Introduction to Quantum Computing Hardware Platforms

Karen Wintersperger, 20.05.2022

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Agenda

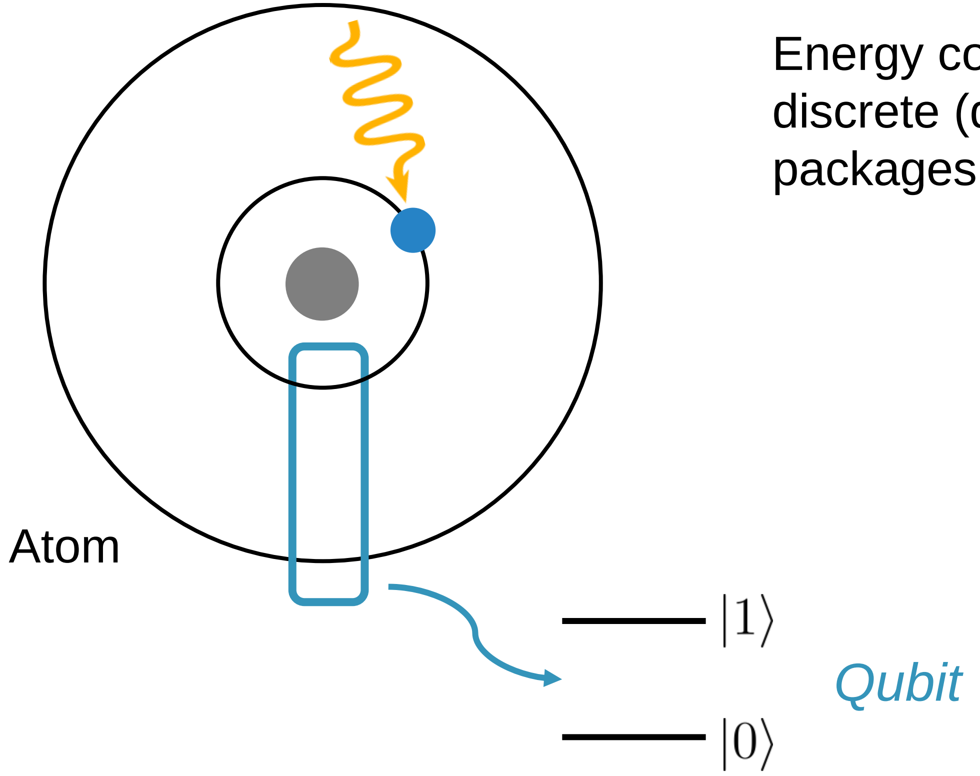
1. Introduction to quantum computing
2. Trapped ions
3. Cold neutral atoms
4. Superconductors
5. Photonics
6. Other approaches

Introduction

What is a quantum computer?

… not just a better classical computer

- Use properties of quantum particles for computations
- Built from *quantum bits* (= qubits)



Energy comes in discrete (quantized) packages

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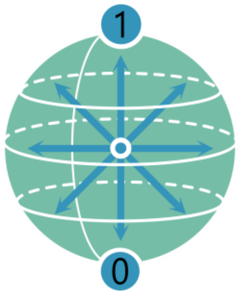
Properties of qubits

1) Superposition

Bit

0 *or* **1**

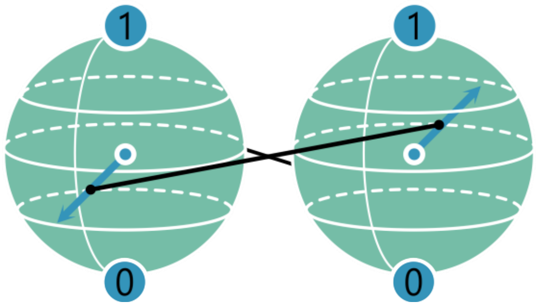
Qubit



0 *and* **1**

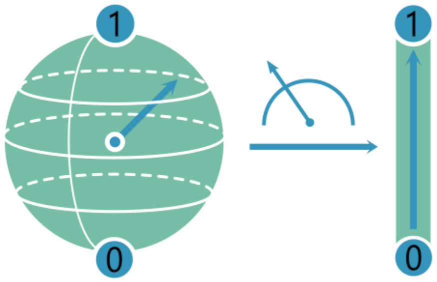
2) Entanglement

- Shared superposition state of several qubits
- State of qubit 1 depends on state of qubit 2



3) Measurement

- Measuring qubits changes their state
- Superposition is destroyed → get 0 or 1



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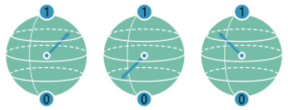
How to leverage quantum properties

Describe exponentially more information

- The possible superposition states of **3** qubits are described by **8** bit:



$$|Q_1 \, Q_2 \, Q_3\rangle$$

$$c_1|000\rangle + c_2|001\rangle + c_3|010\rangle + c_4|100\rangle + c_5|011\rangle + c_6|101\rangle + c_7|110\rangle + c_8|111\rangle$$

- **N** qubits can describe **2^N** bits

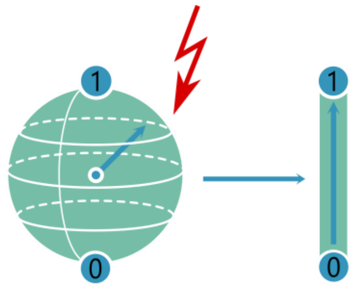
Parallelization of operations using superposition and entanglement

Quantum computers can solve *certain problems* faster (or solve them at all)

Challenges

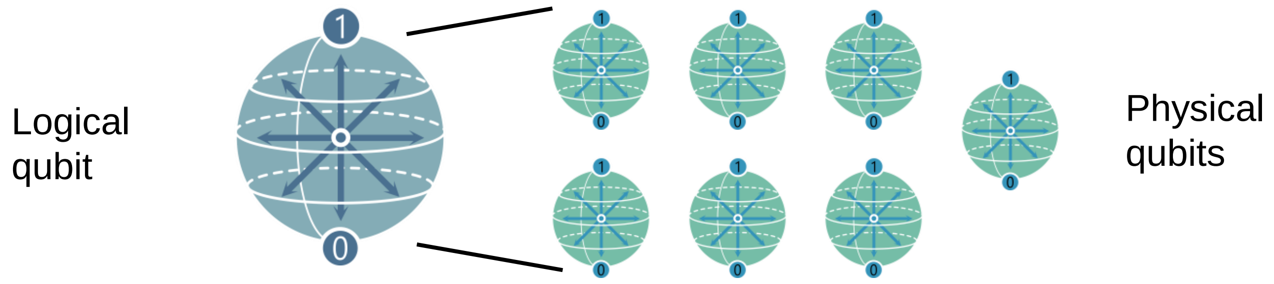
Decoherence

- Superposition states are destroyed when interacting with environment
- Some interaction is needed to control the qubits



Error correction

- Classical computer: Copy information 0 → 000
- Quantum computer: Bit flip or phase flip errors due to interaction with environment, noise, etc.
- Qubits cannot be copied
- Quantum error correction



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How to build a quantum computer

Requirements for a quantum computer: DiVincenzo's criteria

1. A scalable physical system with well-characterized qubit → *also high connectivity*
2. The ability to initialize the state of the qubits to a simple fiducial state
3. Long coherence times → *Low error rates, fast gates*
4. A universal set of quantum gates → *Usually we take single-qubit rotations + CNOT-gate*
5. A qubit-specific measurement capability

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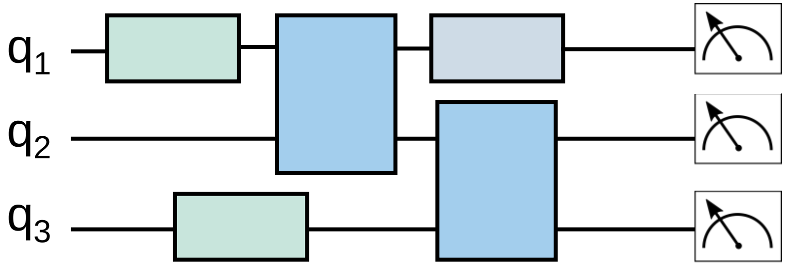
There are many kinds of quantum computers

Models for quantum computing

- Gate-based



- Measurement-based / One-way
- Adiabatic
- Topological

- Quantum simulation (digital and analog)

Hardware platforms

- Trapped ions
- Neutral atoms
- Superconductors
- Photons
- …

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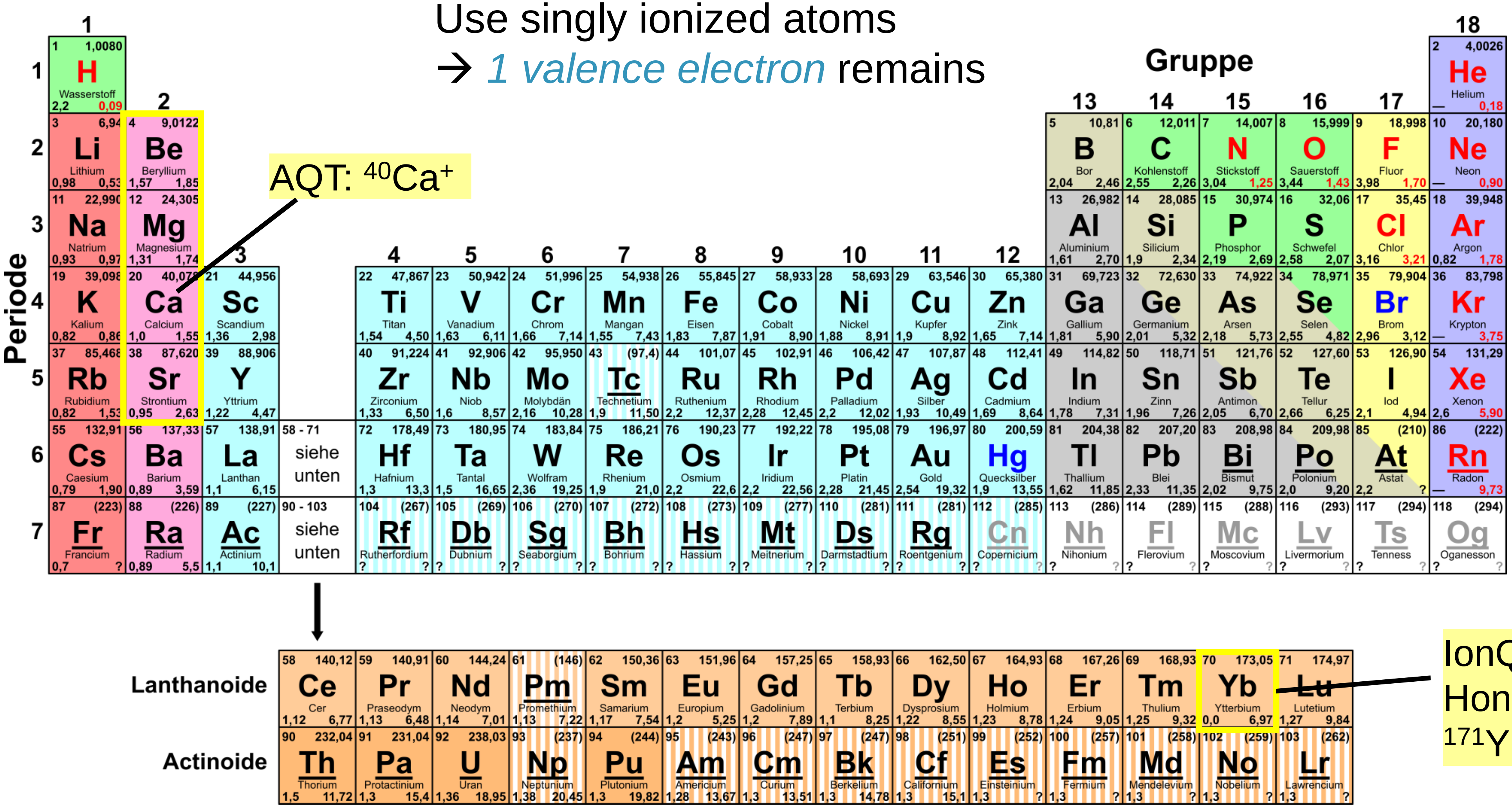
Trapped ions

Trapped ions as qubits

Use singly ionized atoms

→ *1 valence electron* remains

AQT: $^{40}Ca^{+}$



IonQ, Honeywell: $^{171}Yb^{+}$

Wikipedia, [4]

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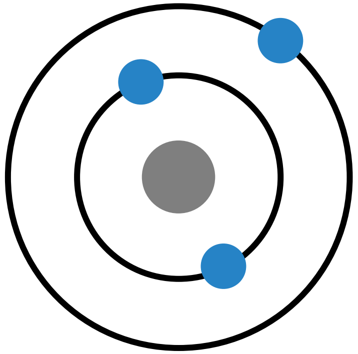
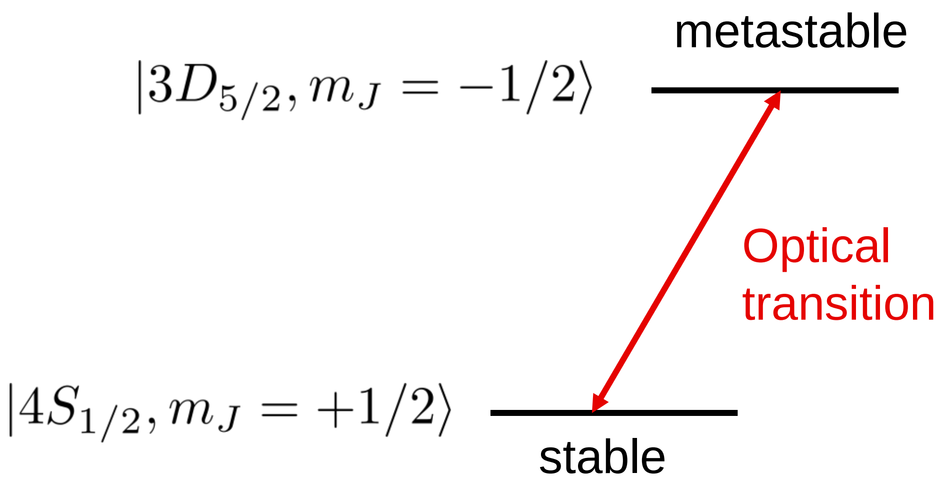
Qubit: Energy levels of ions

Optical qubit: $^{40}Ca^{+}$





→ Qubit manipulation with lasers

Other approaches: Hyperfine qubit ($^{171}Yb^{+}$) → Microwave transition

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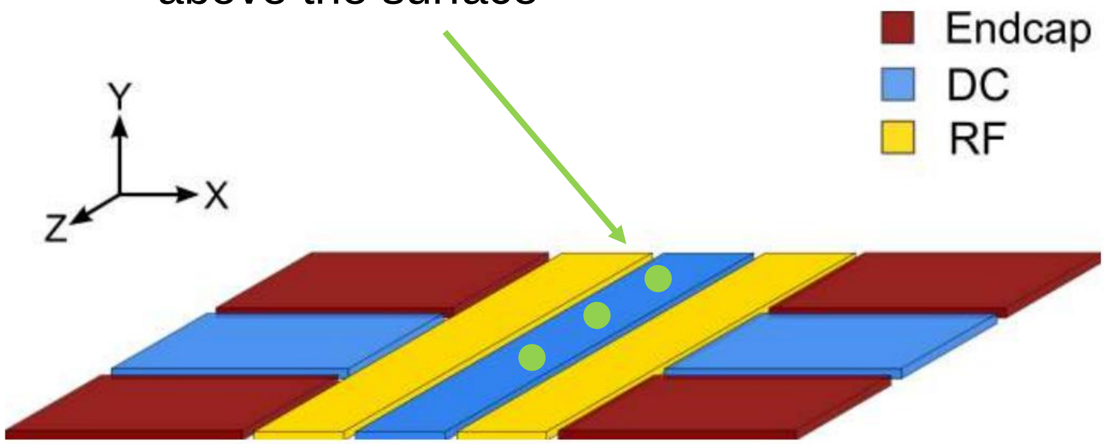
Trapping ions with electric fields

Linear Paul trap

- Ions are changed particles → Trap using electric fields
- Static electric field + time-dependent electric field
- Surface trap: Easy to fabricate



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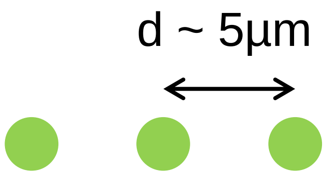

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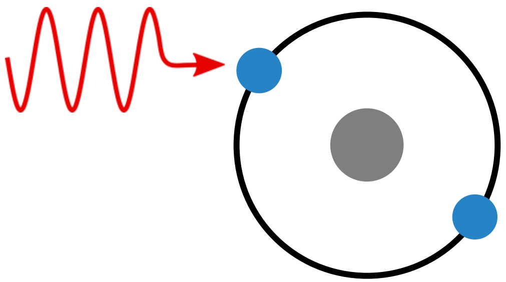
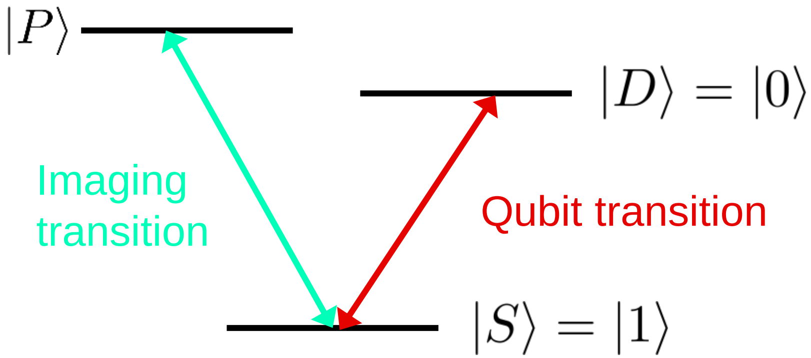
Sequence for Quantum Computing



1. Start with atomic vapor in vacuum cell
2. Ionize with lasers
3. Trap ions
4. Cool ions with lasers to their motional ground state
5. Computing: Apply gates
6. Measure qubits: State-dependent detection

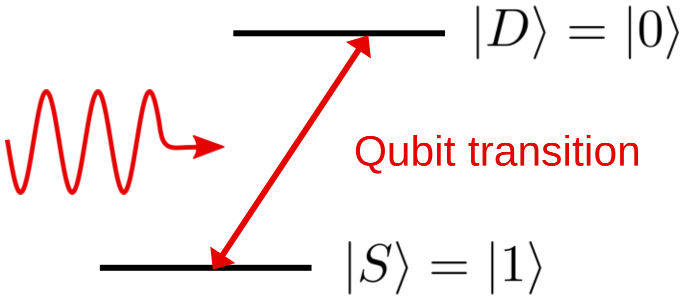
- Excite flourescence on $|S\rangle \rightarrow |P\rangle$ transition
- State $|0\rangle$ appears dark, $|1\rangle$ appears bright



Single-qubit gates

Single-qubit gates (optical qubits): Rotations

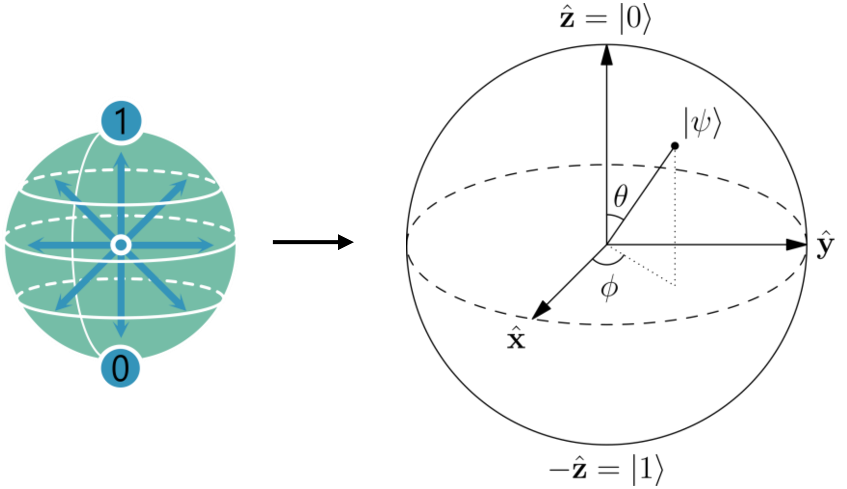
- Excite qubit transition with laser pulses
- Duration t and phase φ of laser determine angles θ and ϕ



$$U(\Omega, \varphi, t) = \begin{pmatrix} \cos\left(\frac{\Omega t}{2}\right) & -ie^{-i\varphi}\sin\left(\frac{\Omega t}{2}\right) \\ -ie^{i\varphi}\sin\left(\frac{\Omega t}{2}\right) & \cos\left(\frac{\Omega t}{2}\right) \end{pmatrix}$$

$$\theta = \Omega t$$

$$\phi = \varphi$$



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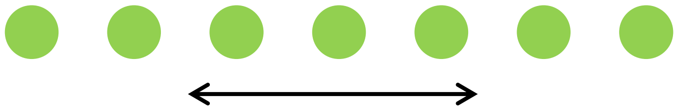
Implementing multi-qubit gates for trapped ions

Multi-qubit gates: Coupling via common vibrational mode

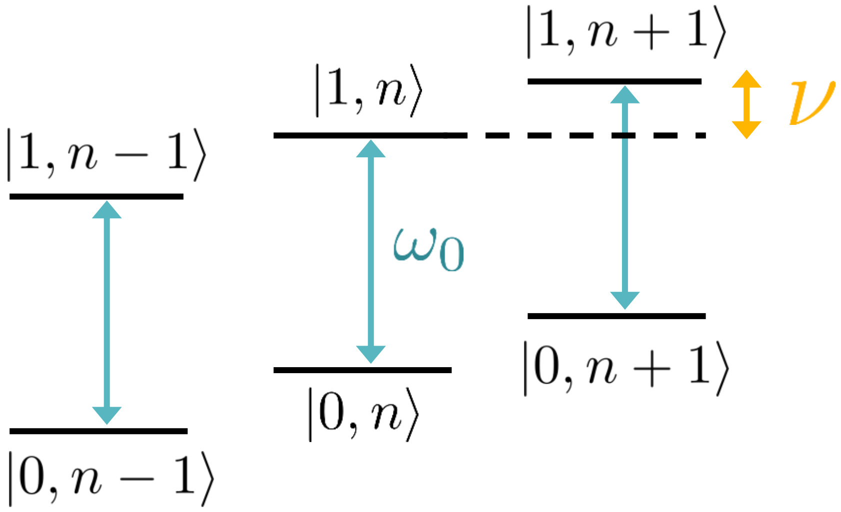
- Ions perform collective motion

Lowest vibrational mode:
Center of mass motion (rigid body)



Higher modes: e.g., stretching

Motional energy levels $|n\rangle$



Total energy of each ion:
internal energy + motional energy

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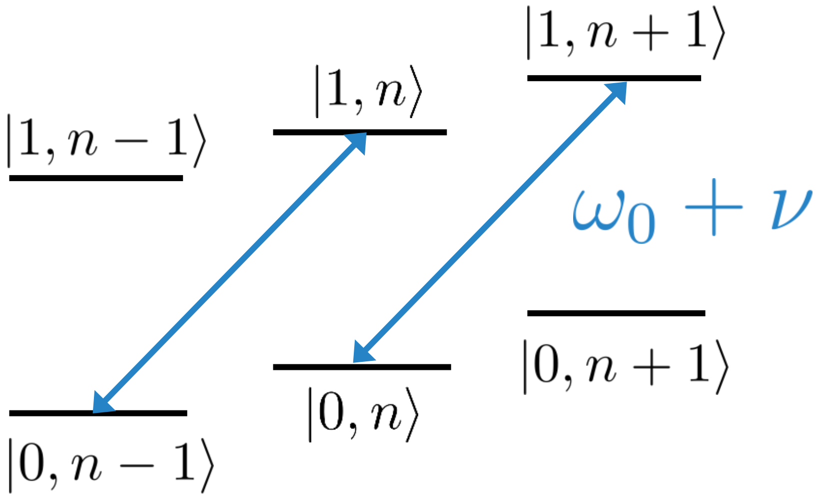
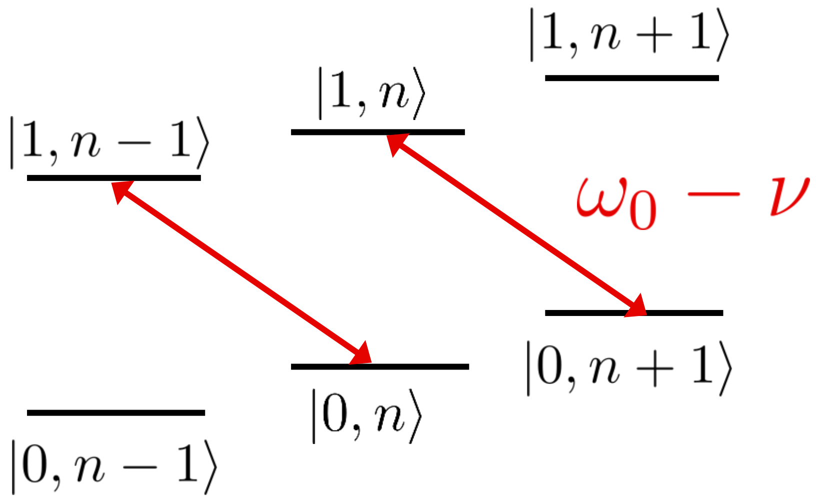
Multi-qubit gates: Coupling via common vibrational mode

Use the shared motional modes to transfer quantum information





Blue sidebands:
Increase motional state

Red sidebands:
Decrease motional state

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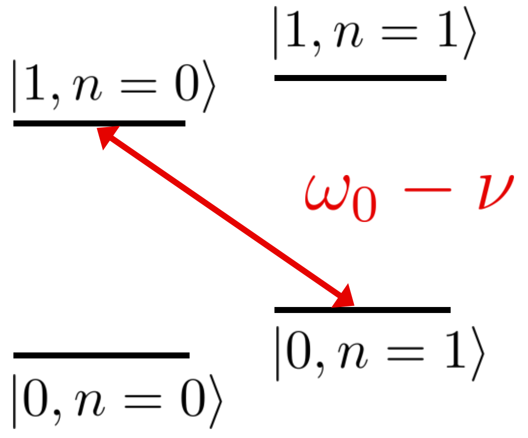
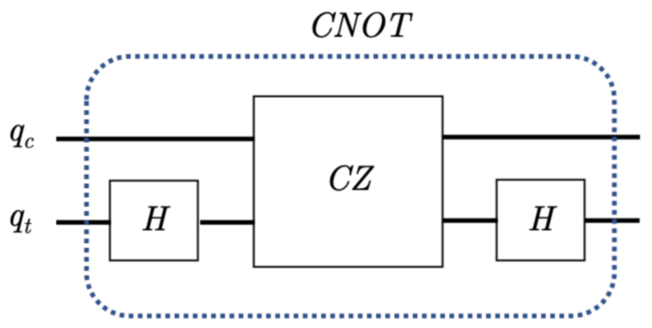
Multi-qubit gate: CZ-gate

3-pulse scheme





[10]

- Laser tuned to red sideband
- Ions are in the motional ground state $|n=0\rangle$
- If an ion is in $|0, n=0\rangle$, it cannot be excited

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} = CZ$$

Puls sequence:

(1) π-puls on control qubit

(2) 2π-puls on target qubit

(3) π-puls on control qubit

control ↘ target ↓	(1) →	(2) →	(3) →
$\|00, n=0\rangle$	$\|00, n=0\rangle$	$\|00, n=0\rangle$	$\|00, n=0\rangle$
$\|01, n=0\rangle$	$\|01, n=0\rangle$	$\|01, n=0\rangle$	$\|01, n=0\rangle$
$\|10, n=0\rangle$	$-i\|00, n=1\rangle$	$i\|00, n=1\rangle$	$\|10, n=0\rangle$
$\|11, n=0\rangle$	$-i\|01, n=1\rangle$	$-i\|01, n=1\rangle$	$-\|11, n=0\rangle$

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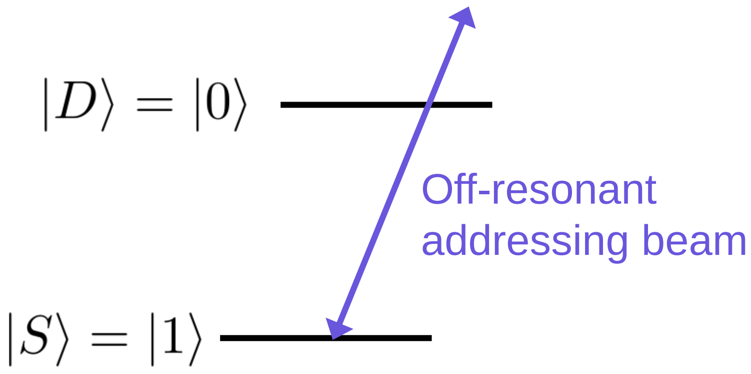
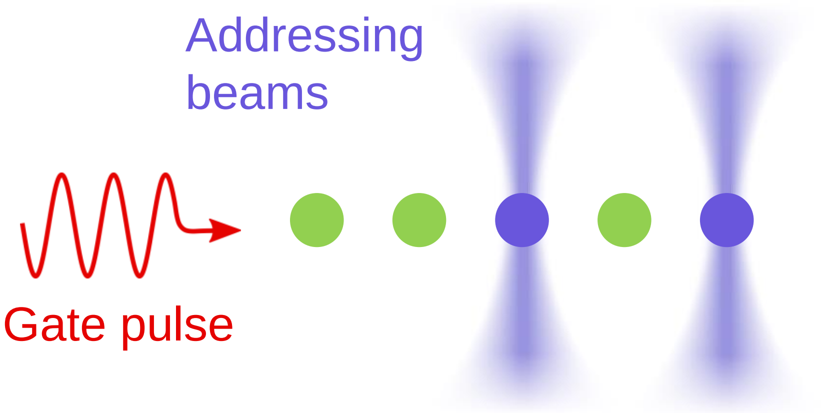
Local vs. Global operations

So far: *global* operations

Addressing of single ions for *local* operations

- Apply additional off-resonant laser to shift the qubit transition of selected ion(s)
- Only these qubit(s) are resonant with the gate pulses
- Realize local single-qubit rotations & entanglement





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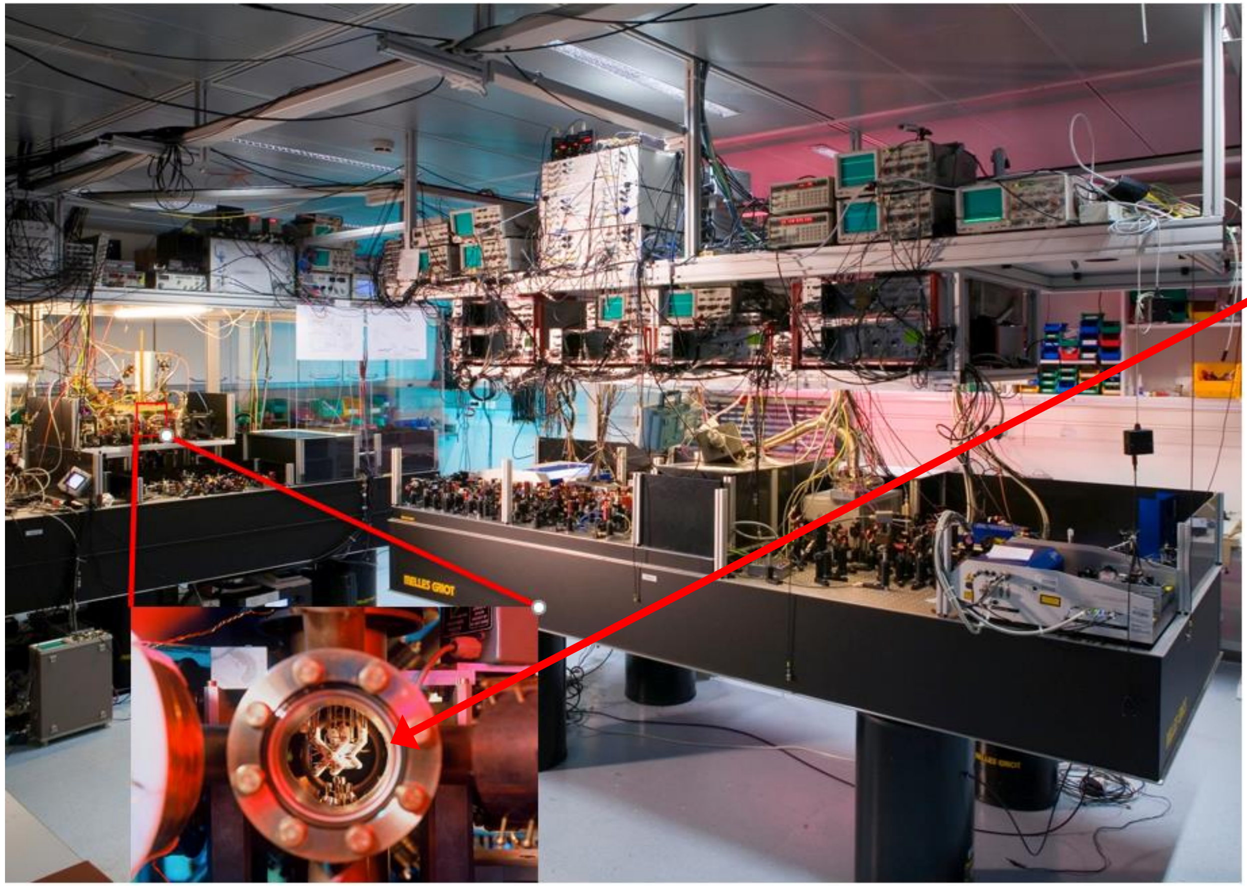
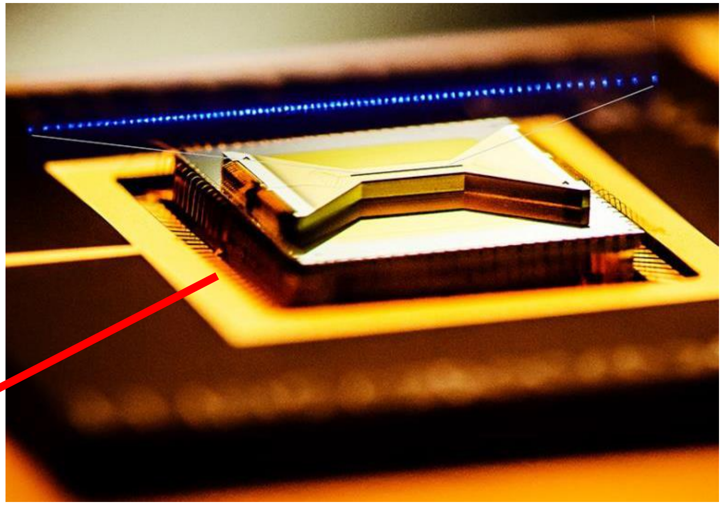
Typical setup



https://thequantumaviary.blogspot.com/2021/03/heres-how-ion-trap-quantum-computers.html



https://physicsworld.com/a/ion-based-commercial-quantum-computer-is-a-first/

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Trapped ion qubits: Overview

Typical characteristics

- Number of qubits 2022: 24 (AQT), 11 (IonQ, 79 with only SQ-gates), 10 (Honeywell)
- Single-qubit gates:
  - Optical qubits ($^{40}Ca^{+}$): Fidelity 99.995%, duration ~ µs
  - Hyperfine Qubits ($^{171}Yb^{+}$): Fidelity 99.0%, duration 5 ps (!)
- Multi-qubit gates (MS): Fidelity 99.6%, duration 50µs (optical), 99.91% & 30µs (hyperfine)
- Coherence times: 0.2s (optical), 600s (hyperfine)
- Key players: IonQ, AQT, Honeywell/Quantinuum

Advantages	Disadvantages
+ All-to-all connectivity	– Hard to scale for > 50 ions
+ Identical qubits	– Vacuum and cooling (noise reduction) needed
+ Long coherence times	

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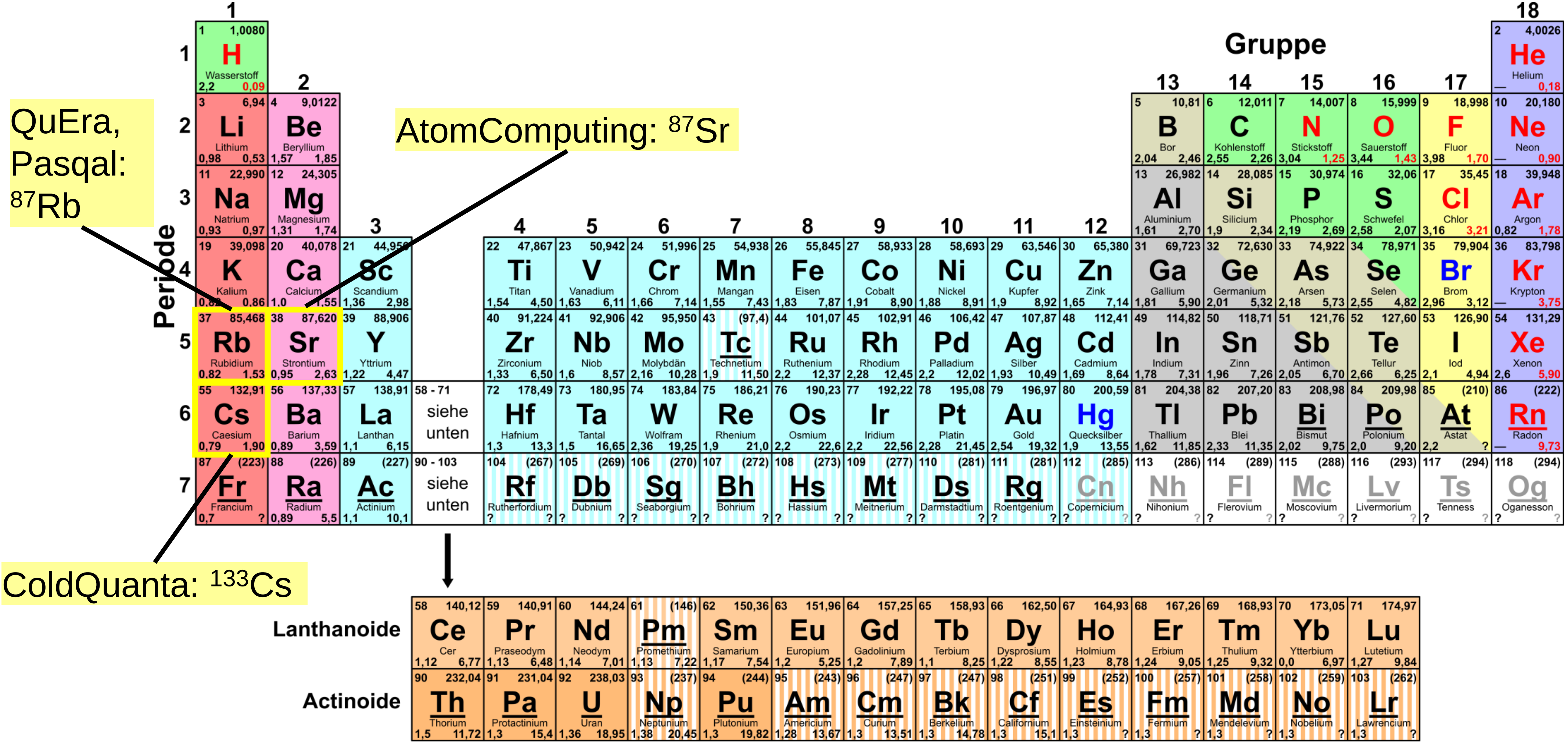
Cold neutral atoms

Atoms as qubits



Wikipedia, [4]

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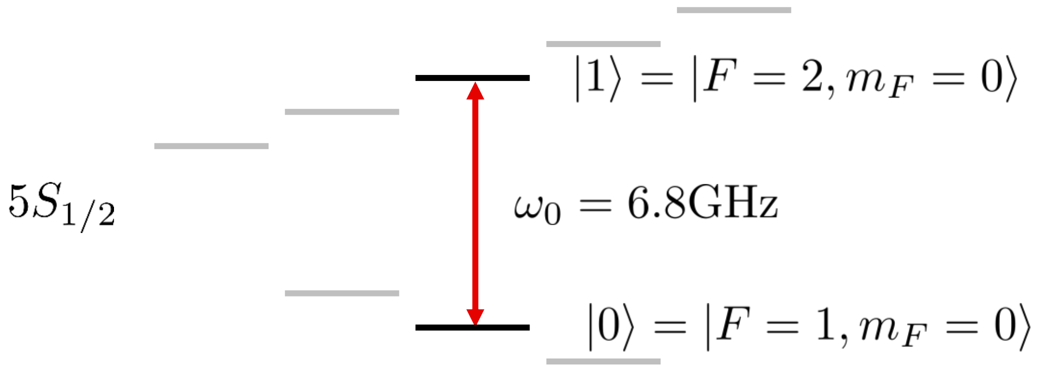
Neutral atom qubits

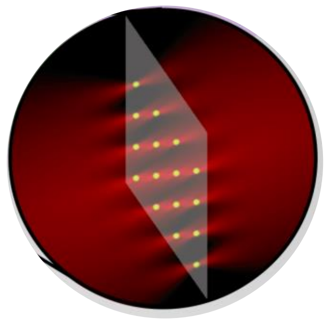
Qubit: Ground state energy levels (^{87}Rb)



- Hyperfine qubits: ^{87}Rb, ^{133}Cs
- Nuclear spin qubits: ^{87}Sr

How to trap neutral atoms

- Array of optical tweezers
- Fixed and movable tweezers possible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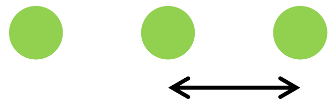

Currently ~100 qubits per array

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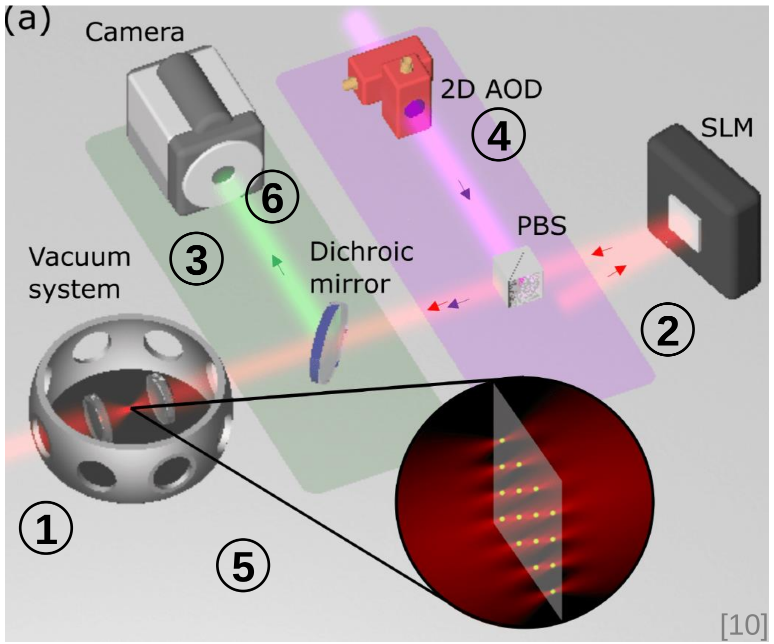
Quantum Computing sequence

1. Laser cooling in vacuum cell
2. Load trap array

   Each trap is loaded with p=0.5: 1 atoms or no atom
3. Image atoms via flourescence
4. Rearrangement

   Arrange atoms using mobile traps to form a homogeneously filled area = qubit register
5. Apply gates
6. Readout: State-selective detection

   Excite atoms in $|1\rangle$ to higher level → push out of trap
   Image remaining atoms in $|0\rangle$ via flourescence



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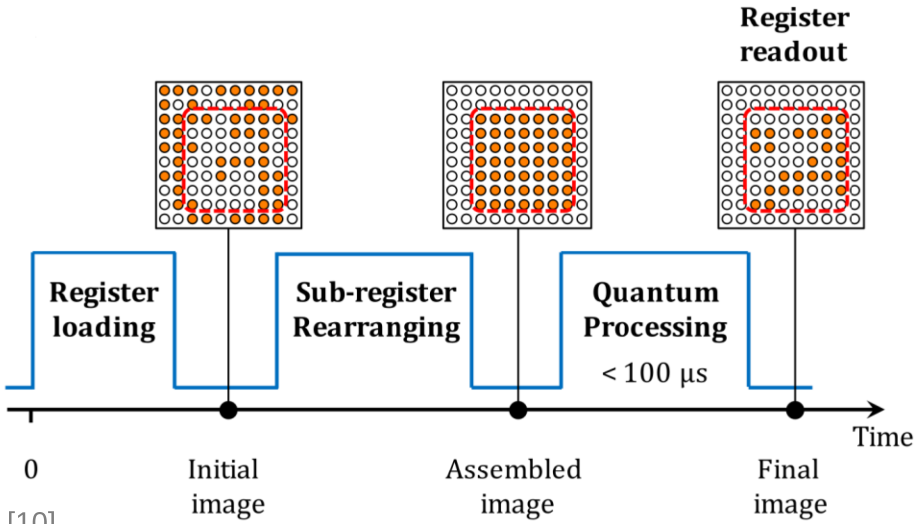

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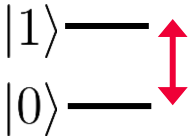
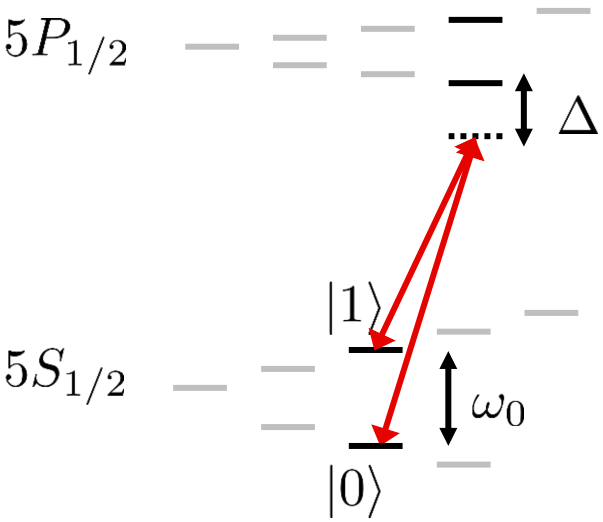
Single-qubit gates

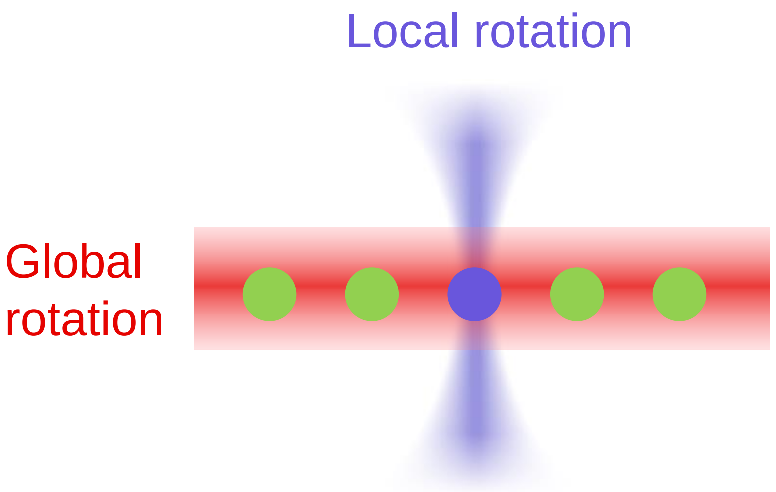
Single-qubit gates: Rotations

- Direct excitation with microwaves (only global)



- Optical excitation with bichromatic lasers via intermediate state (local and global)



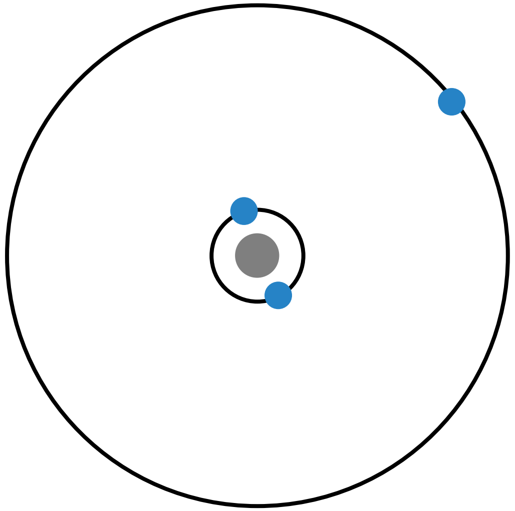


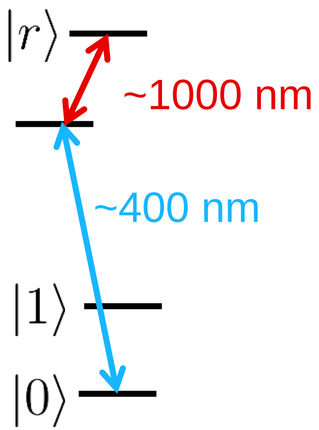
- Arbitrary rotations by tuning duration, intensity, frequency, and phase of the lasers

Multi-Qubit gates: Interactions via Rydberg-States

Rydberg state: Highly excited state of atoms

- High principal quantum number: $n \sim 100$
- Valence electron very far away from ionic core
- Strong dipole moment and *dipole-dipole interaction*

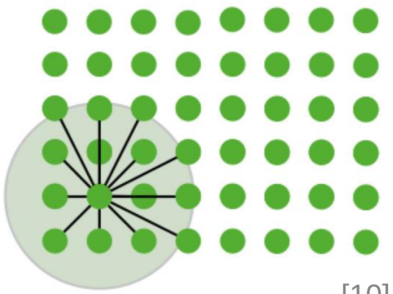




Excite with two lasers

Create *state-dependent interaction*

- Two Rydberg atoms repel each other
- Rydberg Blockade: Neighboring atoms cannot be excited simultaneously



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Blockade radius
$R_B \sim 2 - 50$ lattice sites

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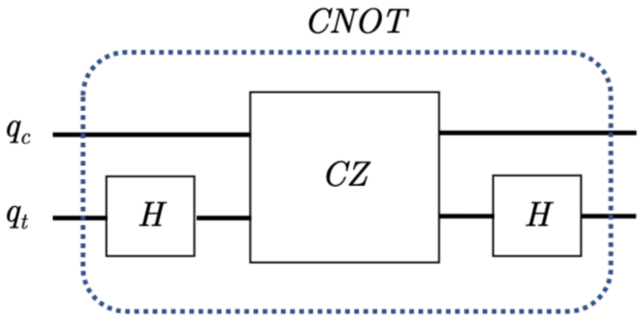
Multi-Qubit gates: Realize CZ-gate



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$$e^{i\pi}\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & -1\end{pmatrix} = e^{i\pi}\, CZ$$

3-pulse scheme

- Can be realized between two atoms within the blockade radius
- Focus two laser beams on two atoms: Couple states $|0\rangle$ and $|r\rangle$

Puls sequence:

(1) π-puls on control qubit

(2) 2π-puls on target qubit

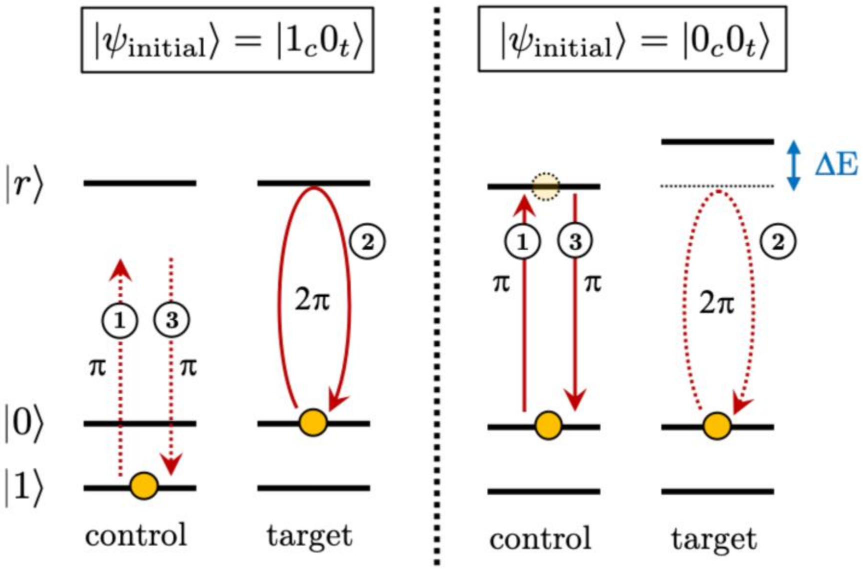
(3) π-puls on control qubit

$|1_c1_t\rangle$: All off-resonant → $|1_c1_t\rangle$

$|1_c0_t\rangle$: (1), (3) off-resonant → -$|1_c0_t\rangle$

$|0_c1_t\rangle$: (2) off-resonant → -$|0_c1_t\rangle$

$|0_c0_t\rangle$: (2) off-resonant via blockade → - $|0_c0_t\rangle$



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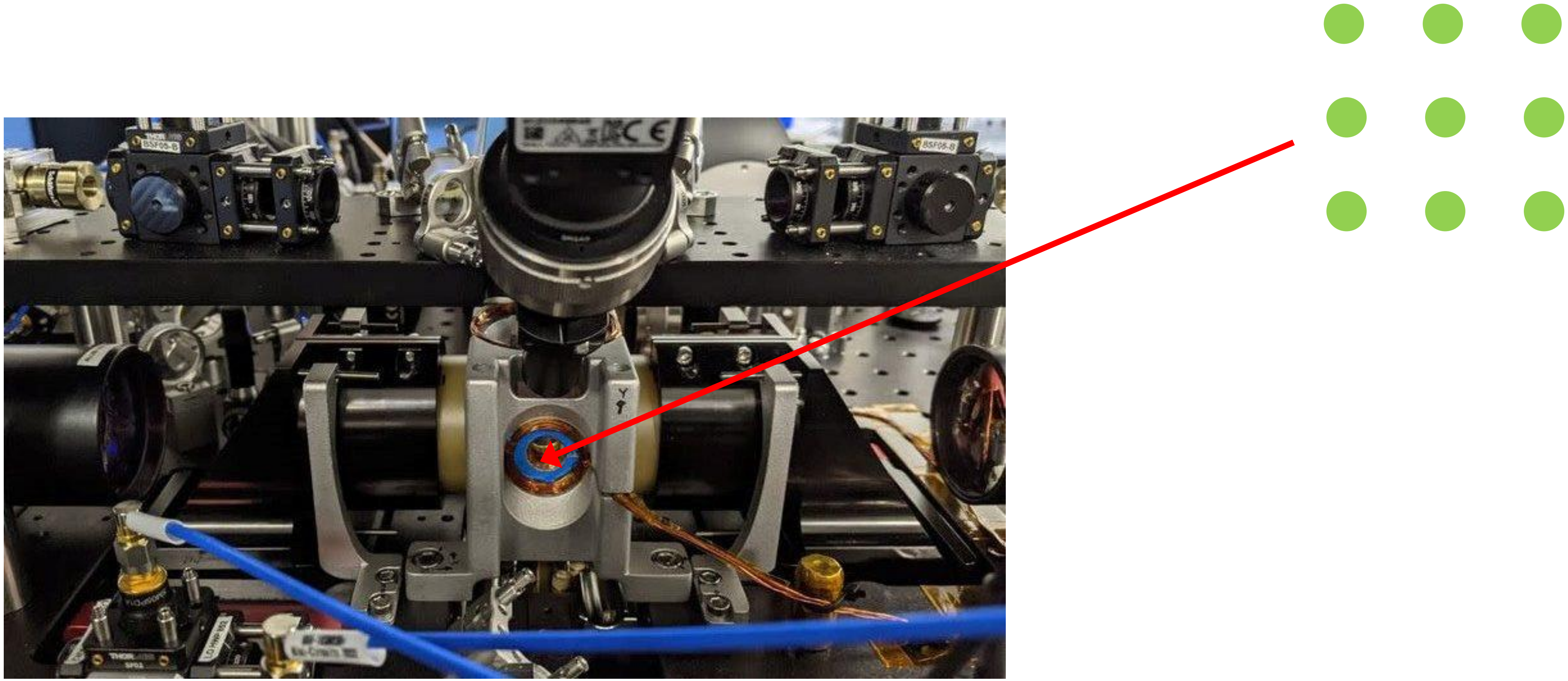
Typical setup



https://www.nextplatform.com/2021/07/16/coldquanta-uses-cold-atoms-to-build-a-quantum-computing/

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Atom qubits: Overview

Typical characteristics

- Number of qubits 2022: ~ 100 (> 1000 announced for 2024)
- Single-qubit gates: Fidelity > 99.5%, duration ~ µs
- CZ-gate: Fidelity ~ 97% (99% announced), duration ~ 200ns
- Coherence times ~ ms - s
- Key players: ColdQuanta, Pasqal, QuEra, AtomComputing

Advantages	Disadvantages
+ Good scalability	– Ultrahigh vacuum needed
+ Identical Qubits	– Slow clock speed
+ Good connectivity (up to 50 or arbitrary by moving atoms around)	– Relatively low CZ gate fidelities
+ (so far no cooling necessary)	

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Superconductors

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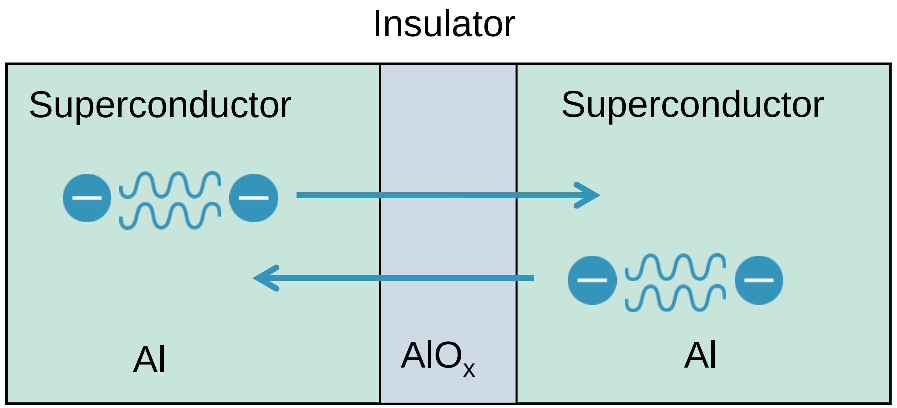
Building blocks of superconducting qubits

Josephson junctions

- Interface of two superconducting islands
- Superconductor: No electrical resistance for $T < T_C$
- Qubit transition: *Tunneling of Cooper pairs*



Different types of SC qubits:

- Charge qubit, flux qubit, phase qubit,…
- Differ by number of SC islands and junctions between them

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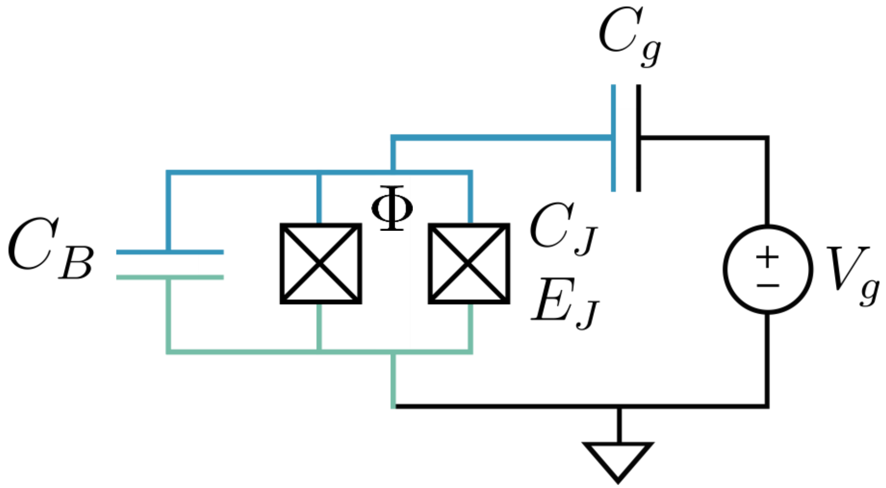
Transmon qubit

Most commonly used: Transmon (transmission line shunted plasma oscillation) qubit

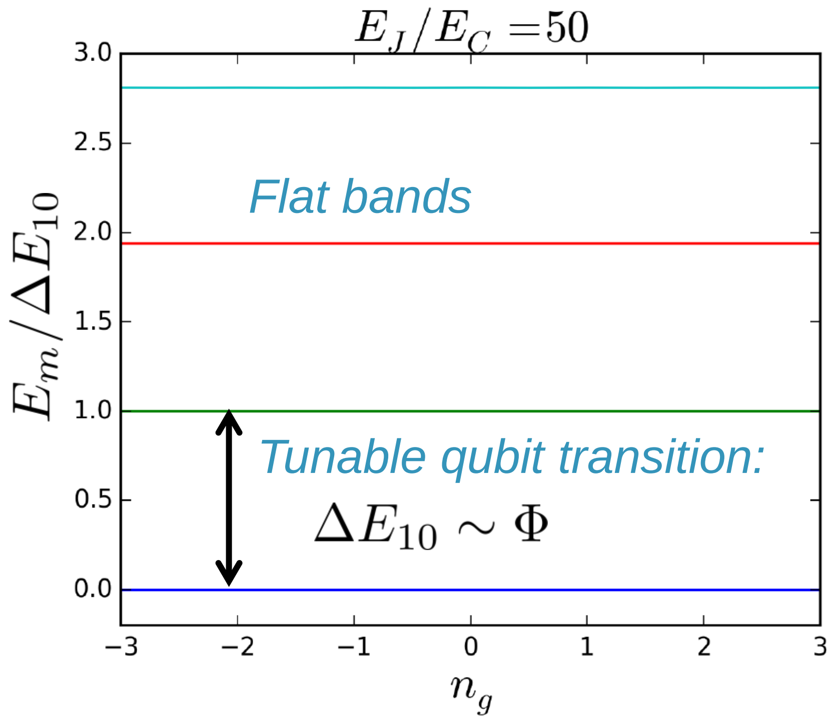
- *Two Josephson junctions* shunted by *large capacitor*



Tune qubit properties by external magnetic flux Φ

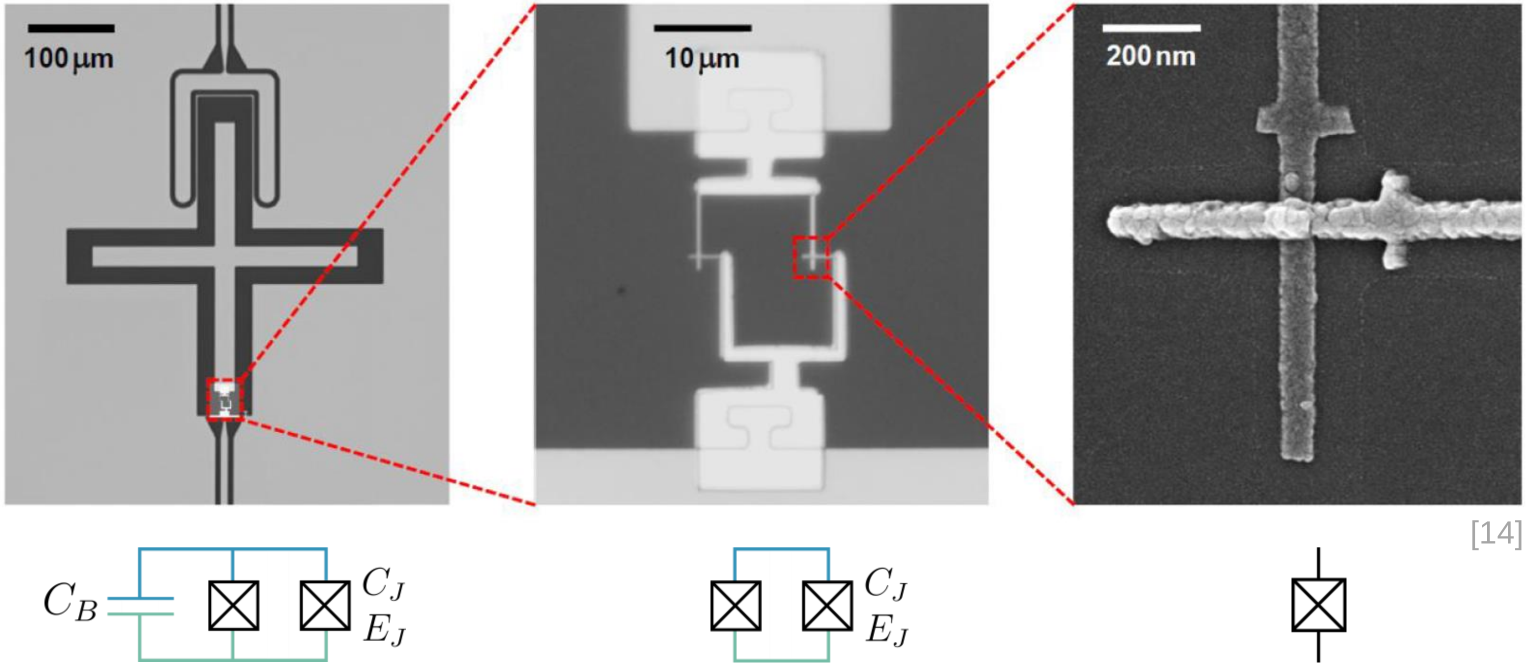
- Less sensitive to charge noise
- More sensitive to magnetic flux noise and lower anharmonicity

Energy levels



Transmon qubit

Large capacitor is often realized by cross shape:



Transmon qubit SQUID Josephson Junction

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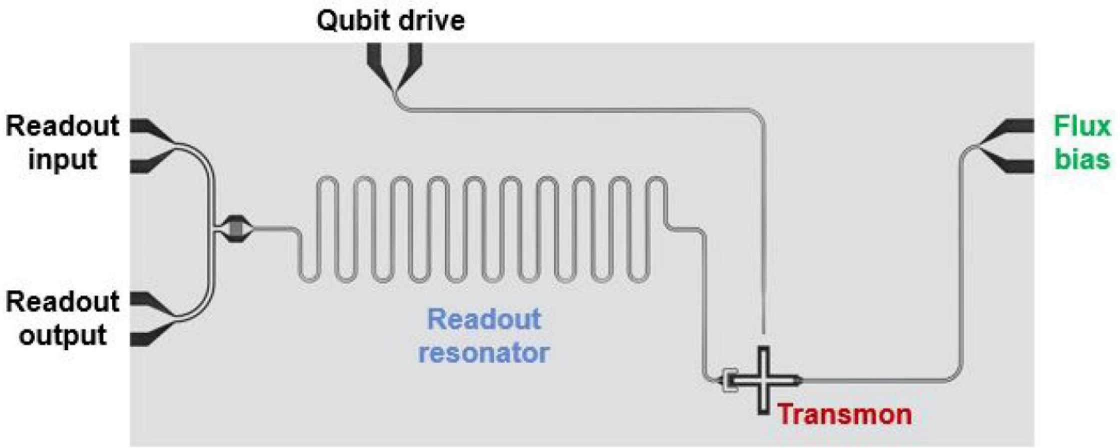
Control and read-out of superconductiong qubits

Single-qubit gates: Rotations

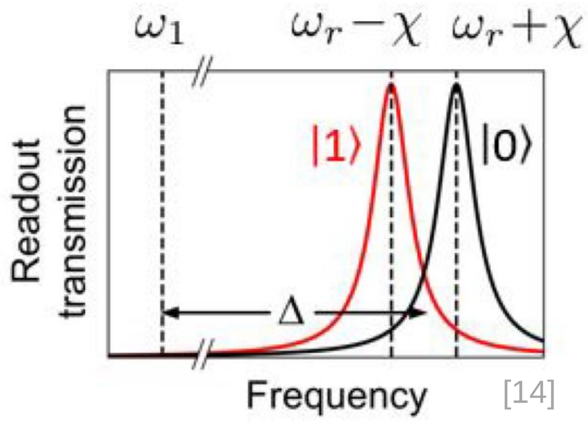
- Apply microwave (MW) pulses
- Rotation angle ~ MW phase



[14]

Read-out of the qubit state:

- Couple capacitively to resonator
- Frequency of resonator ω_r is shifted depending on qubit state
- Measure resonance shift via spectroscopy



[14]

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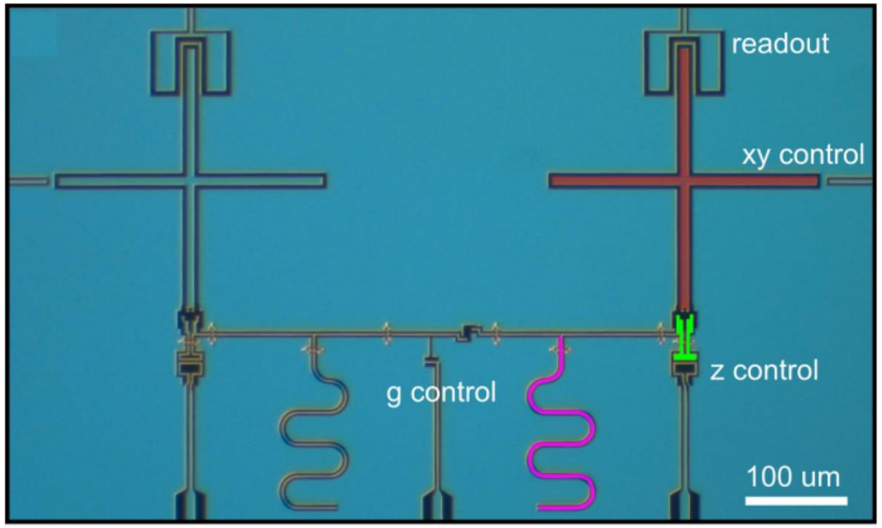
Multi-qubit gates for superconducting qubits

Cross resonance (CR) gate

- Two qubits coupled to a resonator
- Excite qubit 1 with resonance frequency of qubit 2 to realize CZ gate
- Implemented, e.g., by IBM with fixed frequency qubits



[15]

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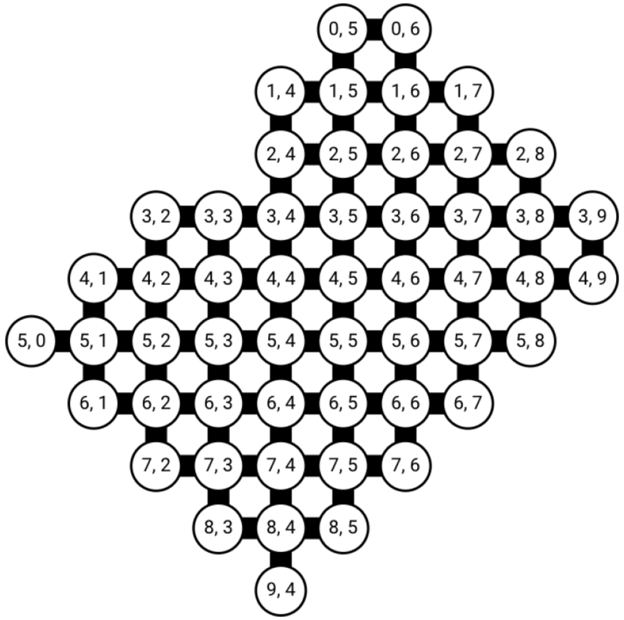
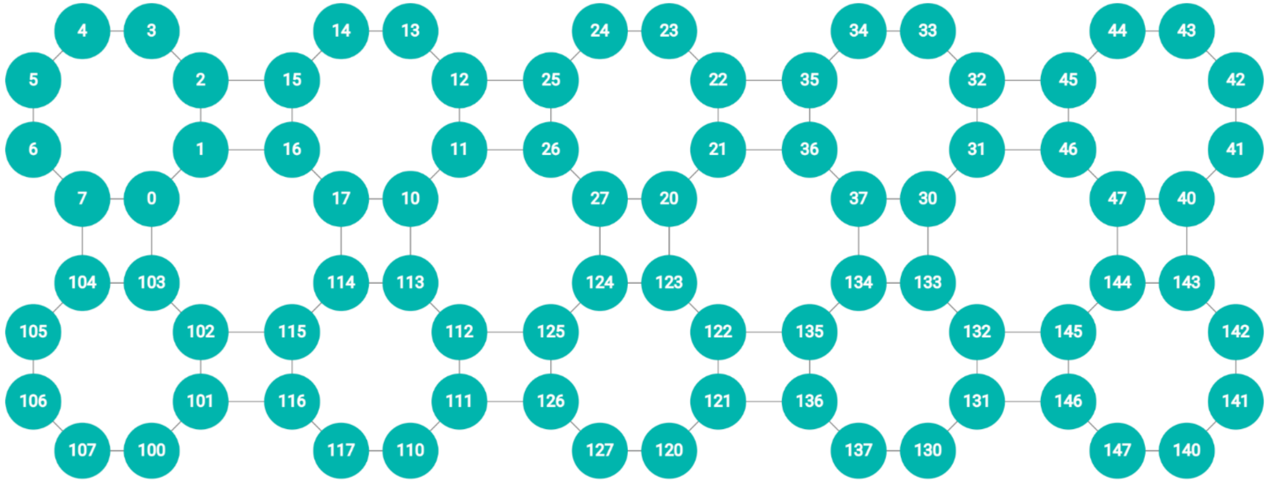
Qubit topology and connectivity

Google Sycamore (53 Qubits)



https://quantumai.google/hardware/datasheet/weber.pdf

Rigetti Aspen-M (80 Qubits)



https://aws.amazon.com/de/braket/quantum-computers/rigetti/

- Qubits need to be connected physically
- Maximum connectivity: nearest neighbor (4)

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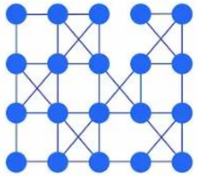
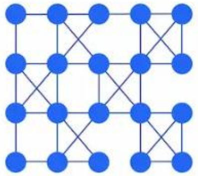
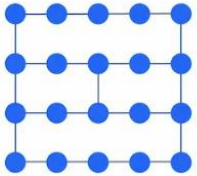
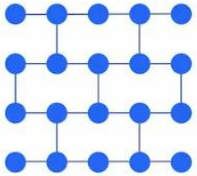
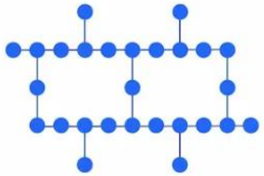
Qubit topology and connectivity

IBM topologies

Processor	Penguin v1	Penguin v2	Penguin v3	Penguin v4	Falcon r4
					
Avg. qubit connectivity	3.9	3.7	2.3	2.3	2.1

https://research.ibm.com/blog/heavy-hex-lattice

- Connectivity is *lowered* to reduce errors
- Sparse topology with fixed frequencies:
  less cross-talk when executing multi-qubit gates

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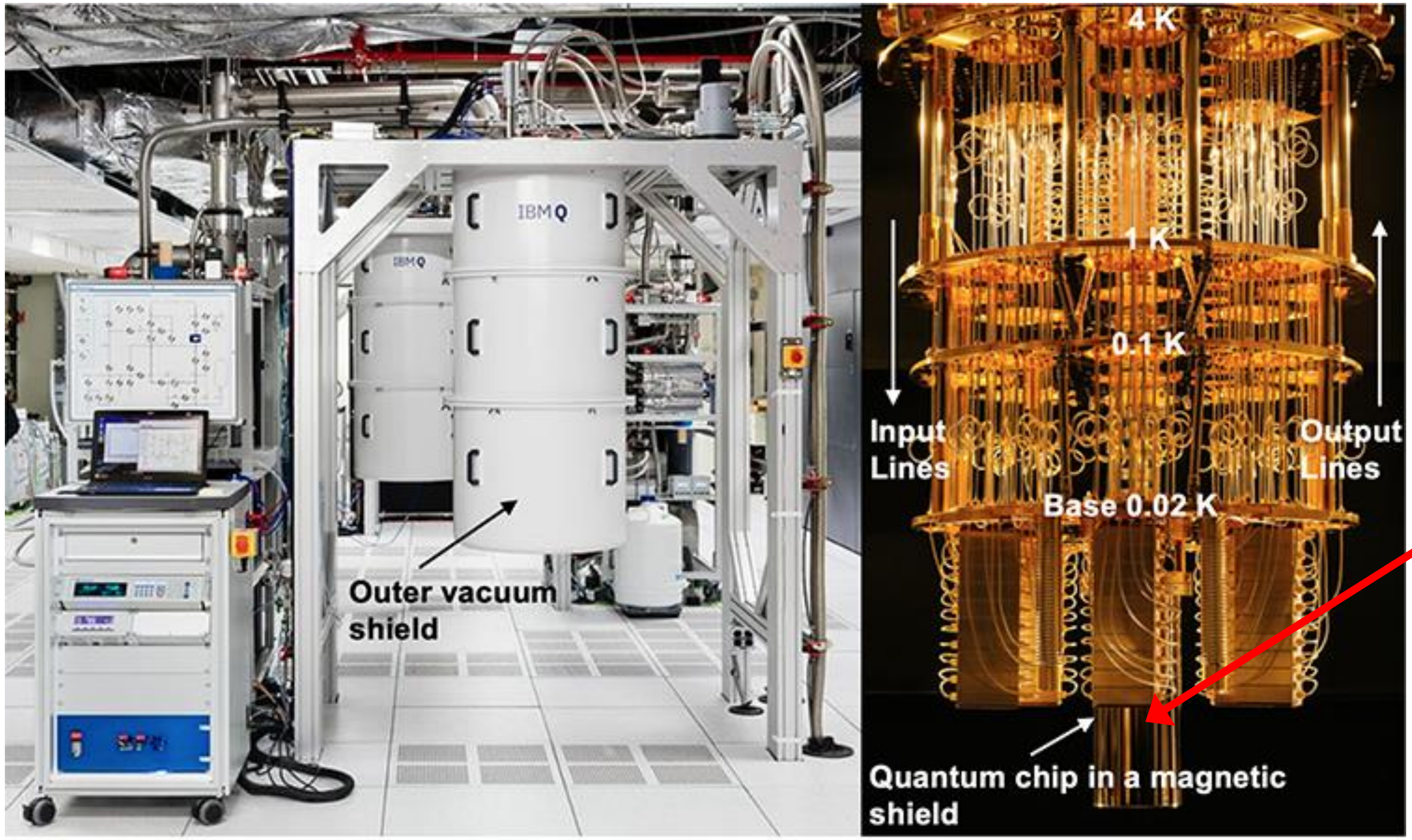
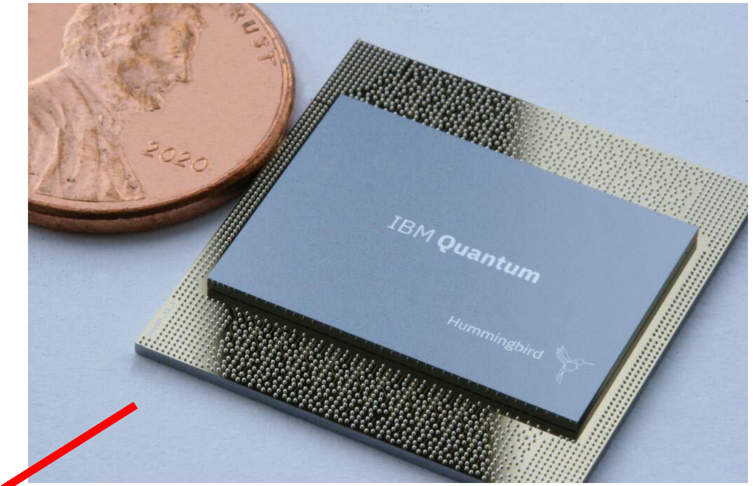
Typical setup



Dilution fridge setup: outside view **Dilution fridge setup: inside view**

https://www.ibm.com/blogs/research/2020/01/quantum-limited-amplifiers/



https://miro.medium.com/max/1400/0*2xf3QTMAHWz19Hpn

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Superconducting qubits: Overview

Typical characteristics

- Number of qubits 2022: 50-127 (127 by IBMs Eagle Processor)
- IBM roadmap: 433 qubits announced for 2022, 1121 for 2023 (modular designs)
- Single-qubit fidelities $1-\epsilon$ and CZ gate fidelities ~ 99.9%
- Gate times ~ ns, coherence times > 100µs
- Key players: IBM, Google, Rigetti, IQM, Alice & Bob, Amazon (announced)

Advantages	Disadvantages
+ Fast operation	– Lower connectivity
+ Solid-state based, use existing technology	– Shorter coherence times
+ Many players, quickly advancing field	– Operation in refrigerator
	– Inhomogeneity: need to calibrate each qubit

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Photonics

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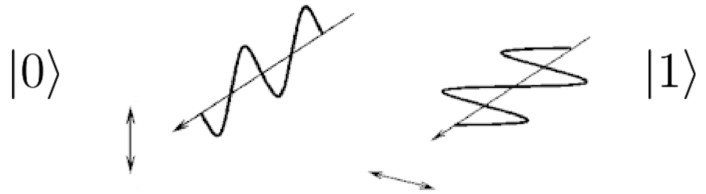
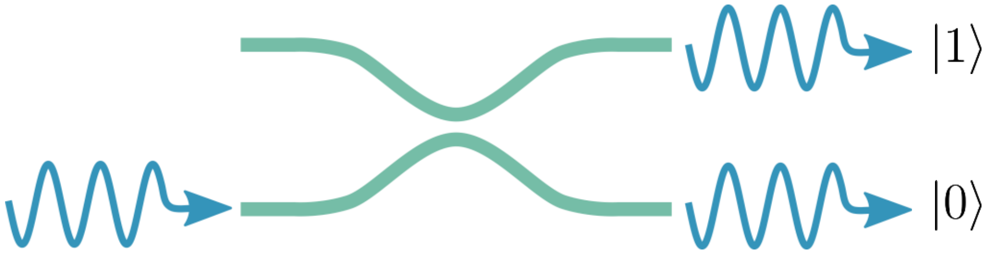
Photons as qubits

Photons can be used as qubits in different ways

- Polarization of light:



- Spatial mode:



- (Number of photons (GKP states))
  → Use continuous variables to encode qubit

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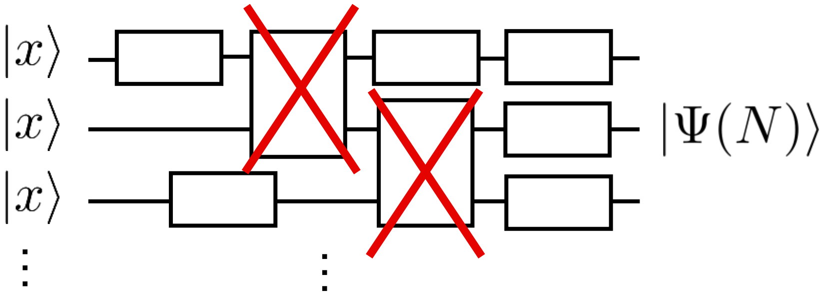
Measurement-based QC

Gate-based QC

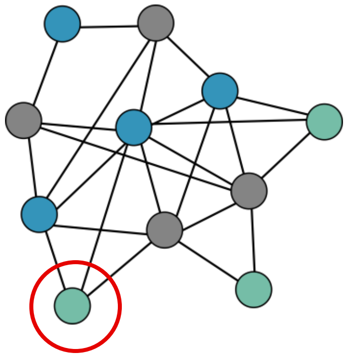


Photons do not interact with each other

Create entangled state of N qubits

1. Compute: Apply gates
2. Measure

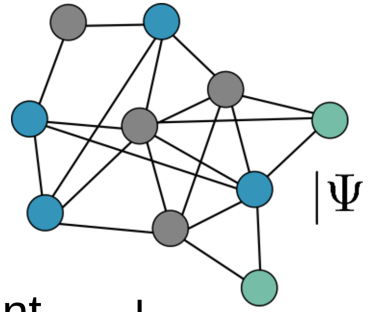
Measurement-based QC: Measurement = Computing



$|\Psi(N+M)\rangle$

Measure aux. qubit 1

Depending on measurement outcome: choose next measurement on aux. qubit 2



$|\Psi\rangle_1$

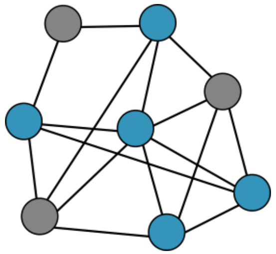
Measure aux. qubit 2

$|\Psi\rangle_2$

Start with entangled state of N computational + M auxiliary qubits

= Cluster-state (can be built fault-tolerant)

End up with same entangled state of N qubits



$|\Psi(N)\rangle$

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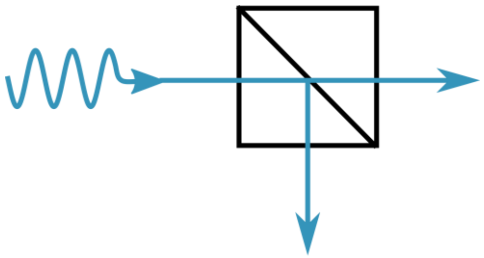
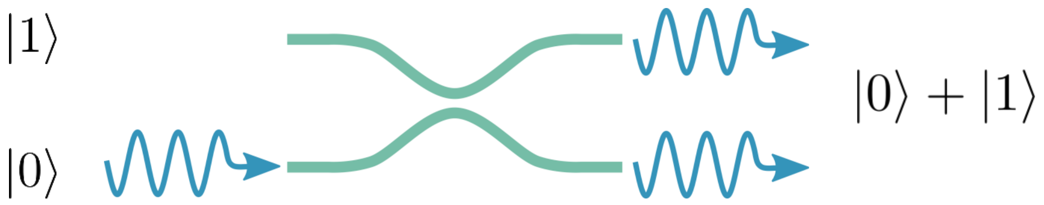
Toolbox of photonic QC

Use photonic integrated circuits (PIC)

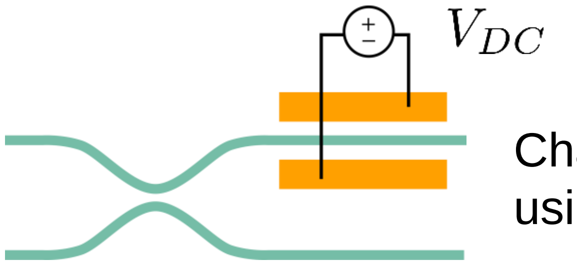
- Waveguide: Planar structure to guide light (Silicon-based), ~1.55µm wavelength
- Linear optical elements: modify single qubits
- Beam splitters:





Create single-qubit superposition states

- Phase shifters:



Change refractive index using electric fields

- Delay lines:

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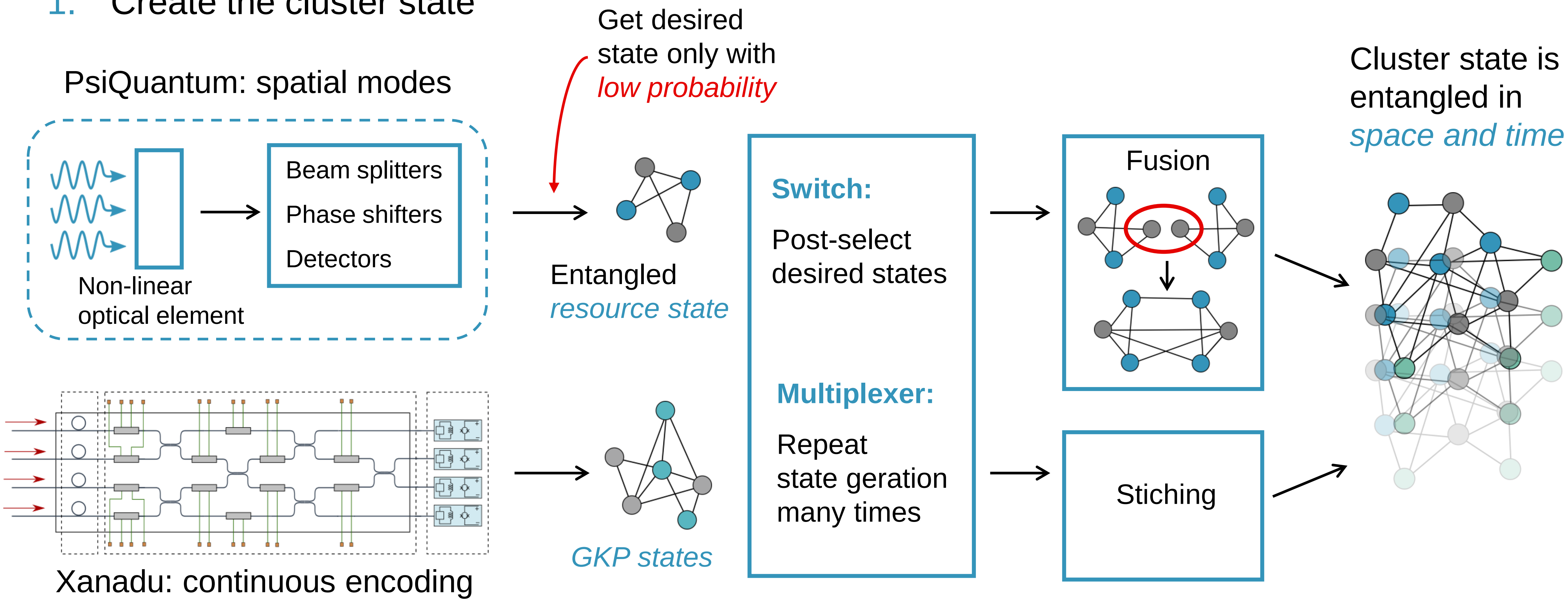
Quantum computing sequence

1. Create the cluster state



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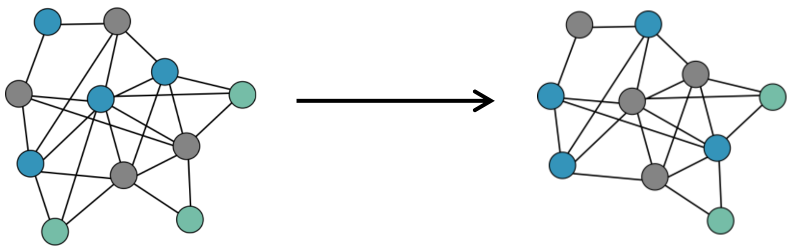
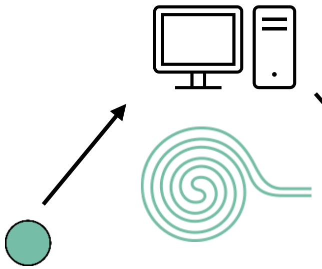
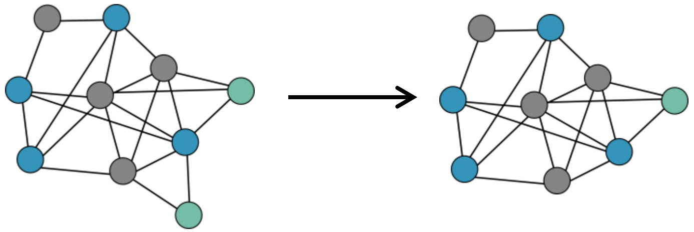
Quantum computing sequence

2. Computation = Measurements





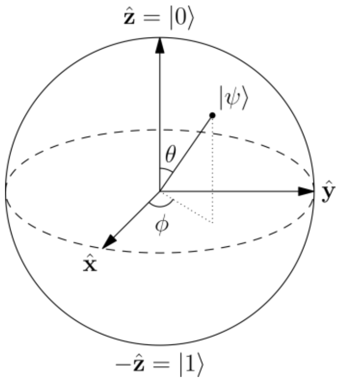
Analyze result on classical computer



Measure: project out auxiliary qubit

Depending on outcome: measure next qubit in a different basis

Basis change: single-qubit operations (tunable phase shifts, etc.)



3. Detection

- For spatial mode encoding: need SC-single-photon detectors → Chip resides in cryostat at 4K
- GKP-encoding: final detectors work at room temperature but generator modules need SC detectors as well

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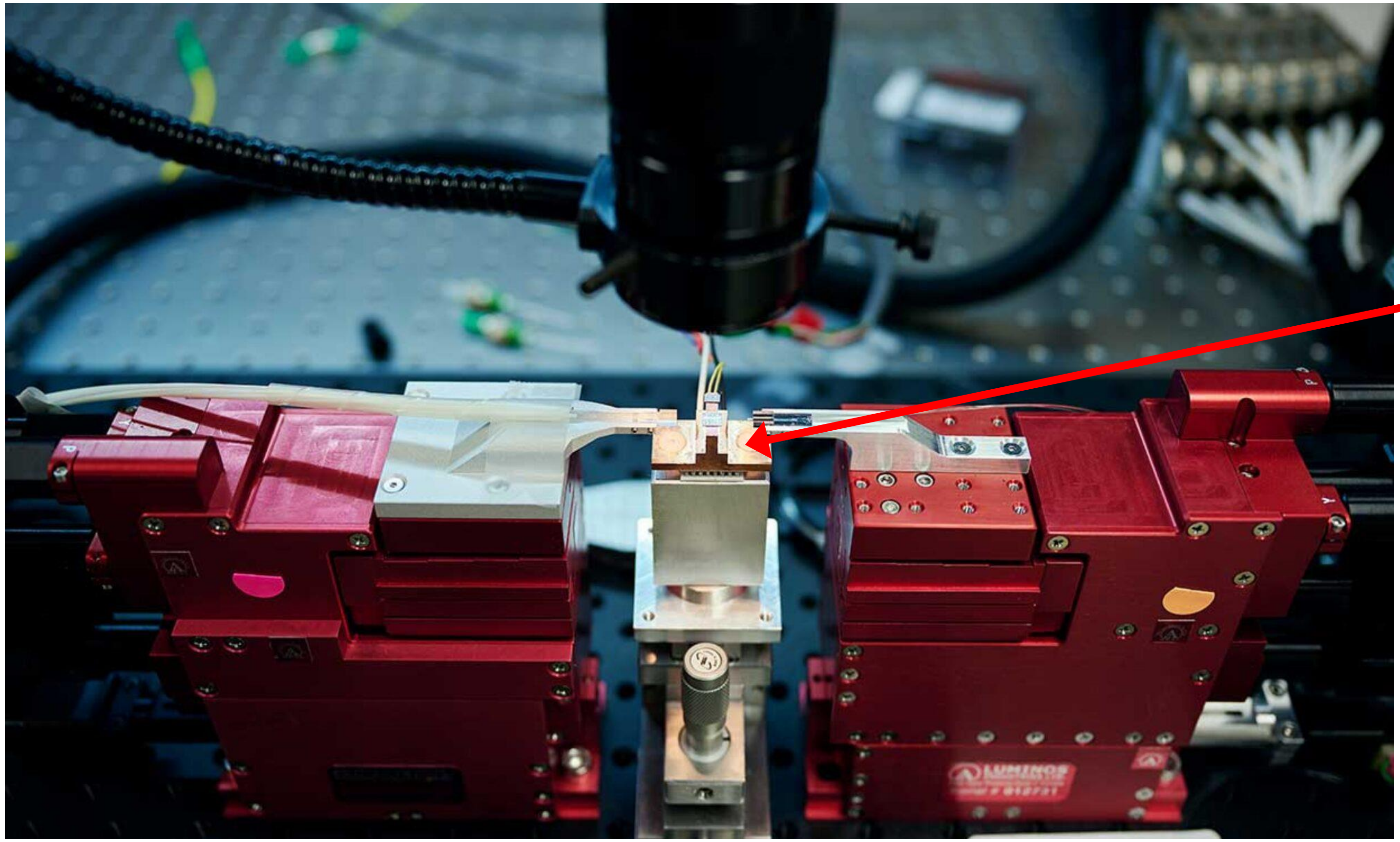
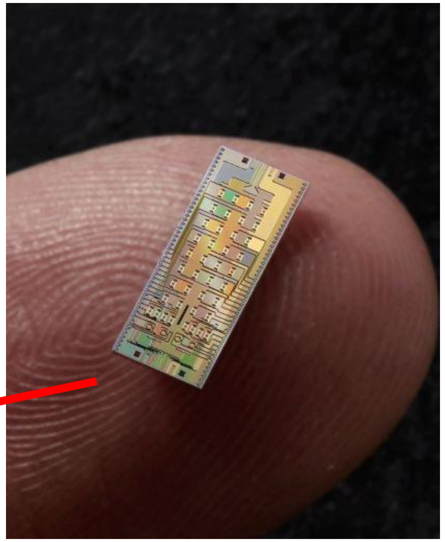
Typical setup



https://www.i-micronews.com/first-photonic-quantum-computer-on-the-cloud/?cn-reloaded=1



https://physicsworld.com/a/programmable-photonic-chip-lights-up-quantum-computing/

Photonic qubits: overview

Typical characteristics

- Number of qubits 2022:
  - Xanadu: 8 modes (12 and 24 in progress), goal: 1 Mio
  - PsiQuantum: goal 1 Mio
- Key players: PsiQuantum, Xanadu, Q.ANT (Trumpf), Orca

Advantages	Disadvantages
+ Solid-state based, use existing technology	– Large overhead of photons needed (probabalistic creation)
+ Highly scalable	– Limited coherence time: Photons cannot be stopped
+ Built-in error-correction	– (Cooling needed for detectors)

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Other approaches

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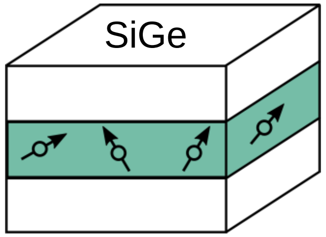
Other platforms for Quantum computing

Quantum dots

- Trap single electrons in 2D-heterostructures
- Qubit: Spin of single electron

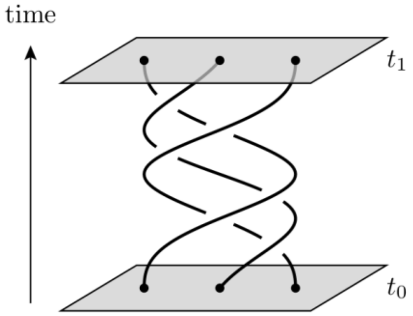


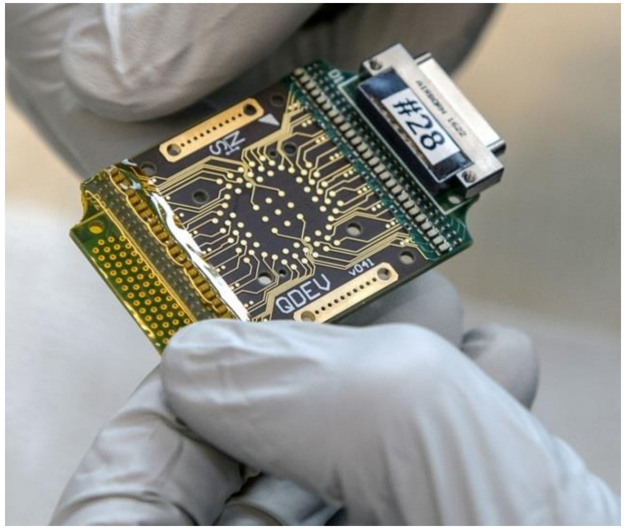
NV centers in diamond

- Replace 2 C atoms with N and vacancy
- Qubit: Electron spin of NV center

Topological qubits (Microsoft)

- Qubits: Majorana Fermions (1/2 electrons)
- Braiding of Majoranas
- Resistant against noise
- Superconductor-semiconductor heterostructures





https://cloudblogs.microsoft.com/quantum/2018/09/06/developing-a-topological-qubit/

Quantum annealing

Adiabatic quantum computing

- Start in ground state of known Hamiltonian H_0 which is easy to prepare
- Adiabatically change parameters to transform H_0 into the Hamiltonian H_P describing the problem to solve
  → End up in ground state of H_P = solution of the problem

Quantum annealing (D-Wave)

- Vary Hamiltonian over time similar to adiabatic QC
- Start in arbitrary state, not in the ground state
  → Probability of converging to a solution
- Not equivalent to universal QC, can only tackle special problems
- D-Wave: use superconducting qubits but with low connectivity

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Summary and Outlook

- Coexistence of several hardware platforms for quantum computing
- Different platforms might be used for different applications
- Compare hardware: quantum volume (first defined by IBM)
- Typical values: 128 (IBM Montreal with 27 qubits), 4096 (Honeywell with 12 qubits)

Outlook:

- Reduce errors and increase number of qubits
- Quantum computers as supercomputers for special purposes or hardware accelerators
- Coexistence with classical computers

Thank you!

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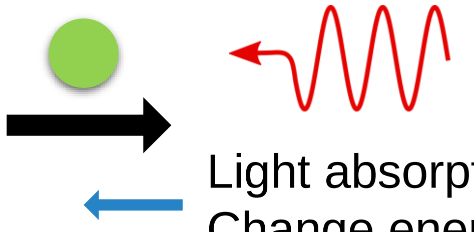
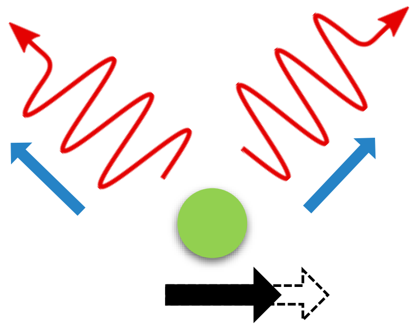
[19] https://iopscience.iop.org/article/10.1088/2058-9565/aab822/pdf

Preparation for Quantum Computing: Ions & atoms

How to cool ions/atoms with light



Light absorption:
Change energy
and momentum



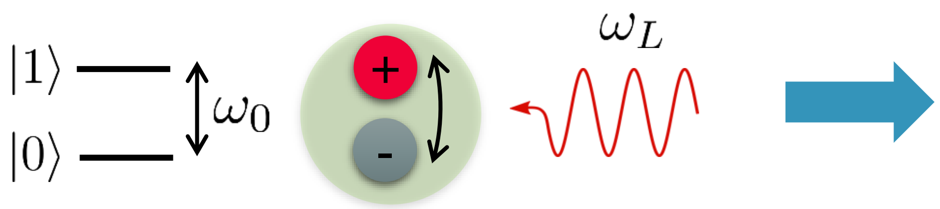
Emit light in arbitrary direction

Net momentum along opposite direction → *Slow down*

Get to T ~ μK

How to trap atoms with light

Light induces a *dipole moment* in the atom

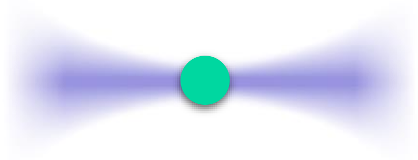


Dipole force: depends on detuning $\Delta = \omega_L - \omega_0$

Atom oscillates in (out of) phase for $\Delta < 0$ ($\Delta > 0$)

= attractive (repulsive) Potential

$U_{\text{dip}}(\vec{r}) \propto \frac{I(\vec{r})}{\Delta}$ Depends on laser *intensity* $I(\vec{r})$



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