Beyond Bits: Exploring the Quantum Realm and its Promises

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Student Seminar

11th December 2023

Outline

- Why do we need quantum computers?
- Quantum Computer for Material Scientists
- Classical Computer vs Quantum Computer
- Qubits and Quantum Gates
- Superposition, Interference, and Entanglement
- Superconducting Qubit
- Material Platforms for Qubit
- Other Quantum Technology
- Challenges

Why do we need Quantum Computing?

Multiplication

7177 X 3001

↓

21538177

Efficient Classical Algorithm

Factorization

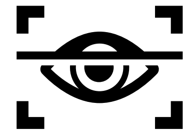
21538177

↓

7177 X 3001

No Efficient Classical Algorithm!

Encryption



RSA-617

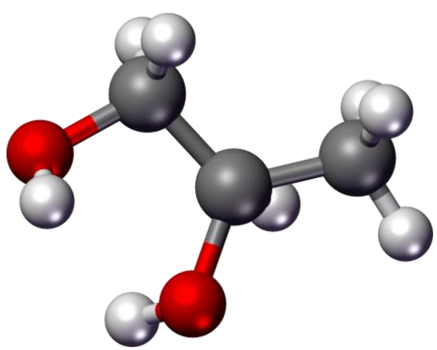
Shor's Algorithm (Quantum Algorithm)

20 million qubits — 1 day time → Factorize 617-digit RSA number

IBM : 1000 qubit chip (4th Dec 2023)

RSA-250 → product of two 125-digit prime numbers (2700 core-year)

Quantum Simulation



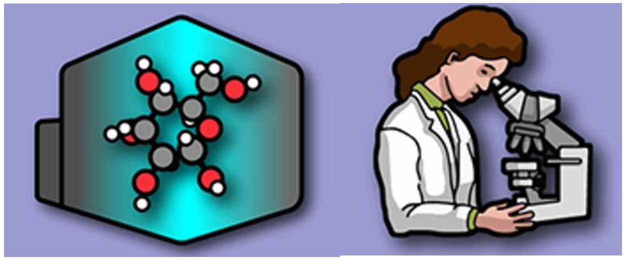
Optimization Problems

Financial Modelling

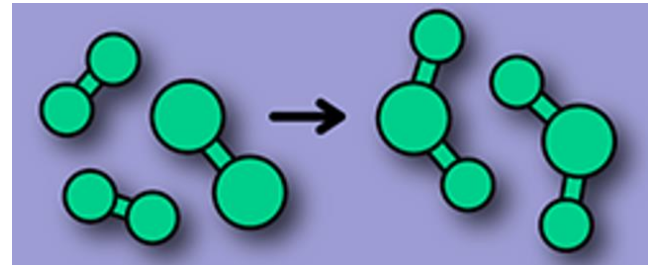
SciTech Daily, SIAM J.Sci.Statist.Comput. 26 (1997), Castelvecchi D., Nature.

Quantum Computer for Material Scientists

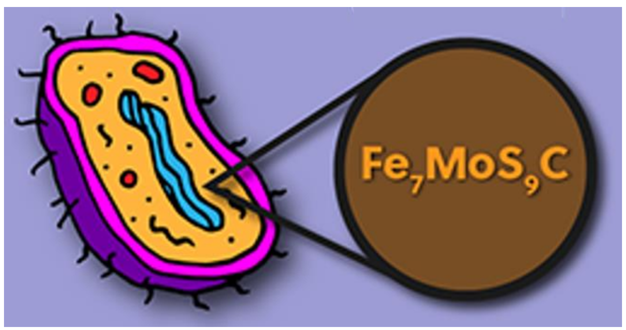
Rapid Prototyping



Chemical Reaction



Better Catalyst



Drug Development

Materials for Aerospace

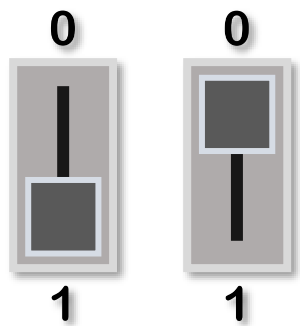
Improved Battery

Map of Quantum Computing, Phys. Rev. A. 106.032428(2022)

Classical vs Quantum Computer

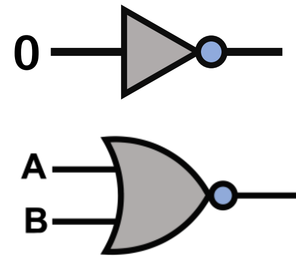
Classical

BITS



Bits are independent

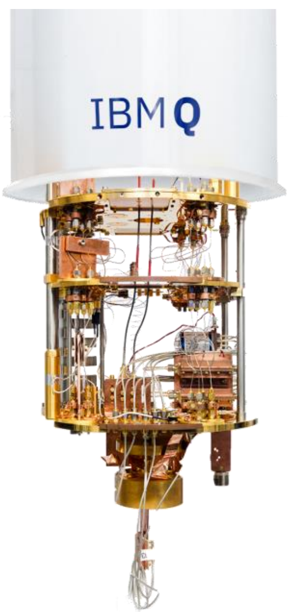
Classical Gates



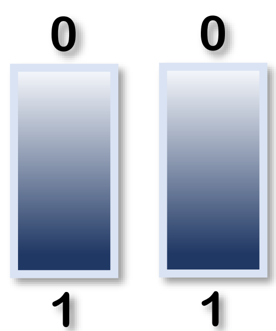
A	B	Out
0	0	1
0	1	0
1	0	0
1	1	0

One state at a time

Quantum

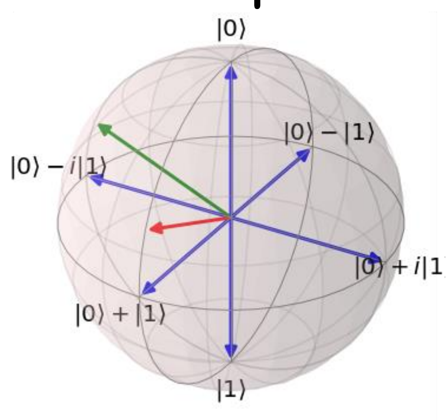


QUBITS

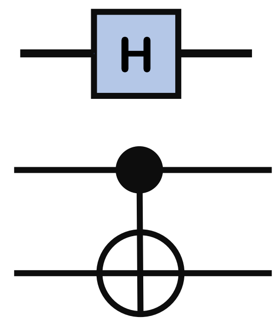


Qubits may not be independent

Bloch Sphere



Quantum Gates



Many States at a time

Image Credit: pngarts, qiskit, IBM Research

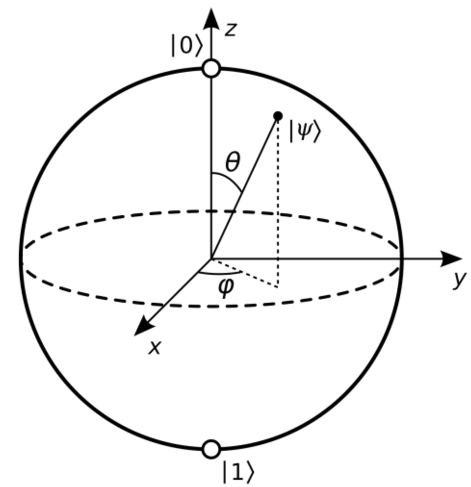
Qubit and Quantum Gate

Quantum Bit: a point in the Bloch sphere

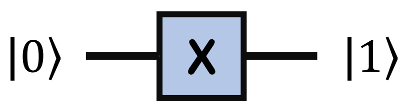
$$|0\rangle = \begin{pmatrix}1\\0\end{pmatrix},\quad |1\rangle = \begin{pmatrix}0\\1\end{pmatrix},\qquad |\psi\rangle = \alpha|0\rangle + \beta|1\rangle;\ \alpha,\beta \in C$$

$$|\psi\rangle = cos\frac{\theta}{2}|0\rangle + e^{i\phi}sin\frac{\theta}{2}|1\rangle,\quad \langle\psi|\psi\rangle = 1$$

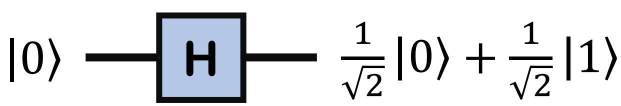
$$|00\rangle = |0\rangle \otimes |0\rangle = \begin{pmatrix}1\begin{pmatrix}1\\0\end{pmatrix}\\0\begin{pmatrix}1\\0\end{pmatrix}\end{pmatrix} = \begin{pmatrix}1\\0\\0\\0\end{pmatrix},\quad |01\rangle = \begin{pmatrix}0\\1\\0\\0\end{pmatrix}, \ldots$$



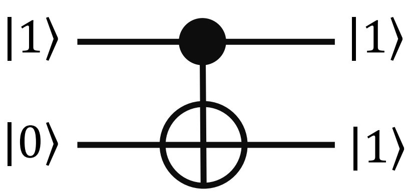
Quantum Gate: Rotation in the Bloch sphere



$$X = \begin{pmatrix}0 & 1\\1 & 0\end{pmatrix}$$

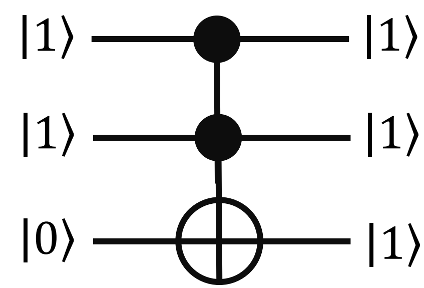


$$H = \frac{1}{\sqrt{2}}\begin{pmatrix}1 & 0\\0 & 1\end{pmatrix}$$



CNOT

$$CNOT = \begin{pmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 0 & 1\\0 & 0 & 1 & 0\end{pmatrix}$$



Toffoli Gate

↓

Universal Quantum Gate!

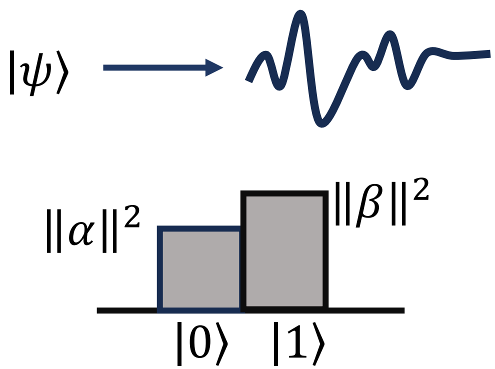
Qiskit Textbook

Superposition, Interference and Entanglement

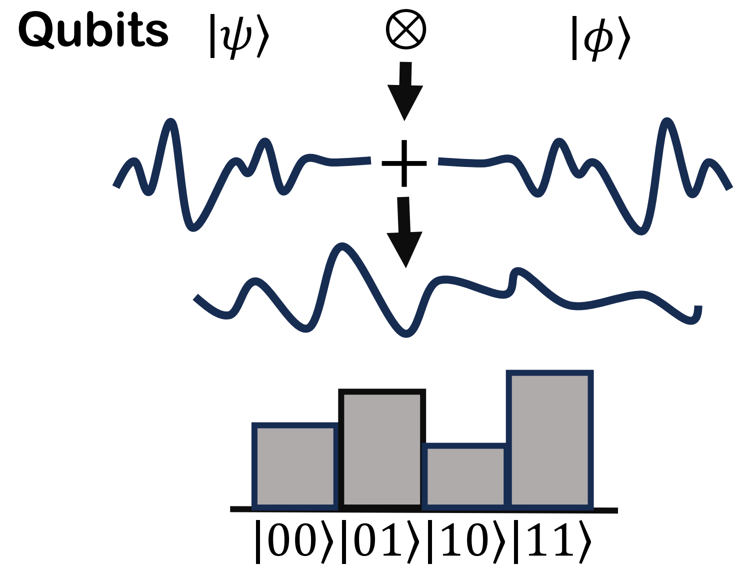
Superposition

Qubit

$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle;\ \alpha, \beta \in C$



Interference



Entanglement

Independent Qubit

$|\psi\rangle \otimes |\phi\rangle = |\Psi\rangle$

$|\psi\rangle \otimes |\phi\rangle = a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle$

Measurement

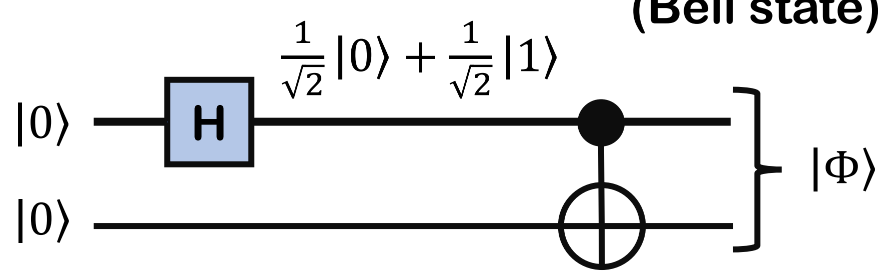
If 1st Qubit is in $|0\rangle$ state, then

2nd Qubit : $\frac{1}{\sqrt{\|a\|^2+\|b\|^2}}(a|0\rangle + b|1\rangle) = |\phi\rangle$

Entangled Qubits: No direct product

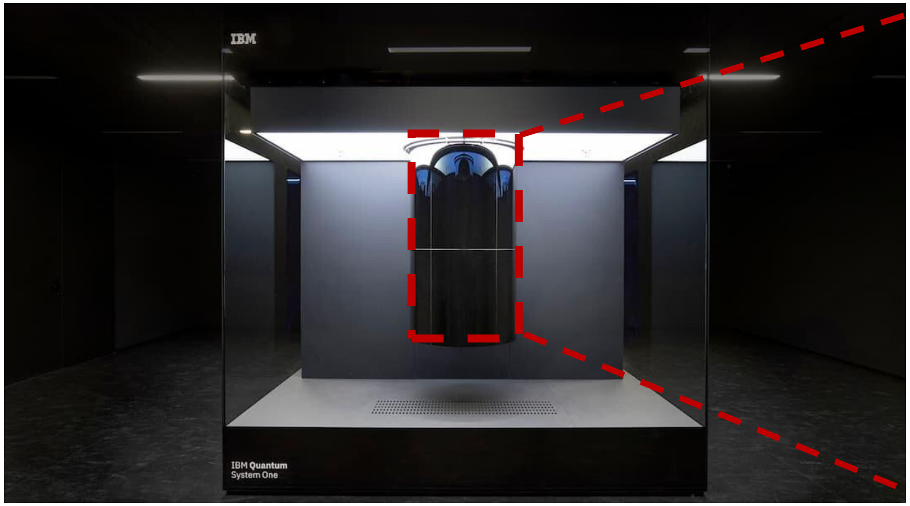
$$|\Phi\rangle = \frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|11\rangle \neq |\psi\rangle \otimes |\phi\rangle$$

(Bell state)

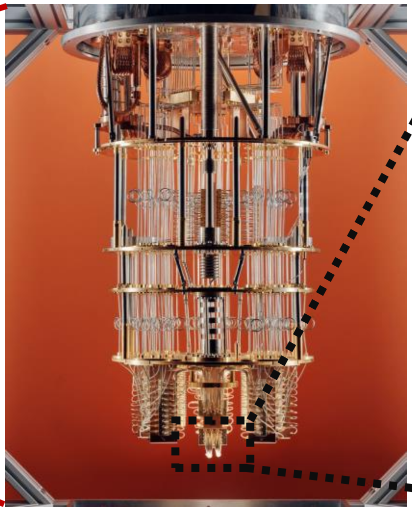


Qiskit Textbook

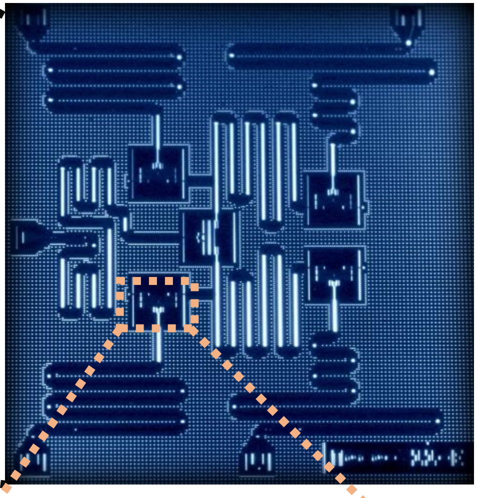
Superconducting Quantum Computer



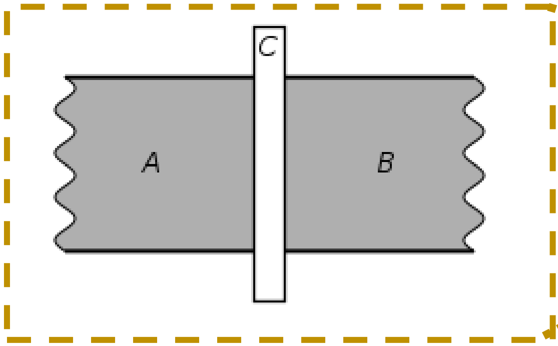
IBM Quantum System One

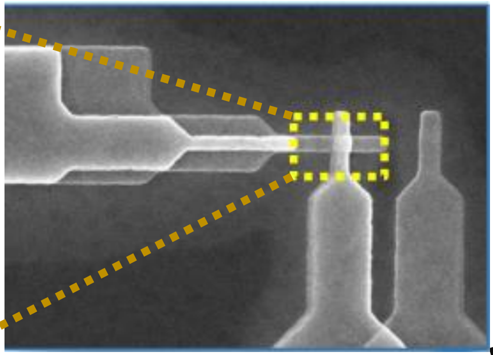


Cryostat

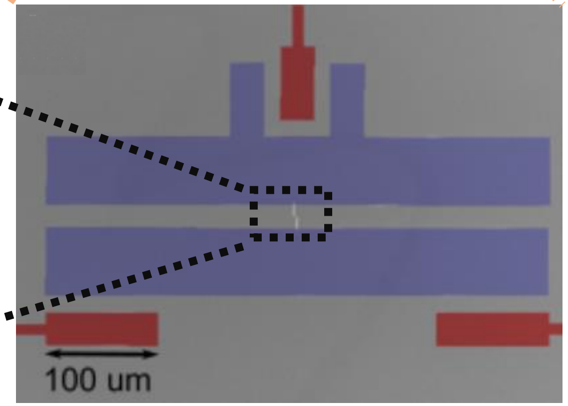


Chip





Josephson Junction

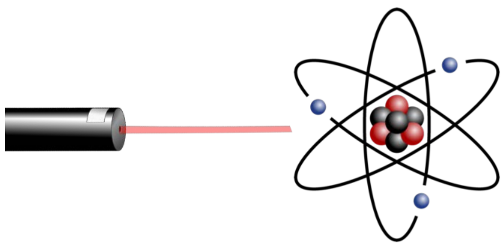


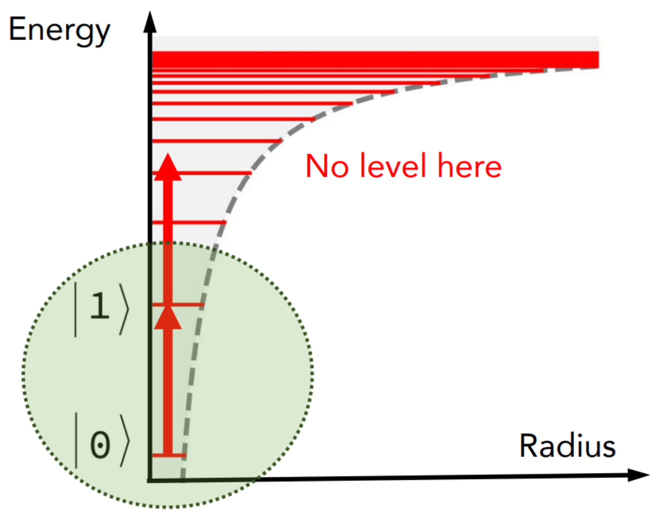
Transmon Qubit

Image Credit: IBM Research

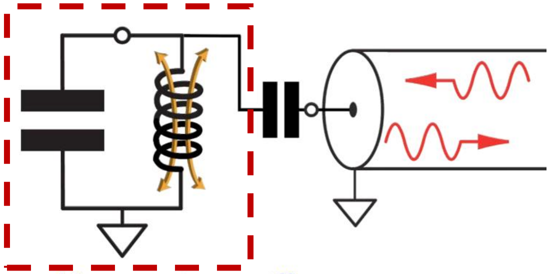
Natural to Artificial Atom

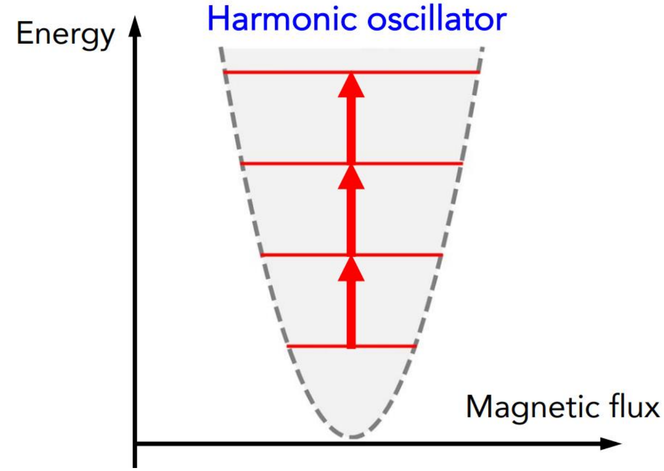
- Requirement for qubit
  - Two-level system
  - Isolated from the environment
  - Mechanism to read and control
  - Anharmonic energy level

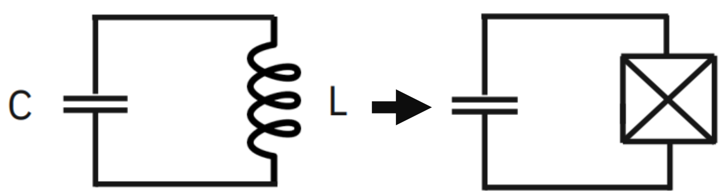




Harmonic LC circuit



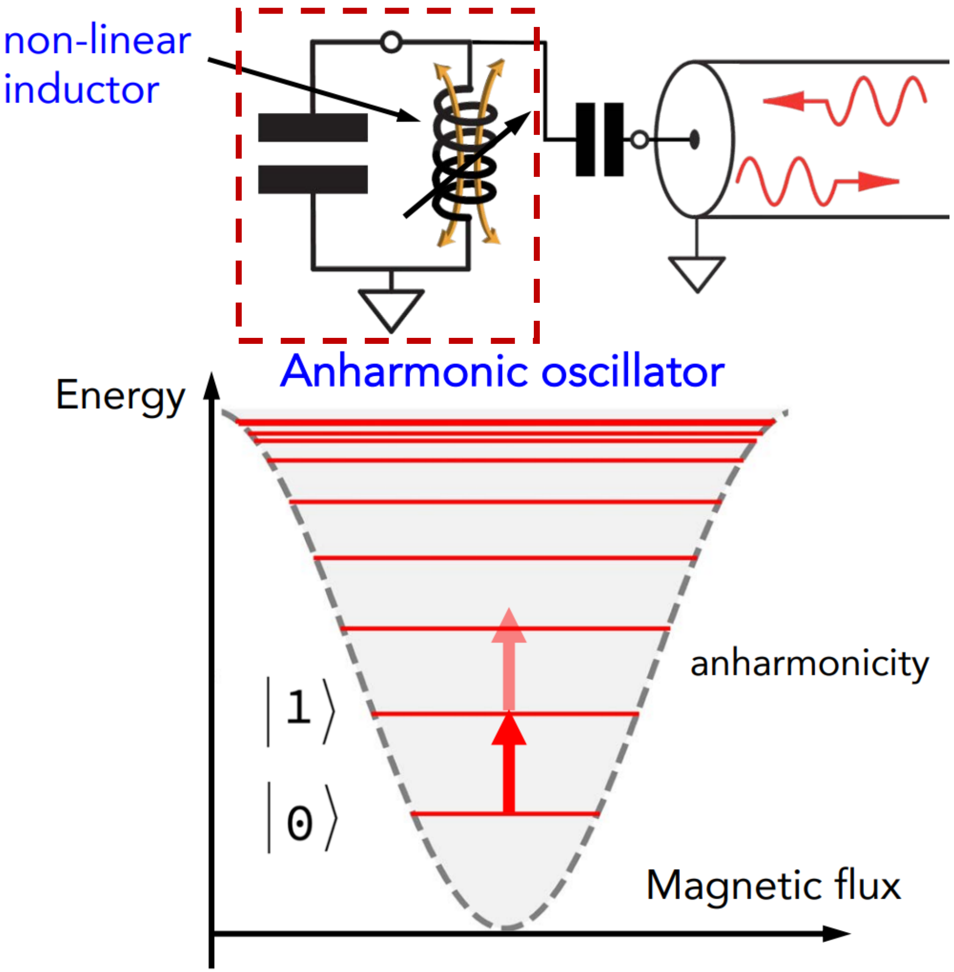




Josephson Junction (Nonlinear Inductor)

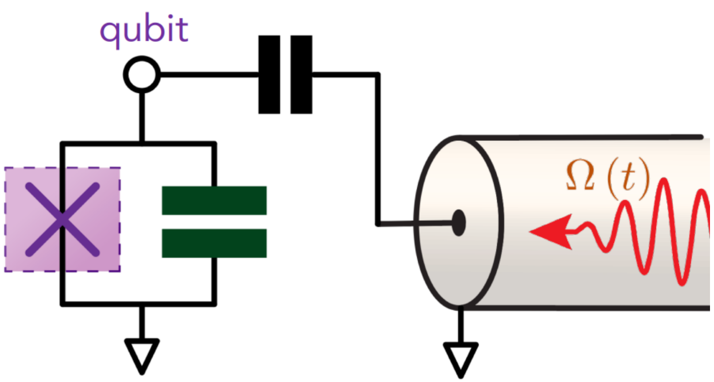
Qiskit Global Summer School, arXiv:1904.06560v5.

Transmon Qubit

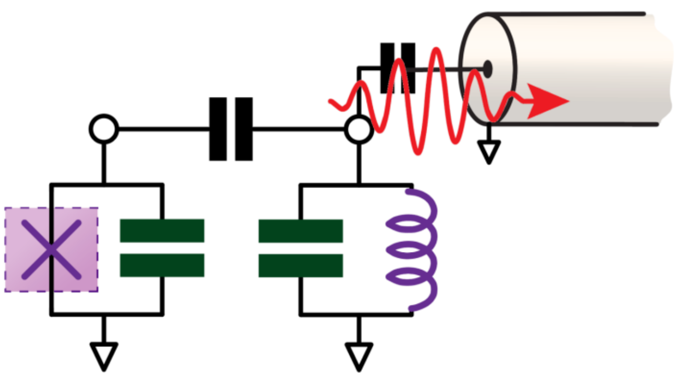


Qubit Control and Measurement

Demolition



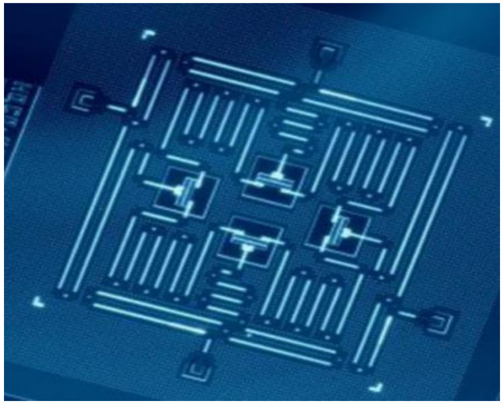
Non-Demolition



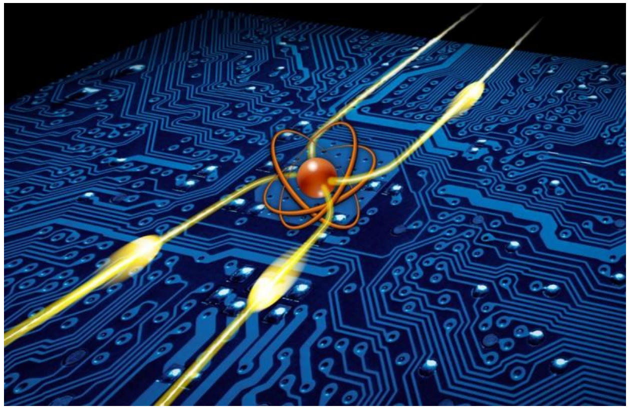
Qiskit Global Summer School, arXiv:1904.06560v5.

Material Platforms for Qubit

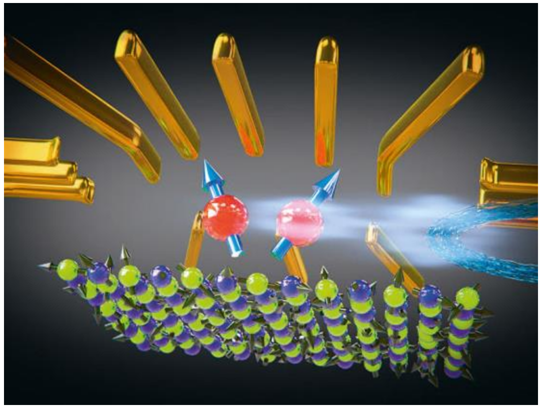
Superconducting Qubit



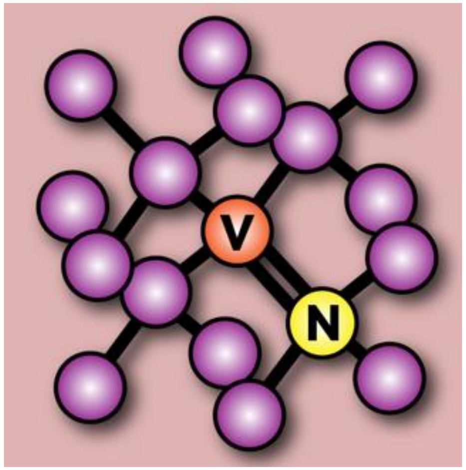
Photonic Qubit



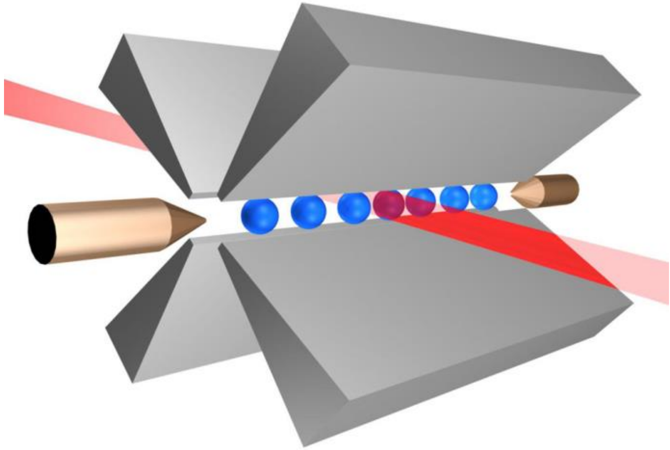
Quantum Dot



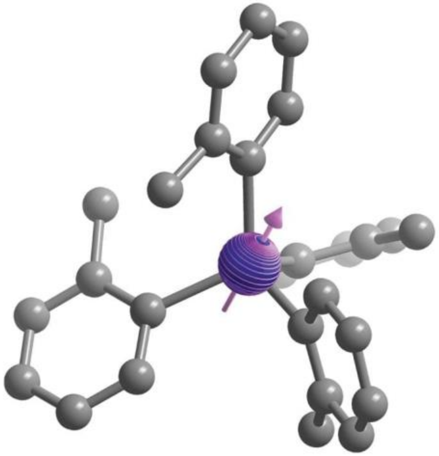
Spin Defect in Solid



Trapped Ion



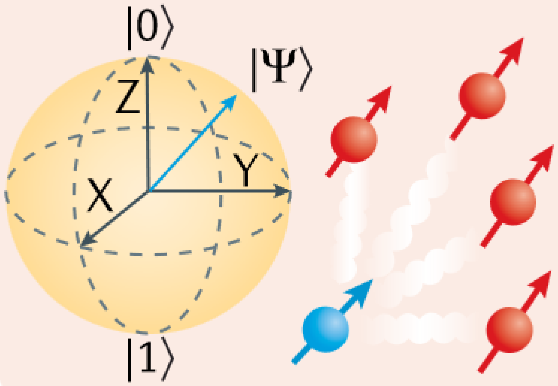
Magnetic Molecule



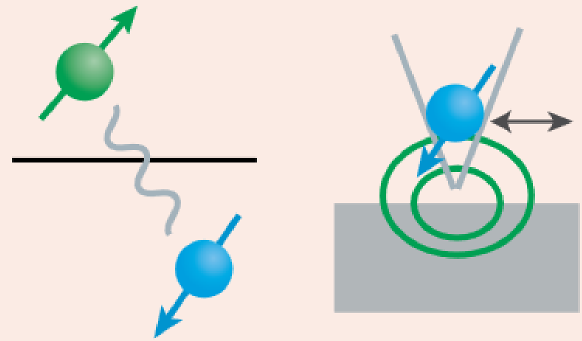
Nature 464.7285 (2010), Science 10.1126 (2023)

More Quantum Technologies

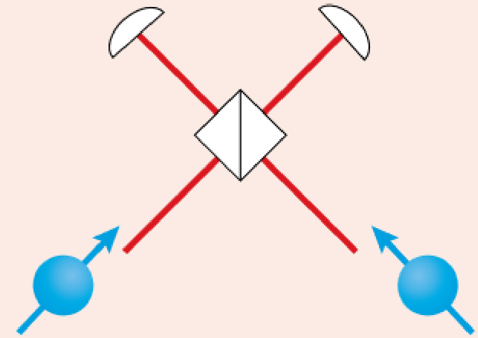
Computing



Sensing

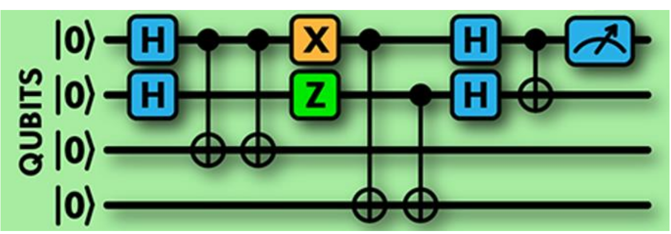


Communication

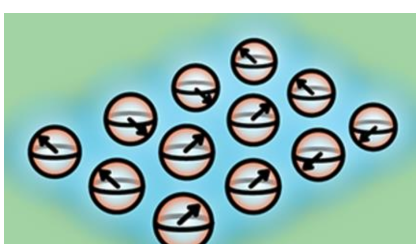


Models of Quantum Computing

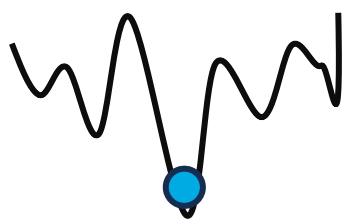
Gate Model

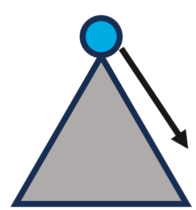


Measurement-Based

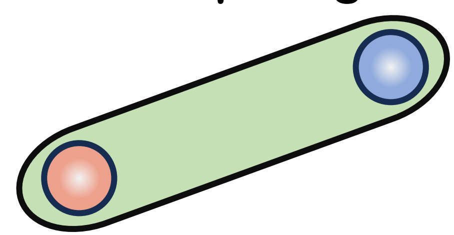


Quantum Annealing (Adiabatic)





Topological Quantum Computing

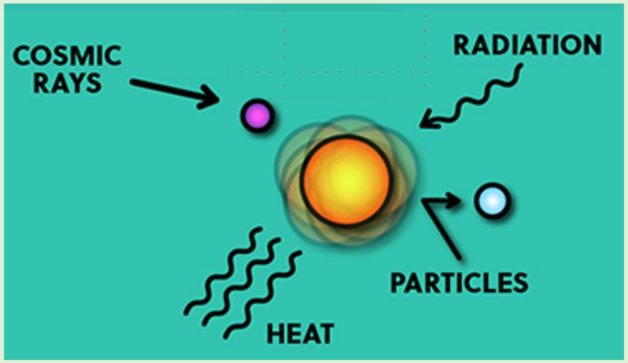


Majorana Zero mode Quasi-particle

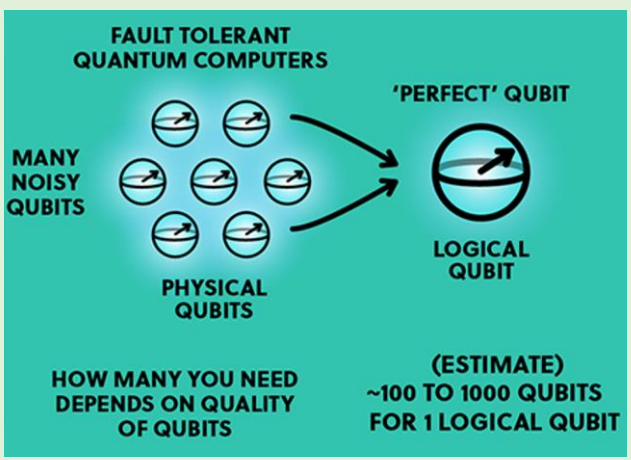
Nat. Rev. Mat. 6.10 (2021), Science 339.6124 (2013)

Challenges

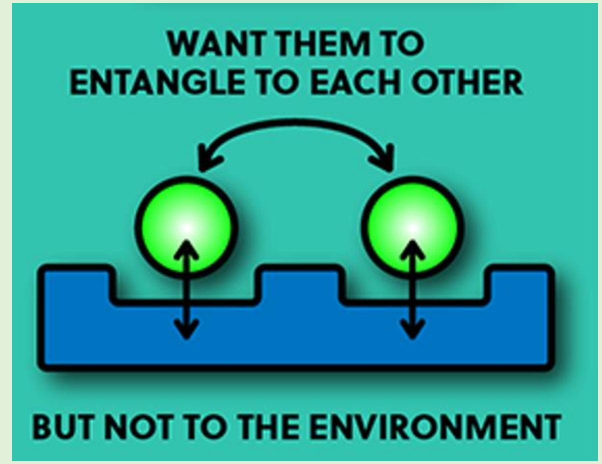
Noise



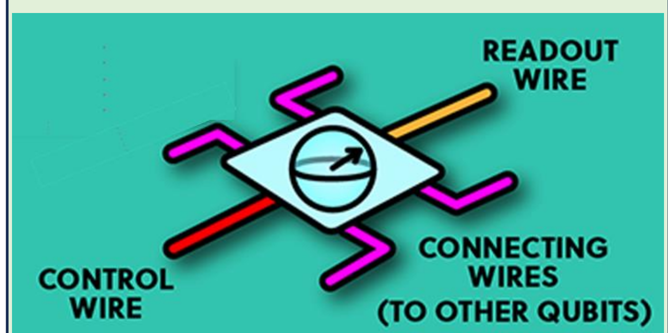
Quantum Error Correction



Decoherence



Scalability



Map of Quantum Computing, Nat. Commun. 13.1 (2022)

Further Learning

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Thank You For Your Attention!!