



**Northwestern
University**

Feb 4, 2023

Sievert Lecture Series: The Rise of Quantum Machines

Lecture V: Quantum Computing Hardware and Operation

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Fermi National Accelerator Laboratory

Why Quantum Computing?

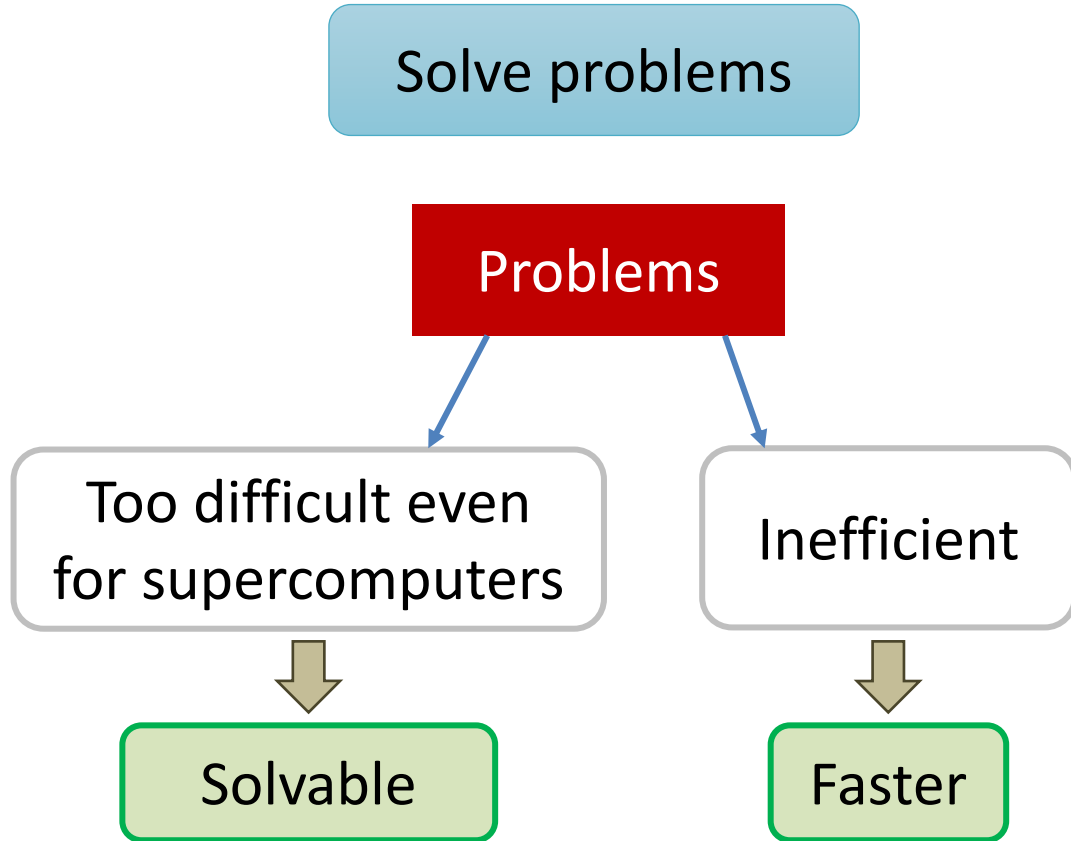
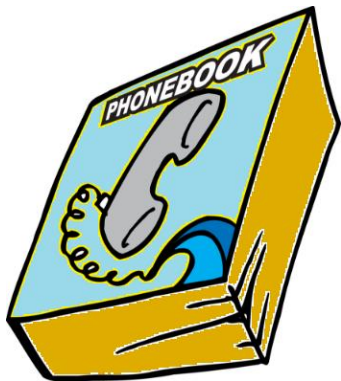


Image: poppyseedprojects.com

One Example: Searching Unsorted Database



Lov Grover

- N entries require $\sim N/2$ attempts
- Grover's algorithm: $\sim \sqrt{N}$
 - 10000 entries: 5000 vs. 100

Name	Phone no.
AAA	245...89
BBB	236...45
CCC	398...72
...	...
...	...
...	...
SSS	291...56
UUU	307...89
VVV	273...02

Quadratic speedup with Quantum Computer

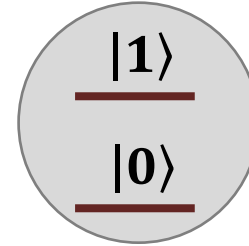
Fundamental Unit



1



0



Quantum bit
Qubit

Classical bit:
"0" or "1"

Quantum bit:
"0" and "1"

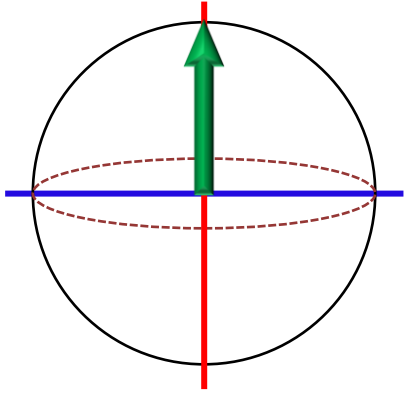


Superposition: $|0\rangle \pm |1\rangle$

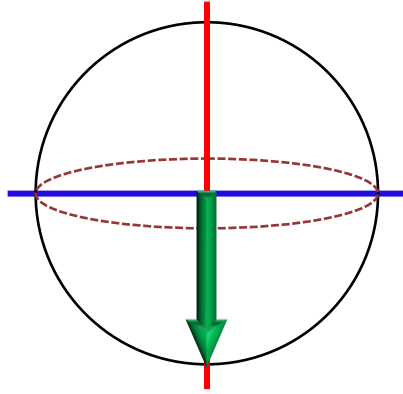
Entanglement

Qubit Visualization

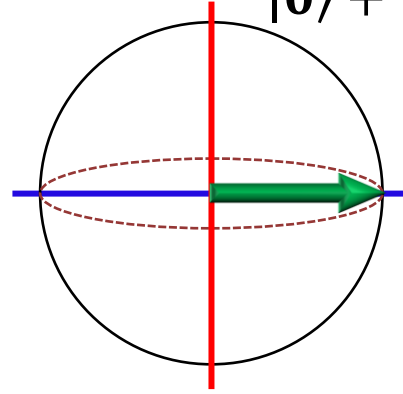
$|0\rangle$



$|1\rangle$

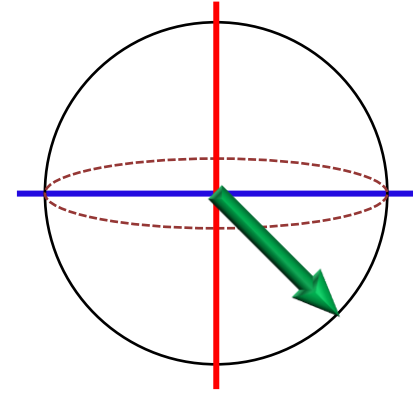


$|0\rangle + |1\rangle$

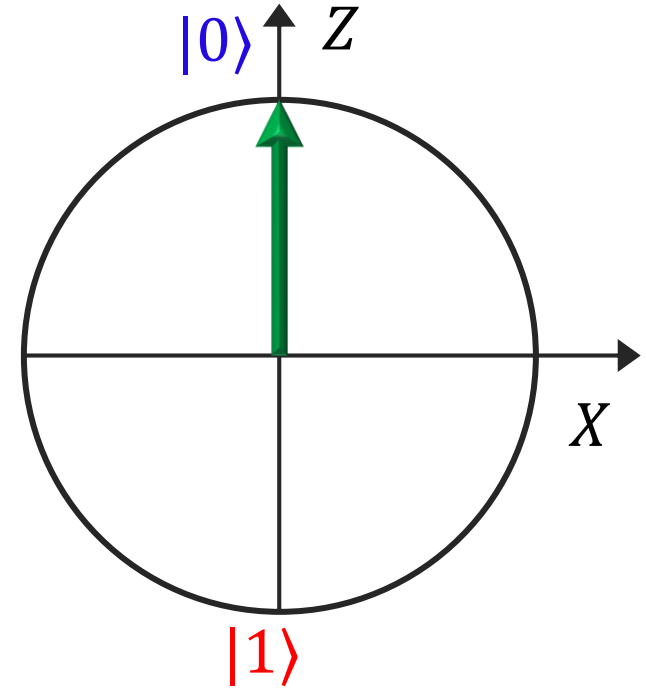


Superposition states

General state: $a|0\rangle + b|1\rangle$



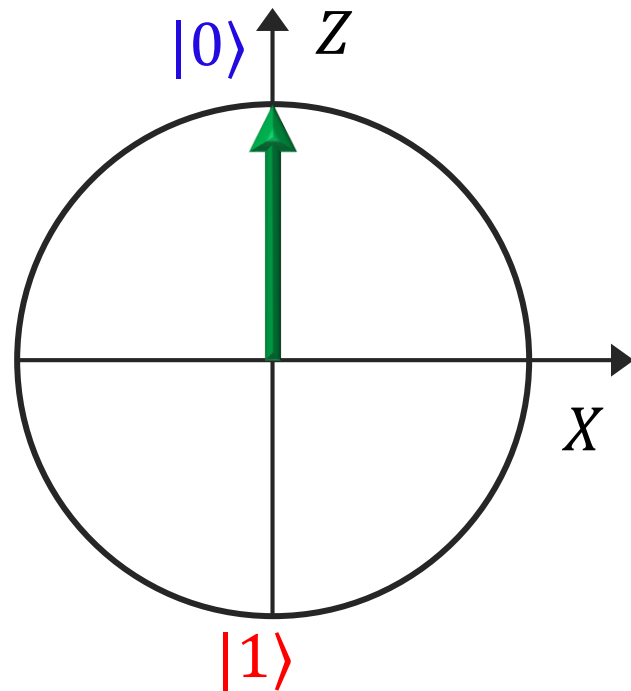
Single-qubit Gates



Rabi Oscillation

Single-qubit Gates

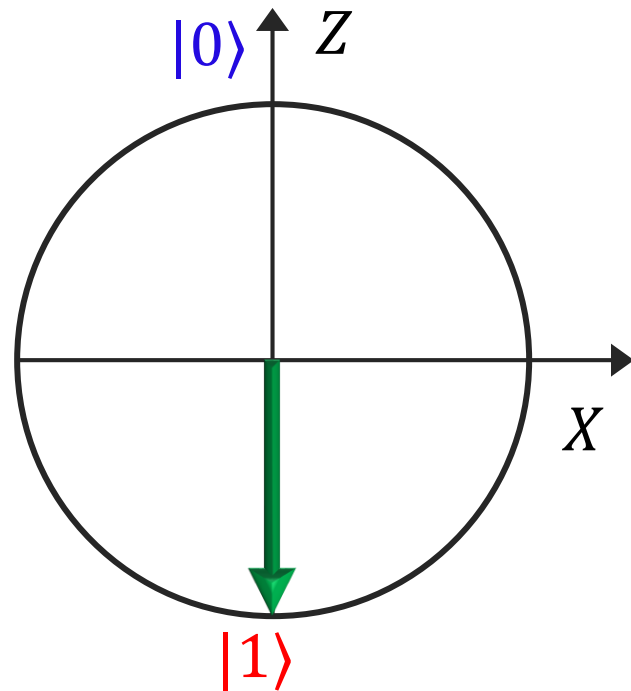
$\pi/2$ pulse: $|0\rangle \rightarrow (|0\rangle + |1\rangle)/\sqrt{2}$



Single-qubit Gates

$\pi/2$ pulse: $|0\rangle \rightarrow (|0\rangle + |1\rangle)/\sqrt{2}$

$|1\rangle \rightarrow (|0\rangle - |1\rangle)/\sqrt{2}$



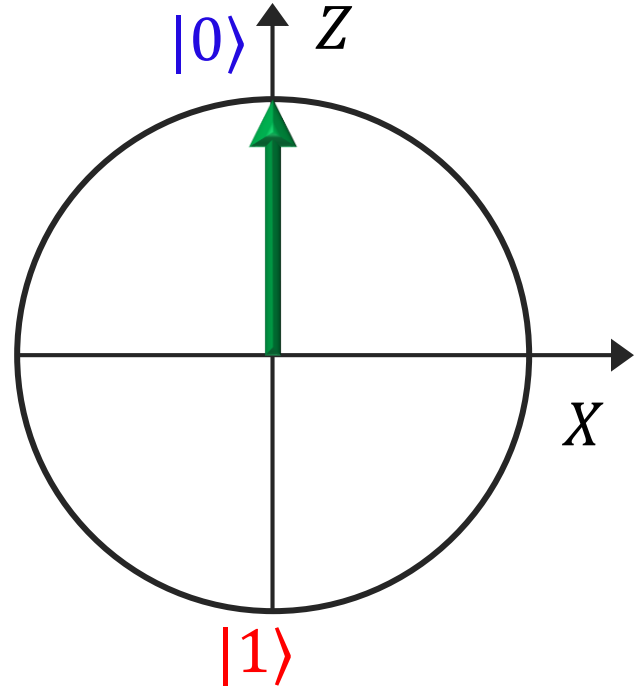
Single-qubit Gates

$\pi/2$ pulse: $|0\rangle \rightarrow (|0\rangle + |1\rangle)/\sqrt{2}$

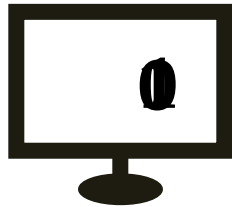
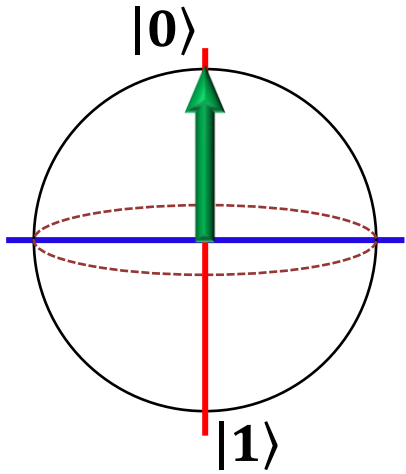
$|1\rangle \rightarrow (|0\rangle - |1\rangle)/\sqrt{2}$

π pulse: $|0\rangle \rightarrow |1\rangle$

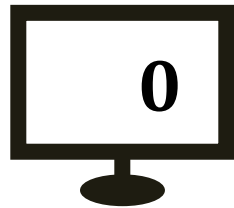
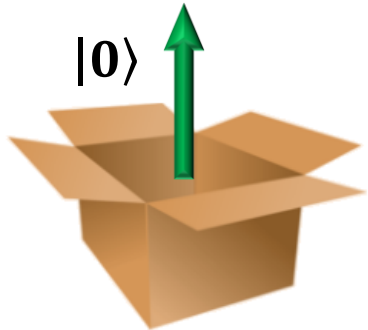
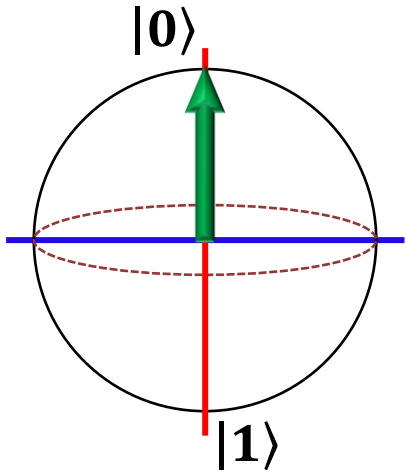
$|1\rangle \rightarrow |0\rangle$



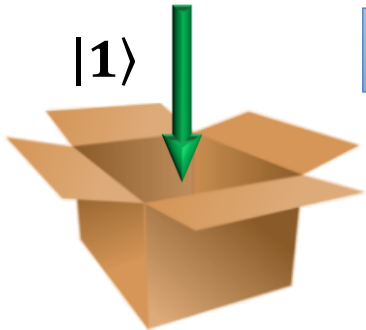
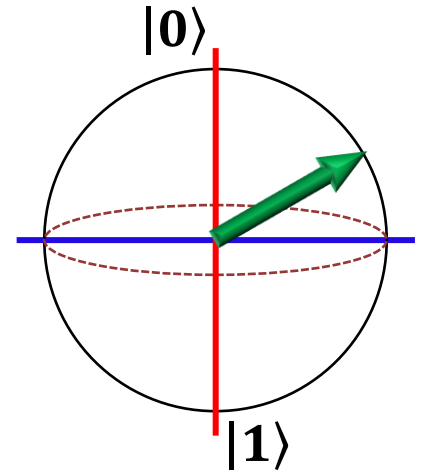
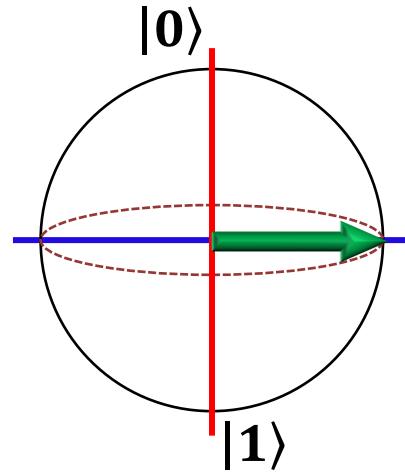
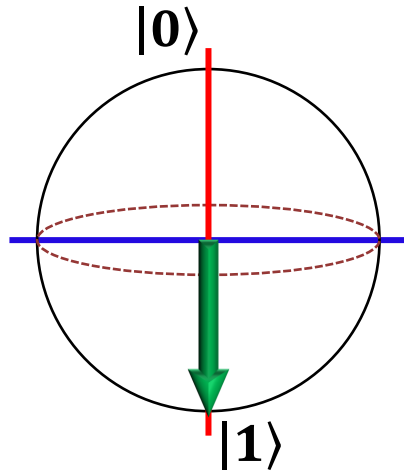
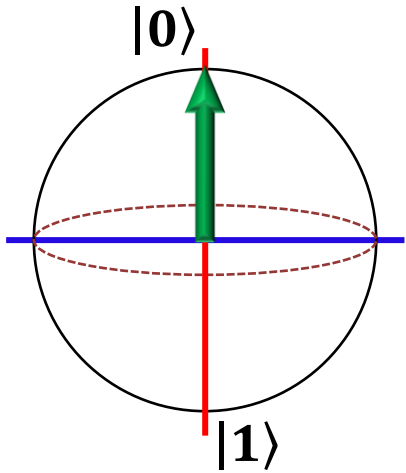
Single-qubit Measurement



Single-qubit Measurement



Single-qubit Measurement



Either 0 or 1



50% $|0\rangle$

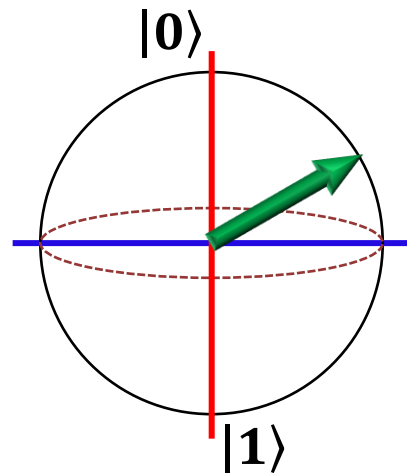
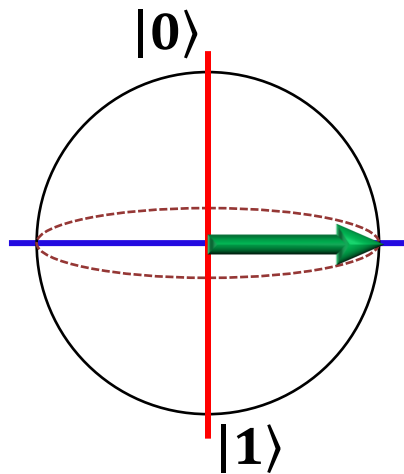
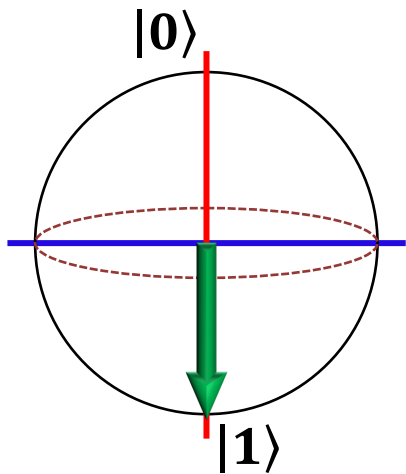
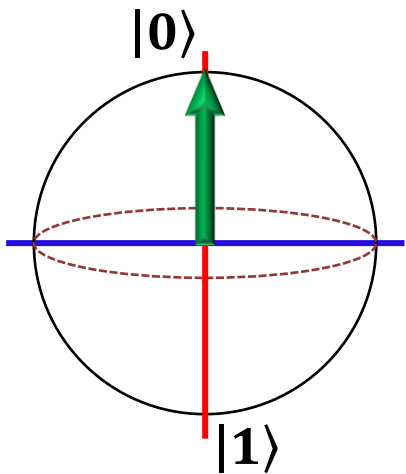
50% $|1\rangle$

$$\sqrt{0.75}|0\rangle + \sqrt{0.25}|1\rangle$$

75% $|0\rangle$

25% $|1\rangle$

Single-qubit Measurement



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

$$P(0) = a^2$$

$$P(1) = b^2$$



Superposition

Qubit 1: $a|0\rangle + b|1\rangle$

Qubit 2: $a|0\rangle + b|1\rangle$

Full: $(a|0\rangle + b|1\rangle)(a|0\rangle + b|1\rangle)$

$(|0\rangle + |1\rangle)(|0\rangle + |1\rangle)$

$= |0\rangle|0\rangle + |1\rangle|1\rangle$

$+ |0\rangle|1\rangle + |1\rangle|0\rangle$

n qubits: **all** of 2^n states

Bit 1:

0

Bit 2:

0

Full:

0	0
---	---

$$2^n = 2 \times 2 \times 2 \dots n \text{ times}$$

0	0
---	---

1	1
---	---

0	1
---	---

1	0
---	---

n classical bits: **1** of 2^n states

Inherent quantum parallelism

Two-qubit Measurement

Full: $|0\rangle|0\rangle + |1\rangle|1\rangle$

+ $|0\rangle|1\rangle + |1\rangle|0\rangle$

= $(|0\rangle + |1\rangle)(|0\rangle + |1\rangle)$

Qubit 1: ?

$|0\rangle + |1\rangle$

Qubit 2: ?

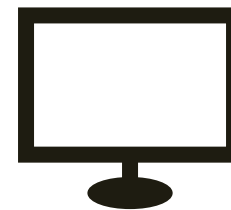
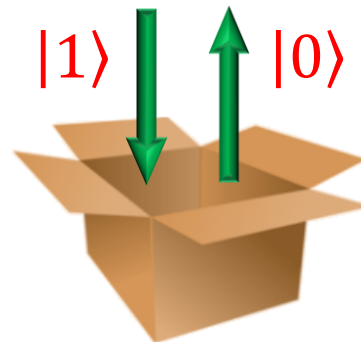
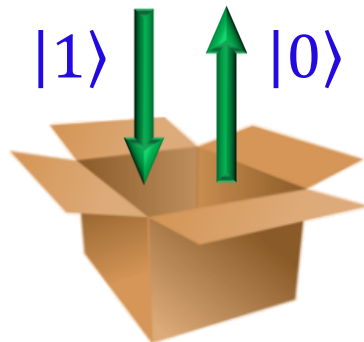
$|0\rangle + |1\rangle$

0 0

1 1

0 1

1 0



A Weird State

$$\text{Full: } |0\rangle|0\rangle + |1\rangle|1\rangle \\ + |0\rangle|1\rangle + |1\rangle|0\rangle$$

$$= (|0\rangle + |1\rangle)(|0\rangle + |1\rangle)$$

$$\text{Bell: } |0\rangle|0\rangle + |1\rangle|1\rangle$$

Qubit 1: ? $|0\rangle + |1\rangle$

Qubit 2: ? $|0\rangle + |1\rangle$

0 0

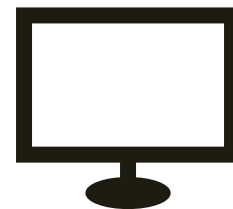
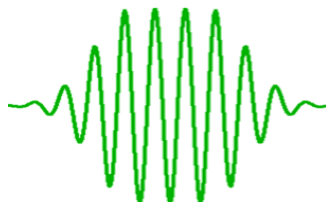
1 1

0 1

1 0

Qubit 1: ?

Qubit 2: ?



A Weird State

Full: $|0\rangle|0\rangle + |1\rangle|1\rangle$

+ $|0\rangle|1\rangle + |1\rangle|0\rangle$

= $(|0\rangle + |1\rangle)(|0\rangle + |1\rangle)$

Bell: $|0\rangle|0\rangle + |1\rangle|1\rangle$

Qubit 1: ? $|0\rangle + |1\rangle$

Qubit 2: ? $|0\rangle + |1\rangle$

$|0\rangle|0\rangle$

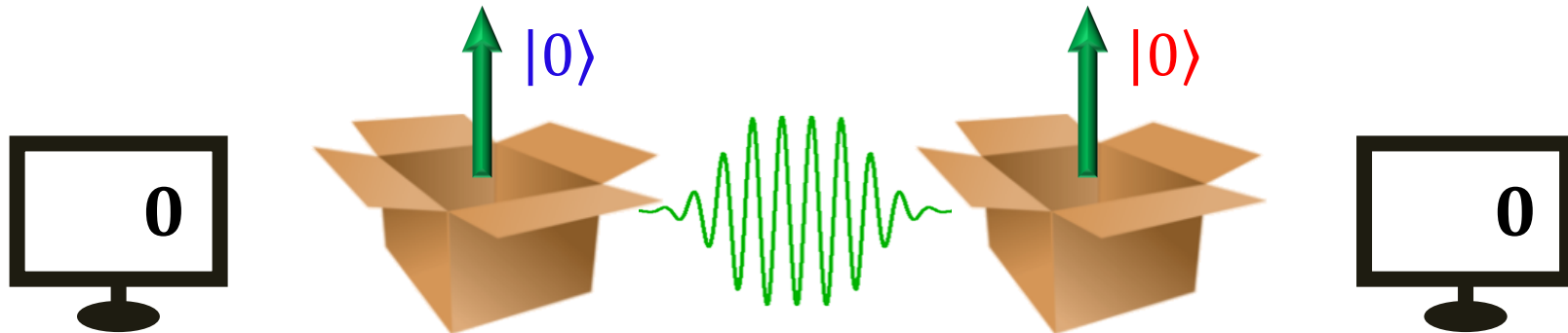
$|1\rangle|1\rangle$

$|0\rangle|1\rangle$

$|1\rangle|0\rangle$

Qubit 1: ? $|0\rangle|0\rangle$

Qubit 2: ?



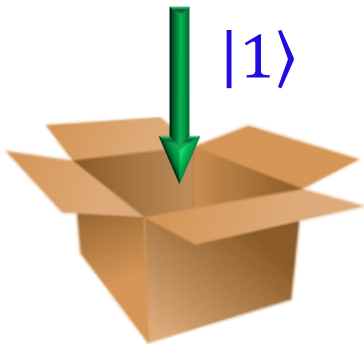
A Weird State

Full: $|0\rangle|0\rangle + |1\rangle|1\rangle$

+ $|0\rangle|1\rangle + |1\rangle|0\rangle$

= $(|0\rangle + |1\rangle)(|0\rangle + |1\rangle)$

Bell: $|0\rangle|0\rangle + |1\rangle|1\rangle$



Qubit 1: ? $|0\rangle + |1\rangle$

Qubit 2: ? $|0\rangle + |1\rangle$

0 0

1 1

0 1

1 0

Qubit 1: ?

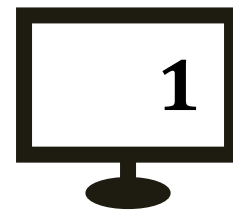
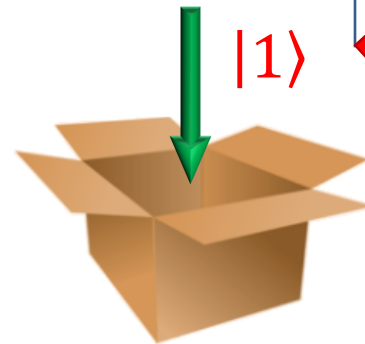
0 0

1 1

Qubit 2: ?

~~0 1~~

~~1 0~~



A Weird State

Full: $|0\rangle|0\rangle + |1\rangle|1\rangle$

+ $|0\rangle|1\rangle + |1\rangle|0\rangle$

= $(|0\rangle + |1\rangle)(|0\rangle + |1\rangle)$

Bell: $|0\rangle|0\rangle + |1\rangle|1\rangle$

Qubit 1: ? $|0\rangle + |1\rangle$

Qubit 2: ? $|0\rangle + |1\rangle$

0 0

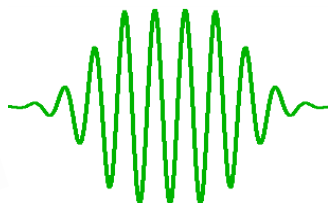
1 1

0 1

1 0

Qubit 1: ?

Qubit 2: ?



A Weird State

Full: $|0\rangle|0\rangle + |1\rangle|1\rangle$

+ $|0\rangle|1\rangle + |1\rangle|0\rangle$

= $(|0\rangle + |1\rangle)(|0\rangle + |1\rangle)$

Bell: $|0\rangle|0\rangle + |1\rangle|1\rangle$

Qubit 1: ? $|0\rangle + |1\rangle$

Qubit 2: ? $|0\rangle + |1\rangle$

0 0

1 1

0 1

1 0

Qubit 1: ?

Qubit 2: ?



Opposite ends of Milky Way



A Weird State

$$\text{Full: } |0\rangle|0\rangle + |1\rangle|1\rangle \\ + |0\rangle|1\rangle + |1\rangle|0\rangle$$

$$= (|0\rangle + |1\rangle)(|0\rangle + |1\rangle)$$

$$\text{Bell: } |0\rangle|0\rangle + |1\rangle|1\rangle$$

Entangled

Qubit 1: ? $|0\rangle + |1\rangle$

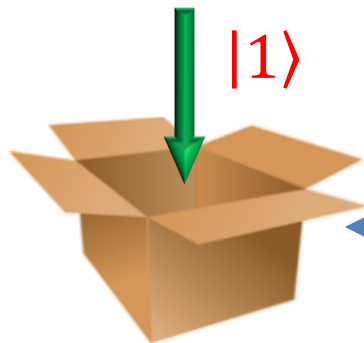
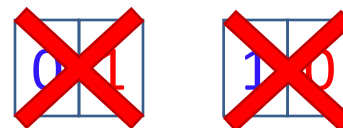
Qubit 2: ? $|0\rangle + |1\rangle$



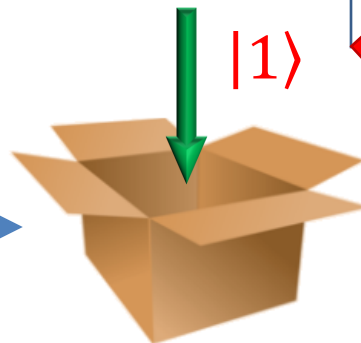
Qubit 1: ?



Qubit 2: ?



Opposite ends of Milky Way



Spooky action at a distance

Quantum Properties

Superposition



Entanglement

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

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

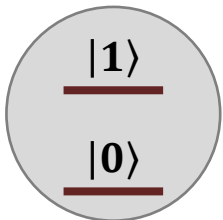


Clever algorithms

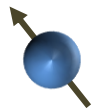


Quantum advantage

Basic Requirements

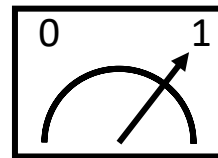


Quantum two
level systems

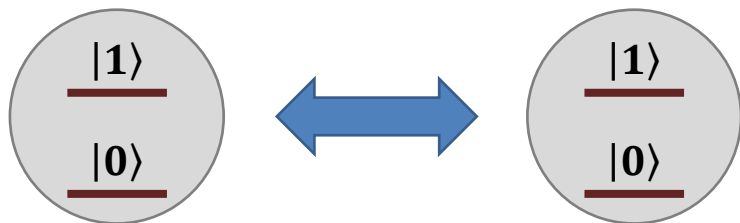


$$\alpha|0\rangle + \beta|1\rangle$$

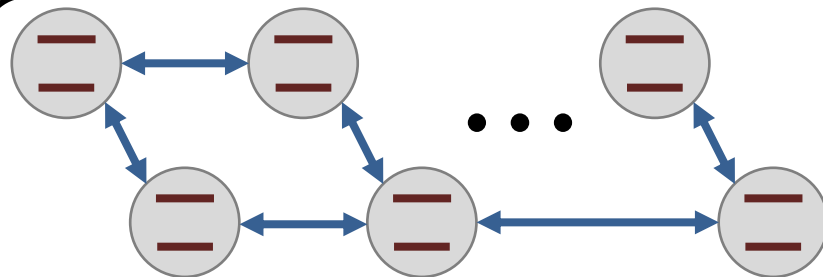
Create arbitrary
states



Measure
quantum states



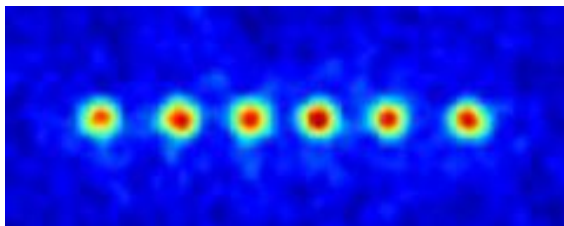
Couple multiple qubits



Scalable architecture

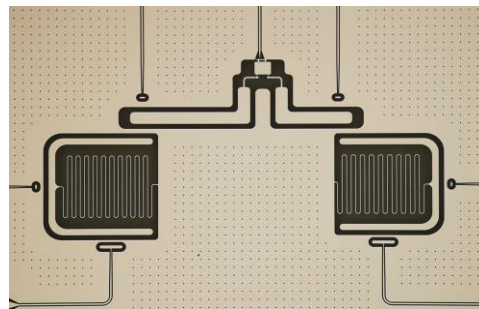
Different Platforms

Ion trap



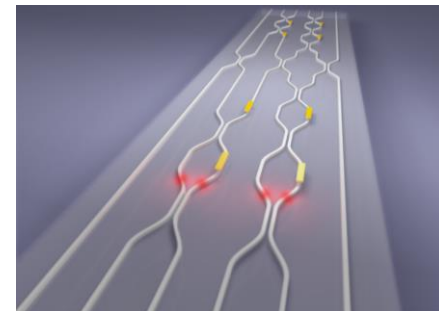
quantumoptics.at

Superconducting qubits



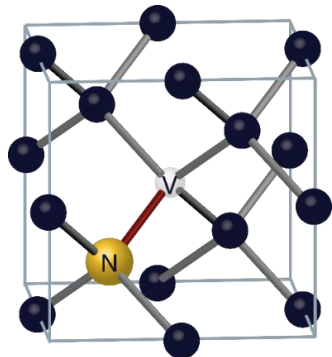
Schuster lab

Photonic crystals



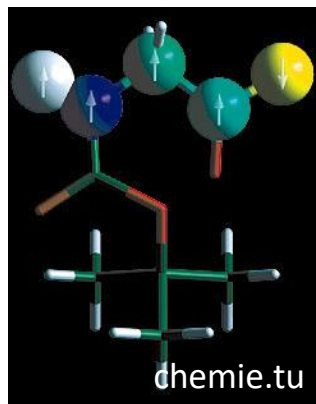
phys.org

NV centers



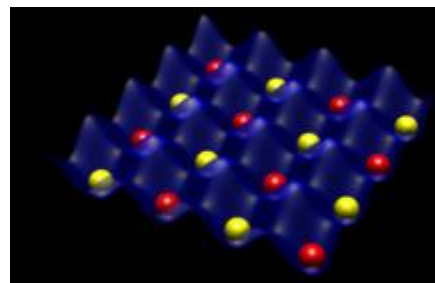
phys.org

NMR



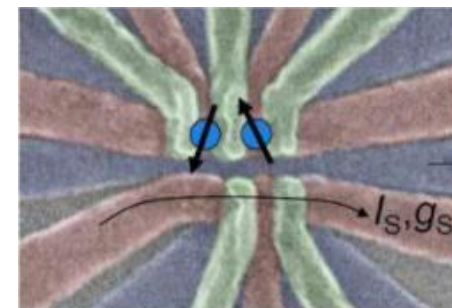
chemie.tu

Neutral atoms



NIST

Quantum dots



sciencemag.org

Superconductor



Normal conductor

- Generates heat
- Energy is lost



Superconductor

- No resistance
- Energy is not lost

Make electrical circuits using superconductor

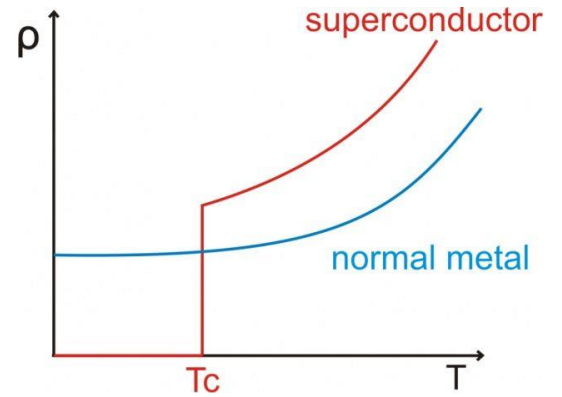
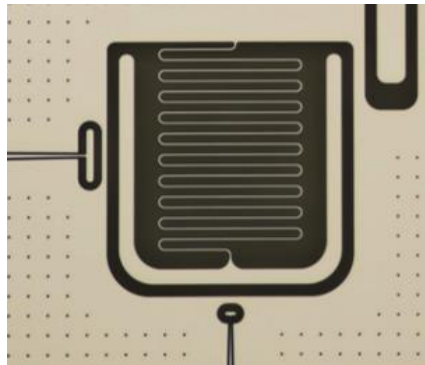


Image: bitlanders.com

The Circuits



Inductors and capacitors



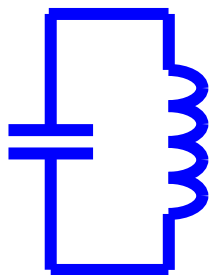
~5 GHz



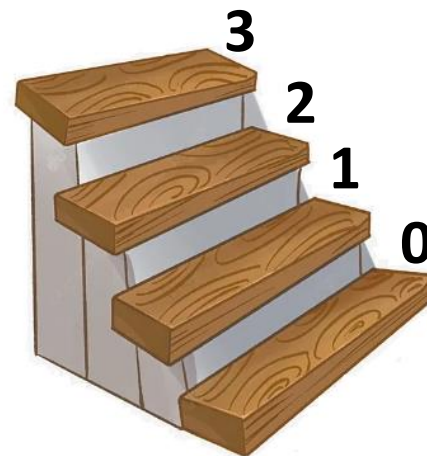
Energy is discrete



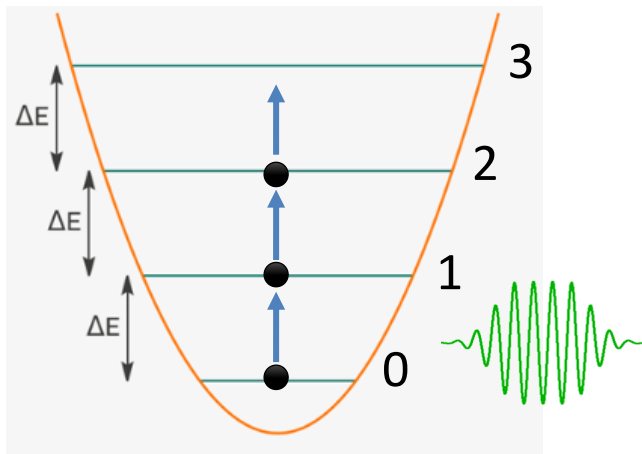
~100 MHz



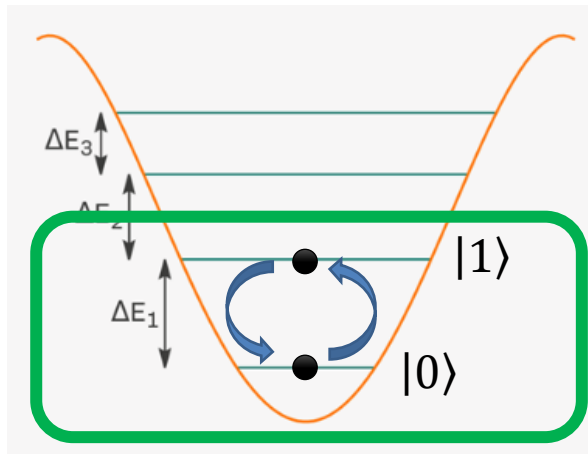
Resonator



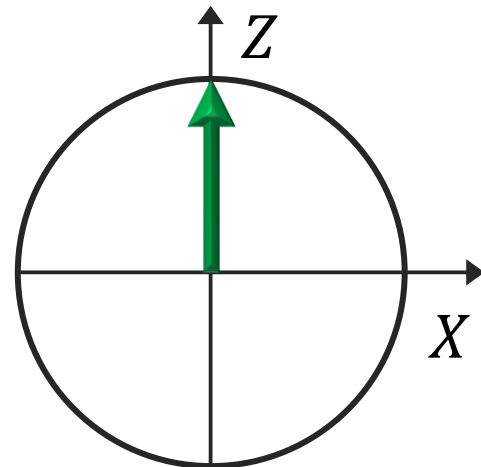
Accessing Two Levels



Harmonic Oscillator

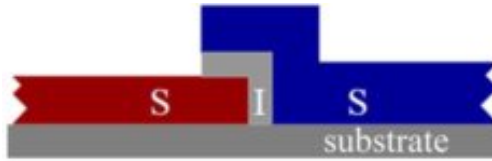


Anharmonic Oscillator



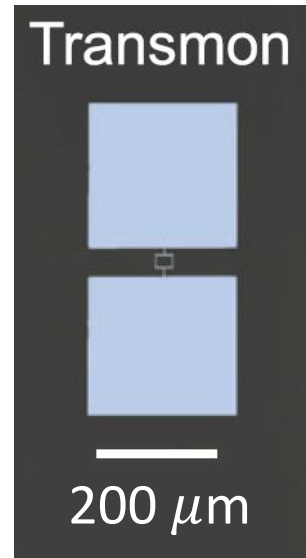
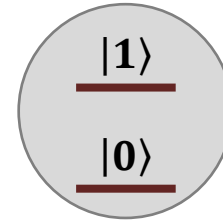
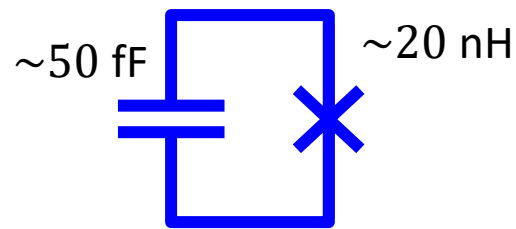
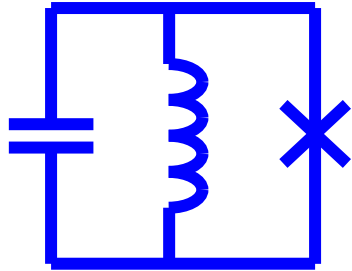
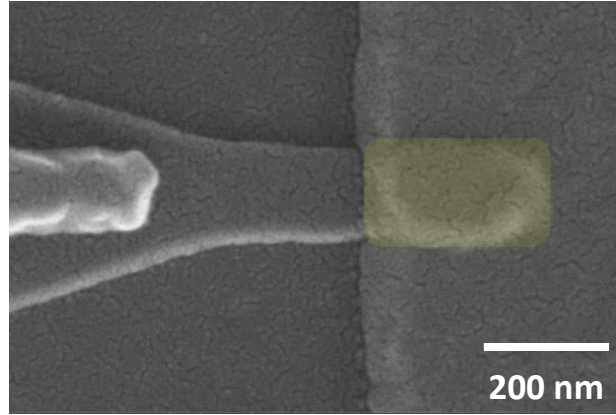
Nonlinear lossless element

Superconducting Qubits

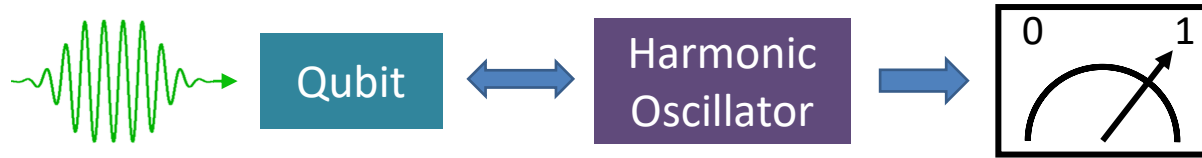


Josephson Junction

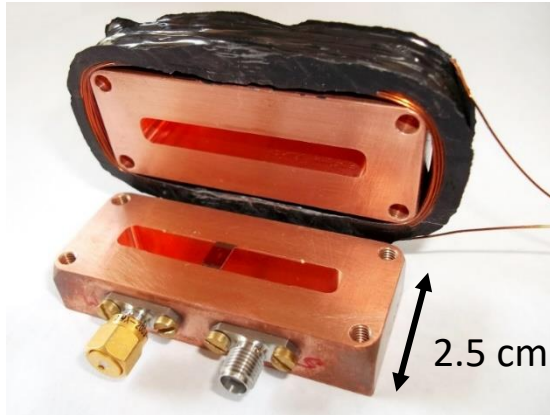
Lossless nonlinear inductor



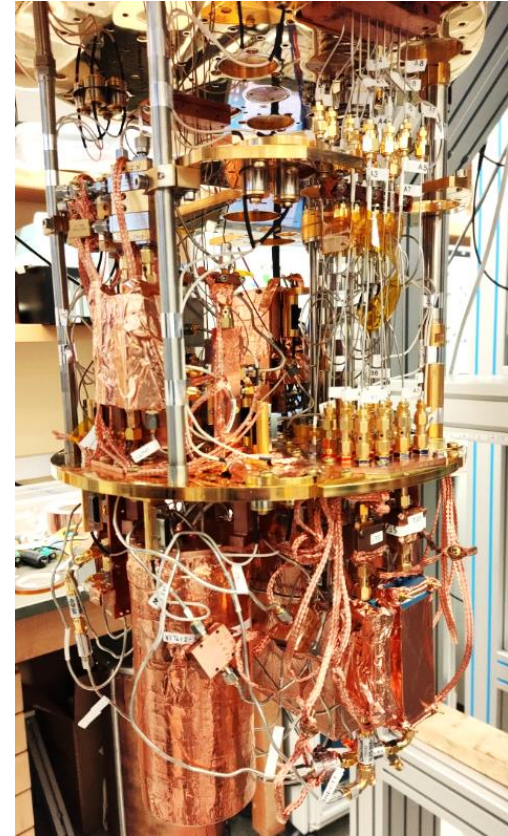
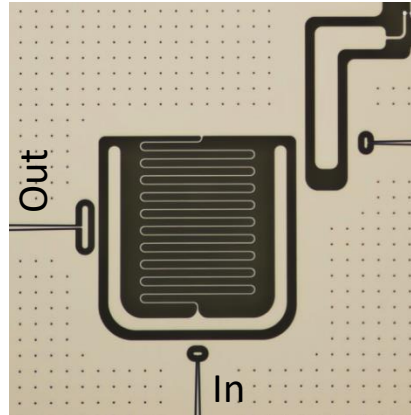
Control and Measurement



3D

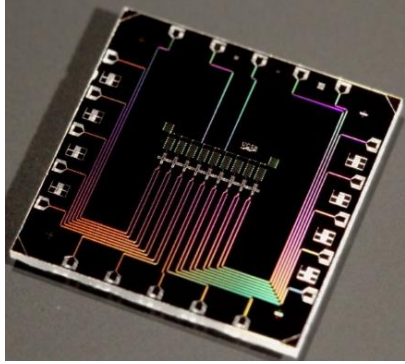


2D

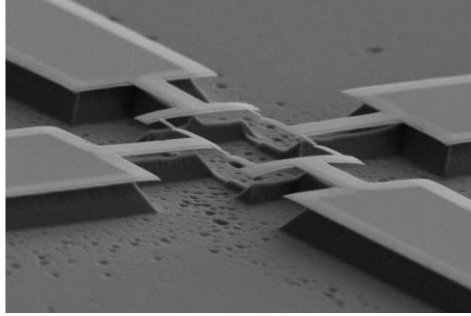


Dilution fridge ~ 20 mK

Multiqubit System



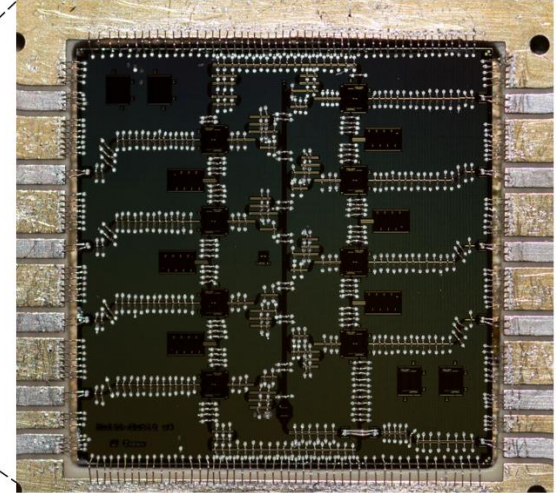
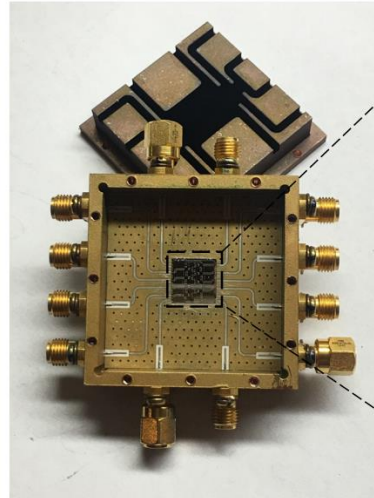
UCSB / Google: 9 qubits



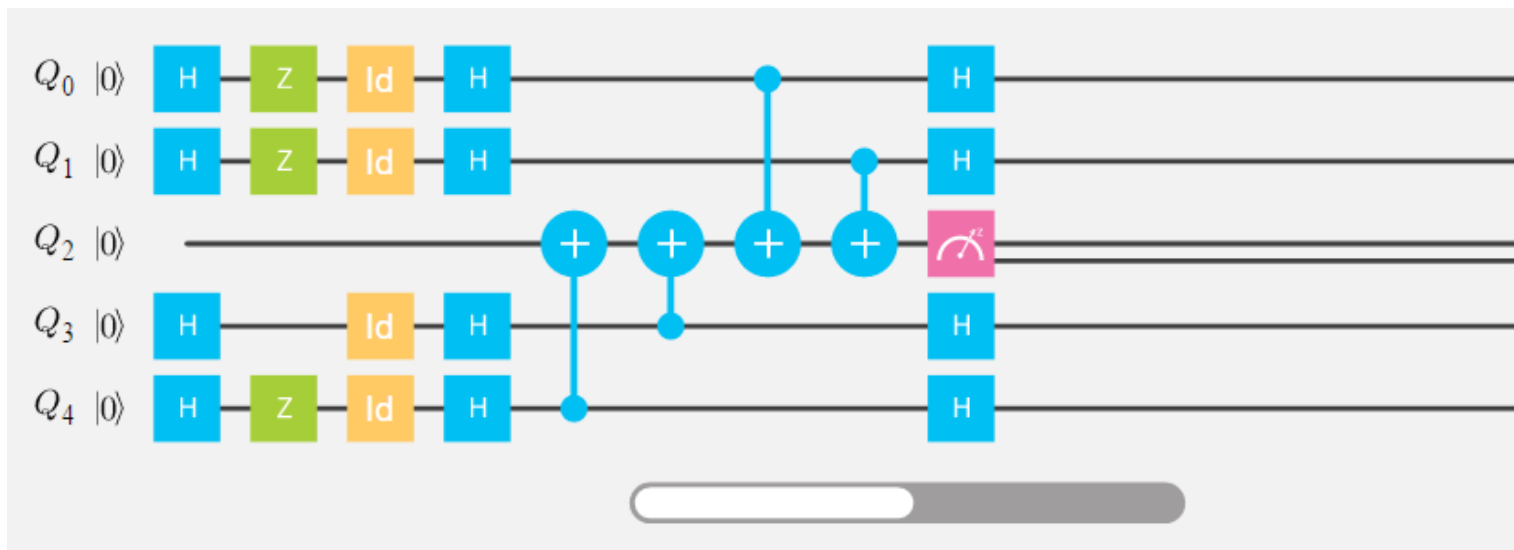
TIFR: 3 qubits



Pan group: 10 qubits



Quantum Circuit



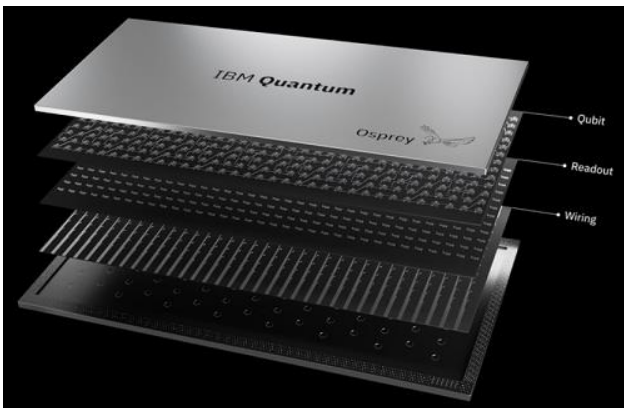
GATES



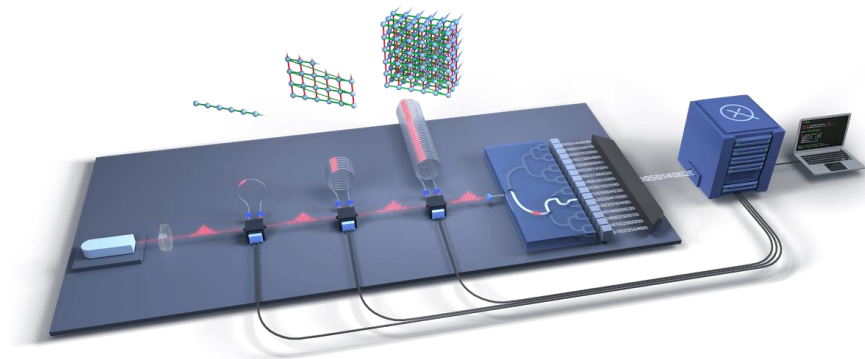
MEASURE



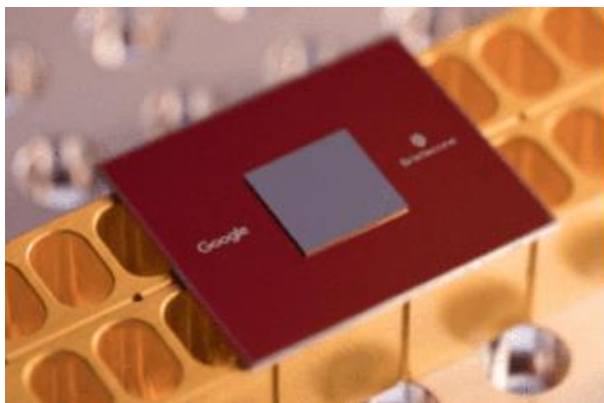
State-of-the-art Processors



IBM: 433 qubits (2022)



Xanadu: 216 qubits (2022)



Google: 72 qubits (2018)

Challenges

Qubits are error-prone

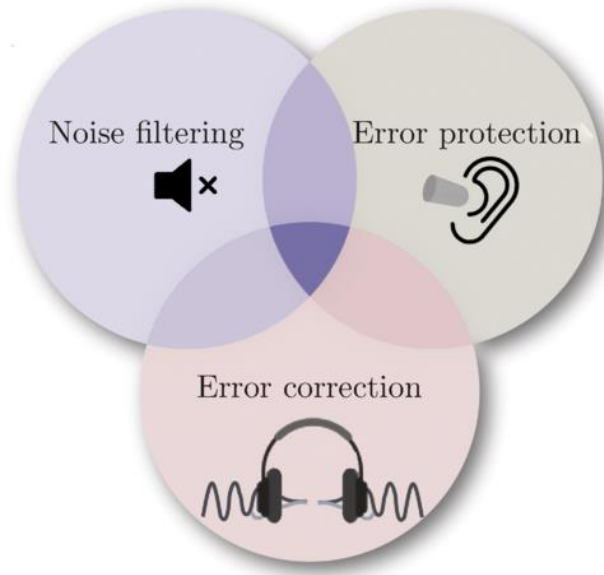


Image: PRX Quantum 2, 030101

Fabrication and control become difficult

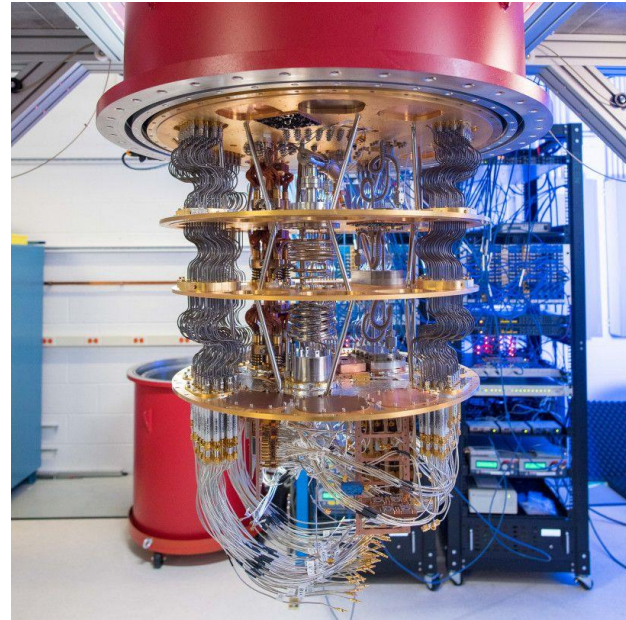


Image: Google

Take Home Message

Superposition

Entanglement

Quantum Algorithms

Few Prototypes

