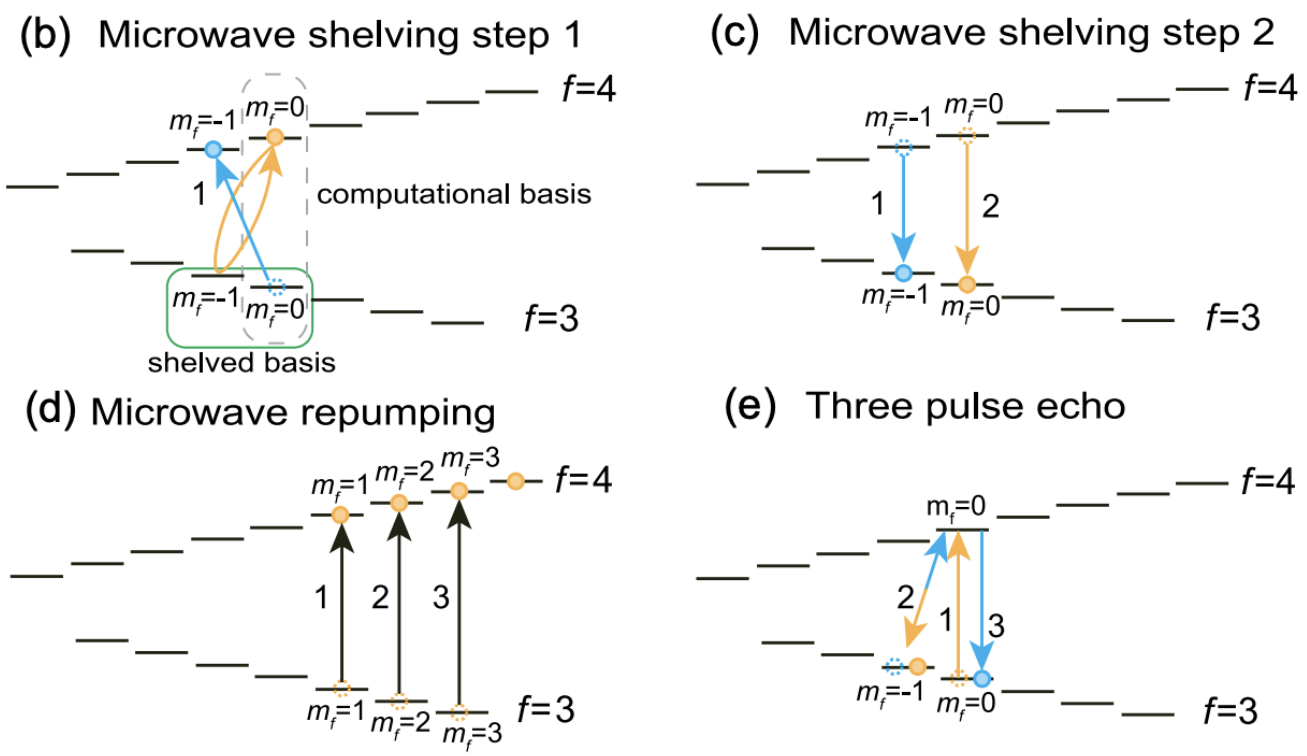




Thompson, 2025

1Q Gates in Neutral-Atom Arrays

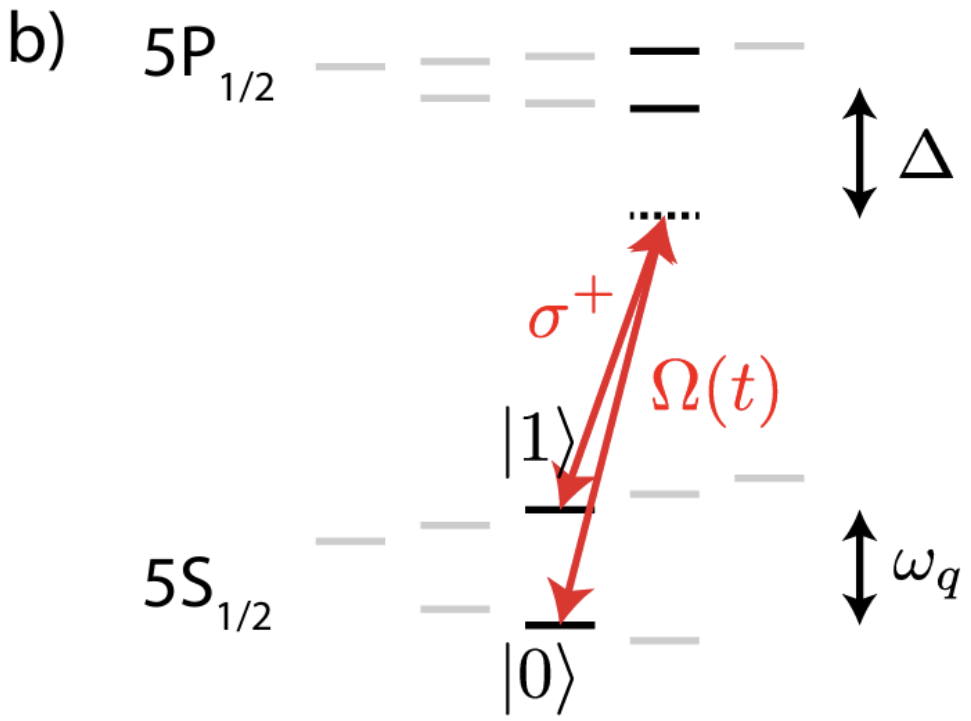
- Depends on choice of qubit sub-space.
- Most commonly done via microwave…



Saffman, 2023

1Q Gates in Neutral-Atom Arrays

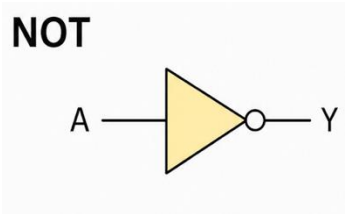
- Depends on choice of qubit sub-space.
- Most commonly done via microwave… or Raman

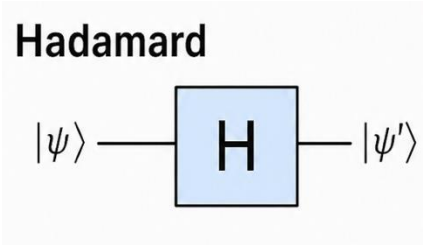


Lukin, 2021

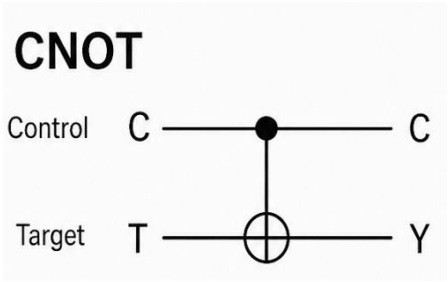
Quantum Logic with Atoms

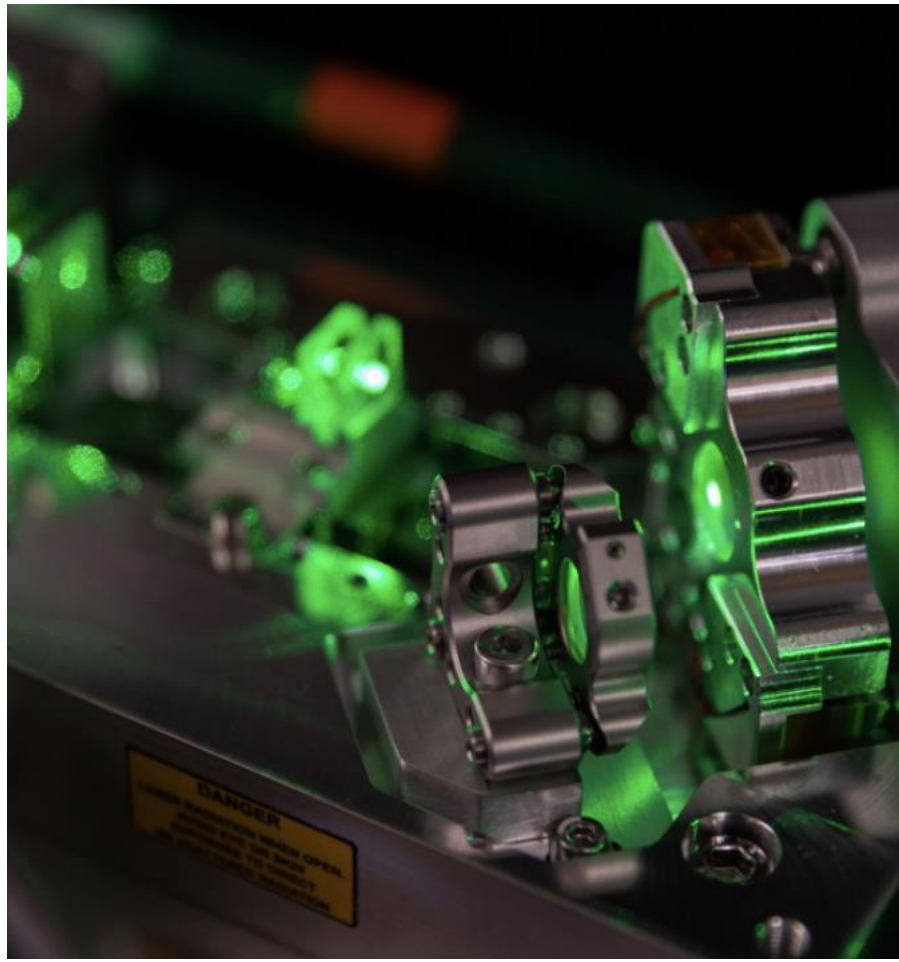
- Use lasers to do single-qubit operations
  - Bit flip
  - Hadamard





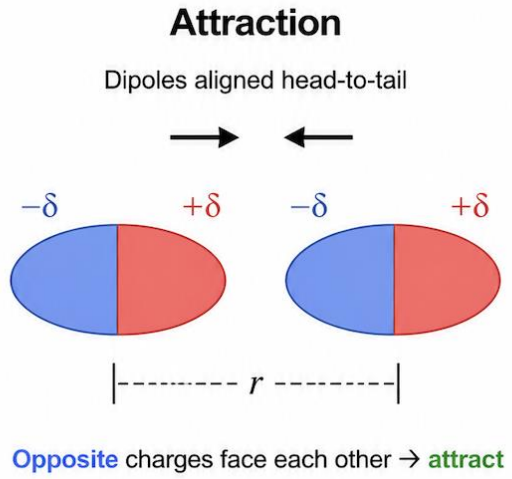
- Also need a way to do 2Q gates

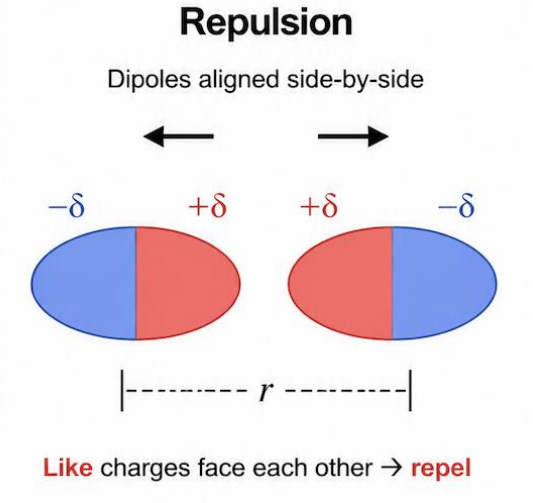




Quantum Logic with Atoms

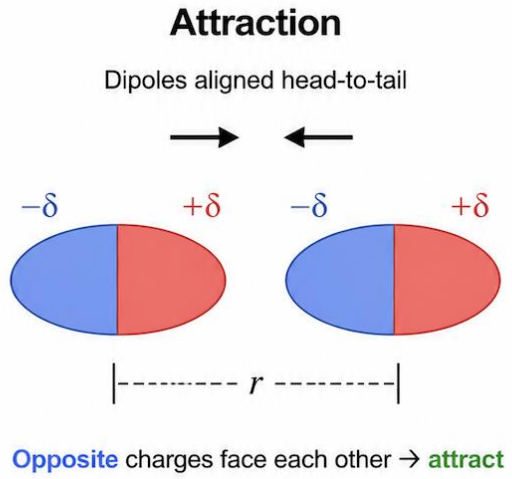
- Need the atoms to interact to do 2Q gates.
- Need one atom to change the state of the other atom in a controlled way (4 forces!)
- Atoms are neutral (no overall charge).
- Atom contains nucleus (positively charged) and electron cloud (negatively charged).
- Possible for dipole-dipole interactions to occur

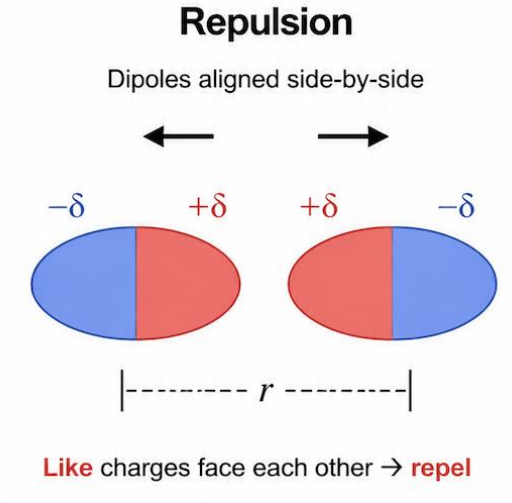




Quantum Logic with Atoms

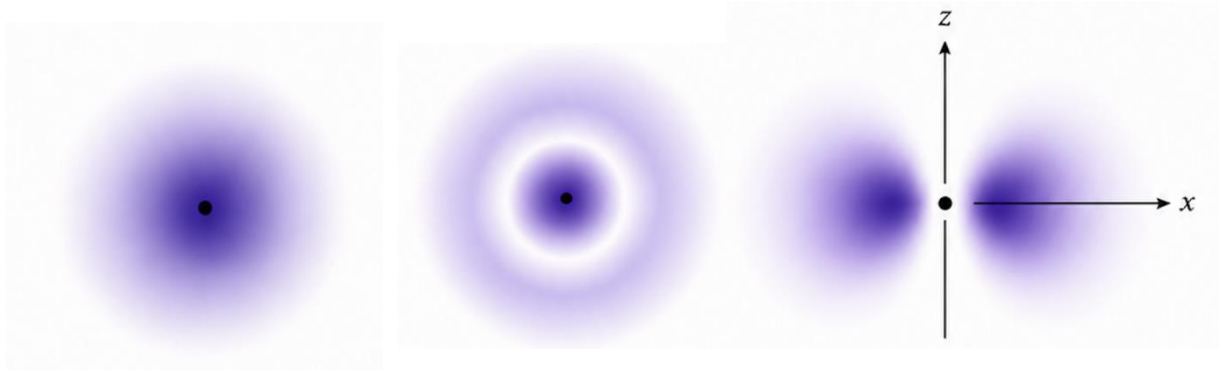
- Dipole interactions are short range.
- For ground state atom, dipole-dipole interactions only strong if atoms are a few nanometers apart.
- This is impractical





Quantum Logic with Atoms

- The solution, is to excite the atom into a very highly excited state where the electron is only weakly bound and the wavefunction is very large.



1s 2s 2p … 50s

Quantum Logic with Atoms

- These highly excited states are called Rydberg states.

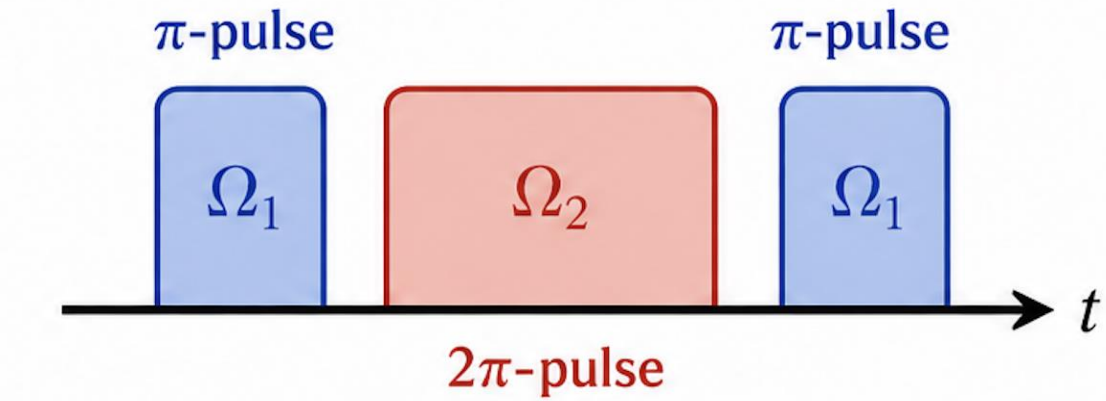
- And some of the pioneering work to harness Rydberg interactions for quantum computing was done right here at UW-Madison!

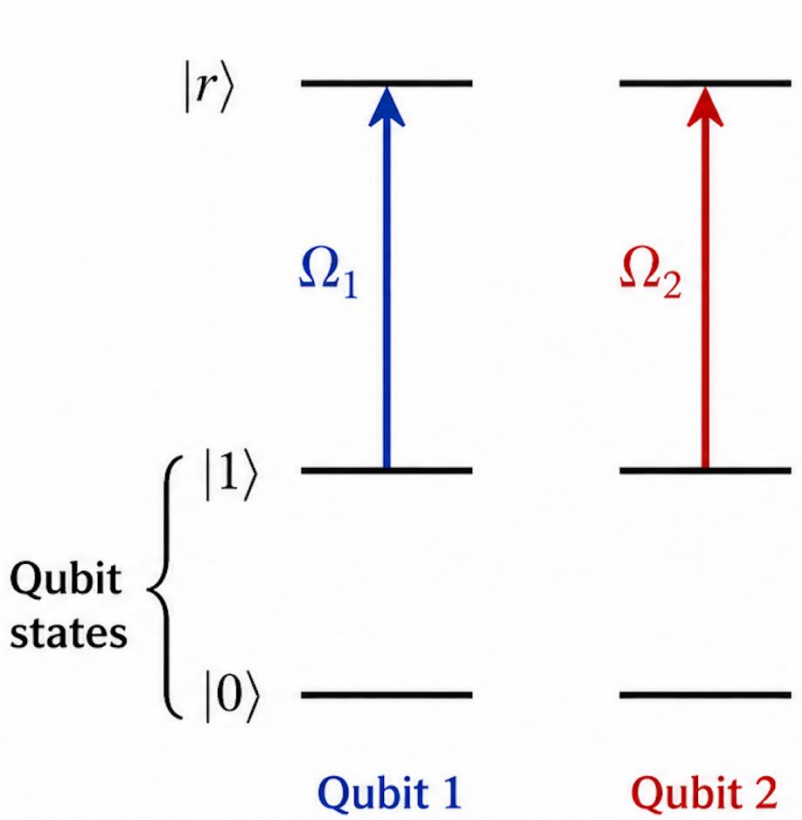
Mark Saffman

Thad Walker

Quantum Logic with Atoms

- The simplest version of the Rydberg gate: one atom being excited to |r> blocks the other.
- Use a laser to drive the control atom from |1> to |r>
- Next, drive target atom from |1> to |r> to |1>
- Finally, drive the control atom from |r> to |1>



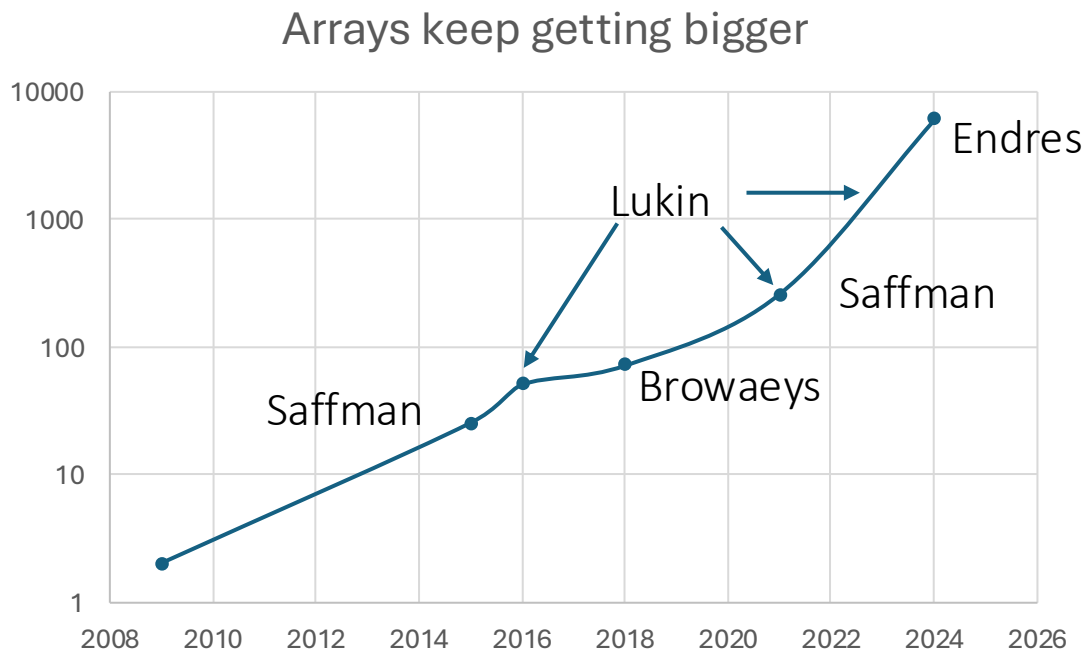


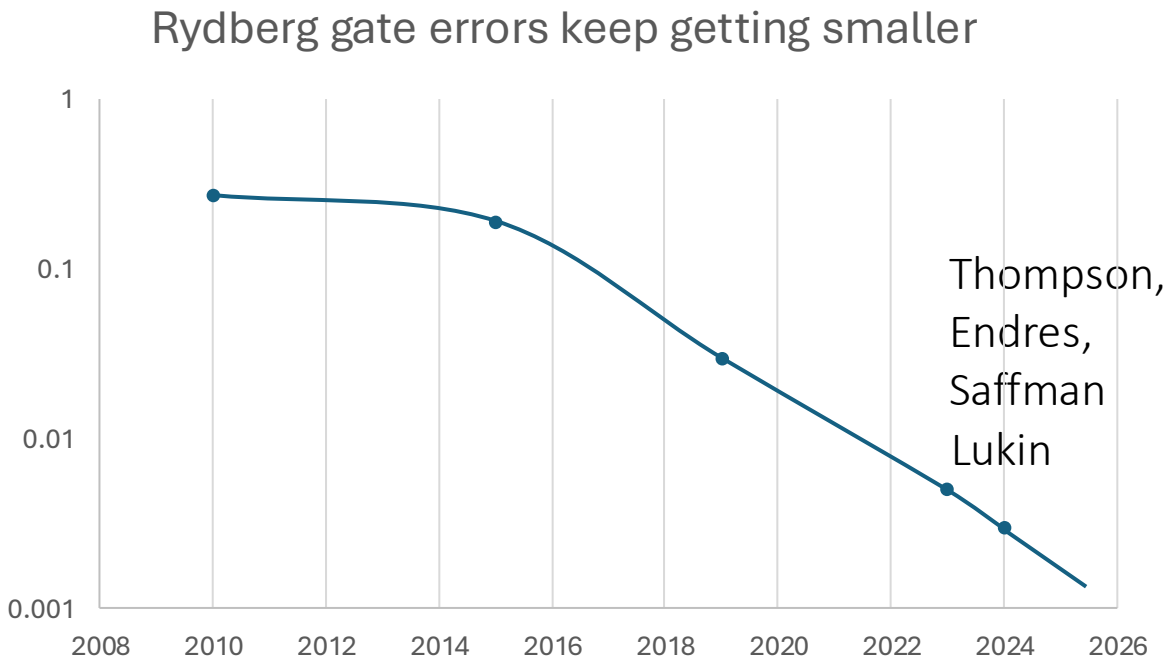
Putting everything together

- Create arrays of single atoms using laser cooling, trapping, and sorting.
- Store a qubit in each atom.
- Manipulate qubit using lasers and microwave fields.
- Rydberg interactions for CNOT gates (red circles)

Lukin 2024

Progress Accelerates!





The Race Is On!

Infleqtion

QuEra

PASQAL

atom computing

planqc

logiqal

NanoQT
Nanofiber Quantum Technologies

Quantum Source

CavilinQ

IT QUANTA

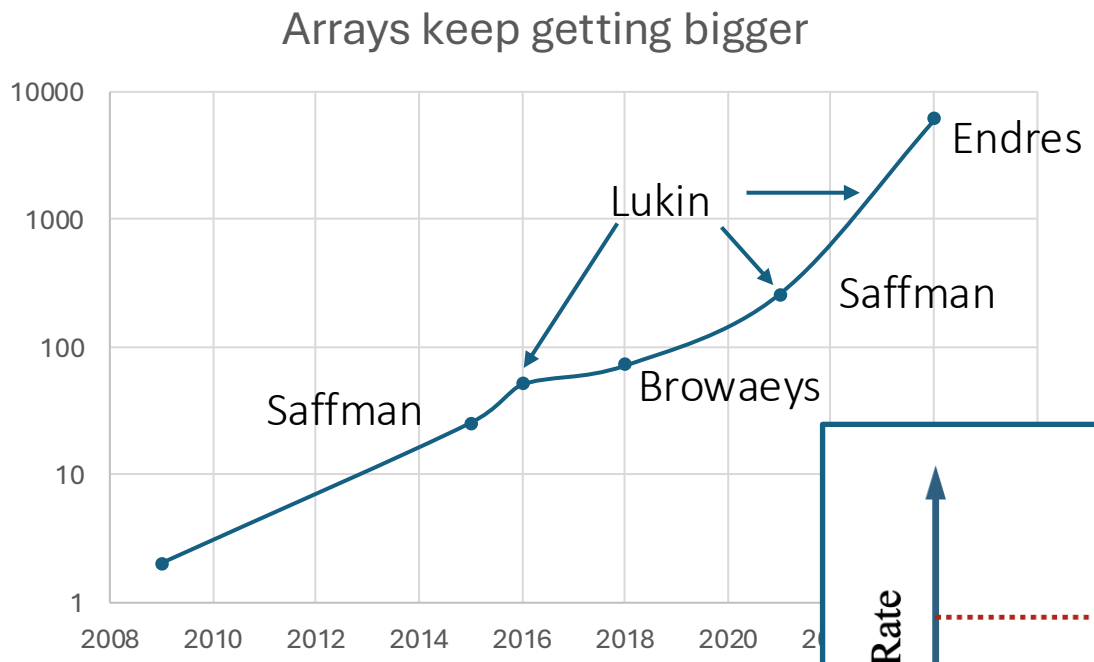
Oratomic

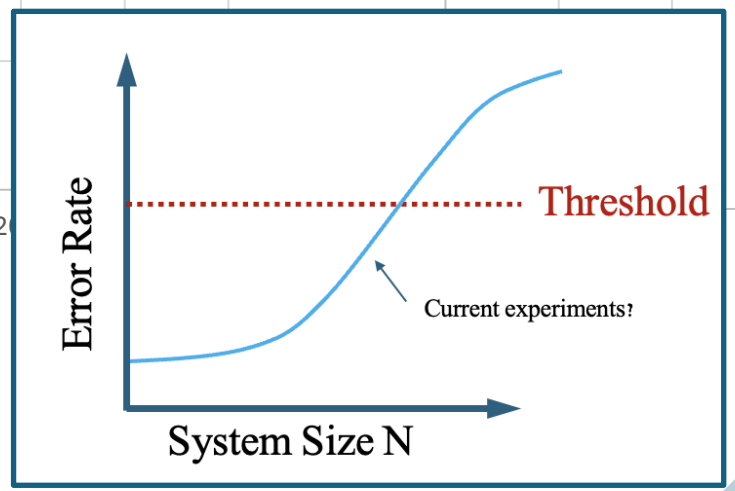
https://www.economist.com/science-and-technology/**2015**/06/20/a-little-bit-better

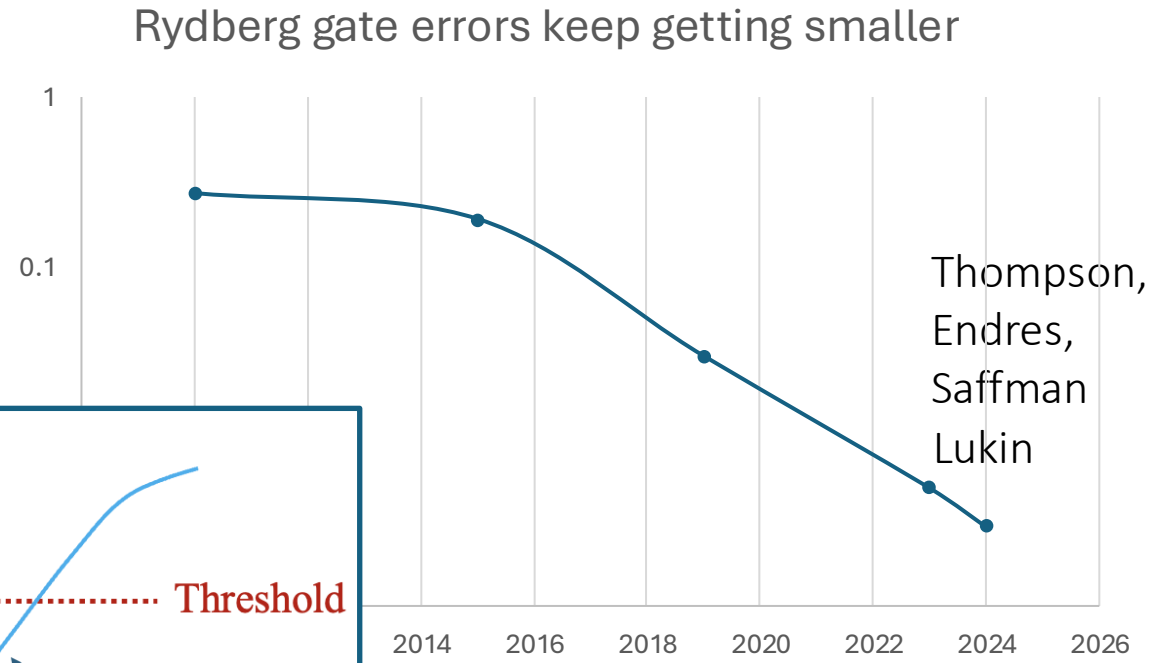
Cartoon from 2015, so notice a conspicuous absence…

Challenge: Size Limits

Max system size	Practical limitation	Explanation
~100,000	Microscope field-of-view	3 um spacing and 1 mm^2 field-of-view
~50,000	Laser power	2 mW per tweezer, 100 W lasers.
~10,000	AOD bandwidth	40 MHz bandwidth, 0.4 MHz spacing

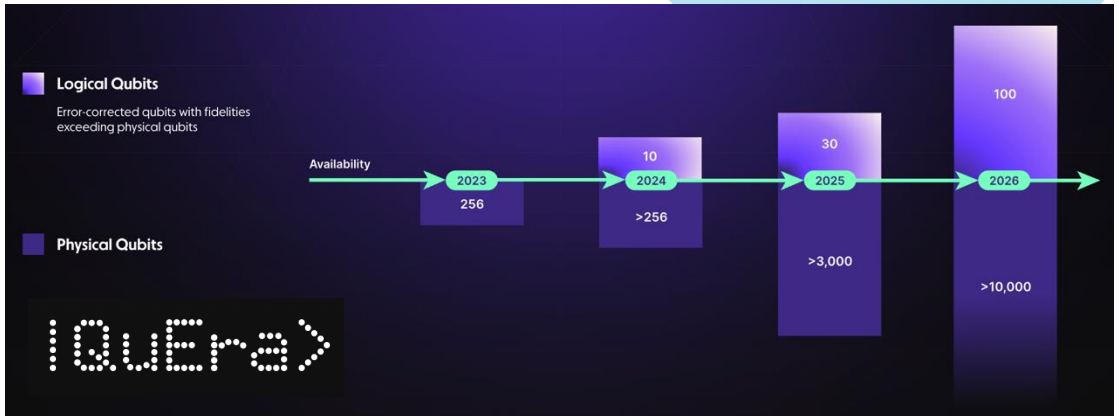


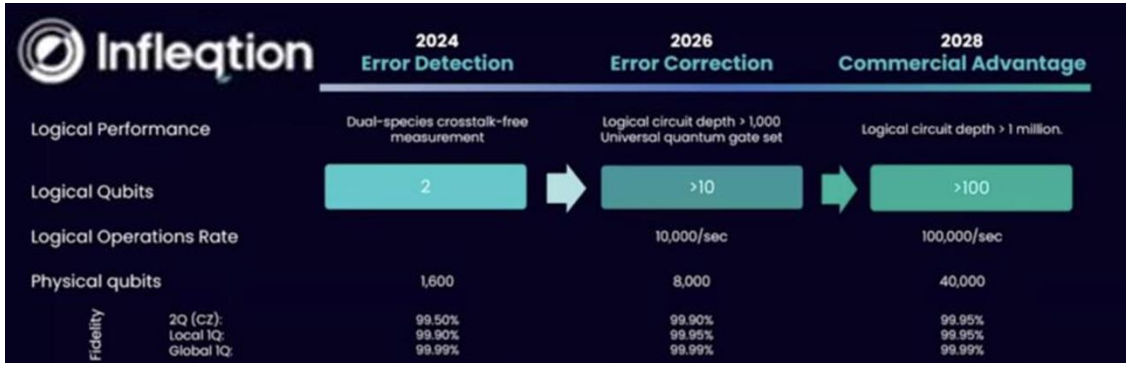


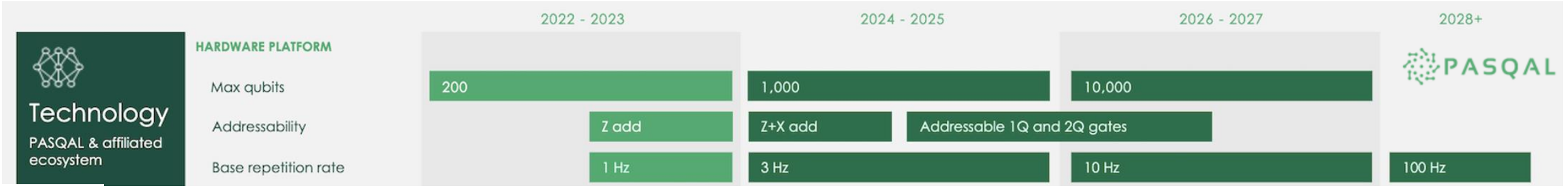


Challenge: Size Limits

- Aggressive roadmaps promising
  - 10,000 physical qubits
  - Deep circuits
  - in the next few years!

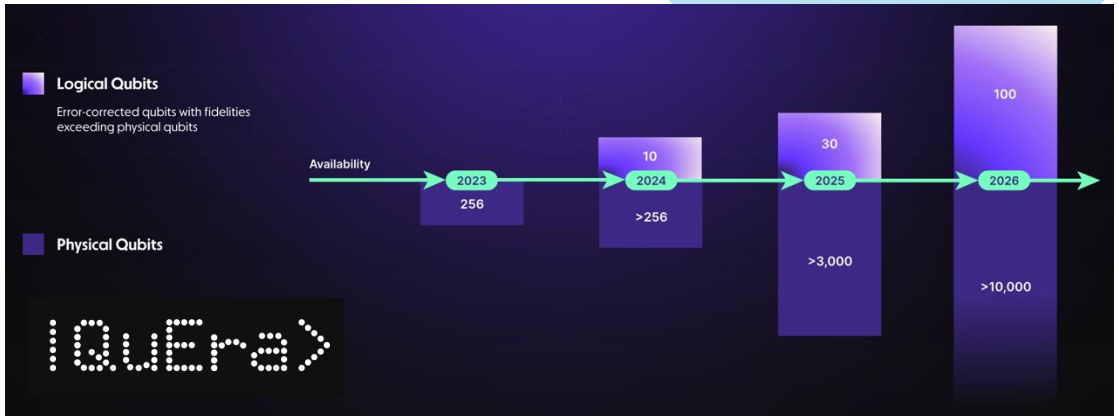


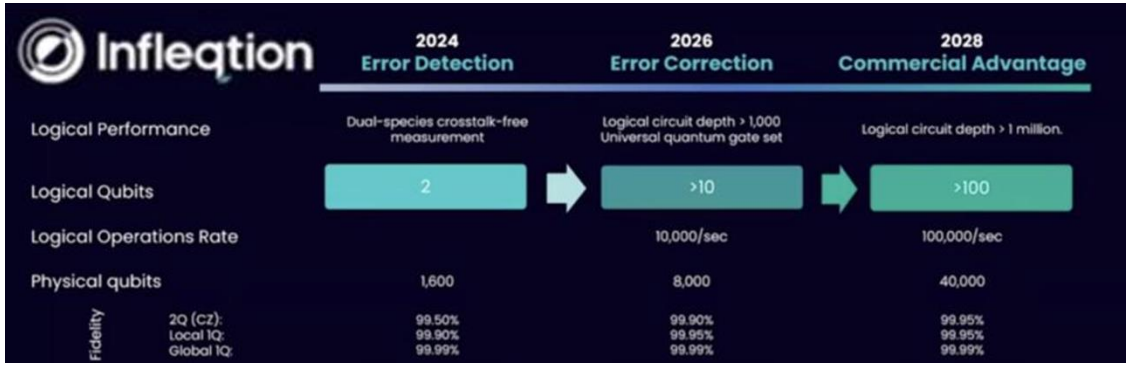


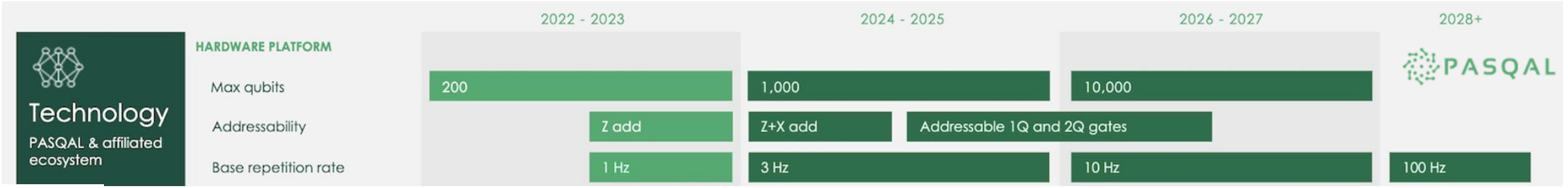


Challenge: Size Limits

- What will the next 10 years hold?
- How to scale beyond where the roadmaps end?

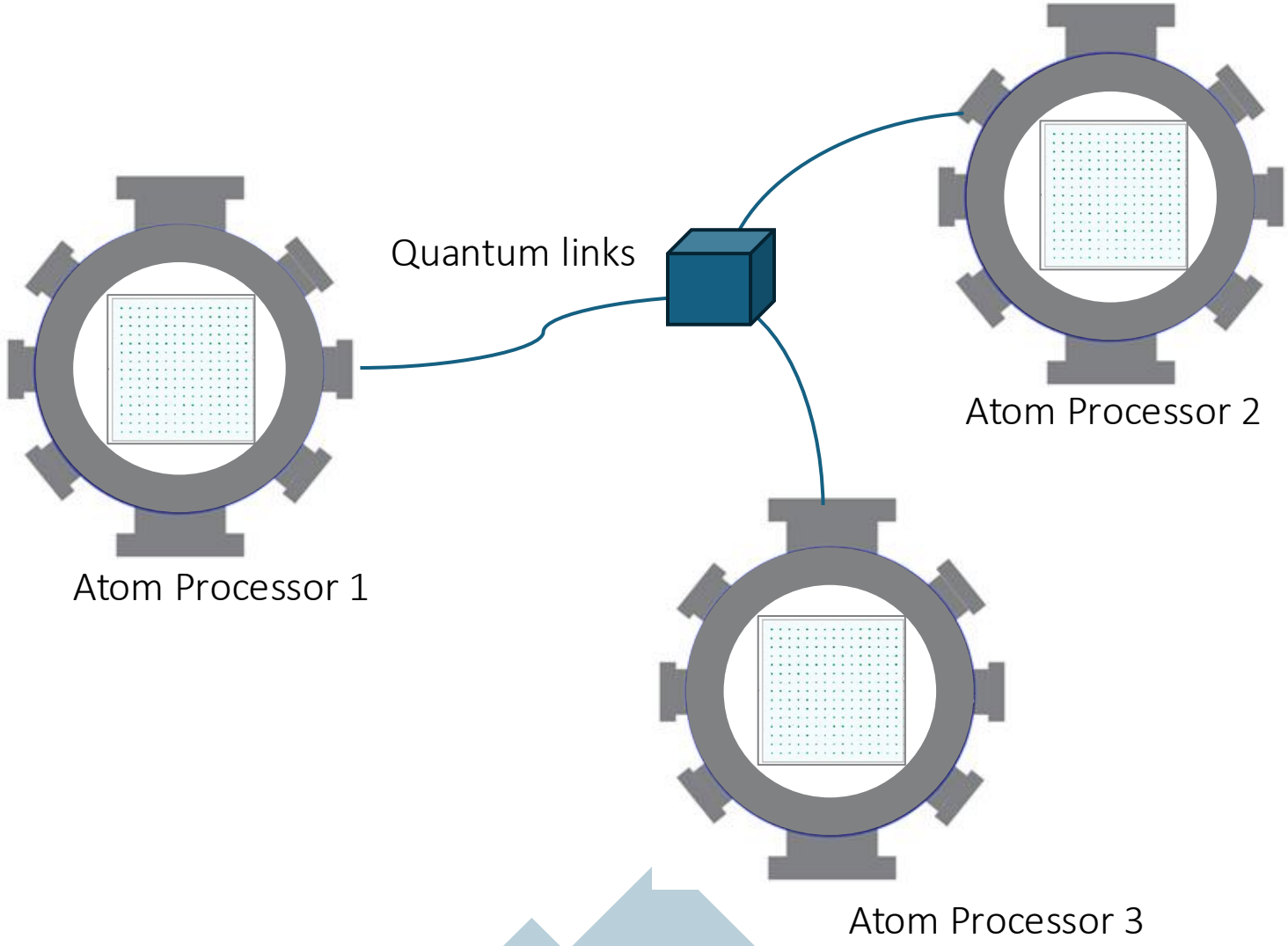






A modular architecture for neutral atoms

- Quantum links between atom array modules.
- Reduces the challenge of scaling to that of designing a unit module with sufficient quantum communication.
- Challenges: links still too slow & noisy, qubits cannot be copied

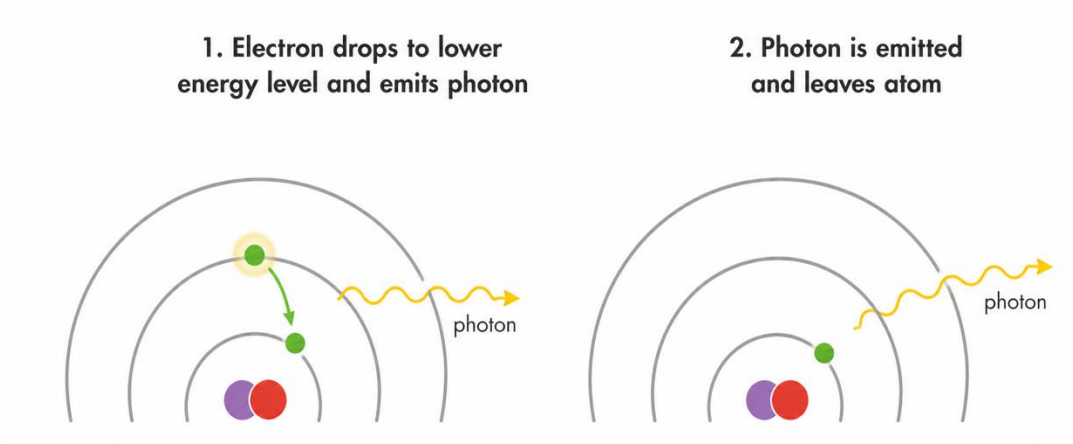


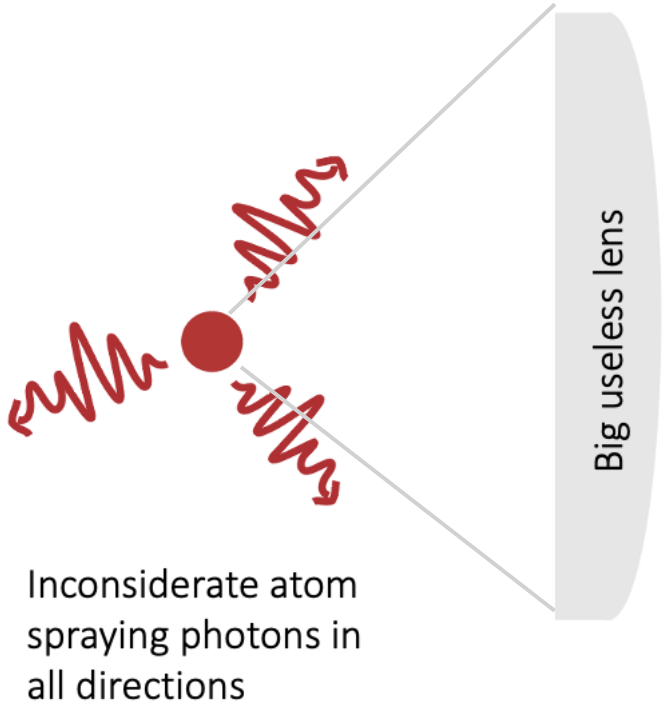
Quantum links: use single photons!

- Step 1: Transfer our qubit from a stationary atom to a flying photon
- Step 2: Transfer back

Interconverting stationary and flying qubits

- Requires deterministically collecting a single photon from a single atom.





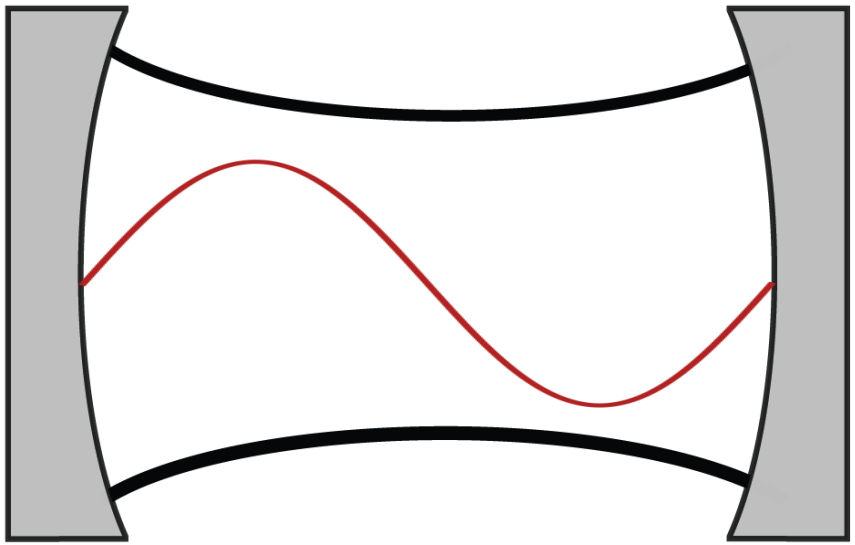
- Atom emission is approximately isotropic.

- Collection efficiency from a large lens is typically a few %, low efficiency hurts you twice.

Interconnected Modules of Atomic Qubits

Sinclair Lab

- Our efficient atom-photon interface will be an optical cavity.
- An optical cavity is a pair of mirrors that light bounces back and forth inside.
- The cavity defines a set of modes of the electromagnetic field..



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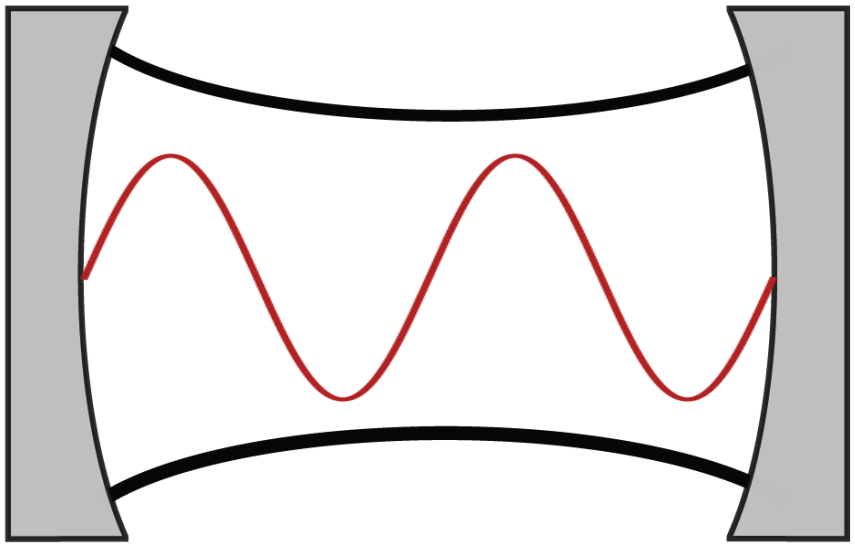

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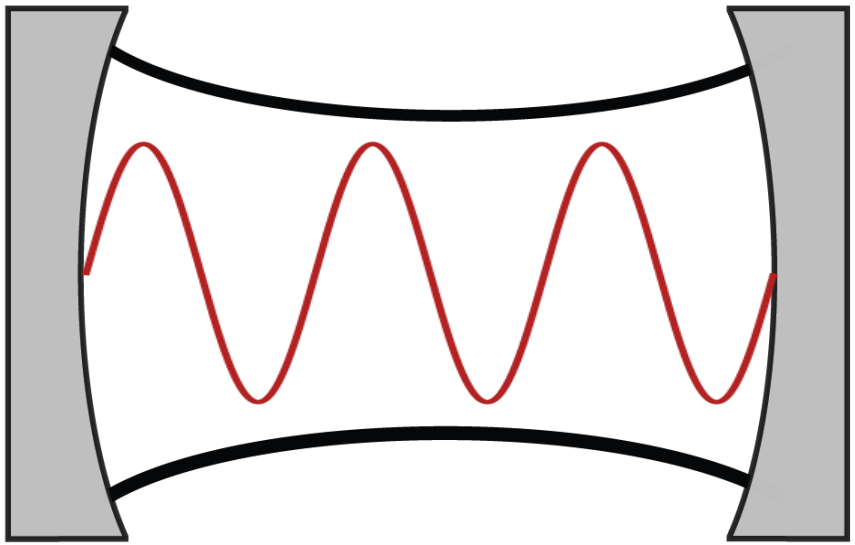
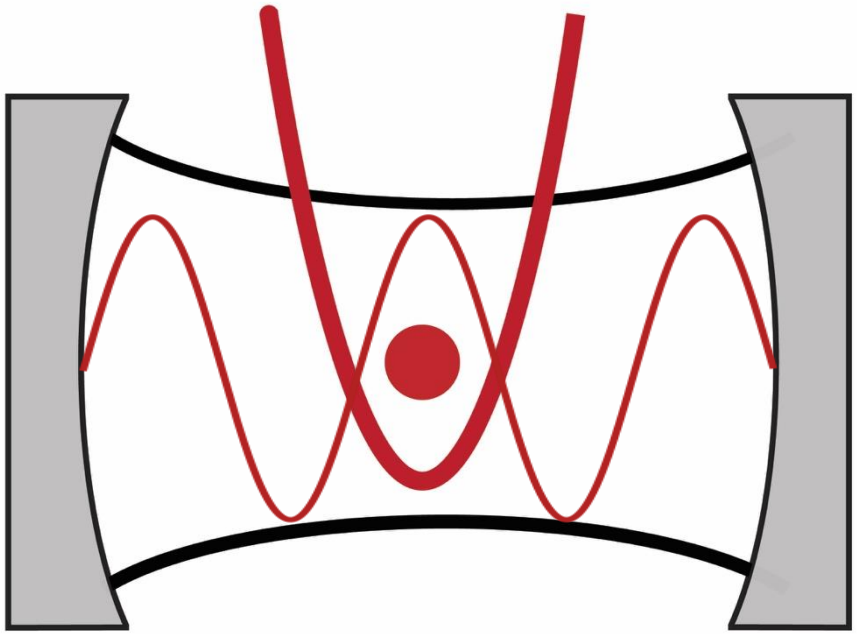


Sinclair Lab

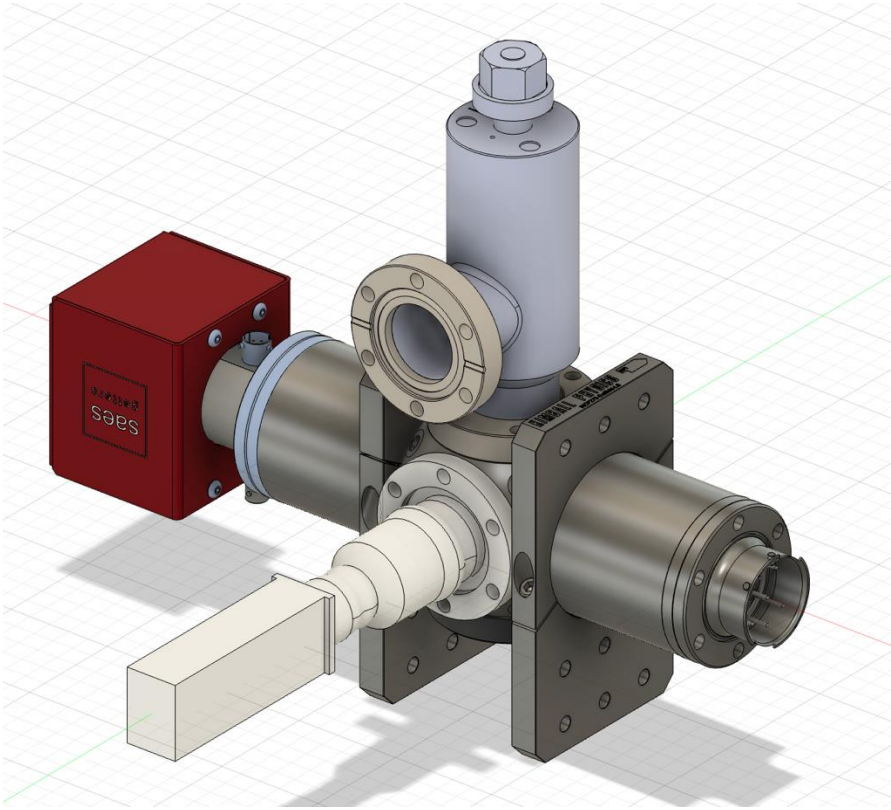
- Our efficient atom-photon interface will be an optical cavity.
- Cavity enables nearly deterministic atom-photon interaction
- Improving absorption and emission efficiency by 100x
- Improving quantum linking speeds by 10,000x



1 pass → 1%
10 passes → 10%
1000 passes → 99.99%

Sinclair Lab

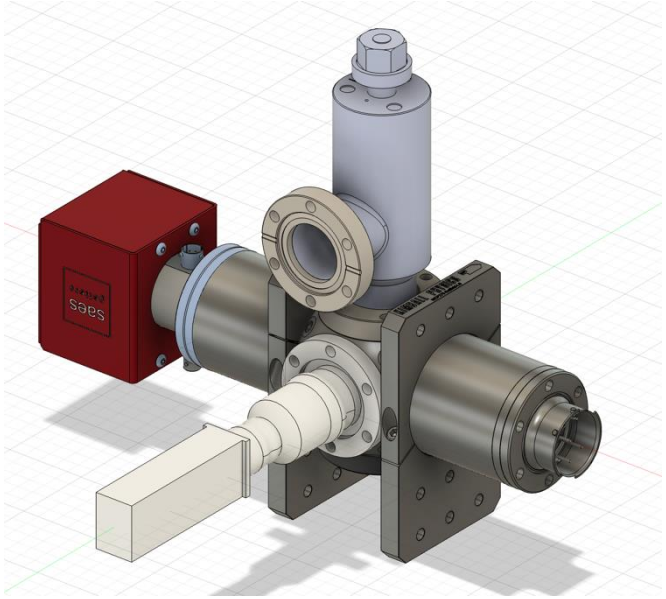
- What will the experiment look like?
- Start with a vacuum chamber.



Sinclair Lab

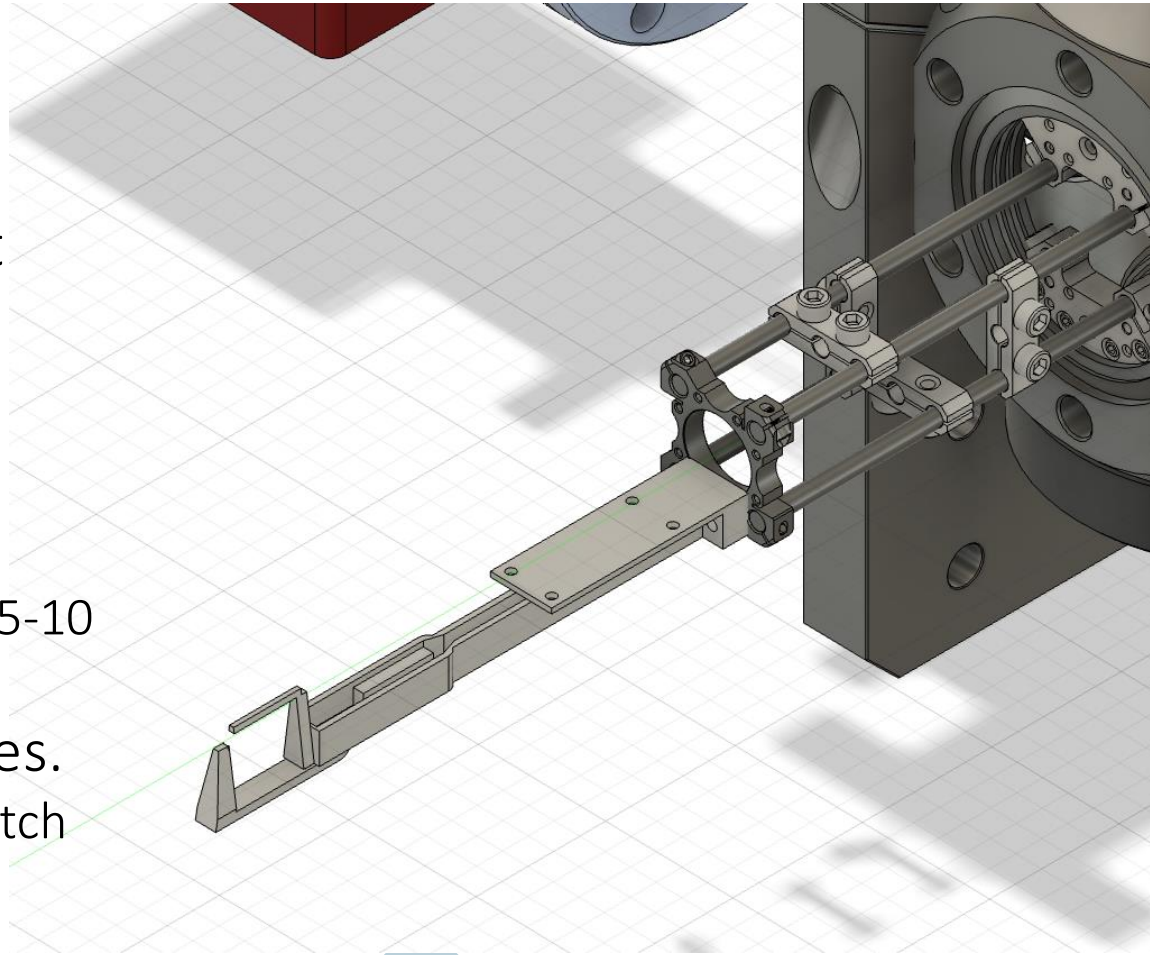
- What will the experiment look like?

- Cavity goes inside a glass cell, giving us lots of optical access



Sinclair Lab

- What will the experiment look like?
- Inside the glass cell, a rod tower and cavity mount structure.
- Cavity optimized for speed.
  - Novel cavities via collaboration with CavilinQ.
  - Target C~5-25, κ ~ 5-10 MHz, length ~ 0.5-2 mm, waist 5-10 um.
- Cavities compatible with high-fidelity Rydberg gates.
  - Exploring transparent conductive coatings to reduce patch charges with Kats Group (ECE)
  - Exploring mm-scale transport schemes to tranquil computation zone



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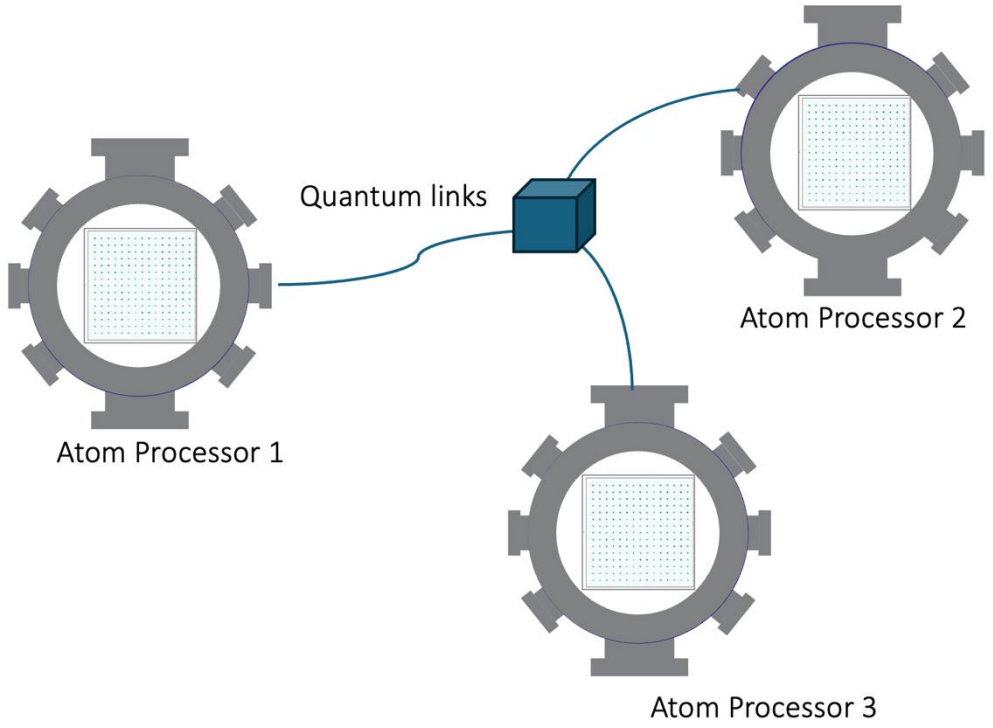
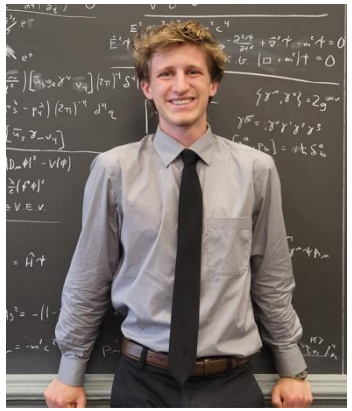
- What will the experiment look like?
- Goal of IMAQ Project is to figure out linking capability for atom array quantum processors.
- We will explore integrating very special optical cavities with state-of-the-art atom arrays.
- Enabling scalable quantum computing with single atoms and single photons.



Sinclair Lab

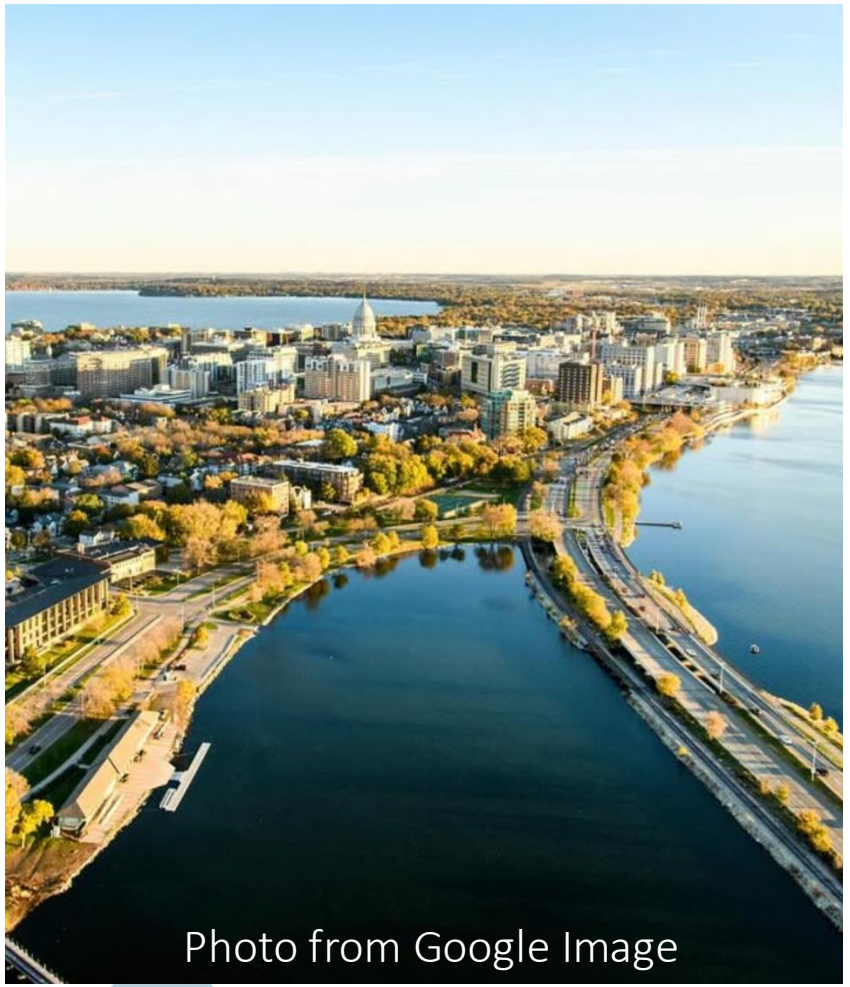
Joonseok Hur (postdoc)



Austin Rosypal (grad)

Min Kim (MS)

Adi Ravi (MS)



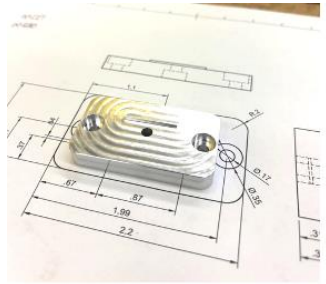
Bhuvanesh Kayarabettu (MS ECE)

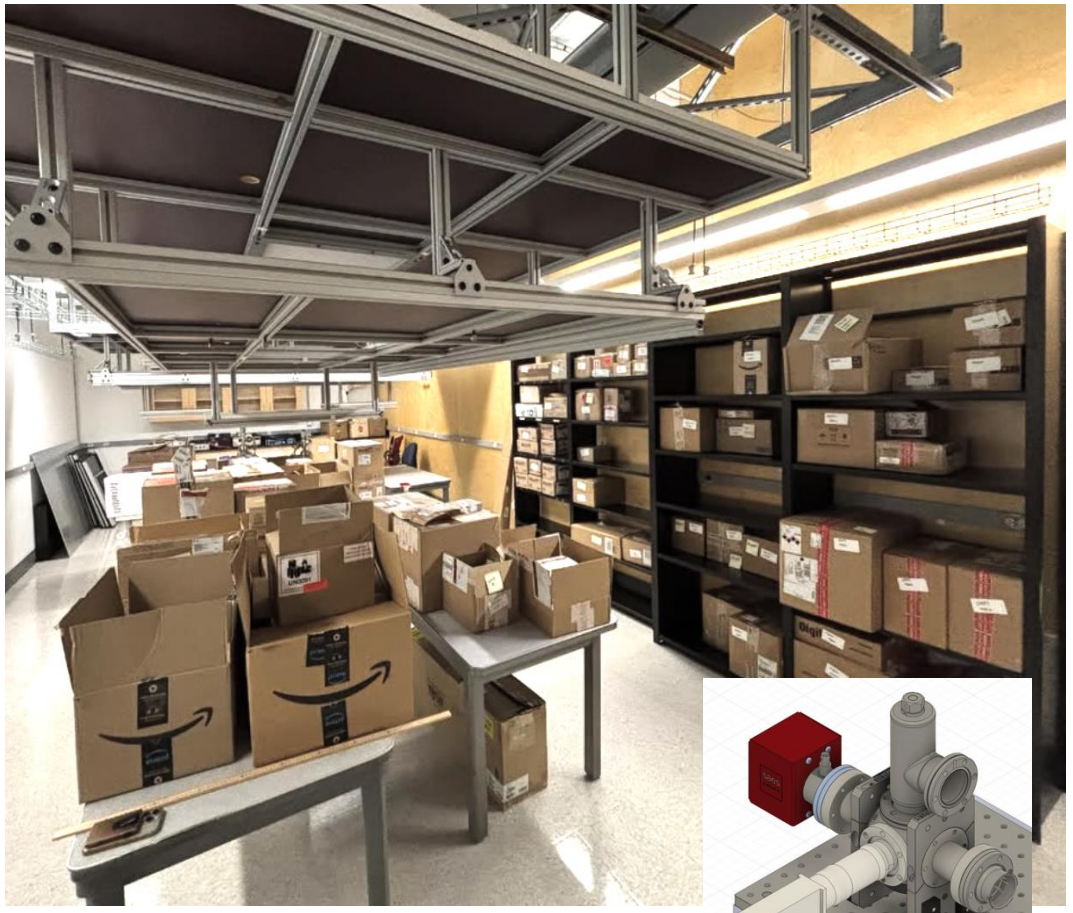
Caleb Kempfer (UG)

Josie Tetzlaff (UG)

To Staff – Thank you!

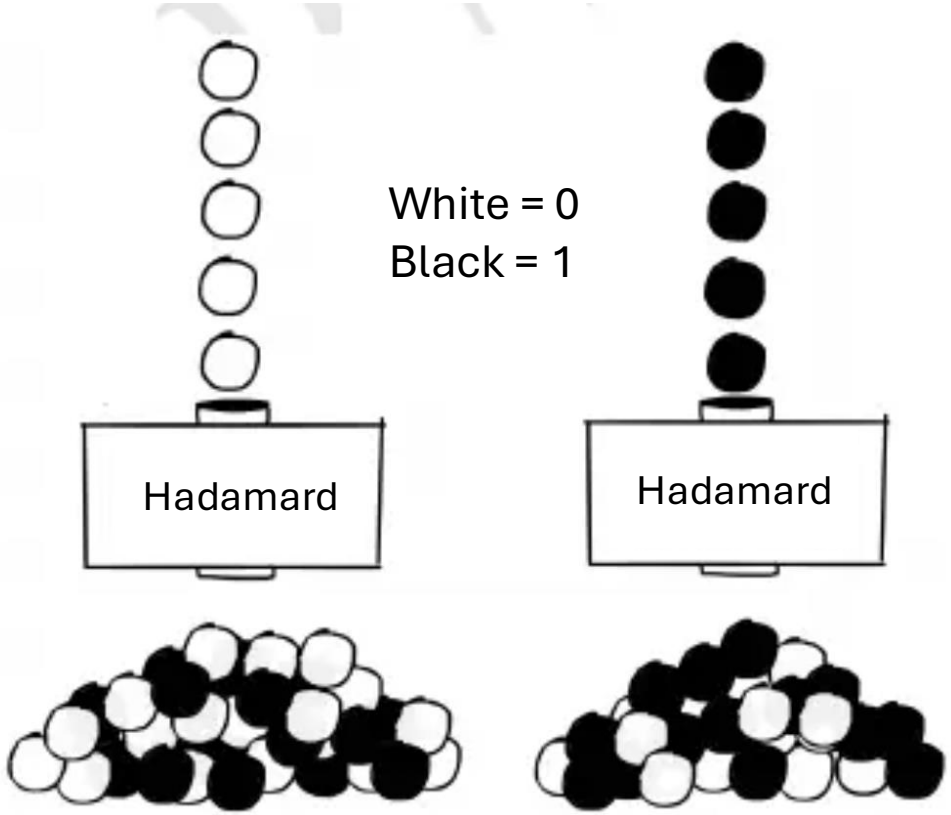
- Instrument & Electronic Shop Staff: Jay, William, Daniel, Craig, Billy
- IT Staff: Dan and Chad
- Purchasing/Admin/Grants/HR:
  Sami, Helen, Aimee, Susan, Rachel
- Everyone involved in ongoing lab renovation.

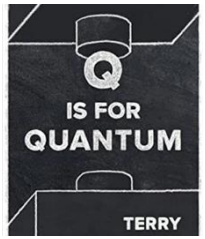




What is a quantum computer?

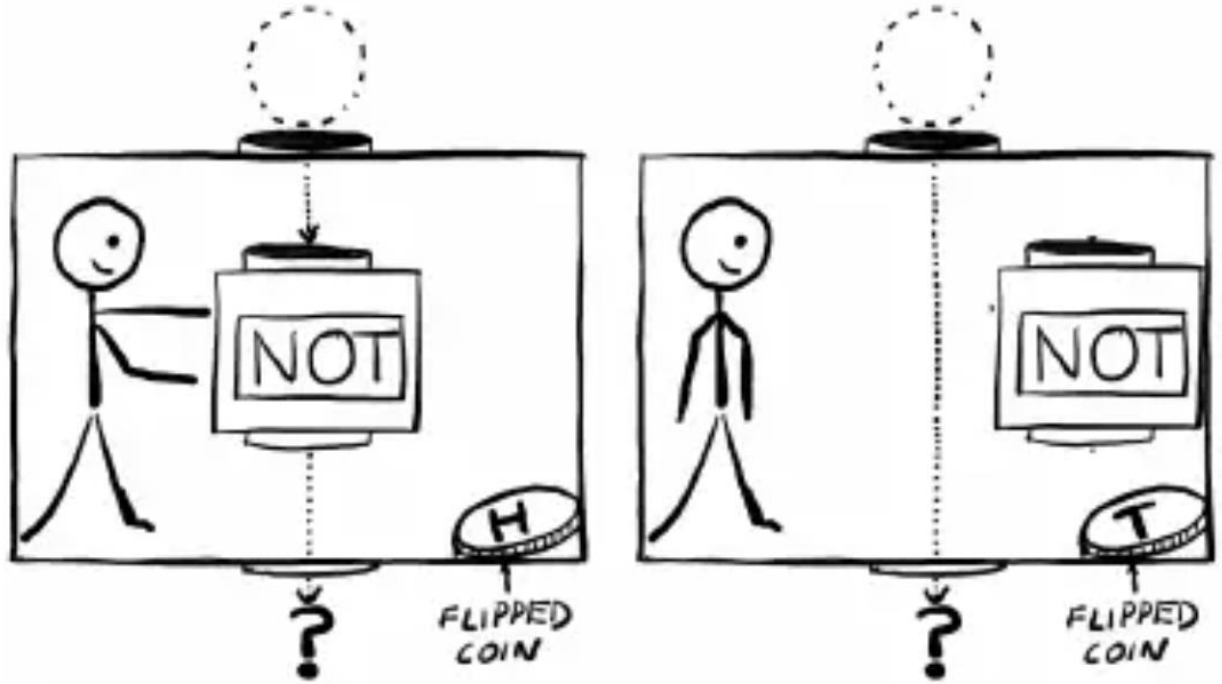
- Hadamard gates
- Reverse engineer!





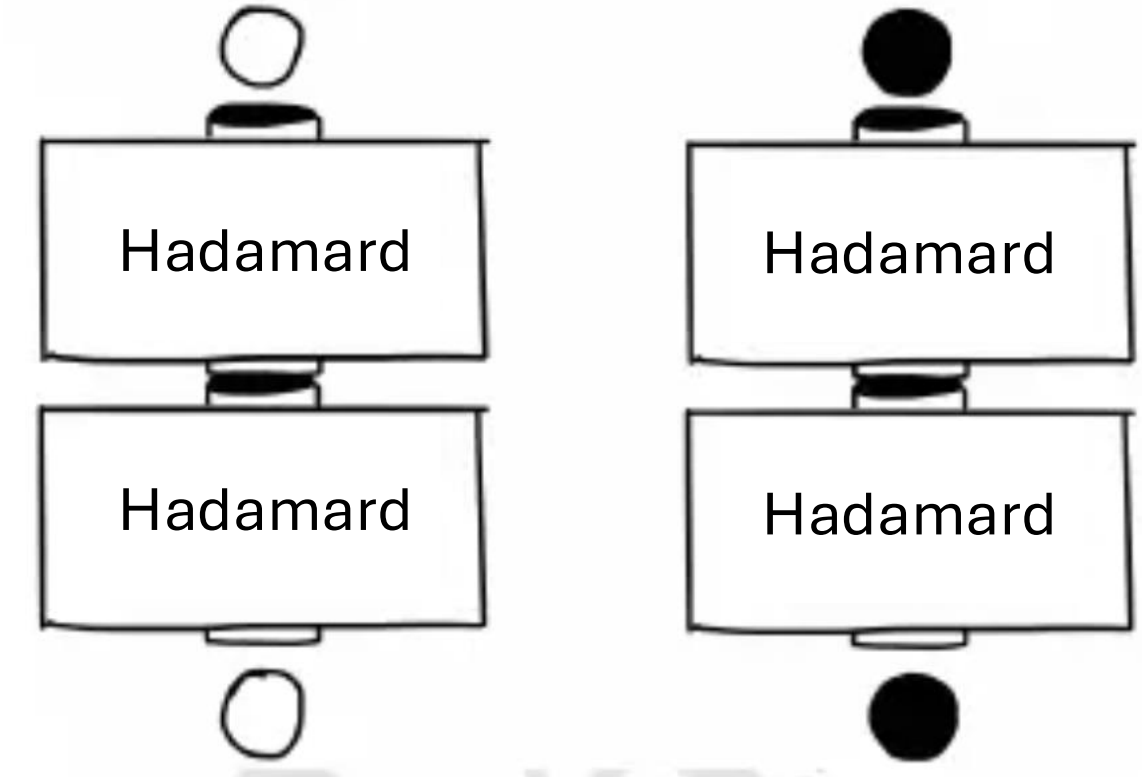
What is a quantum computer?

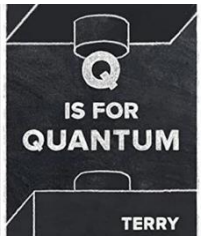
- Hadamard gates
- Is Hadamard just a random bit flip?



What is a quantum computer?

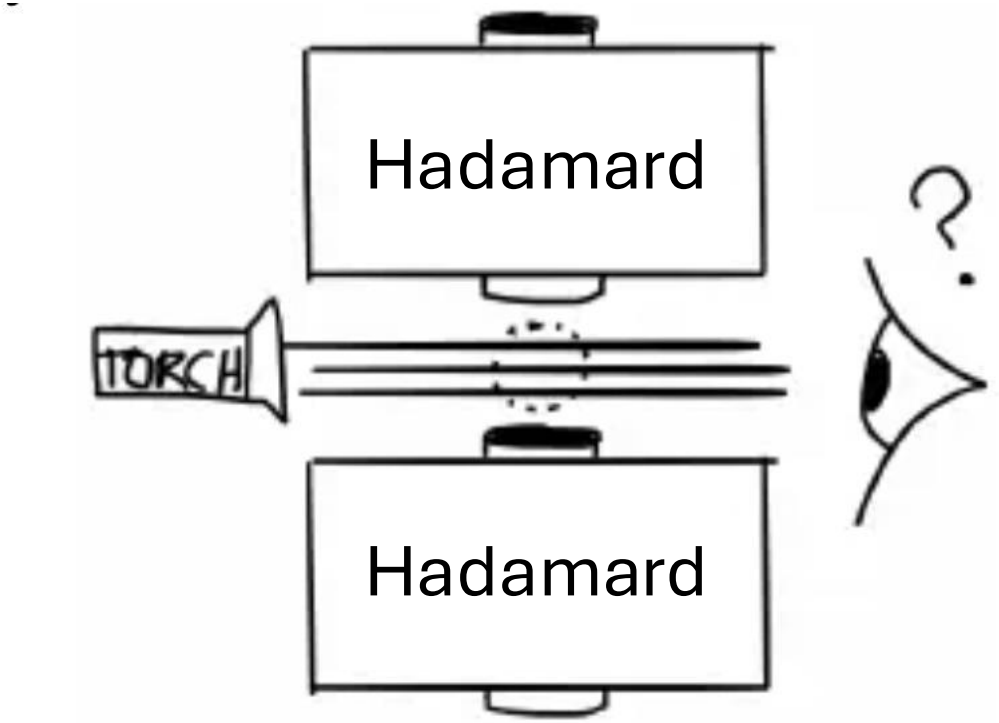
- Hadamard gates
- No, because stacking them makes the output not random!
- What is going on??

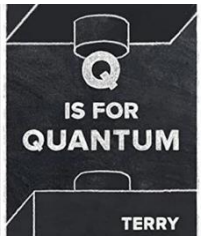




What is a quantum computer?

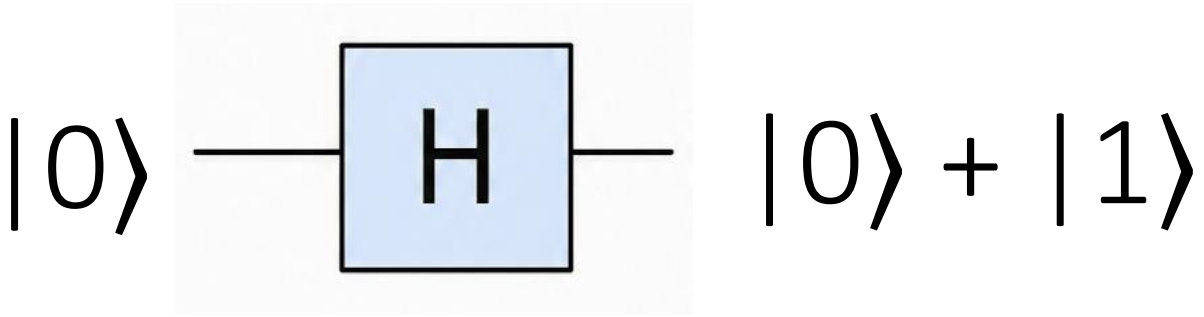
- Hadamard gates
- If we measure the state between the gates, then we get random outputs.
- So our measurement is destroying something.





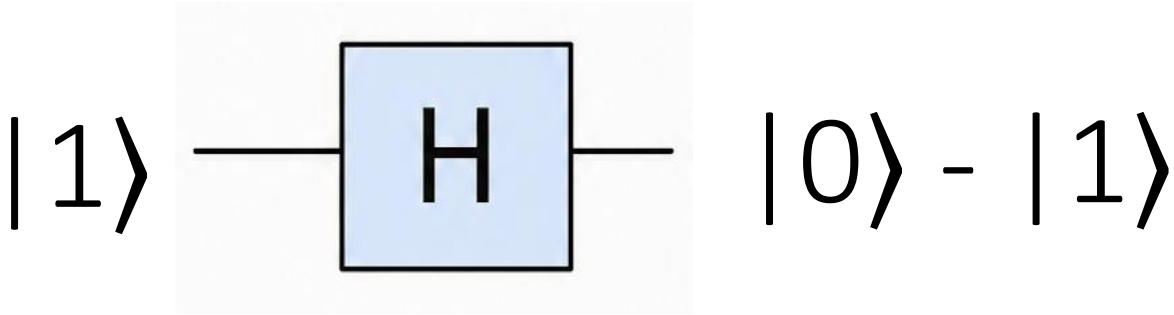
What is a quantum computer?

- Hadamard gates
- Resolution is that the Hadamard gate is doing something fundamentally quantum with no classical analogue.
- Hadamard takes 0 and creates a superposition of 0 and 1.



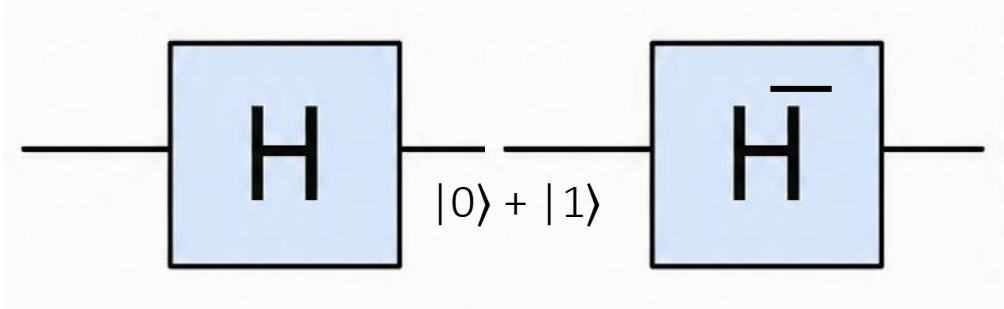
What is a quantum computer?

- Hadamard gates
- Resolution is that the Hadamard gate is doing something fundamentally quantum with no classical analogue.
- Hadamard takes 1 and creates a different superposition of 0 and 1.



What is a quantum computer?

- Hadamard gates create superpositions



- Now you know what quantum superposition is… it's the quantum state created by a Hadamard gate

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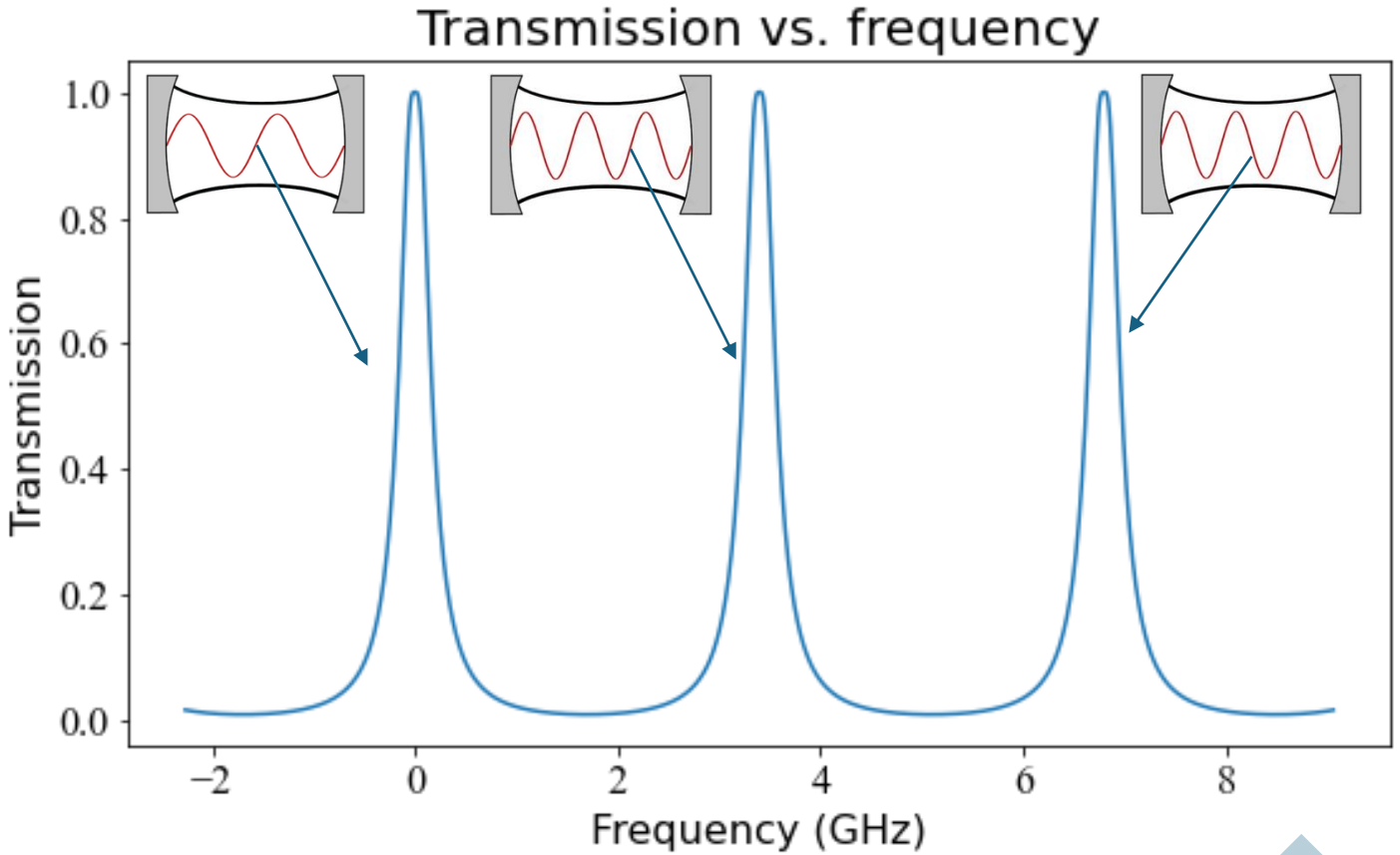

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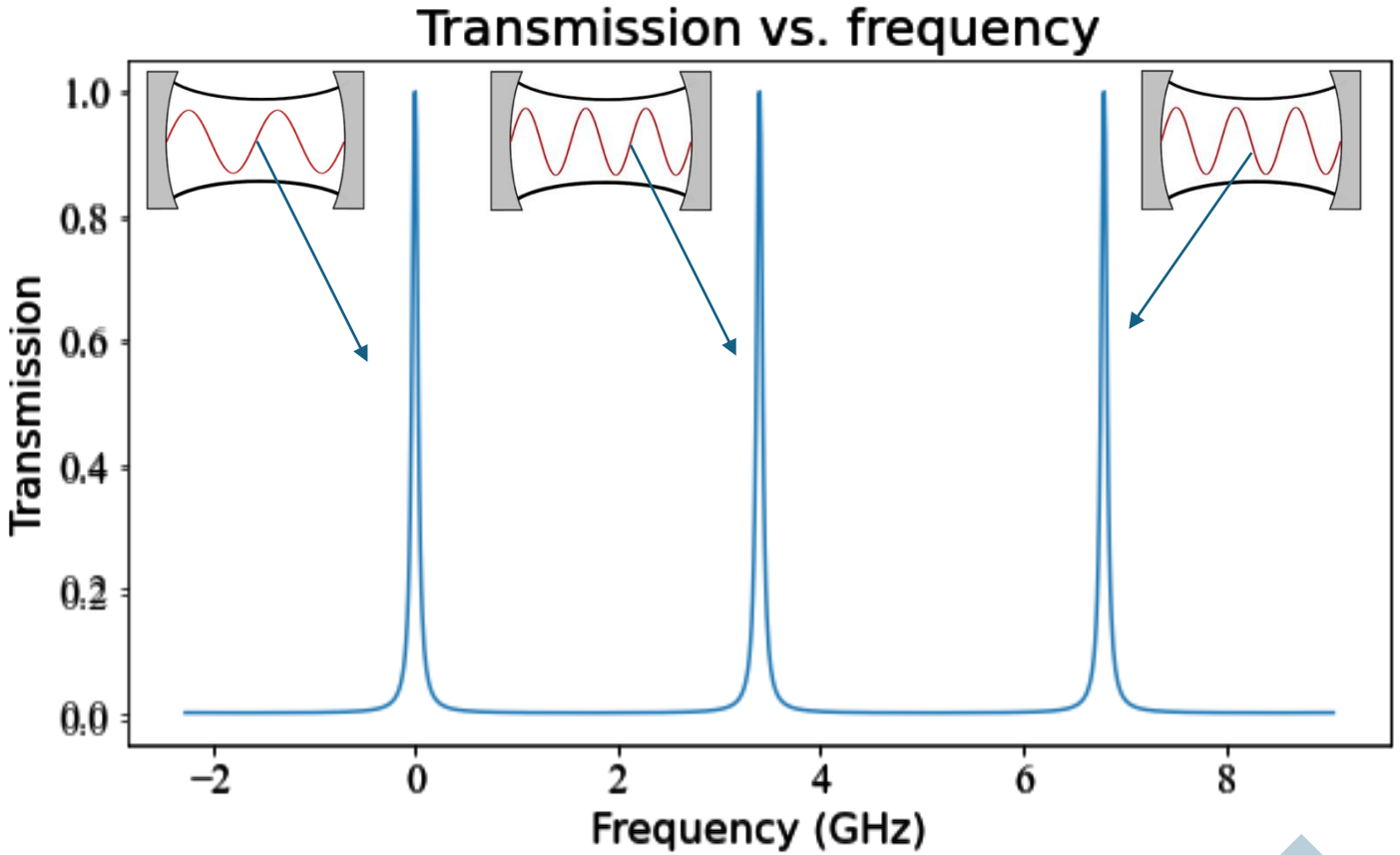
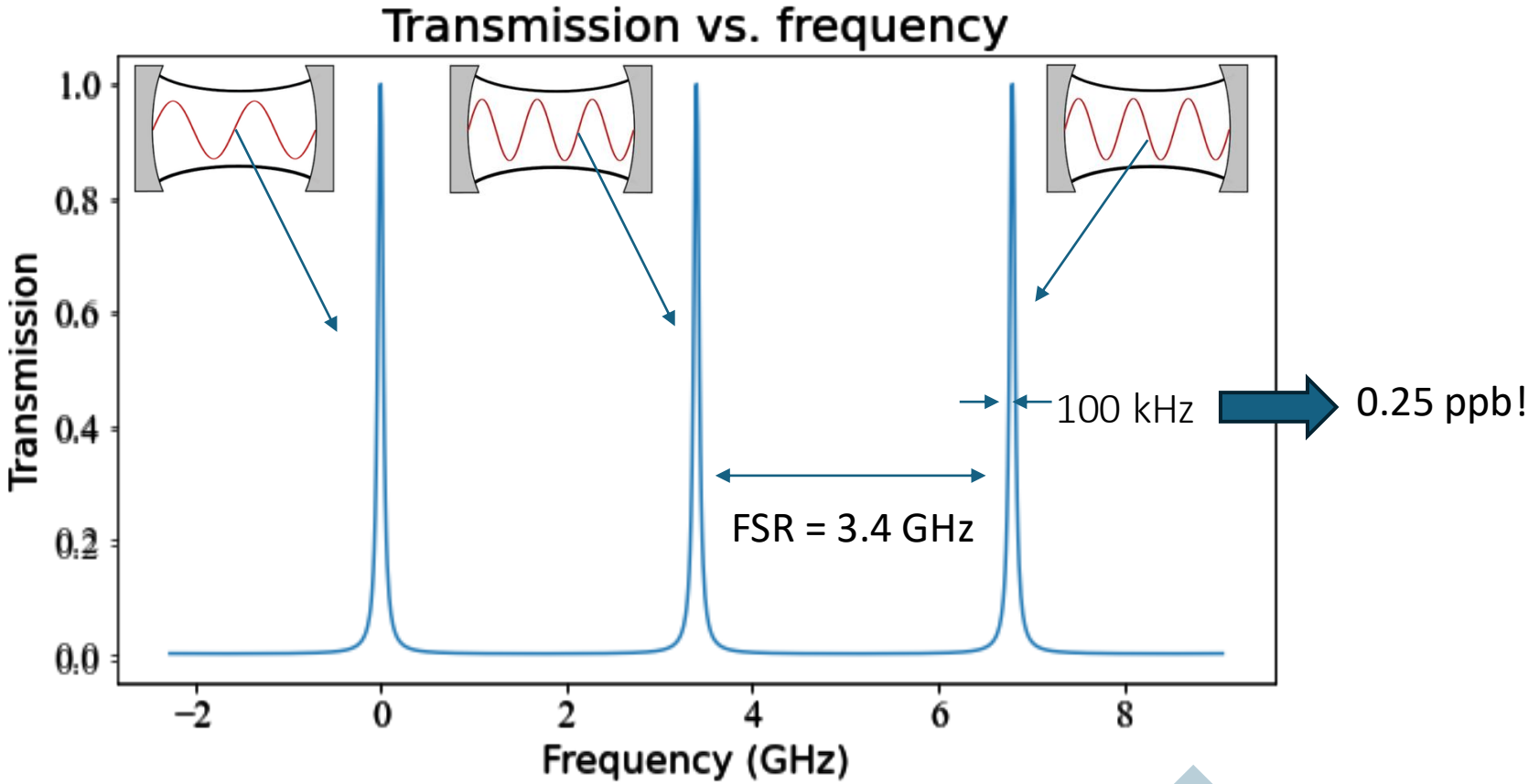
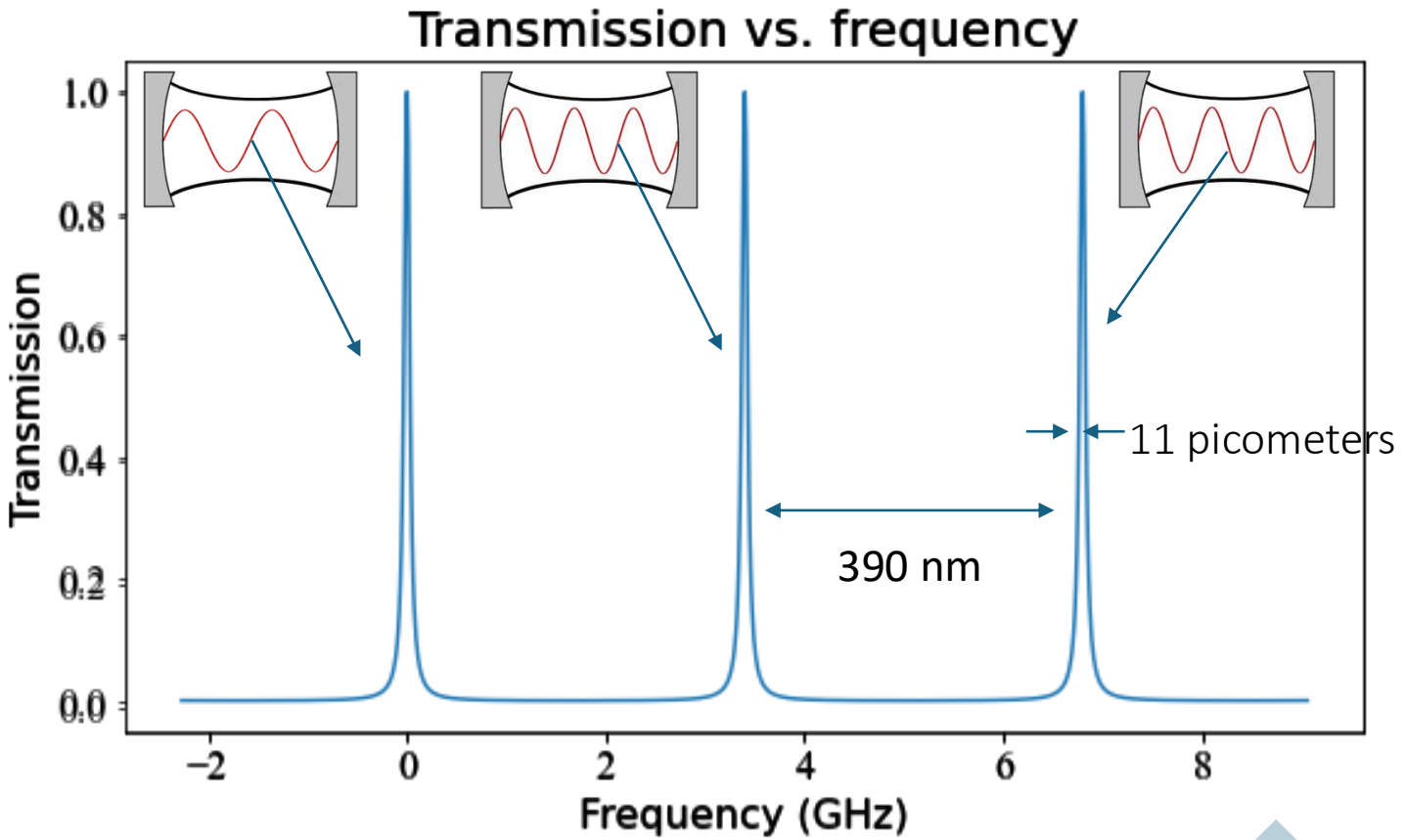


Sinclair Lab



Sinclair Lab

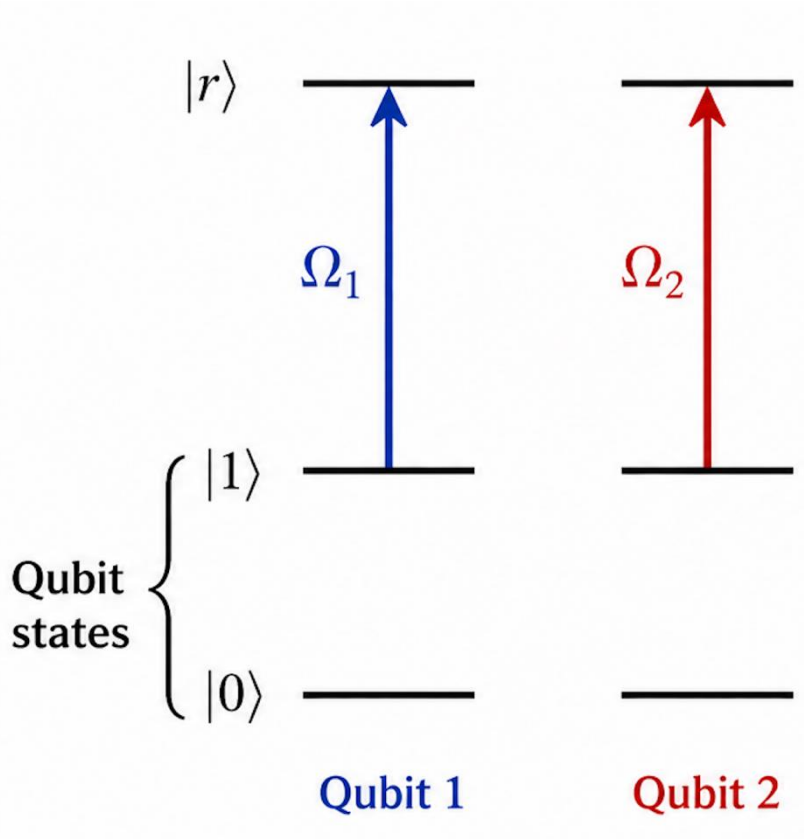


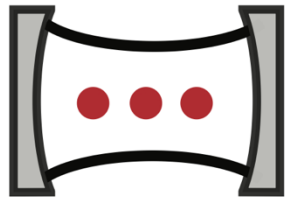
Quantum Logic with Atoms

- Basic ingredients for control-NOT
  - If both atoms are in |0>, nothing happens
  - If one atom in |0>, other in |1> nothing happens
  - If both atoms in 1, something happens!

$$|00\rangle \rightarrow |00\rangle$$
$$|01\rangle \rightarrow -|01\rangle$$
$$|10\rangle \rightarrow -|10\rangle$$
$$|11\rangle \rightarrow -|11\rangle$$

Control-Phase Gate! Equivalent to CNOT + Hadamard





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- Ok, so why put a single atom in a single cavity?
- The cavity can induce the atom to emit a large fraction of it's photons into a single mode.
- Whereas free-space collection

$$\%\ \text{collected} = \frac{\text{cross section}}{\text{focus spot}}$$

- With a cavity…

$$\%\ \text{collected} = \text{Finesse} \cdot \frac{\text{cross section}}{\text{focus spot}}$$