WELCOME TO TUTORIAL

Janus 2.0: Background of Quantum Computing

ACES Lab
ADVANCED COMPUTING AND EMERGING SERVICE LAB

JanusQ Cloud

浙江大学 计算机科学与技术学院
COLLEGE OF COMPUTER SCIENCE AND TECHNOLOGY
ZHEJIANG UNIVERSITY

https://janusq.github.io/tutorials/

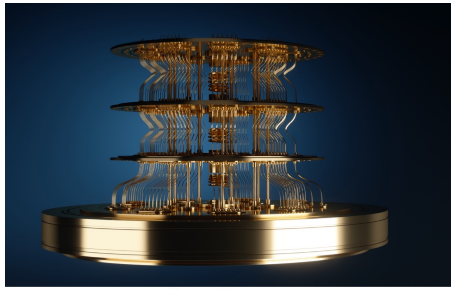
College of Computer Science and Technology,
Zhejiang University

ASPLOS 2024

Background Knowledge

Development of Classical Computing

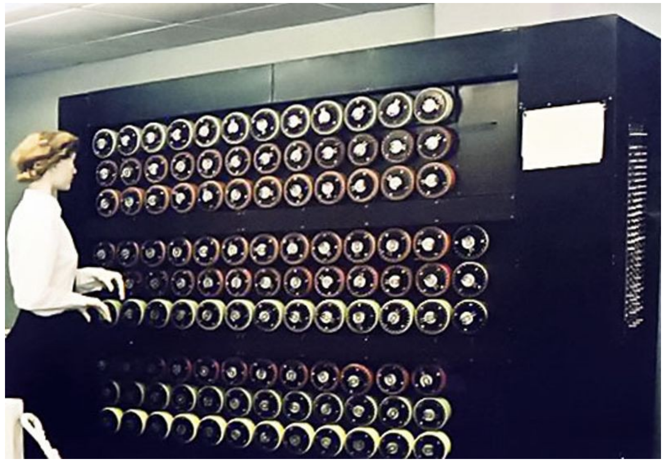
Motivation of Quantum Computing



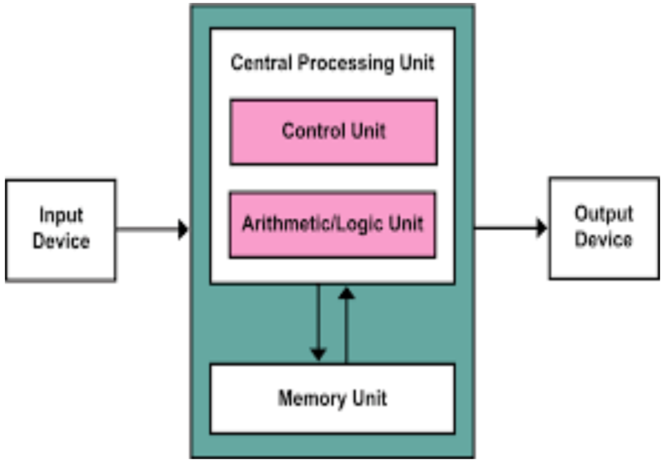
Development of Quantum Computing

Development Of Classical Computing

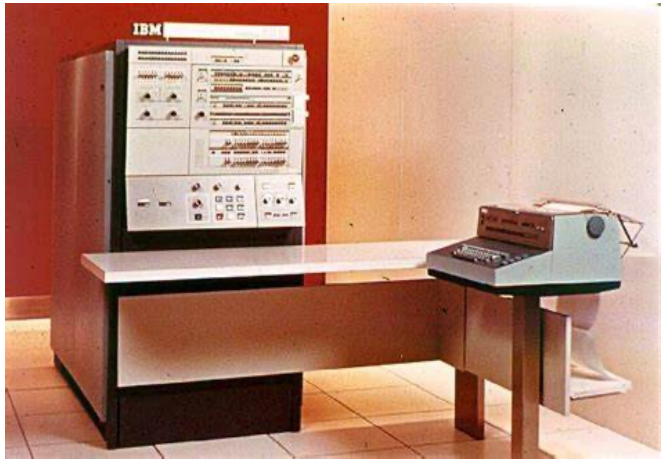
Domain-specific calculator （1939）



Von Neumann architecture (1947)



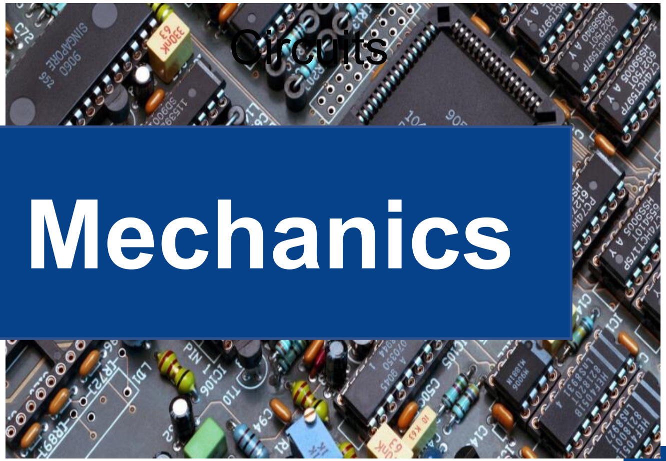
IBM360 Integrated Circuit (1964)



Vacuum Tube Computer ENIAC (1942)

Transistor Computer TRADIC (1954)

Large Scale Integrated Circuits



Macroscopic Effects of Quantum Mechanics

Motivation Of Quantum Computing

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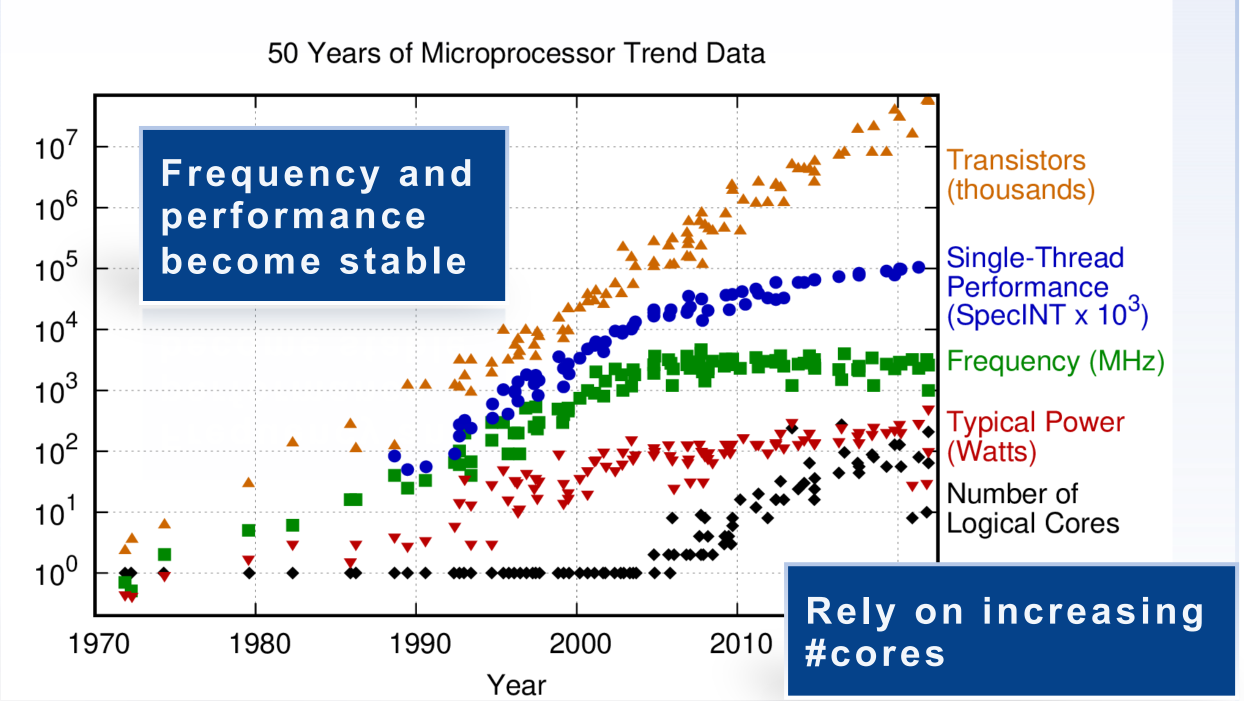
Computation barrier

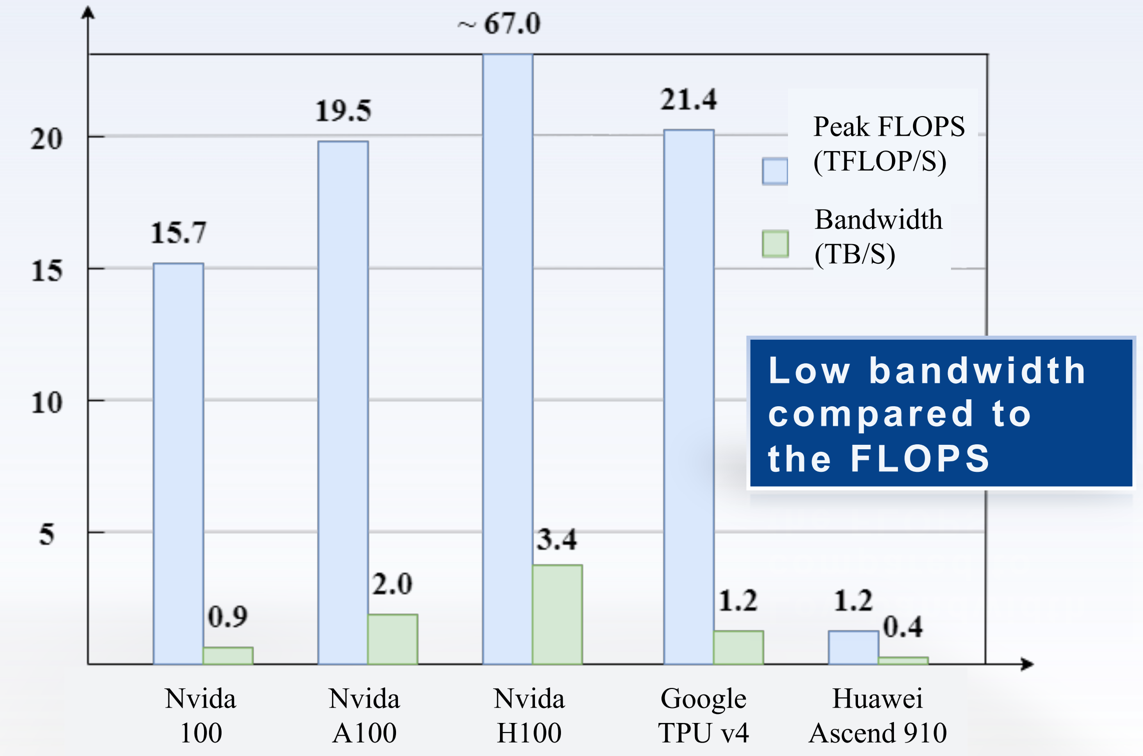


Original dalta up to the year 2010 colecled and plolted by M. Horowitz, F. Labonle, 0. Shacham, K. Olukolun, L. Hammond, and c. BalienNew plot and dala collected for 2010-2021 by K.Rupp

- The research costs and cycles of advanced chip processes are continuously increasing, Moore's Law is approaching obsolescence.
- The computing systems cannot rely solely on the development of traditional single chips. Instead, it requires new chip design methods and computing principles.

Motivation Of Quantum Computing

Storage barrier

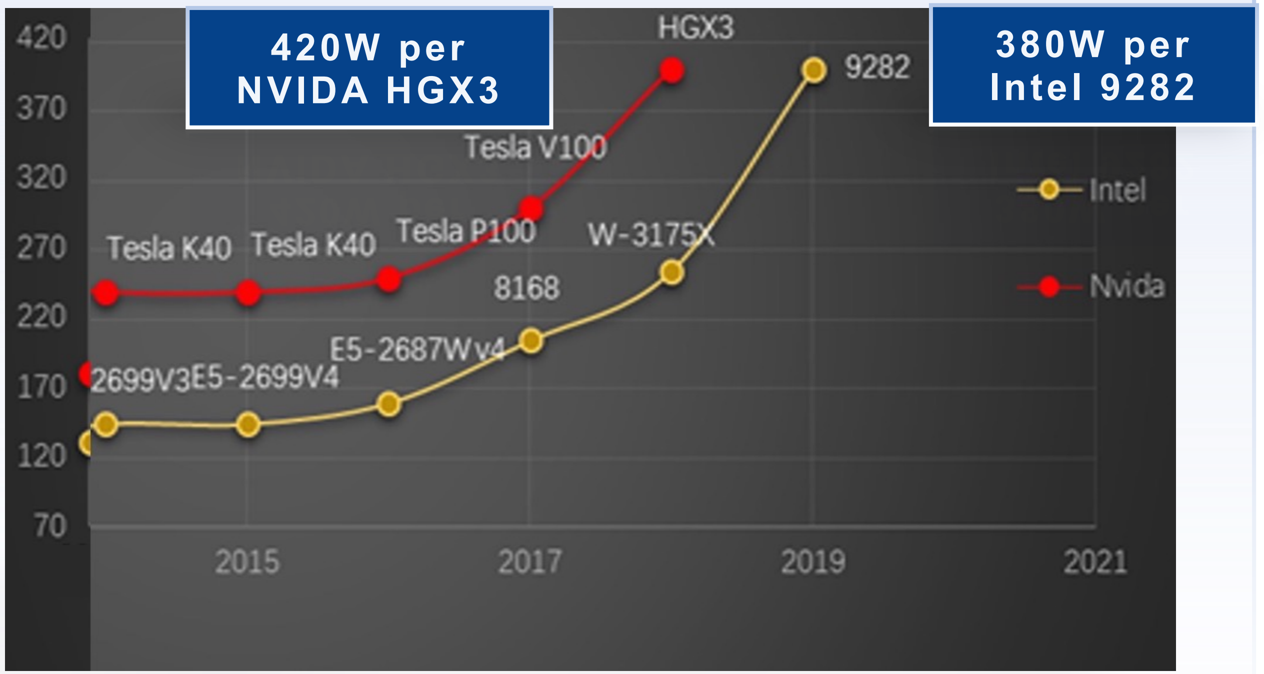


- Computation power and bandwidth is not matched.
- Latency of memory access is high, limiting CPU performance.
- Quantum computing is in memory.
- Non-von Neumann architectures.

Motivation Of Quantum Computing

Power wall

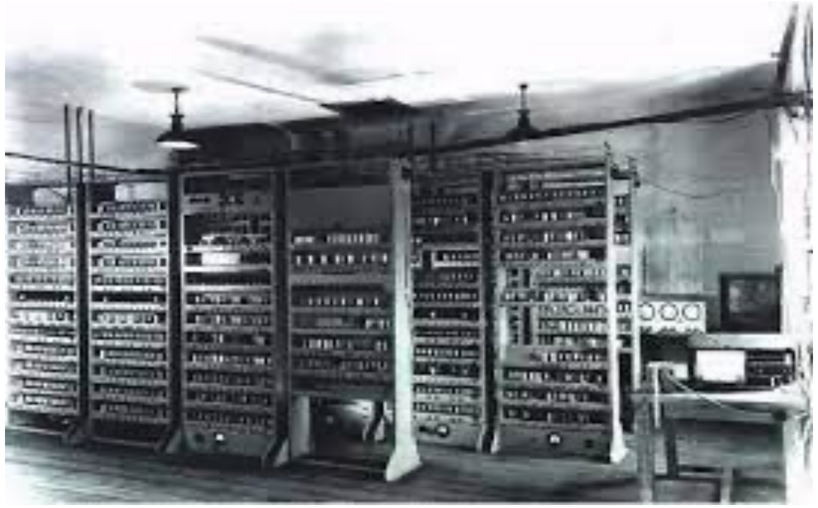
Thermal design power exponentially increases.

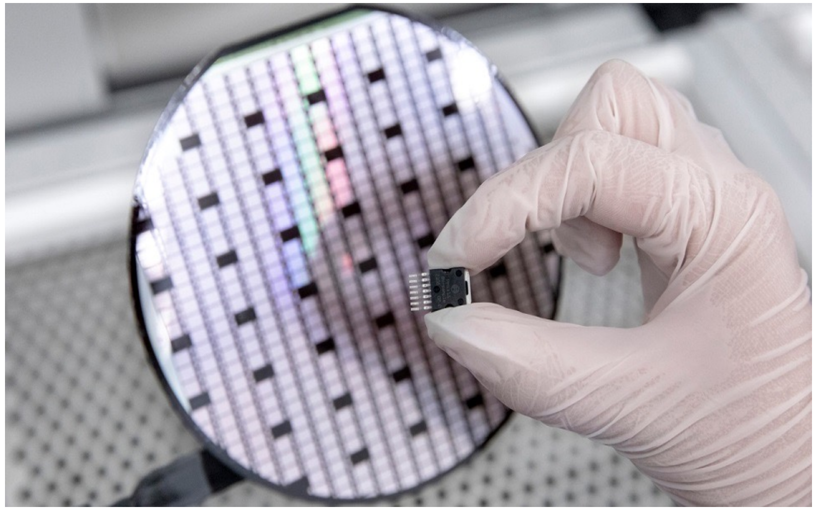


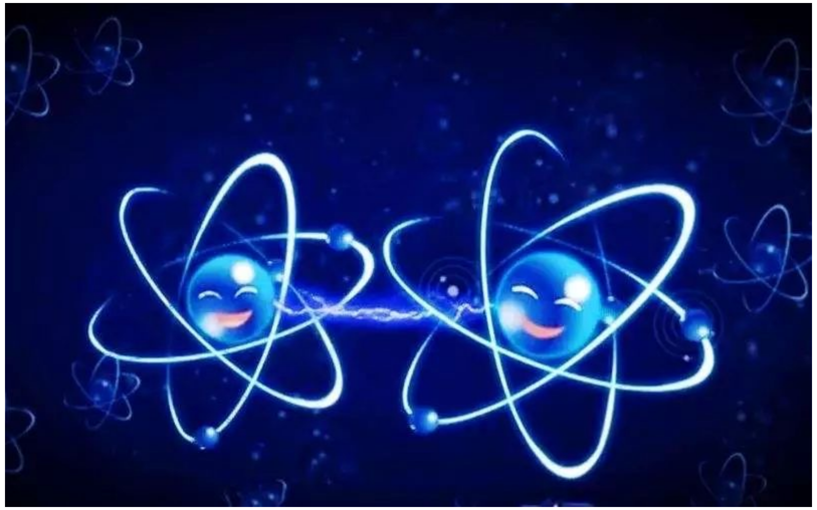
From https://www.blueocean-china.net/faq3/241.html

- The power consumption **increases exponentially** with computing power.
- Energy consumption **restricts** computing power.
- **Systematical resource scheduling** at the architectural level.

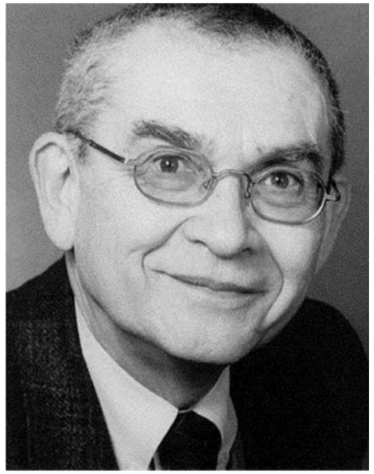
Proposal of Quantum Computing





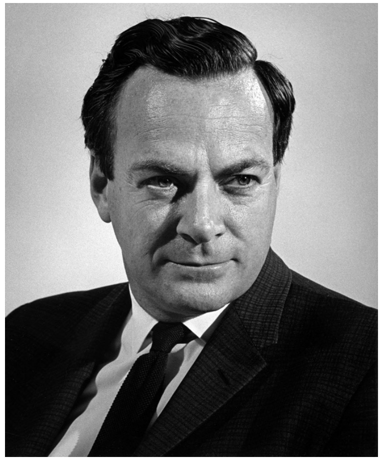


- Classical physics is no longer able to fully describe the underlying physical mechanisms at its core.



Yuri Manin

- Algebraic Geometry
- Discrete Geometry (Diophantine Geometry)
- Manin (1980) and Feynman (1982) were the first to propose the idea of **quantum computing**.



Richard Feynman

- Feynman Path Integral, Feynman Diagram, Feynman Parton Model
- Quantum Electrodynamics, Nobel Prize in Physics
- **Quantum computers** could effectively simulate quantum processes.

Basic Concepts of Quantum Computing

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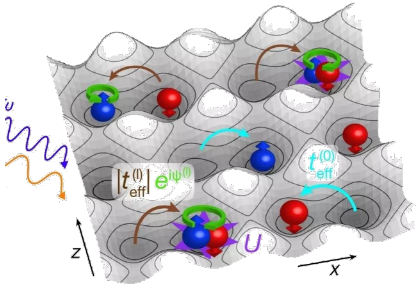
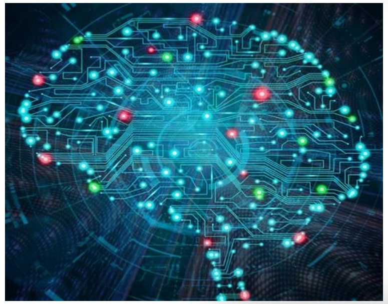


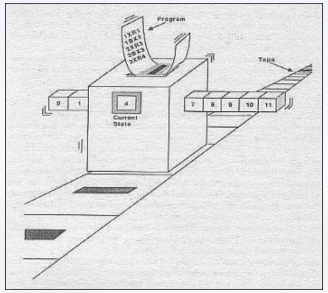
Physical Simulation

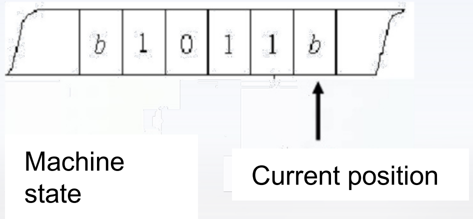


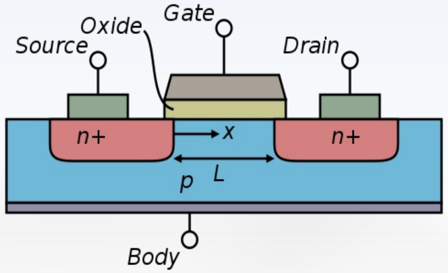
Factor

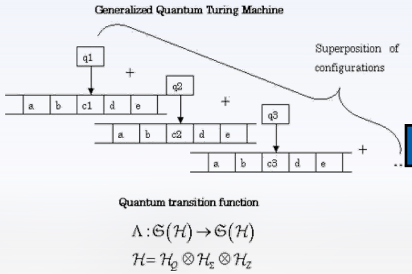
Application

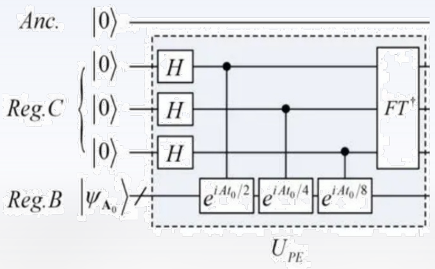
	Computing theory	Encoding	Physical implementation
Classical program	**Classical Turing machine**	**Program based on binary encoding**	**CMOS (0/1)**
Quantum program	**Quantum Turing machine**	**Circuit-based quantum program**	**Superconducting, photon (superposition state)**

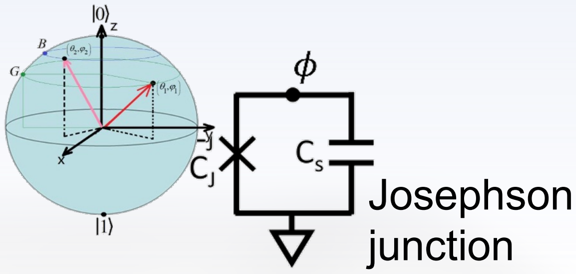












lead to high computational advantages via parallelism.

suffer from complexity due to quantum collapse and entanglement

has low energy consumption due to reversibility and superconductivity.

Quantum Computing Architecture

Increasing order of Abstraction

Increasing order of Complexity

	Classical computer	Quantum computer
Application	LLM Model	SAT problem
Algorithm	Matrix product	Quadratic optimization
High-level Language	Python	QASM
Assembly Language	ADD/MUL	Quantum circuit
Machine Code	0011011	Wave function
Instruction Set	x86	Pulse Control
Micro Architecture	I7 processor	Quantum Architecture
Gates/ Register	AND gate, OR gate	Qubits， Quantum gates
Transistor	CMOS transistor	Superconducting， Ion trap
Physics	Semiconductor physics	Quantum mechanics

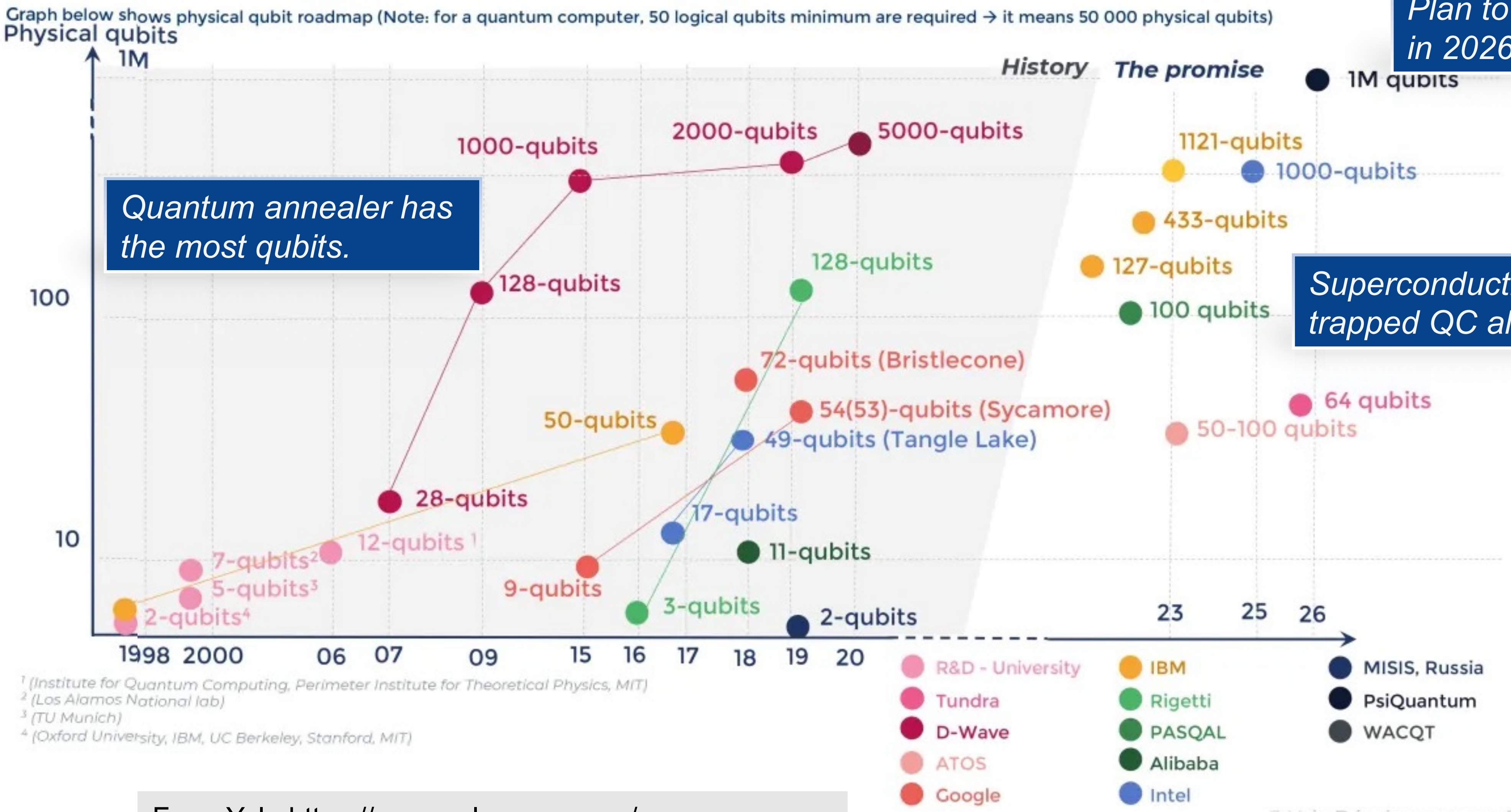
Software

Hardware

From https://www.secplicity.org/2018/09/19/understanding-the-layers-of-a-computer-system/

Classical and quantum computing has similar architecture

Development of Quantum Computer



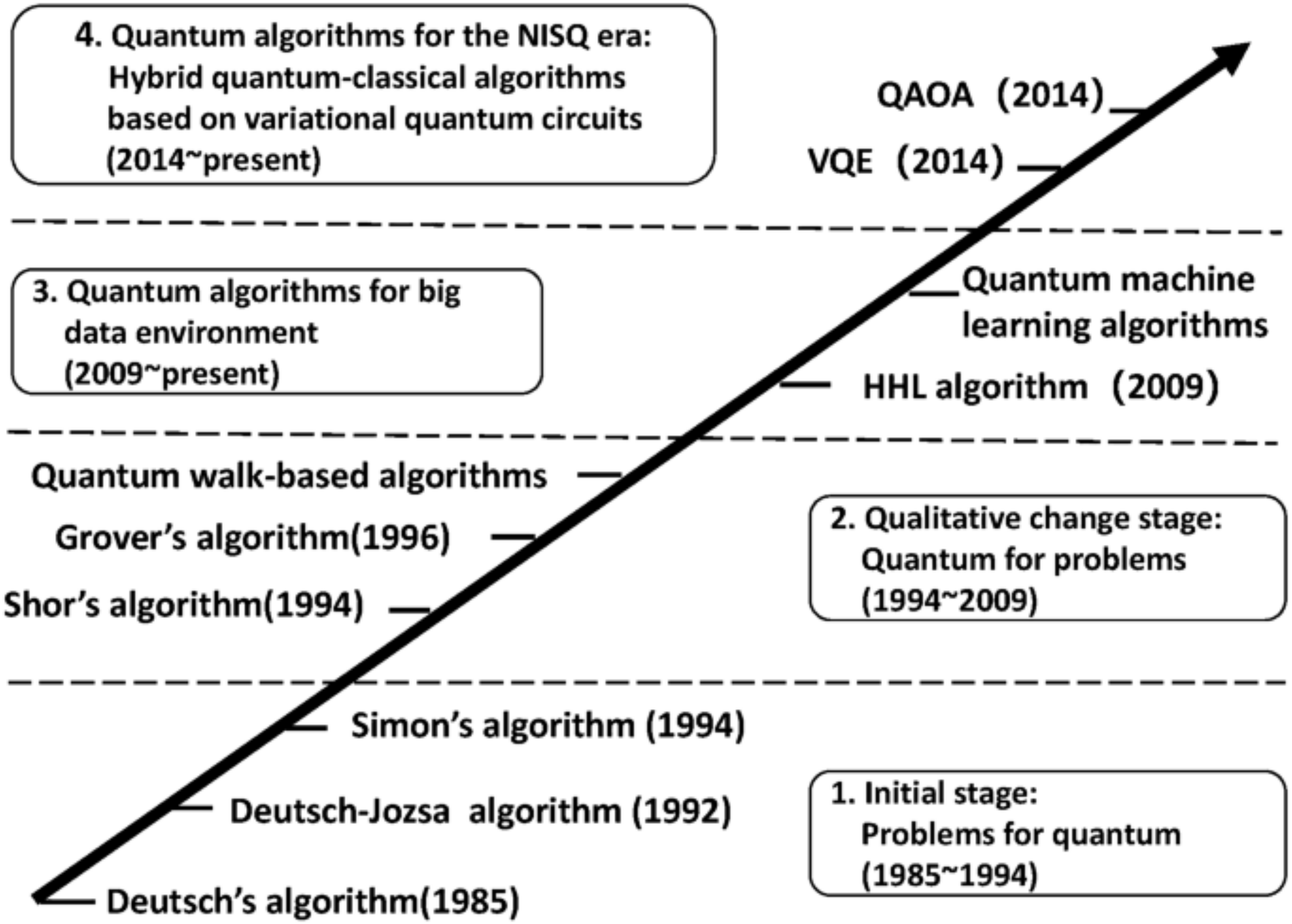
Plan to have 1M qubits in 2026

Quantum annealer has the most qubits.

Superconducting and Ion-trapped QC also increase fast.

From Yole https://www.yolegroup.com/press-release/quantum-technologies-the-market-is-growing/

Development of Quantum Algorithm

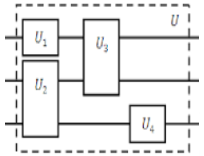


Zhang, S., Li, L. A brief introduction to quantum algorithms. *CCF Trans. HPC* **4**, 2022

Mathematical Model of Quantum Computing

Qubits

Quantum Evolution



Quantum Circuit

Quantum Bit (Qubit)

Single qubit

A **qubit** has two bases $|0\rangle$ and $|1\rangle$. The information stored in its **superposition state** is represented as a **2-dimension state vector** $|\varphi\rangle$.

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$|1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

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

$$|\varphi\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

subject to $|\alpha|^2 + |\beta|^2 = 1$

Quantum Bit (Qubit)

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

$$|\varphi\rangle = \begin{bmatrix}\alpha\\\beta\end{bmatrix}$$

subject to $|\alpha|^2 + |\beta|^2 = 1$

Multiple qubits

N **qubits** has 2^N bases $|00\cdots0\rangle$, $|00\cdots1\rangle\cdots$, $|11\cdots1\rangle$. The information stored in their **superposition state** is represented as a 2^N**-dimension state vector**.

$$|00\cdots0\rangle = \begin{bmatrix}1\\0\\\vdots\\0\end{bmatrix} \quad |00\cdots1\rangle = \begin{bmatrix}0\\1\\\vdots\\0\end{bmatrix} \quad \cdots \quad |11\cdots1\rangle = \begin{bmatrix}0\\0\\\vdots\\1\end{bmatrix}$$

$$|\varphi\rangle = \alpha_0|00\cdots0\rangle + \alpha_1|00\cdots1\rangle + \cdots + \alpha_{2^N}|11\cdots1\rangle$$

$$|\varphi\rangle = \begin{bmatrix}\alpha_0\\\alpha_1\\\vdots\\\alpha_{2^N}\end{bmatrix}$$

subject to $|\alpha_0|^2 + |\alpha_1|^2 + \cdots |\alpha_{2^N}|^2 = 1$

Quantum Evolution

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Unitary matrix

A quantum evolution caused by **quantum gates** is represented as a **unitary matrix (unitary),** which is a square matrix whose conjugate transpose is its inverse.

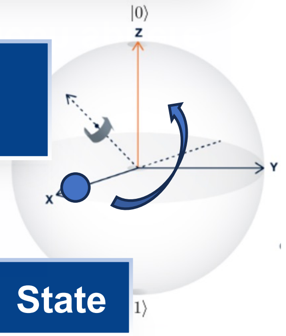
$$UU^{\dagger} = I$$

The evolution of qubit state $|\varphi\rangle$ is represented as:

$$|\varphi'\rangle = U|\varphi\rangle$$

Bloch sphere

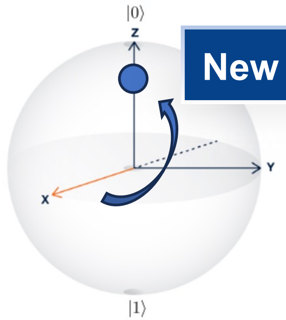
X+Z axes



State

$$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

π rotation around X+Z axes



New state

Quantum Evolution

Unitary matrix

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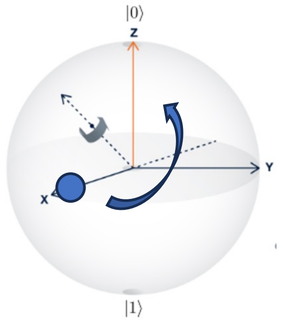
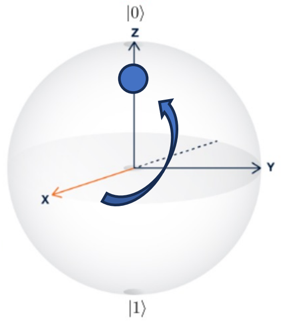


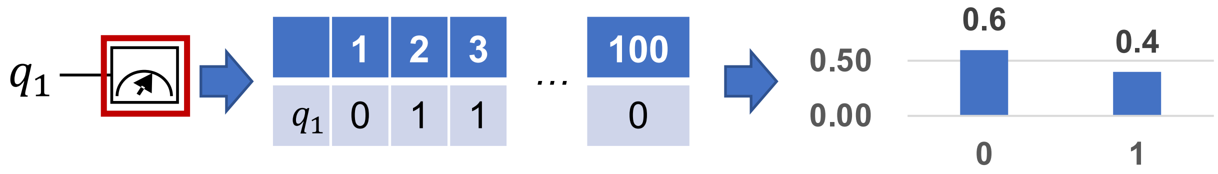
$$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

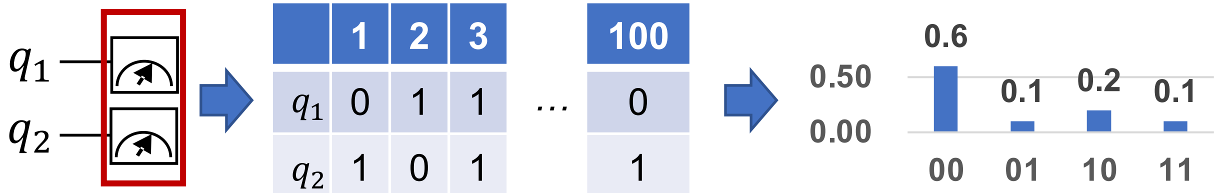
π rotation around
X+Z axis:
Exchanges X and Z



Quantum readout

A sampling of a quantum state is a bitstring. Multiple sampling of this state composes a probability distribution of measuring different bitstrings.



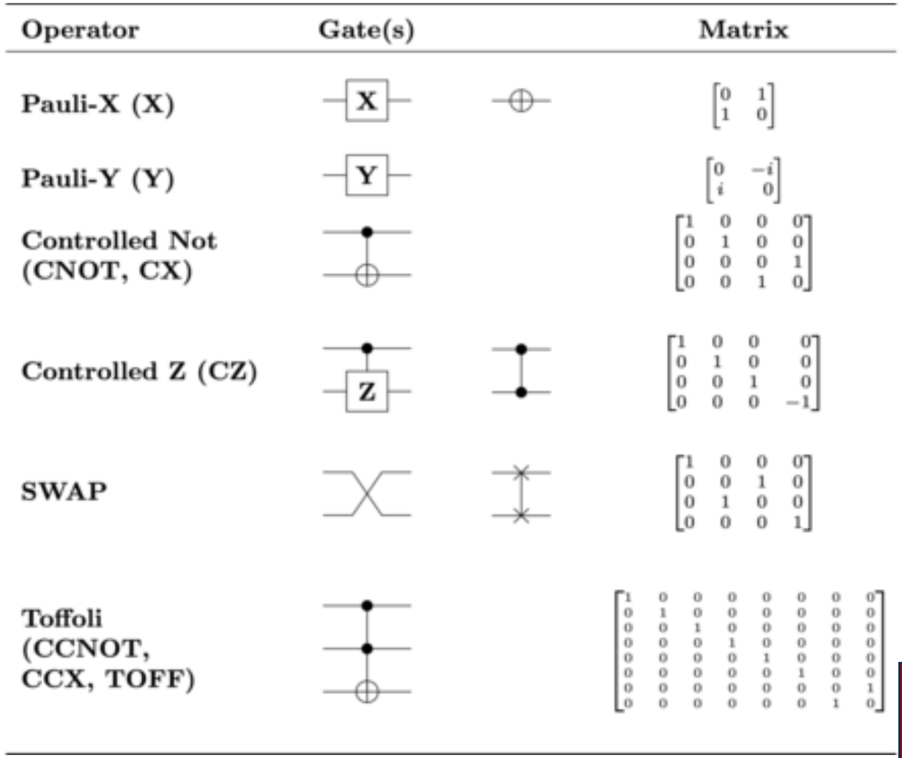


Readout *Measured bitstrings in different samples* *Probability distribution*

Quantum Circuit

Quantum gates

In the quantum circuit model of computation, a **quantum gate** is a **basic quantum circuit operating** on a small number of qubits.



Operator	Gate(s)		Matrix
Pauli-X (X)	X		$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)	Y		$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Controlled Not (CNOT, CX)			$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
Controlled Z (CZ)	Z		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$
SWAP			$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)			$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$

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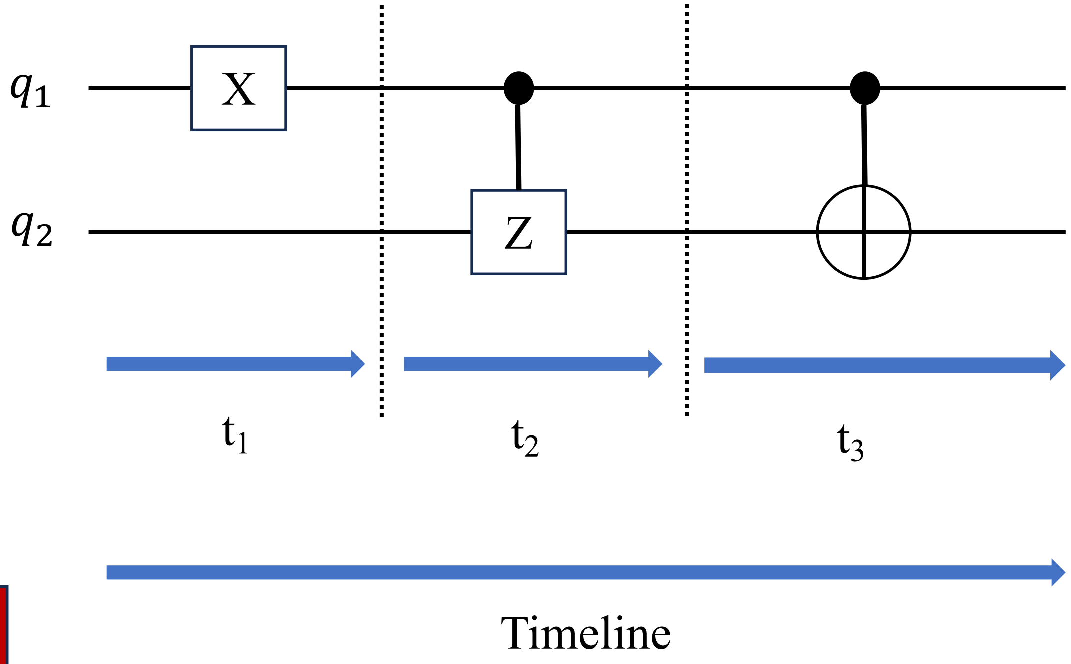
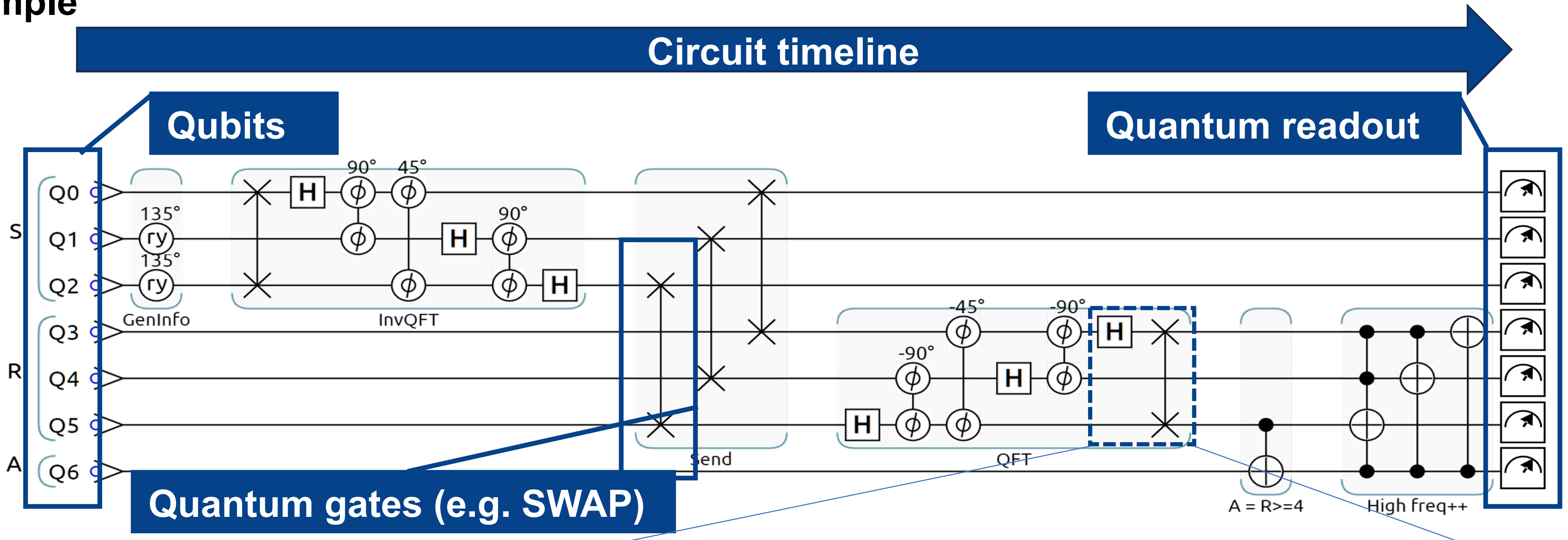
Qubit timeline

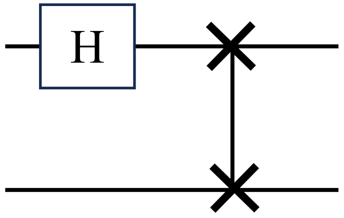
Each line in a quantum circuit represents **a qubit**. The quantum gate in a line is applied on the same qubits **from left to right in time direction.**



Quantum Circuit

For example





$$= \quad SWAP \cdot (H \otimes I) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 & 1 & 0 \\ 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & -1 \end{bmatrix}$$

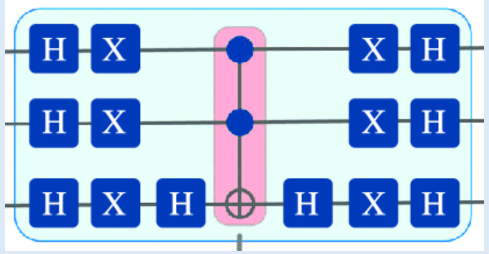
Implementation of Quantum Circuit

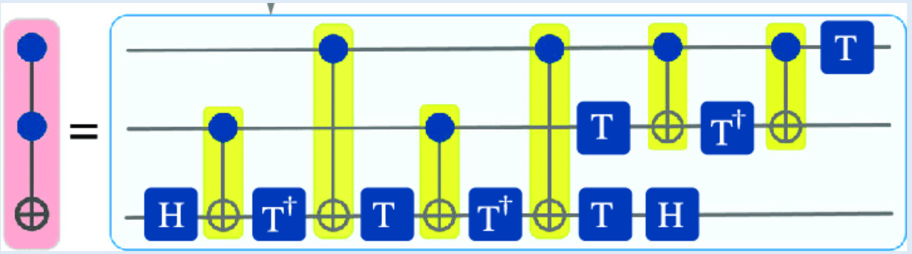
On superconducting quantum computer

Step 1. Circuit statement

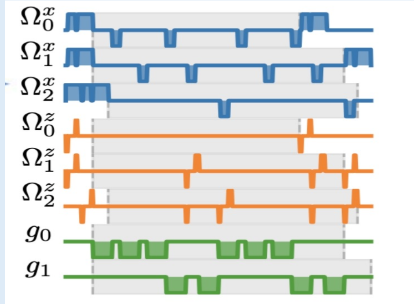
```
OPENQASM 2.0;
qreg qubits[3];
H qubits[1];H qubits[2];
H qubits[3];
X qubits[1];X qubits[2];
X qubits[3];
H qubits[3];
Toffoli qubits[1], qubits[2], qubits[3];
H qubits[3];
X qubits[1];X qubits[2];
X qubits[3];
H qubits[1];H qubits[2];
H qubits[3];
```

Step 2. Circuit compilation

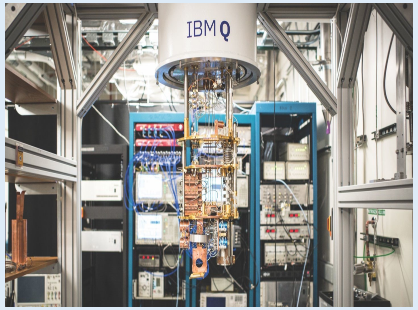




Step3. Circuit execution



Pulse generation

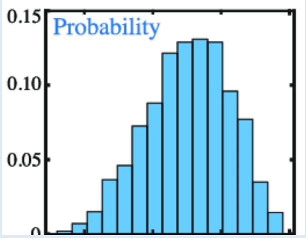


Quantum device

Step4. Result processing

Error emigration

Visualization



Probability distribution

Challenge in Quantum Computing

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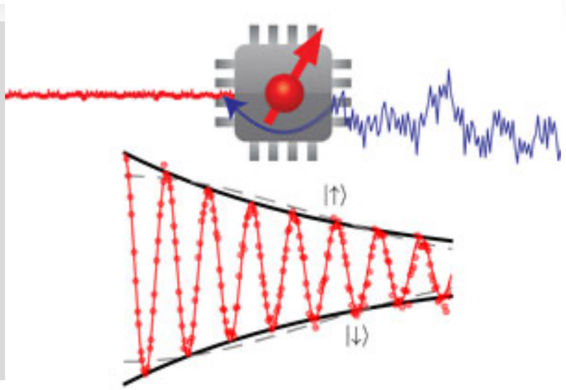
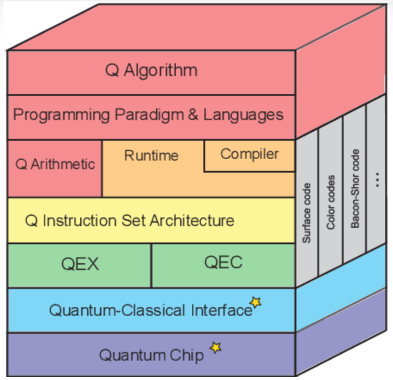
Noise

- Coherence error
- Gate error
- State preparation error
- Readout error
- Crosstalk



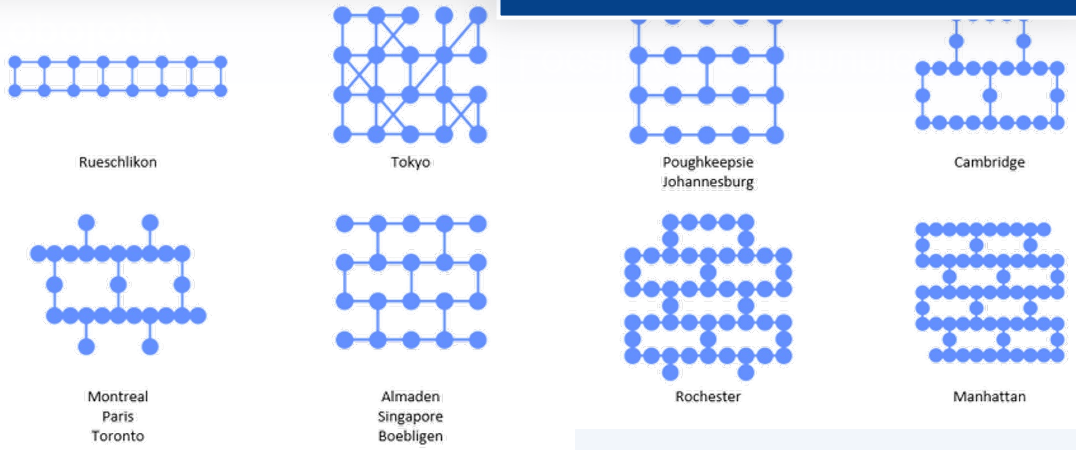
Instructions

- Multi-level compilation
- Micro-architecture instructions
- Quantum-classical communication



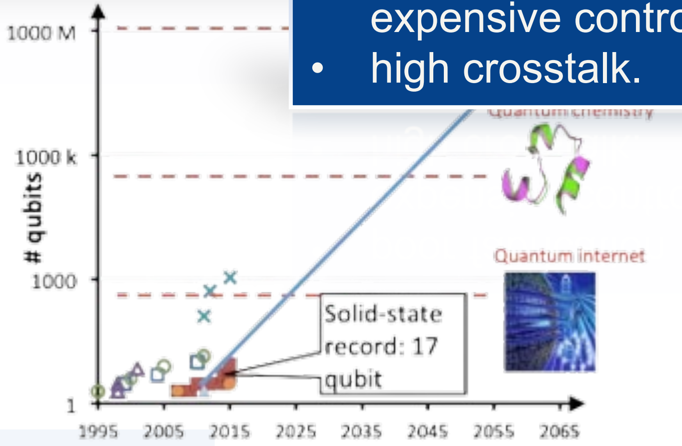
Topology

Locality in communication



Scalability

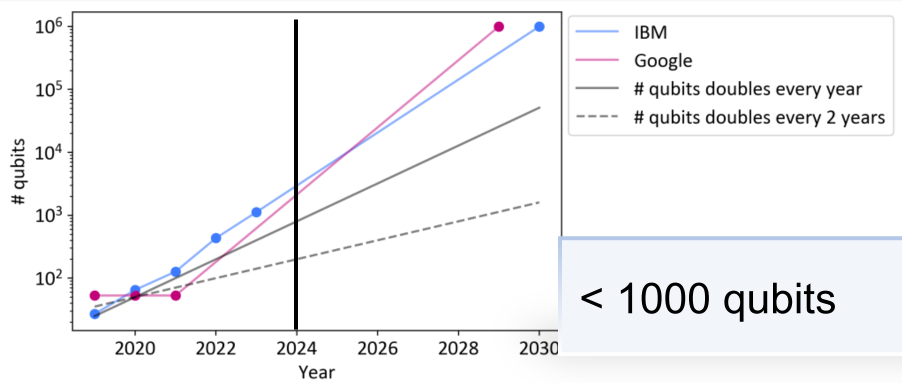
- poor fabrication techniques expensive control systems
- high crosstalk.



Constrained by physical implementation

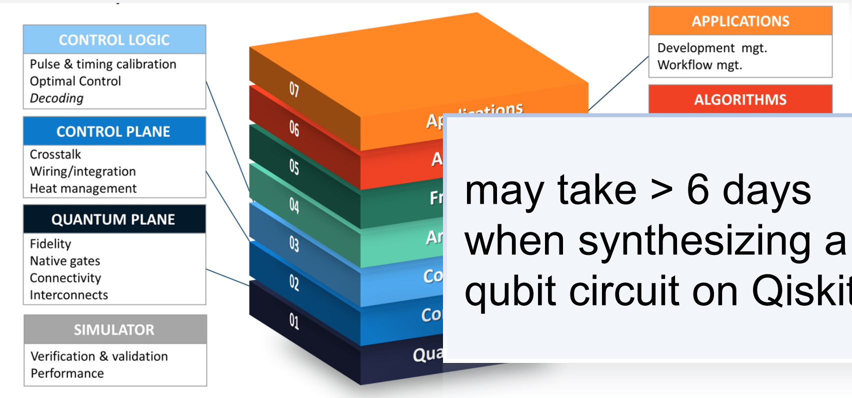
Results of Challenges

Limited Hardware Resource



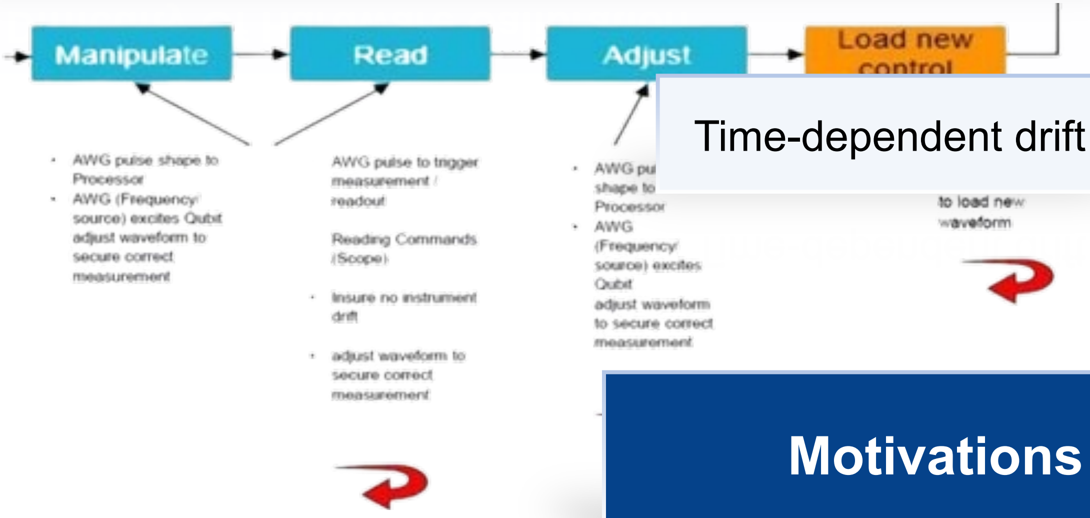
< 1000 qubits

Compilation Complexity



may take > 6 days when synthesizing a 100-qubit circuit on Qiskit

Difficulty Of Hardware Calibration

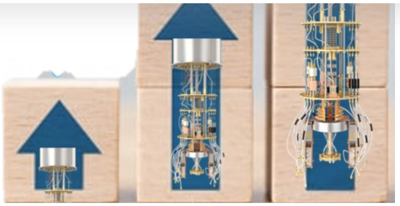


Time-dependent drift

Rare quantum advantage

- Limited qubits resources
- High error rate
- Hard to ensure quantum advantage in real applications

Long calibration time (e.g., readout calibration)



Motivations of JanusQ