Understanding the language of *quantum* computers

量子コンピュータの言語を理解すること

`JSPS Science Dialogue`

Zane Marius Rossi

The University of Tokyo

November 7, 2025

📜 Outline for presentation

1. Self-introduction (自己紹介)
2. The origins of computing (コンピューティングの起源)
3. Physics, computers, and quantum mechanics (物理と計算機と量子力学)
4. My work, and open questions (僕の研究と未解決問題)
5. Paths to international research (国際研究への道)

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Reminder: feel free to ask questions at any time! 👋

Zane Rossi (ゼーン・ロッシ) 🙇‍♂️

Now: JSPS Postdoctoral Fellow at UTokyo

Before: PhD student in physics at MIT

Before²: Undergraduate at the University of Chicago

[1] 翻訳する
[2] 組み合わせる

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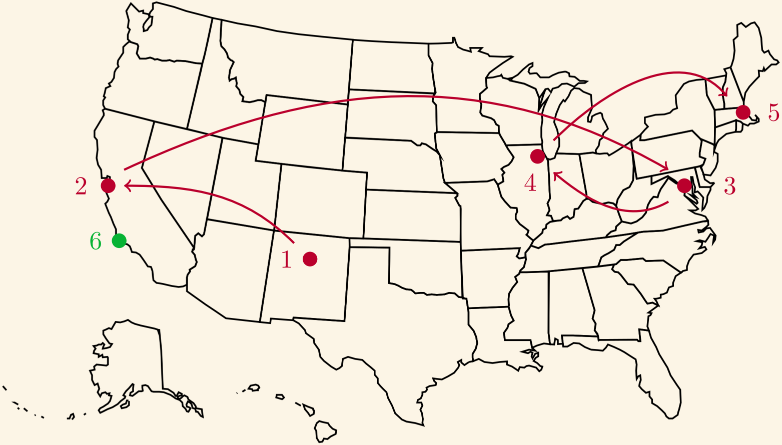
👉 **My favorite question:**

How can we translate[1] and combine[2] methods between **computer science**, **physics**, and **mathematics**?

[1]翻訳する
[2]組み合わせる

My path through the United States

Santa Fe → San Francisco → DC → Chicago → Boston



Distance from 2 to 6 is the same as 東京 to 大阪!

The origin of my interests (興味のきっかけ)

Physics

Support from teachers, parents, and friends

Science focused high-school ⚗️

Afterschool clubs, math team, student outreach

Japan

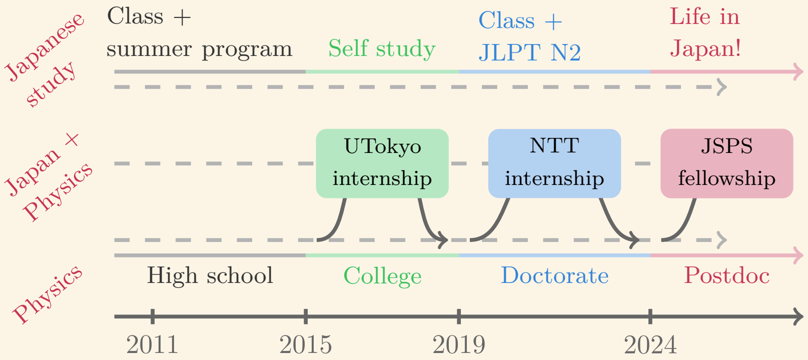
Novels, games, and Japanese friends!

Only 🇪🇸, 🇫🇷, and 🇯🇵 classes at my high school

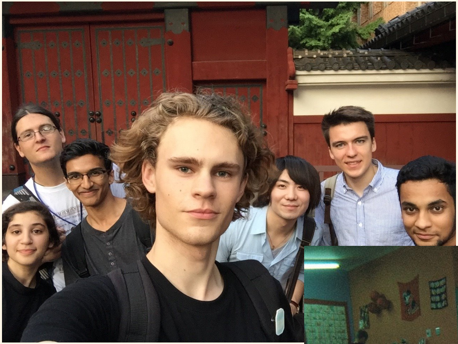
Language summer program in Minnesota

Wherever possible, I've tried to **combine** my interests!

Parallel interests (並行な興味)



Huge help from mentors, teachers, and fellow students!



2017 at UTokyo

2011 in Minnesota

💻 Computers handle broad tasks

Calculate[3]

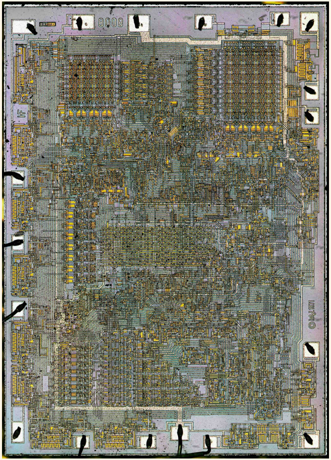
Search, sort, and optimize

Store, and communicate

Predict physics

‘Learn’ and ‘reason’ …

What makes these tasks similar, and how can we understand a **theory of computing**?



[3] The image is the Intel 8008 chip from 1972

🌱 The origins of computing

Extends back long before electronics!

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語源ポイント

computer: person who performs calculations (計算者)
algorithm: the name of a 9th century mathematician

Algorithm: (アルゴリズム)
A series of steps that can be followed by a machine

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Historically, the type of machine has changed!

1804: Jacquard loom[4] (ジャカード織機)

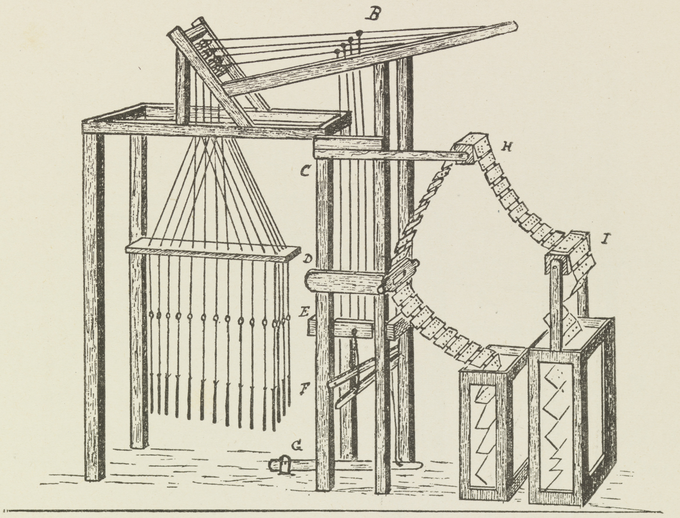
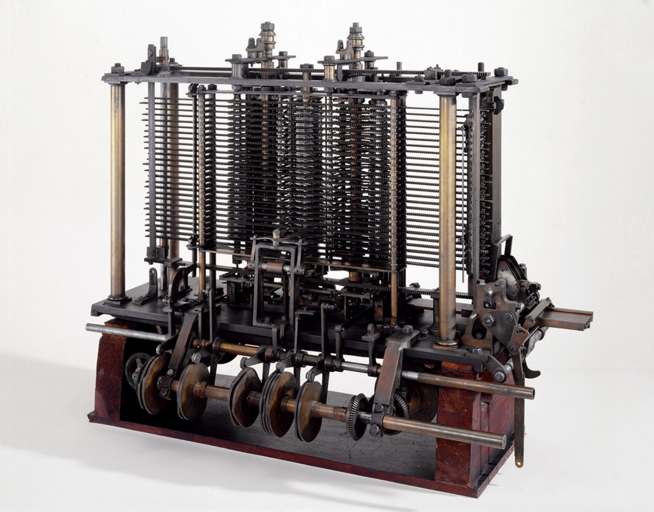


FIG. 12

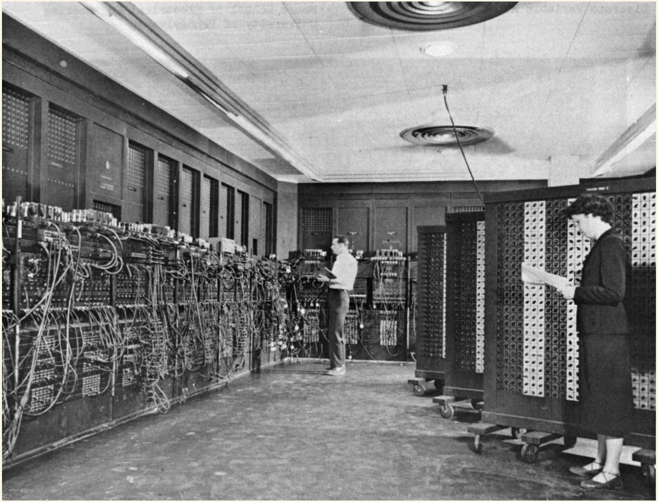
[4] Used punched cards to weave patterns!

1837: Babbage's analytical engine (解析機関)



Steam-powered general-purpose computer
(蒸気機関で動く機械式汎用コンピュータ)

1945: ENIAC (エニアック電子計算機)



Programmable, electronic, digital computer
(プログラム内蔵方式＋電子式＋デジタル式)

Computer vocabulary (コンピュータの語彙)

Computer state (状態): set of information that describes a system at a certain time.

Computer operation (演算): process performed on a computer (例: addition, subtraction, multiplication).

Input/Output (入力/出力): data received by or sent from a computing system.

Circuit (回路): Combination of operations on data; this takes input, makes output, and changes system state.

A computer updates its **state** over time by **operations**.

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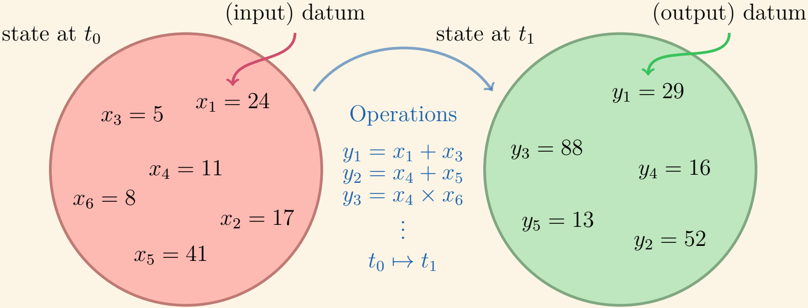

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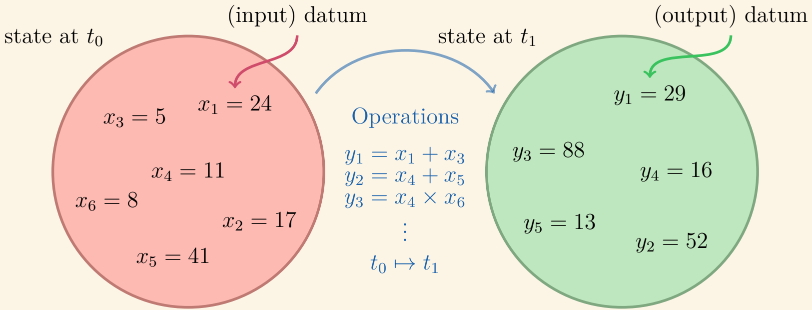

We encode (符号化する) a question in **input data**, run our **algorithm**, and read answer from **output data**.

We can organize operations with a **circuit**.

How do we study computers?

Question 1: what problems can a computer solve?

Question 2: how *efficient* is a solution?

Question 3: how do **Q1** + **Q2** depend on *type of computer*?

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The first question is **computability** (計算可能性); the second question is **complexity** (計算複雑性). The third question (my interest) relates to **Church-Turing thesis**.

🔗 Computers and physics

[5]General recursive functions (帰納的関数).

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Computers follow **physical laws** (物理法則)

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Church-Turing thesis:
The functions computable by physical devices (計算できる関数) are the **same** as those computable by a Turing machine.[5] $\implies$ Physics definition = Math definition.

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⚛️ The origin of quantum mechanics

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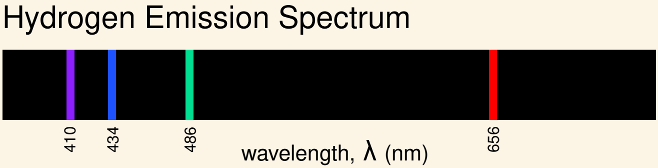

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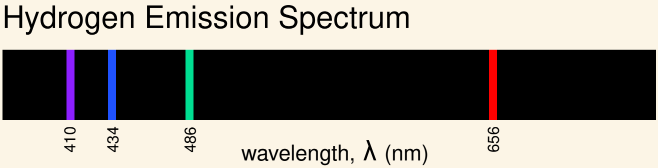

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Quantum (量子) means discrete amount (離散的な量)

The universe is quantum! But quantum effects usually only appear at *small size* and *low temperature*

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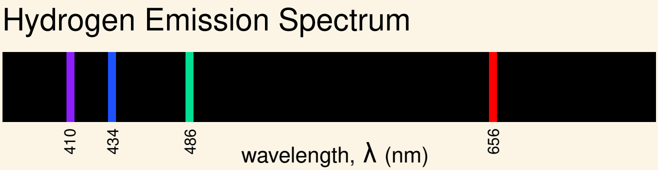

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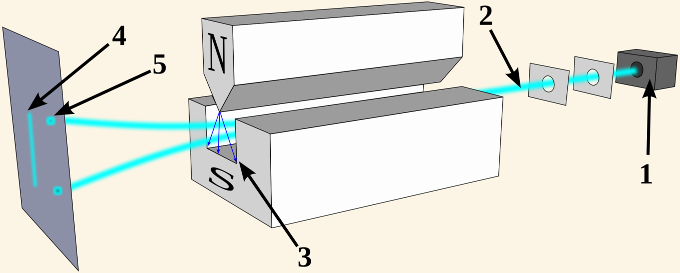
Correspondence principle (対応原理)

1921: Stern–Gerlach experiment



Silver atoms sent through magnetic field 🧲

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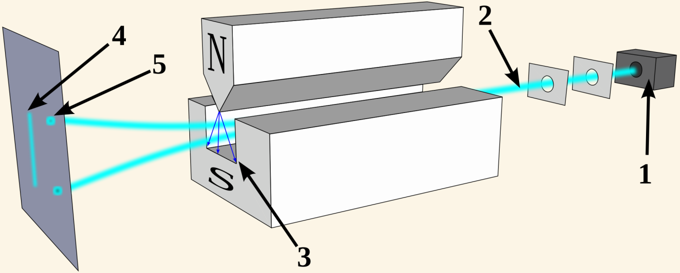

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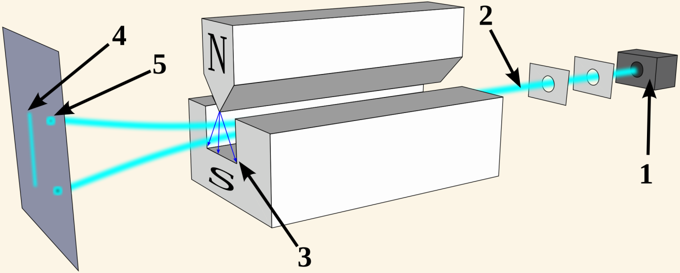

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This spin is a simple **quantum state**.

The experiment is a **quantum measurement** (量子測定)


Hochverehrter Herr Bohr, anbei die Fortsetzung unserer Arbeit (vide Zeitschr. f. Physik VIII. Seite 110. 1921.): Der experimentelle Nachweis der Richtungsquantelung.

Silber. ohne Magnet-Feld

mit Feld

Wir gratulieren zur Bestätigung Ihrer Theorie! Mit hochachtungsvollen Grüssen

Ihr ergebenster Walther Gerlach.

Ffm. $\frac{8}{2}$.22.

The rules of quantum mechanics (量子力学の法則)

[6] H is a linear operator (線形演算子) or matrix (行列).
[7] This is a linear combination (線形結合).

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A quantum state (量子状態) changes in time ($t \mapsto t + \Delta t$) by linear differential equation[6] (線形微分方程式)

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Differential means Δt must be small for the rule in (1) to be correct. H (Hamiltonian) controls dynamics (力学).

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✨ Special quantum mechanical phenomena (現象)

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[9] 古典確率では説明できない相関.

✨ Special quantum mechanical phenomena (現象)

1. **Superposition** (重ね合わせ):
   If ψ_1 and ψ_2 are states,[8] then $\alpha\psi_1 + \beta\psi_2$ can be a state.

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We really do observe these effects, and **they may allow us to do things no classical system can do** (efficiently)!

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The (basic) math of quantum theory

Quantum states are complex unit vectors (ベクトル).
$\psi = (\alpha_0, \alpha_1, \ldots, \alpha_n) \in \mathbb{C}^{n+1}$ with length one:

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Unitary operations: states transform by unitary matrices:[10] $|\psi\rangle \mapsto U|\psi\rangle$. Here U preserves length.[11]

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Quantum mechanical computers

Classical digital computers update binary information with simple rules to solve complex problems.

0 and **1**,

Information stored **physically**: voltages over transistors.

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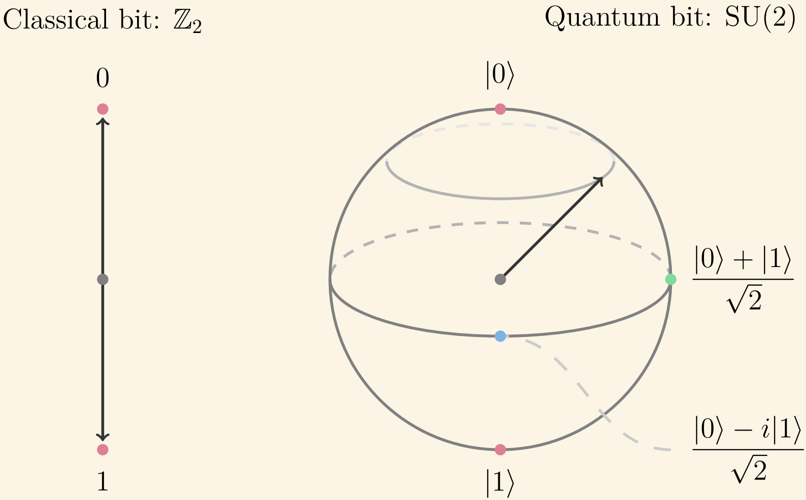
Information stored **physically**: voltages over transistors.

Question: how can we update quantum states? What are the rules? What is a quantum algorithm?

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

Computers following quantum mechanical laws solve problems differently!

Visualizing a single **qubit** state on the *Bloch sphere*
A unitary is a rotation (回転) on the sphere (球面)!



For many qubits, this is much harder to imagine!

Comparing classical and quantum computers

Q $\geq$ **C**. Quantum computers can do everything a classical computer can **(no superposition, no entanglement, only some unitaries)**

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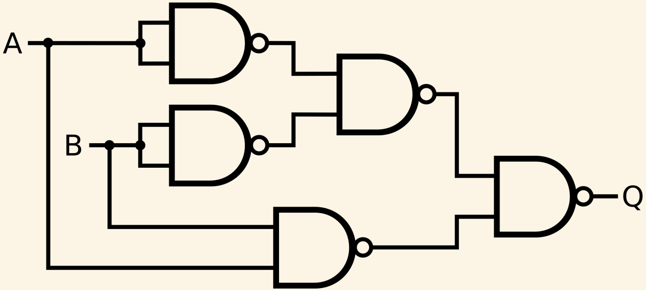
By superposition, entanglement, and properties of measurement, some problems appear to be solved faster!

Factoring integers. Predicting physics.
Solving linear equations. Optimization ...

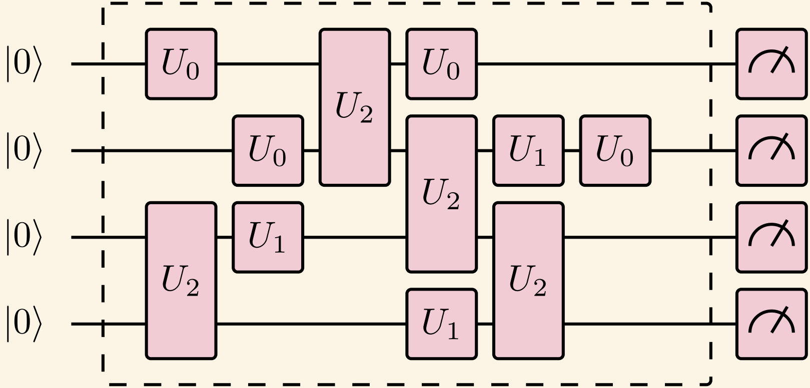
Classical computers operate on binary data: 0 and 1's



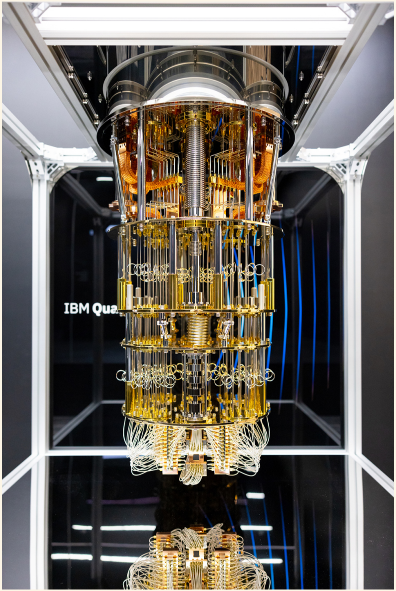
Logic gates take binary input and produce binary output.
Many logic gates combined make a **logic circuit**.

NAND gate:
$(0 \wedge 0 = 1)$, $(0 \wedge 1 = 1)$, $(1 \wedge 0 = 1)$, $(1 \wedge 1 = 0)$.

Quantum computers operate on quantum states: $|\psi\rangle$



Quantum logic gates can be combined into a **quantum circuit**; classical data is given by **measurement**.



Quantum computers exist, but are small and noisy.

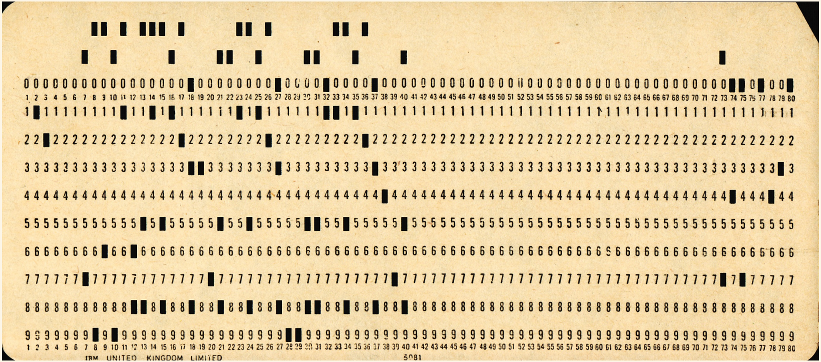
Many different approaches, with different technologies.

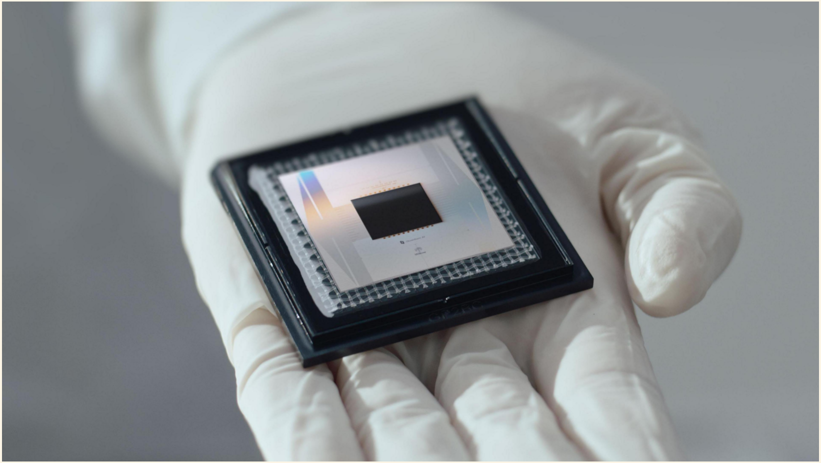
例: IBM uses a superconducting (超伝導) device at ≈25mK.

Many quantum algorithms we understand in theory are still too expensive to run.

Improvement is fast!

An IBM punched card





My research focus 🙇‍♂️

How can quantum computers transform linear operators?
When is a quantum computer faster than classical?

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How can quantum computers transform linear operators?
When is a quantum computer faster than classical?

Q1: How do we efficiently input data?

Q2: Once data is input, what can we change?

Q3: How do we efficiently measure results?

> Building **simple tools** 🔨 and **mathematical techniques** 🧮 to make creating quantum programs easier.

Linear operators and matrices

We can represent relationships with matrices: $Av = b$

$$\begin{aligned} 2x + y &= 4 \\ x + 2y &= 5 \end{aligned} \equiv \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 4 \\ 5 \end{bmatrix}$$

Linear operators and matrices

We can represent relationships with matrices: $Av = b$

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Dimension: size of matrix
Eigenvectors (固有ベクトル) v; **eigenvalues** λ (固有値):

$$Av = \lambda v, \text{ where } A \text{ is matrix and } \lambda \text{ is number}$$

$$\begin{bmatrix} * & * & * & * \\ a & b & c & d \\ * & * & * & * \end{bmatrix} \times \begin{bmatrix} * & d & * \\ * & e & * \\ * & f & * \\ * & g & * \end{bmatrix} = \begin{bmatrix} * & * & * \\ * & \star & * \\ * & * & * \end{bmatrix}$$

$$\star = ad + be + cf + dg = \text{row} \cdot \text{column}$$

We can compute the inverse matrix to solve

$$A^{-1} = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}^{-1} = \frac{1}{3}\begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix} \implies \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 1 \\ 2 \end{bmatrix}$$

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$$\begin{aligned} (2-\lambda)(2-\lambda) - 1 = 0 &\implies \lambda^2 - 4\lambda + 3 = 0, \\ &\implies \lambda \in \{1, 3\}, \end{aligned}$$

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We can write the matrix A using the eigenvalues and eigenvectors (**spectral theorem**)!

$$A = 1(v_1 {v_1}^T) + 3(v_3 {v_3}^T),$$

✨ Linear algebra is powerful

$$x = B^{-1} y \tag{4}$$

$$\dot{x}(t) = A x(t) \tag{5}$$

$$y = F x \tag{6}$$

$$x_n = f(W x_{n-1} + b) \tag{7}$$

$$t = A s + e \tag{8}$$

They appear when solving systems of equations (4), linear differential equations (5), Fourier transforms (6), neural networks (7), and cryptography (8, 暗号理論)!

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Translate many problems to the **same language**!

Transforming matrix eigenvalues

I study quantum algorithms for controlling matrices

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Specifically, I want to change their eigenvalues

$$\mathbf{A} = \sum_k \lambda_k v_k {v_k}^T \longmapsto \sum_k f(\lambda_k) v_k {v_k}^T = f(\mathbf{A})$$

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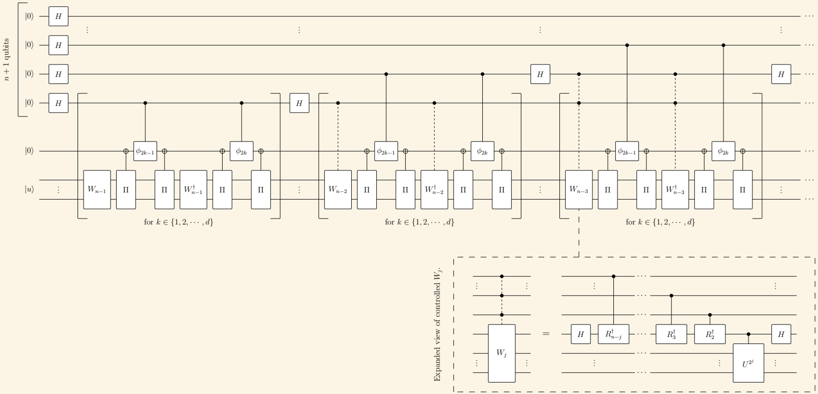
$$U = \begin{bmatrix} \mathbf{A} & * \\ * & * \end{bmatrix} \longmapsto \begin{bmatrix} f(\mathbf{A}) & * \\ * & * \end{bmatrix}$$

Quantum algorithms can do this for **very large matrices**

📌 For example, I helped design a **quantum circuit** to **estimate eigenvalues**!



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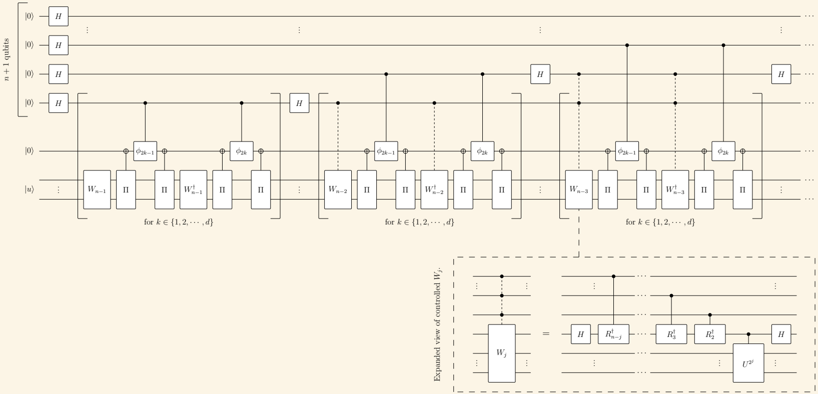

We **divided** the problem into **many smaller problems**.

🤔 New directions and unsolved questions

Functions with many variables (多変数関数)

$$f(x, y, z, \dots)$$

🎛️ Controlling matrix *eigenvectors*

⏱️ Using less time and space

🔗 Combining different types of transformations

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Make it easier to **translate** problems to linear algebra, and then **solve efficiently** on a quantum computer.

Research directions in quantum computing

🧮 **Mathematics**:
Analysis, geometry, linear algebra, group theory ...

💻 **Computer science**:
Programming languages, optimization, graph theory ...

⚛️ **Physics**:
Condensed matter, field theory, information theory ...

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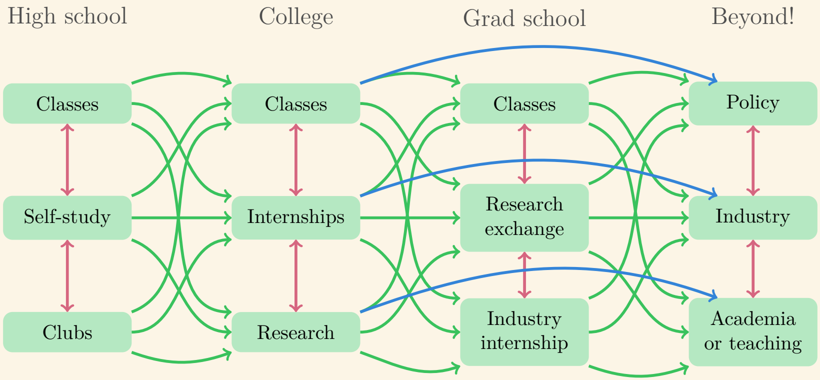
The field is **diverse** and offers problems at every level!

🏃 Getting involved!



Careers in research are varied, and often span many countries!

🤔 Questions for students

1. What have you heard about quantum computers?
2. How do you use computers in your work now?
3. What is the source of your interest, and what problems do you hope to solve?
4. Are there two topics you hope to work between?
5. Are you interested in international exchange?
6. What do you think might help you or others to make international research more common?

Thank you for listening!

🙇‍♂️

ご清聴ありがとうございます!