Quantum Computing

First steps…

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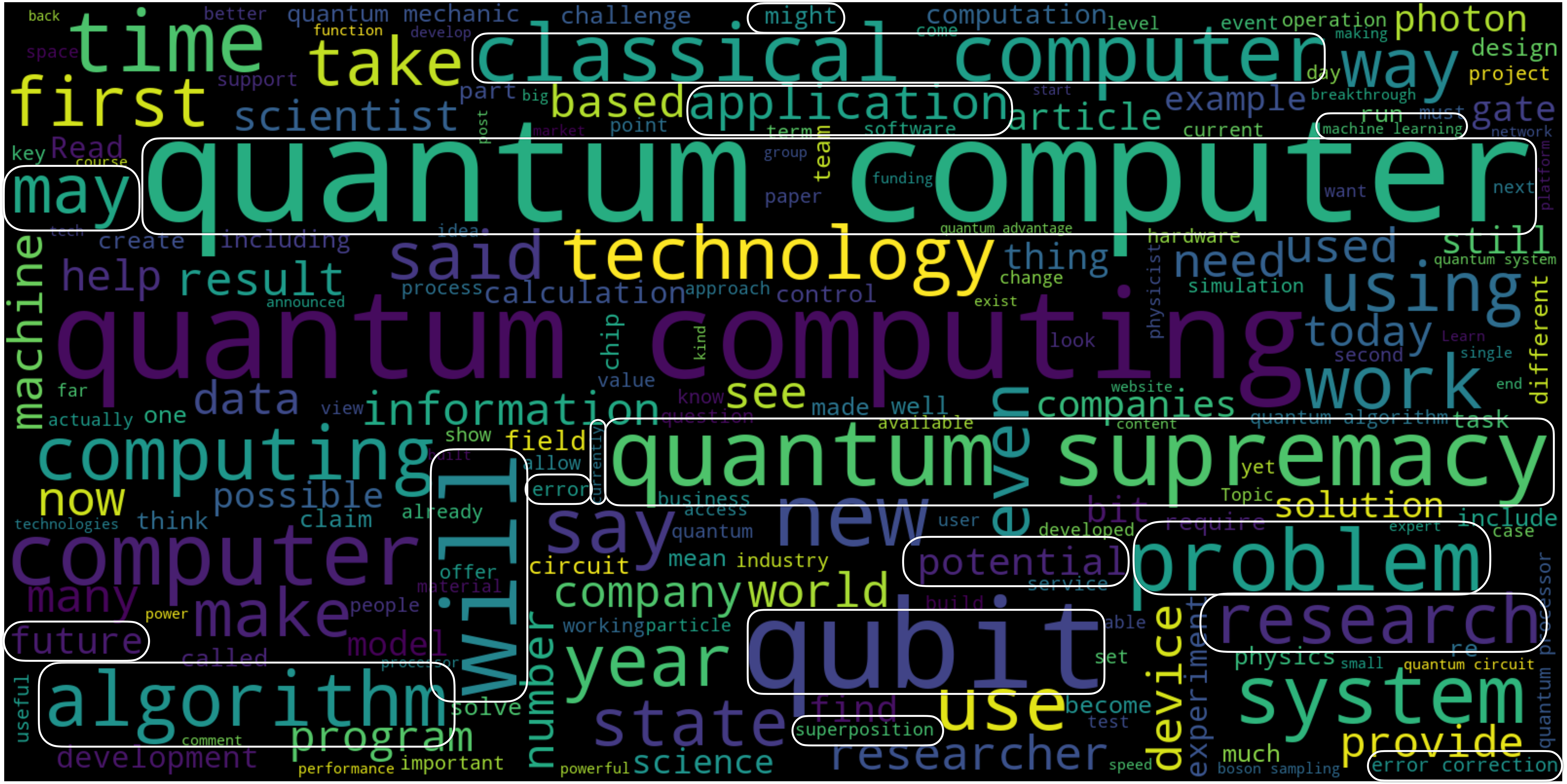
0. What is it ?
1. Why should we care ?
2. How does it work ?
3. What are the problems ?
4. Potential future applications
5. People / organizations involved ?
6. Coding, playing, learning…
7. Where can I learn more ?

0. What is it ?

Some potential - A lot of hype - Probable “winter”

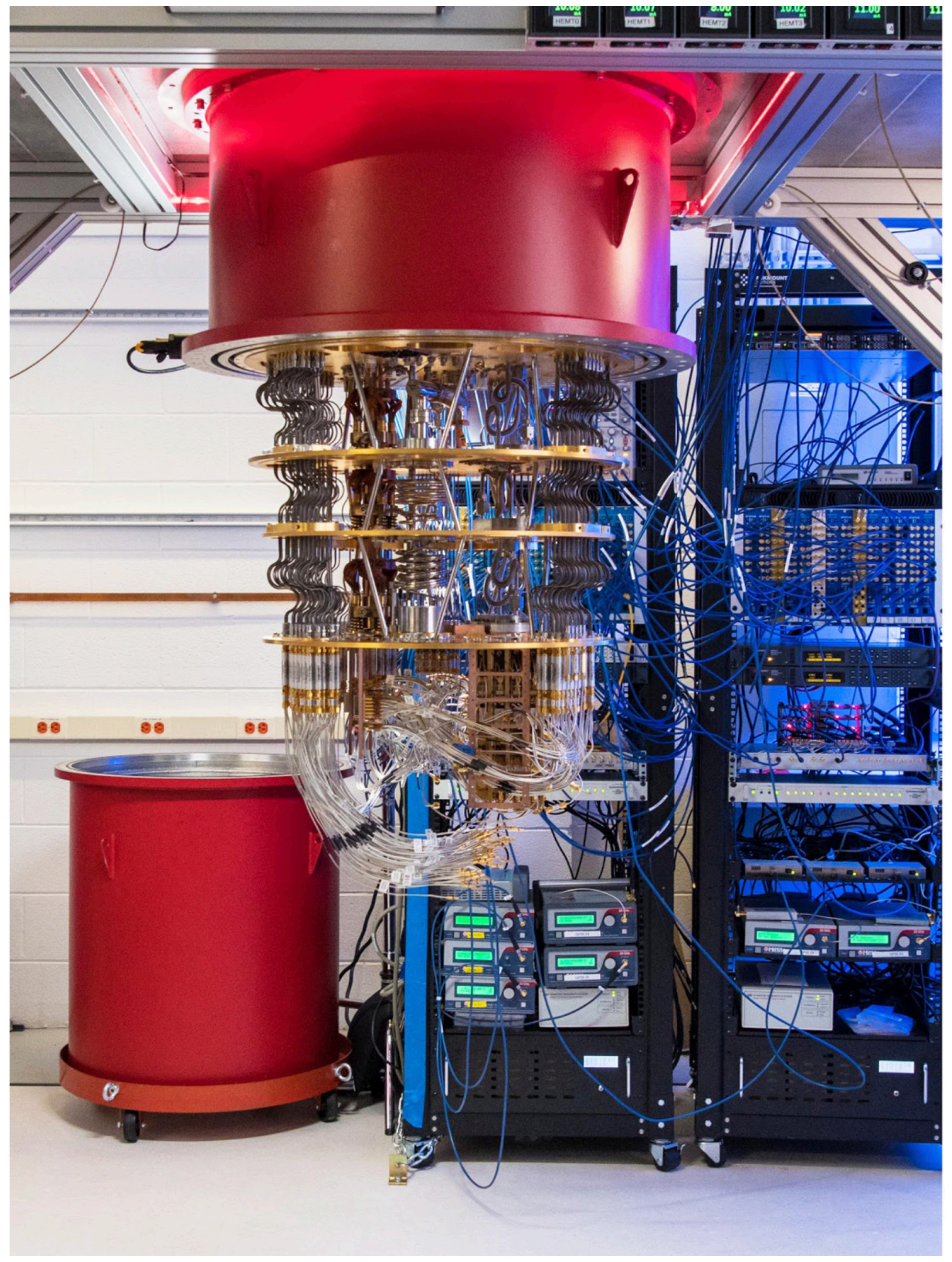


Most frequent words in a few hundred web documents mentioning Quantum Computing

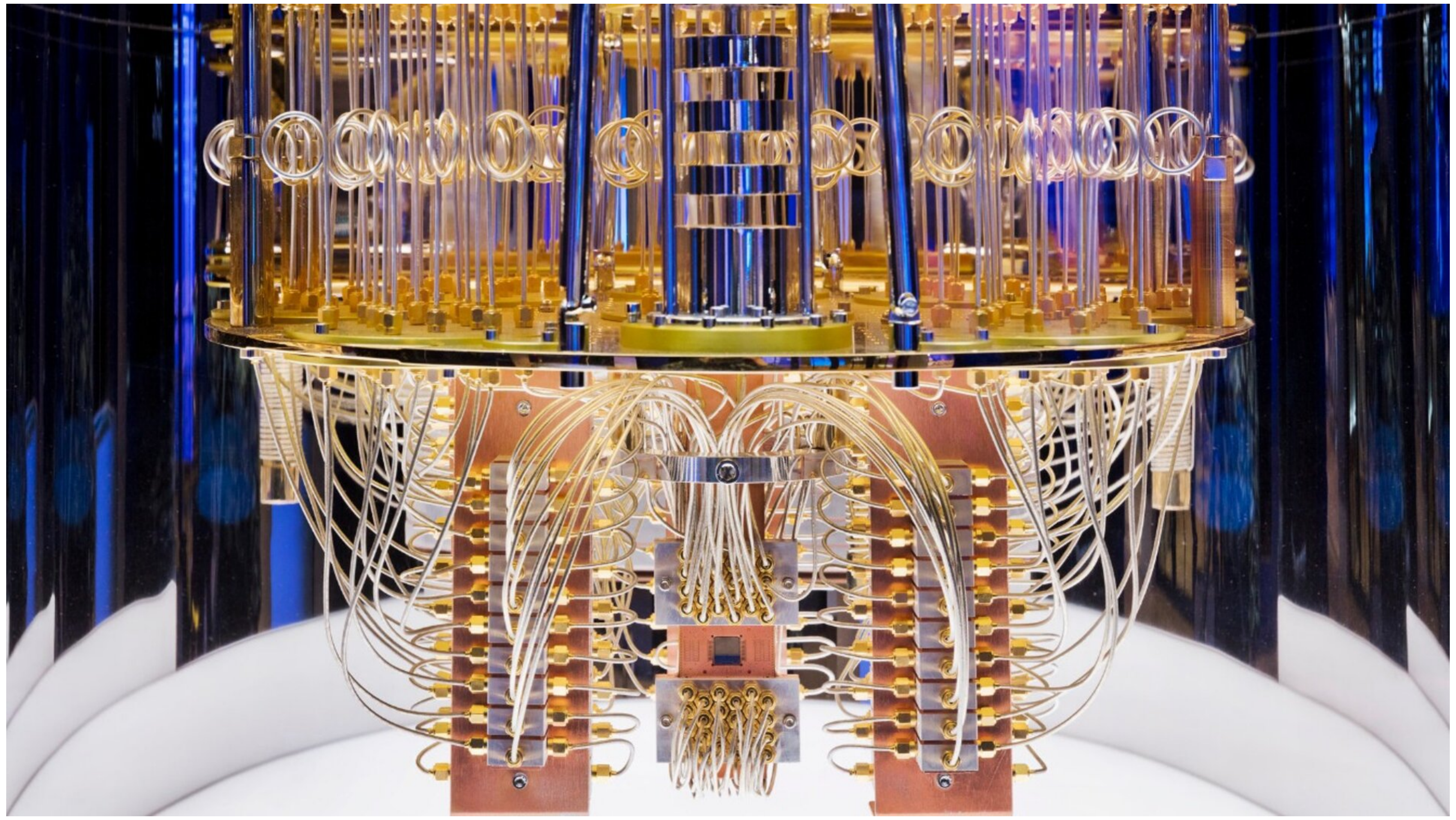
Noisy Intermediate-Scale Quantum (NISQ) ~~computer~~ processor

<u>superconducting</u> processor: operating at close to absolute 0 temperature (0 Kelvin / -273 Celsius) at which particle motion ceases

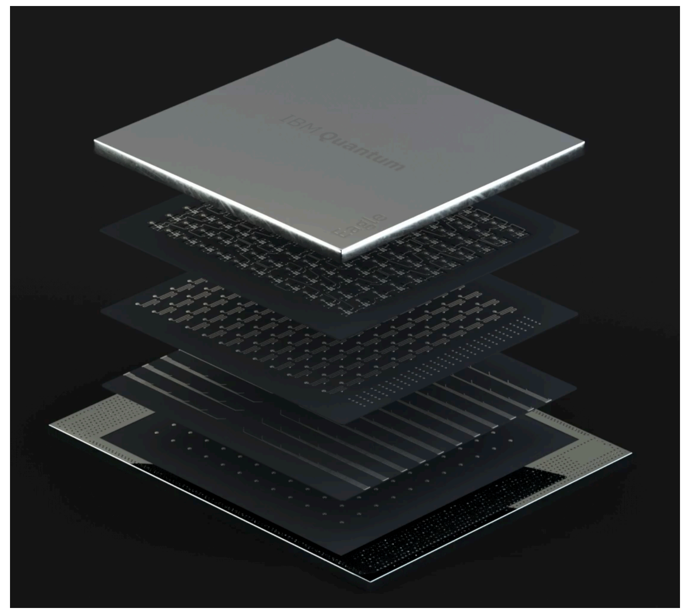
Source: IBM



Source: Google



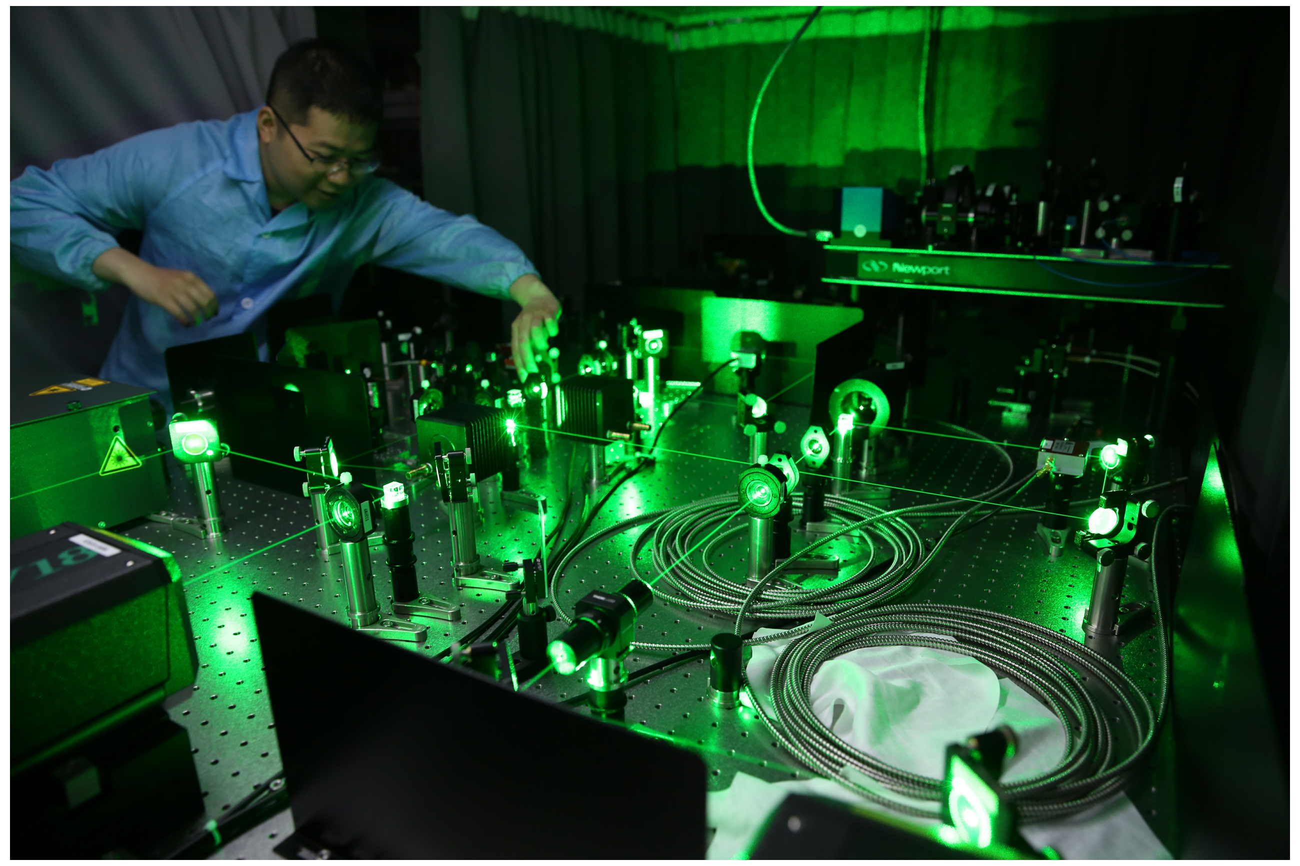
Source: IBM



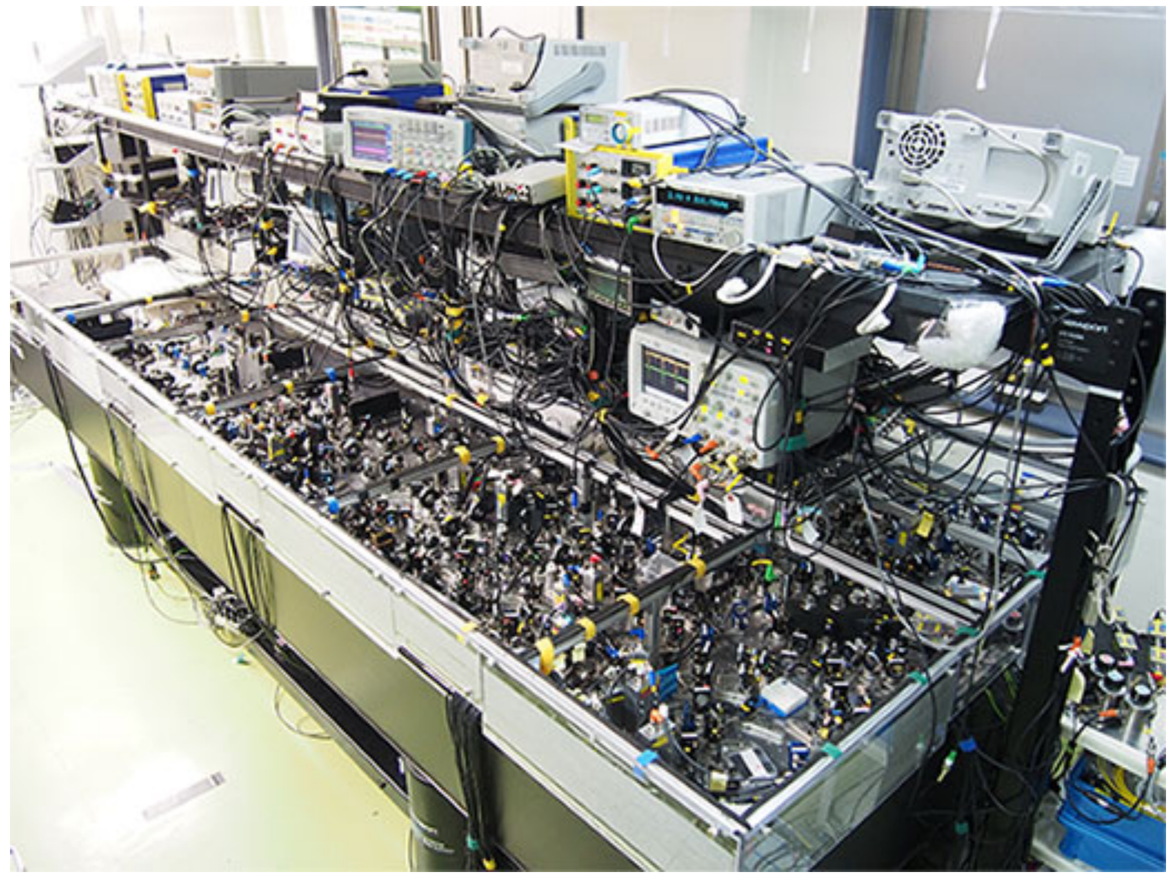
Source: IBM

Source: IBM

<u>photonics</u> processor



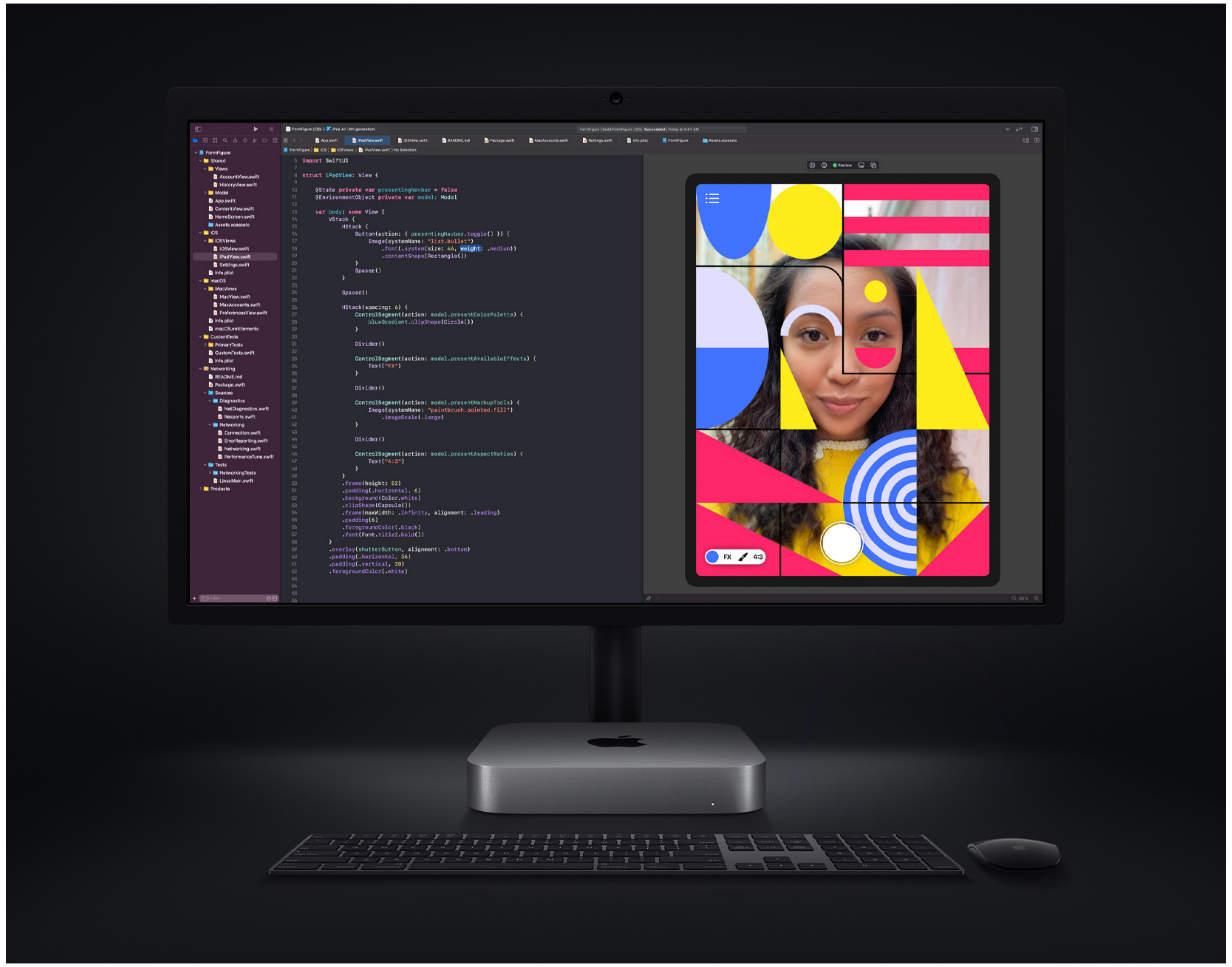
Source: CAS-Alibaba Quantum Computing Laboratory



Source: U. of Tokyo

Master: classical computer

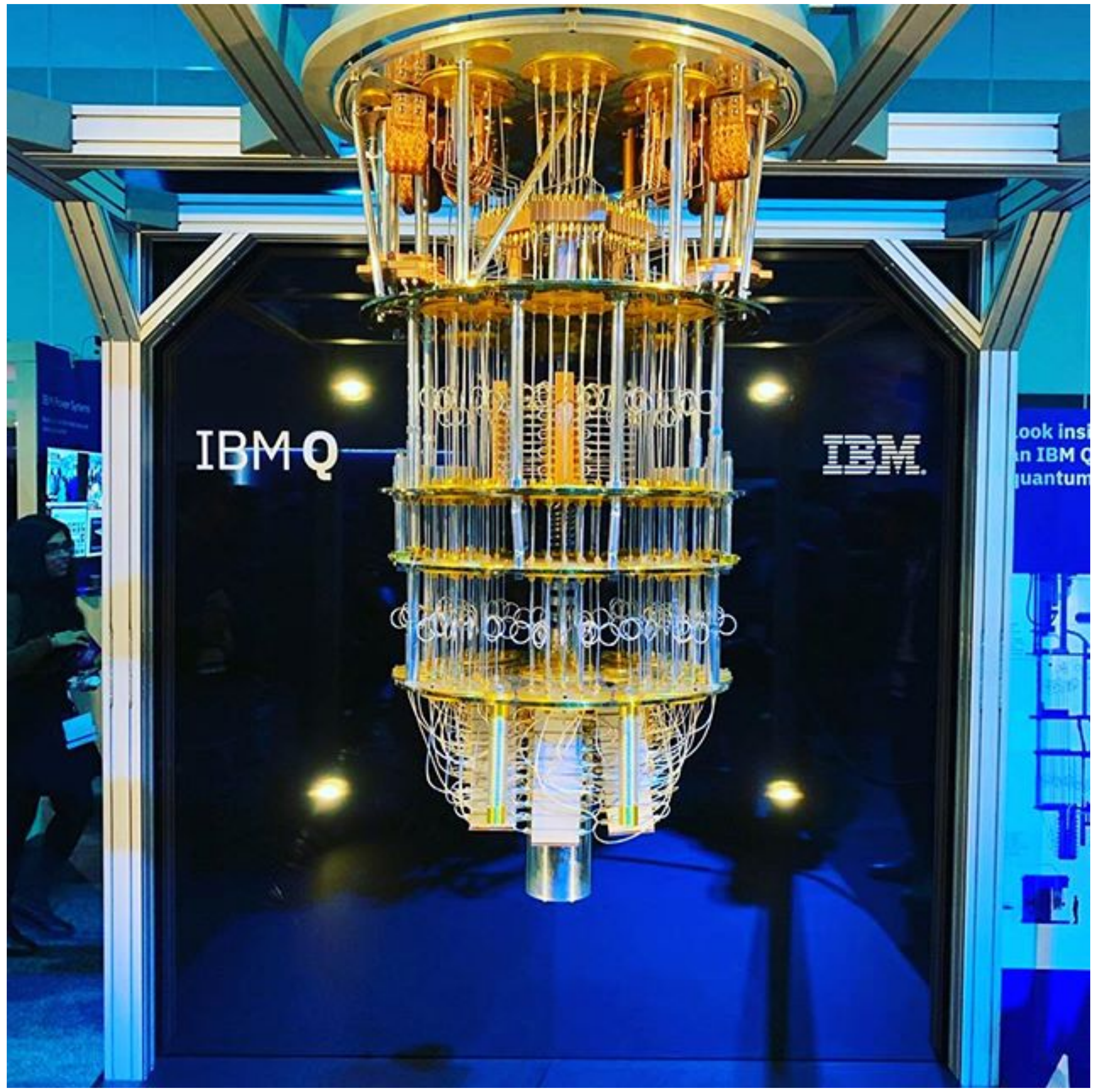
Slave: quantum processor



Source: Apple

Commands →

← Results



Source: IBM

(Relatively) vast amount of storage

Code

NO storage space

NO code

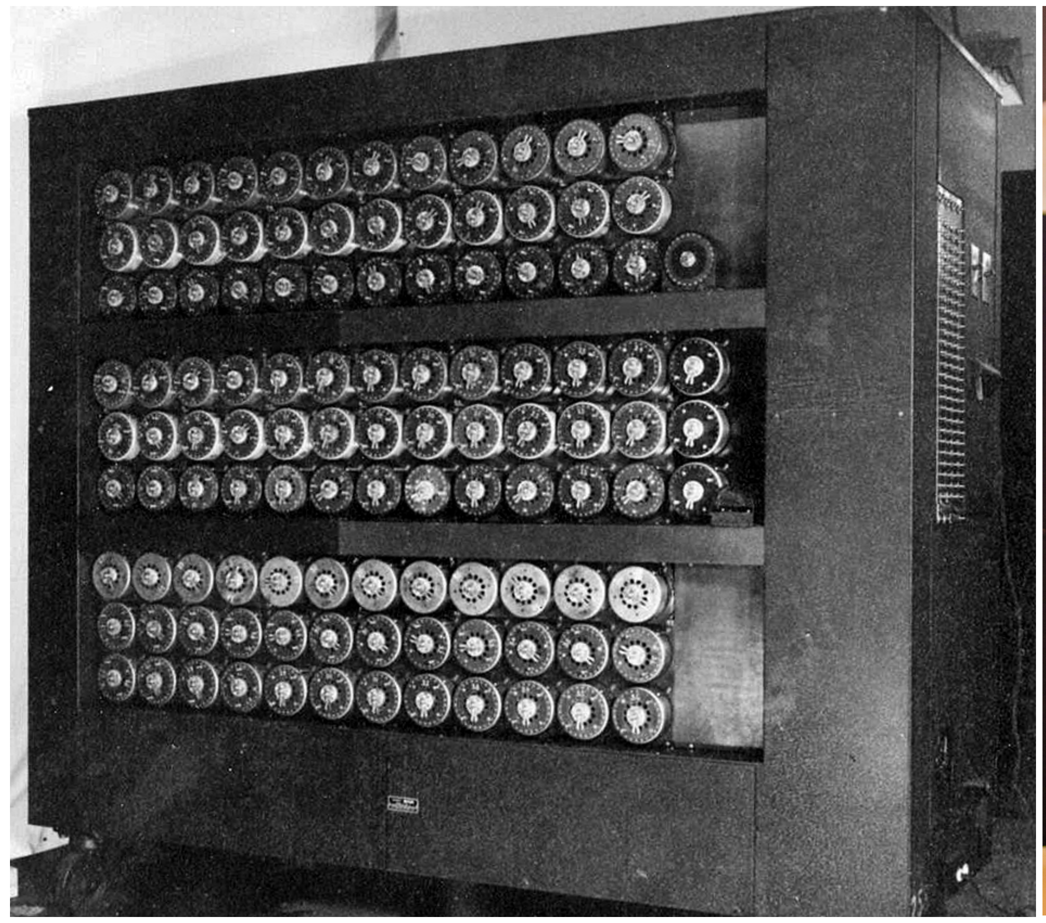
ONLY 100 qubits holding *little information* for a *very short time*

Computing beginnings…

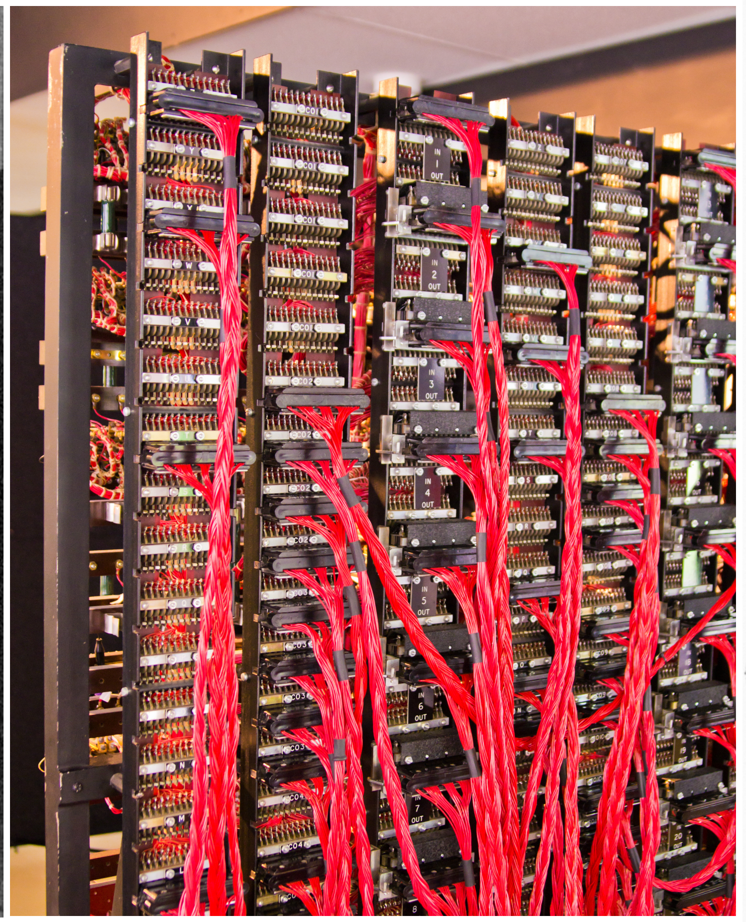
Classical computing (1939-1960)

1939: Electro-mechanical: The Bombe

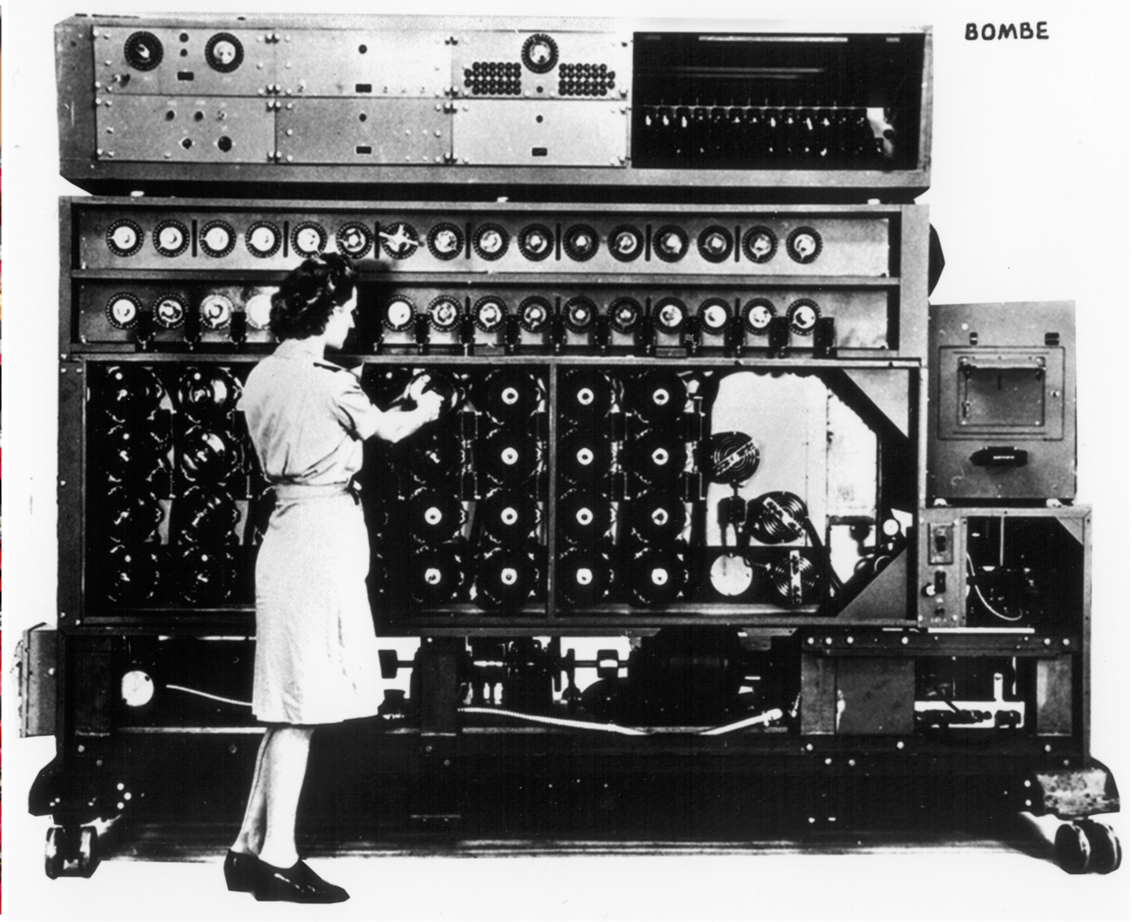
Application: deciphering German encrypted messages during WWII



(Source: Wikipedia)



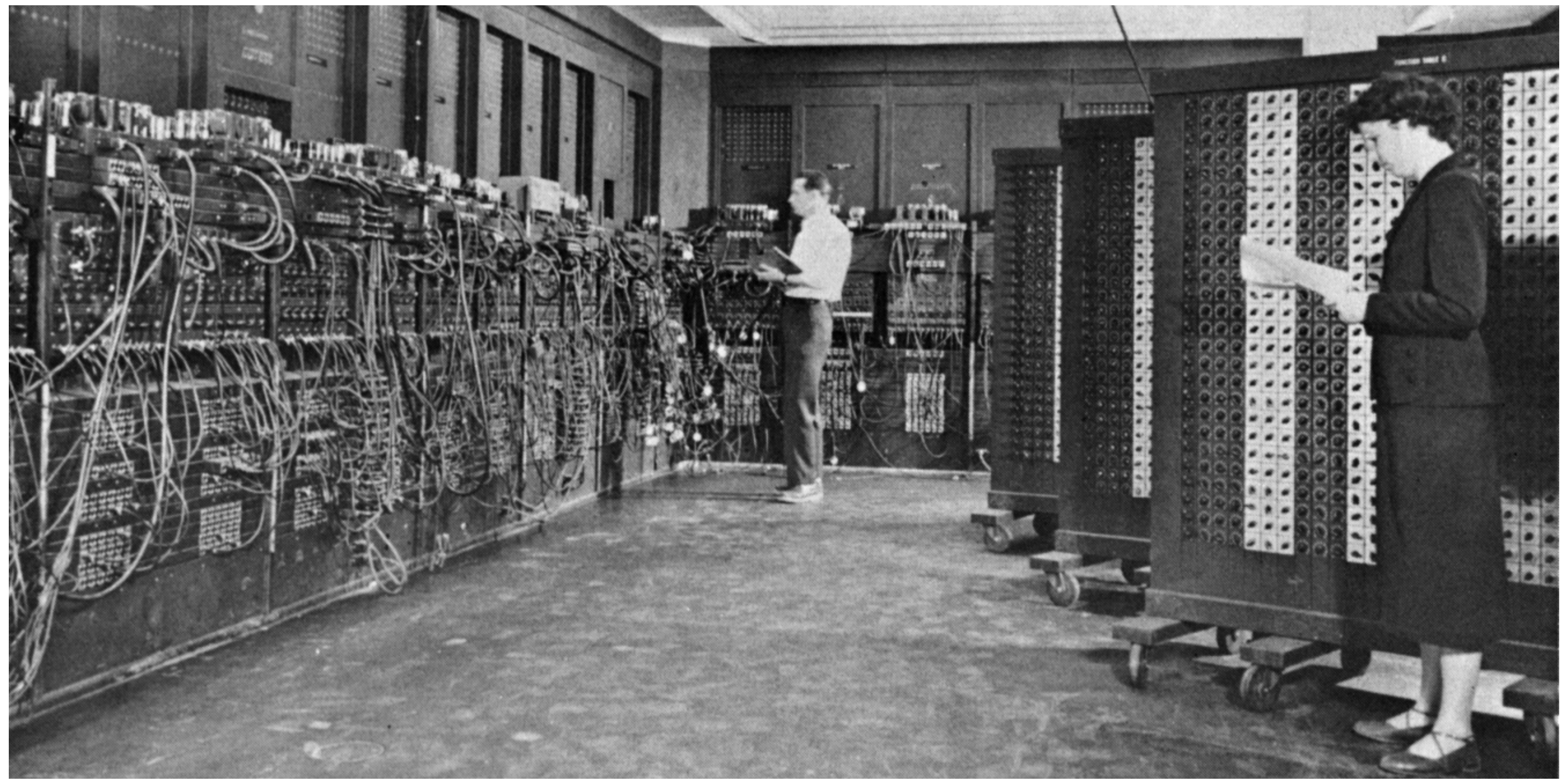
(Source: Wikipedia)



(Source: Wikipedia)

1945: Electronic Numerical Integrator and Computer (ENIAC): first programmable digital computer

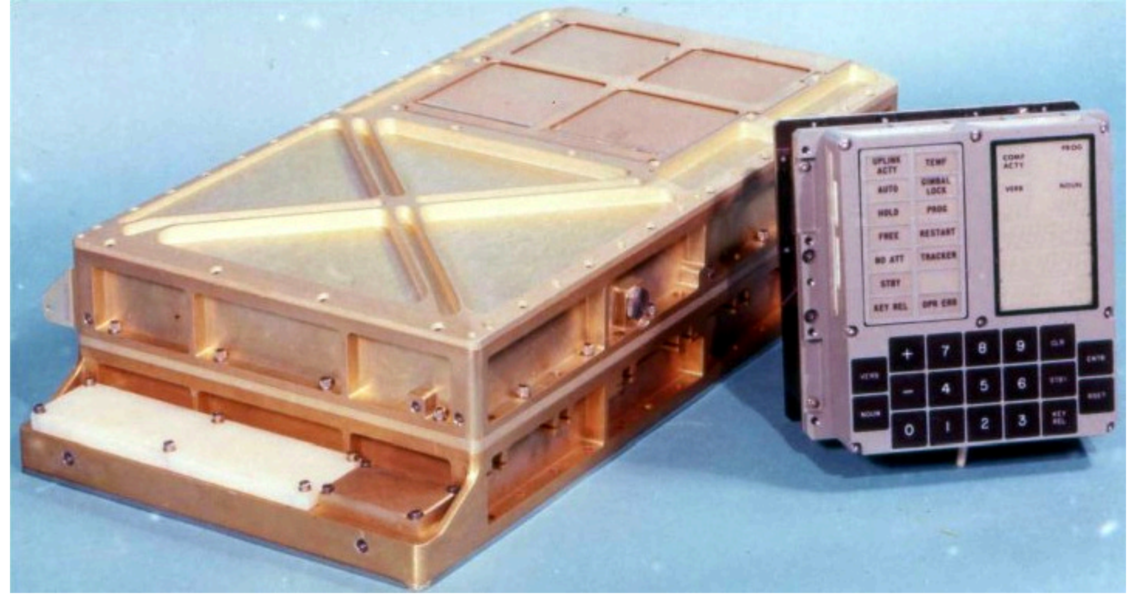
Application: solving numerical problems: artillery firing tables, feasibility of thermonuclear weapons



(Source: Wikipedia)

1966: Apollo Guidance Computer

Application: Landing on the moon



(Source: Wikipedia)

Quantum computing (1981-2023)

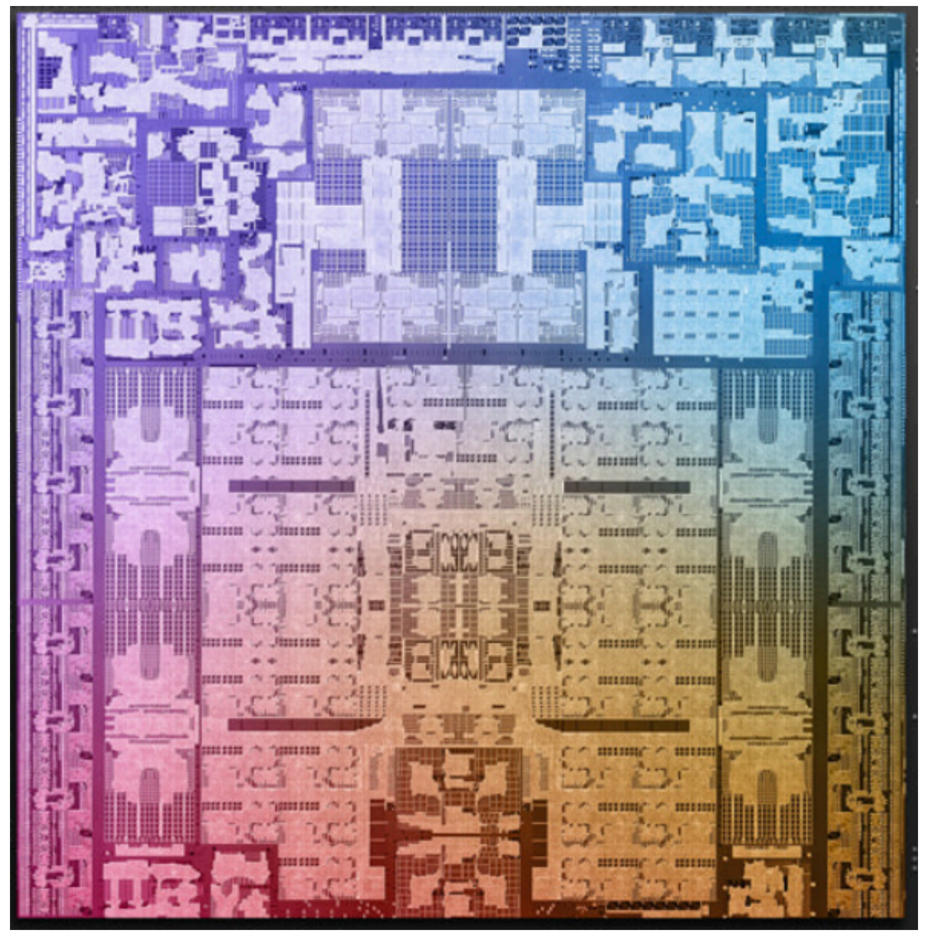
Source: IBM

Classical computing (2022)

2022: iPhone 14 Pro

(Source: Apple)

Apple's M2 chip



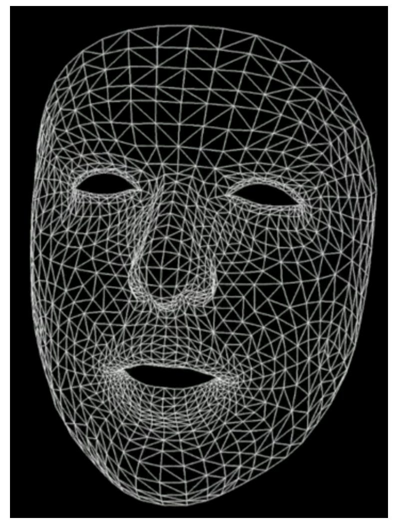
67 billion transistors (Source: Apple)

Applications: …

Facial recognition

(Source: Apple)

Face tracking



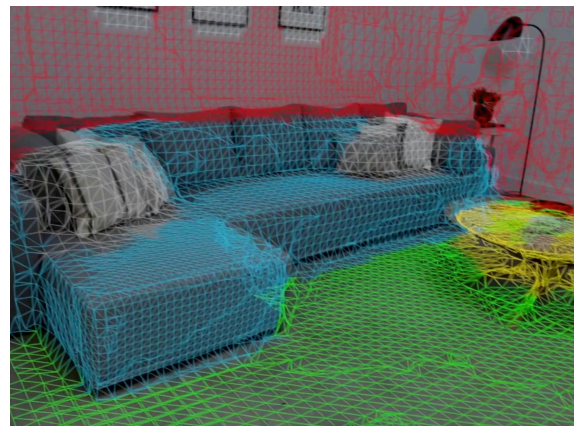
Object detection

Image classification

Generated with Stable Diffusion

Photo artistry

LIDAR 3D scene Modelling and understanding



Quantum computing (2070-2100)

?

Applications (probable)

modelling molecules interactions

chemistry, material design, drug development

finance, agriculture

1. Why should we care ?

A. Potential to break current encryption schemes

Source: Midjourney

RSA cryptosystem relies on the practical difficulty of factoring the product of two large prime numbers (source: Wikipedia)

The world economy (on-line) depends on cryptography: information, traffic encrypted while sent over the web

RSA-250 has 250 decimal digits (829 bits)

```
RSA-250 = 2140324650240744961264423072839333563008614715144755017797754920881418023447
          1401366433455190958046796109928518724709145876873962619215573630474547705208
          0511905649310668769159001975940569345745223058932597669747168173806936489469
          9871578494975937497937
```

```
RSA-250 = 6413528947707158027879019017057738908482501474294344720811685963202453234463
          0238623598752668347708737661925585694639798853367
        × 3337202759497815655622601060535511422794076034476755466678452098702384172921
          0037080257448673296881877565718986258036932062711
```

factored in February 2020 by

Fabrice Boudot, Pierrick Gaudry, Aurore Guillevic, Nadia Heninger, Emmanuel Thomé, and Paul Zimmermann.

Using approximately 2700 CPU core-years

RSA-2048 has 617 decimal digits (2,048 bits)

```
RSA-2048 = 2519590847565789349402718324004839857142928212620403202777713783604366202070
           7595556264018525880784406918290641249515082189298559149176184502808489120072
           8449926873928072877767359714183472702618963750149718246911650776133798590957
           0009733045974880842840179742910064245869181719511874612151517265463228221686
           9987549182422433637259085141865462043576798423387184774447920739934236584823
           8242811981638150106748104516603773060562016196762561338441436038339044149526
           3443219011465754445417842402092461651572335077870774981712577246796292638635
           6373289912154831438167899885040445364023527381951378636564391212010397122822
           120720357
```

?

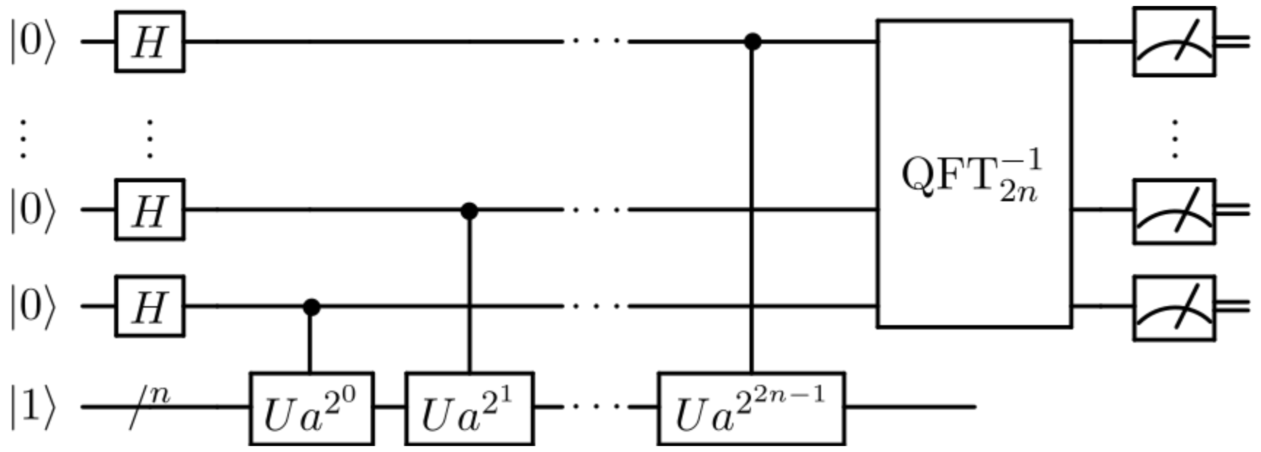
Source: Wikipedia RSA_numbers

1994 - Shor's algorithm

Peter Shor, professor of Applied mathematics at MIT

"Shor's algorithm is a quantum algorithm for factoring the prime factors of an integer" (source: Wikipedia) (semiprime)

Fourier transform on a quantum processor…



Practical implementation

Factoring a 2,048 bit integer would require approx. 4,000 perfect qubits and about 1,000,000,000 gates… (MIT 2017 - Quantum Computational Supremacy)

Today's Noisy Intermediate Scale Quantum (NISQ) processor have about 100 "imperfect" (noisy) qubits… Coherence time of qubits is around milli- to micro-second

With today's technology and knowledge, one would need approximately:

4,000,000 qubits that would not negatively interfere too much with each other and stay coherent for a significant amount of time…

Breaking current encryption schemes

A 2,048 bit integer might *never* be factored on a quantum processor…

Not very likely in the next half century…

Generated with dreamstudio.ai


(Source: Midjourney)

Post-quantum cryptography

Development of post-quantum cryptography (quantum-proof / quantum-resistant schemes)

NIST Post-Quantum Cryptography Standardization

Competition started in 2016: lattice, code-based, hash-based algorithms…

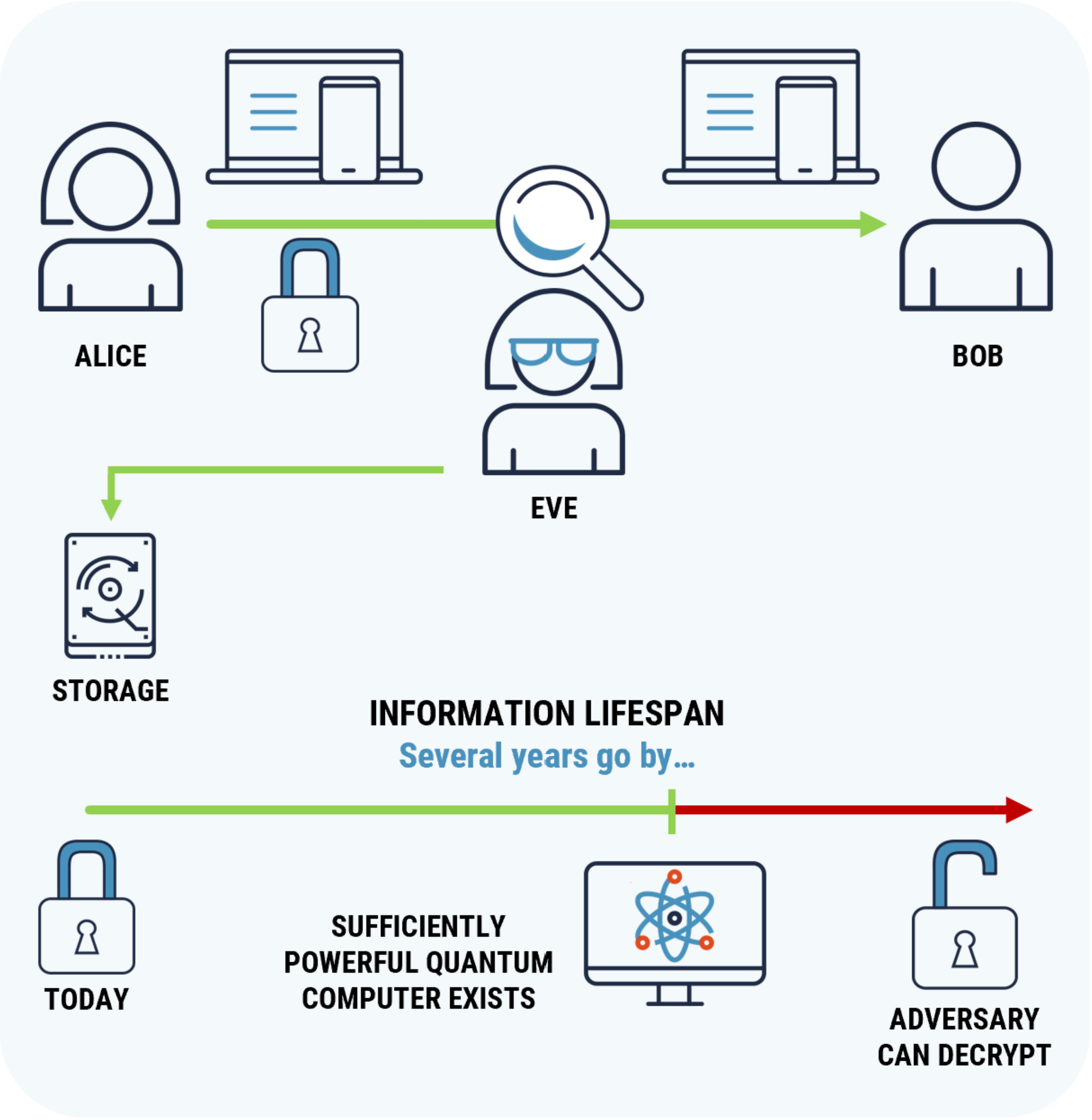
2022-07-05: First winners for standardization: lattice based (CRYSTALS-Kyber) and hash-based (SPHINCS+)

Quantum key distribution

Governments / companies transition to quantum safe encryption

Stashing other countries' encrypted secrets to decrypt later (e.g. Forbes 2023-01)

National defence is getting ready; e.g. Gov. Of Canada Quantum 2030



Source:cyber.gc.ca

Fritz Haber (wikipedia)

Haber–Bosch process, a method used in industry to synthesize ammonia from nitrogen gas and hydrogen gas. (Source: Wikipedia)
(1909)

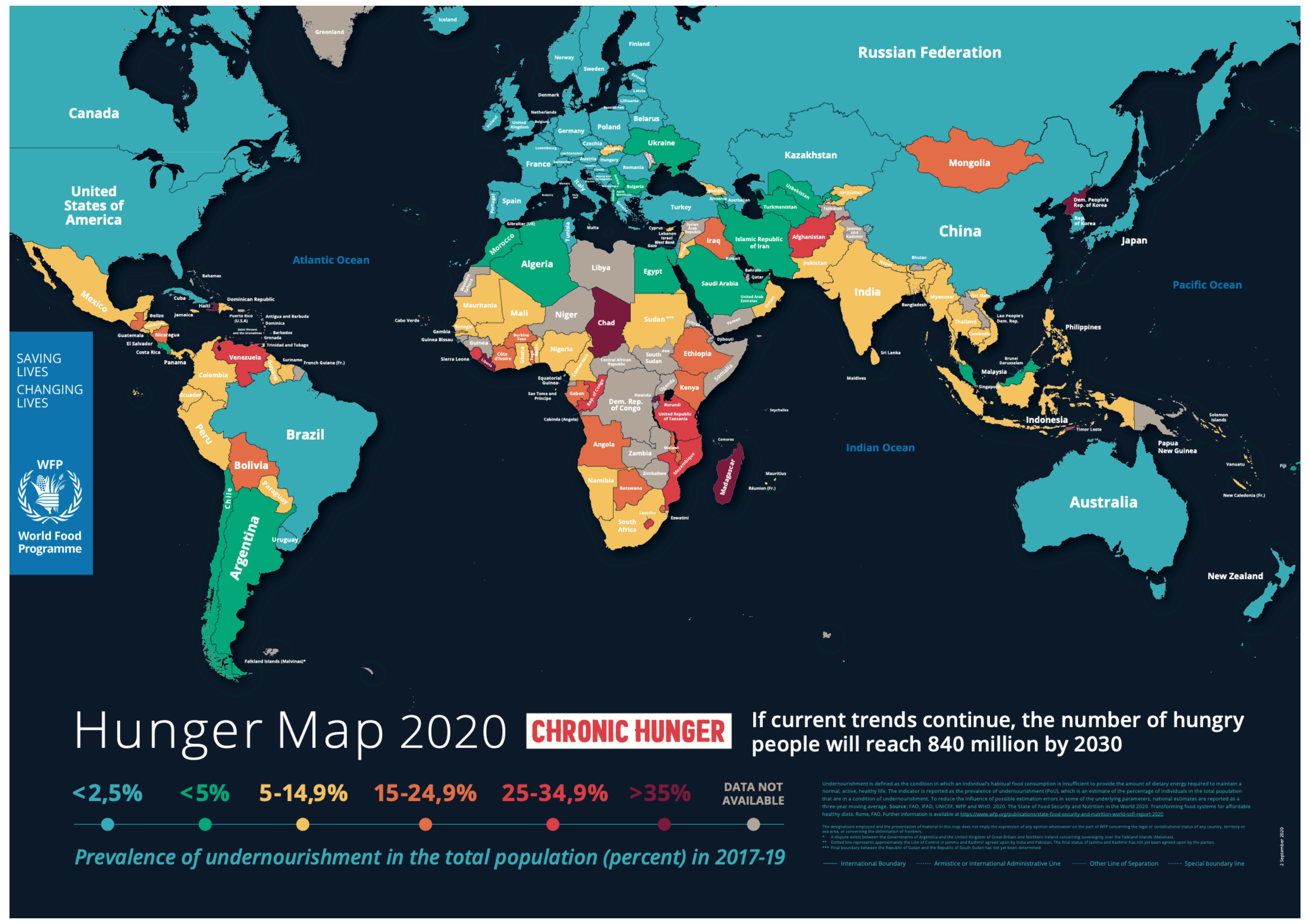
"Solving one of the biggest problem humanity has ever faced" (feeding billions of people) (source: Veritasium)

The Green Revolution (third agricultural revolution)

Fertilizer made using ammonia: Haber-Bosch process $N_2 + 3\,H_2 \longrightarrow 2\,NH_3$

The Haber-Bosch process "consumes 1% of the world's total energy production." (Nature 2019)

The process requires high temperatures (500 degree C) and pressures.



World Food Program hunger map (840 million by 2030)

Finding a better way (less energy requirement) to produce ammonia

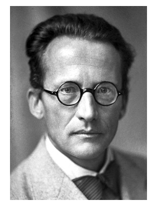
Some plants can synthesize ammonia directly from air and water at room temperature (Nature)

Using quantum processors to simulate quantum processes (molecules interactions)

Quantum Chemistry :

$$i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle = \hat{H}|\psi(t)\rangle$$

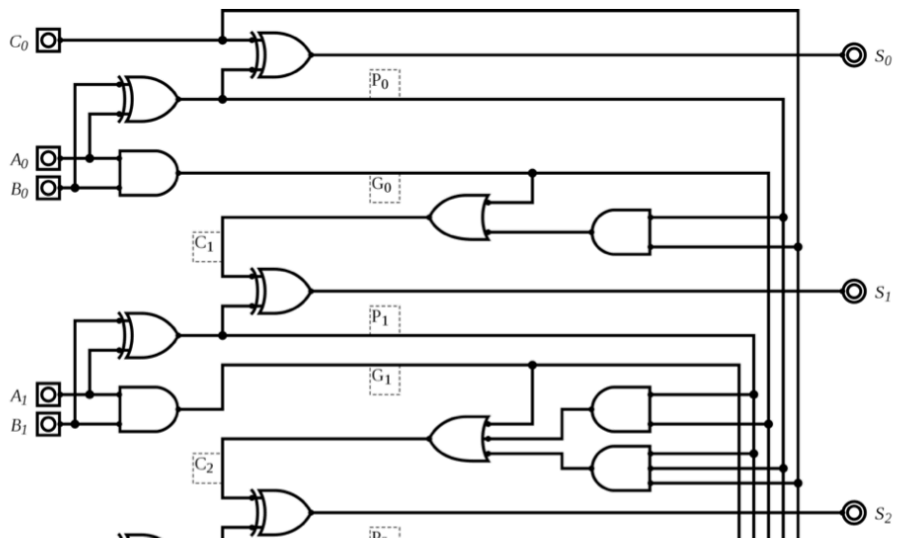
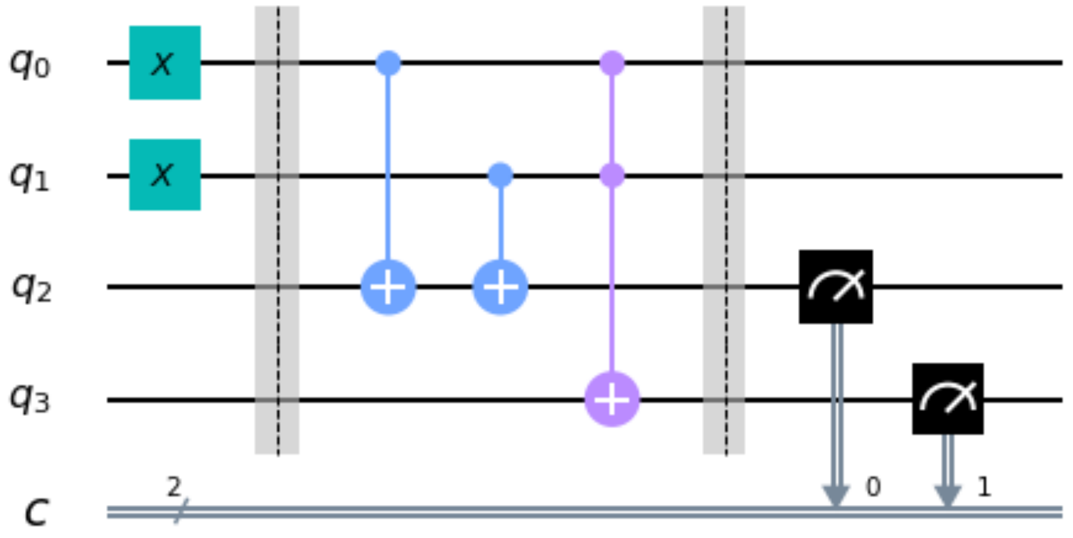
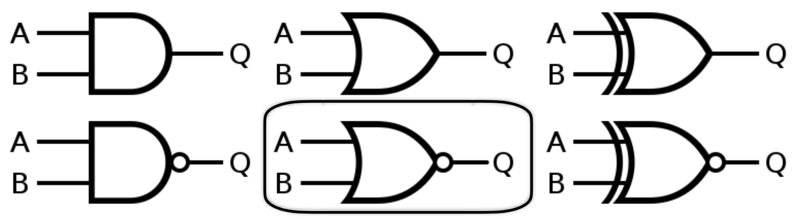
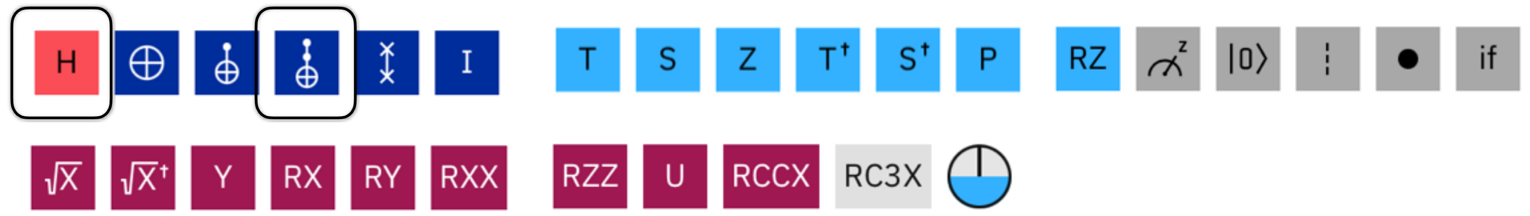
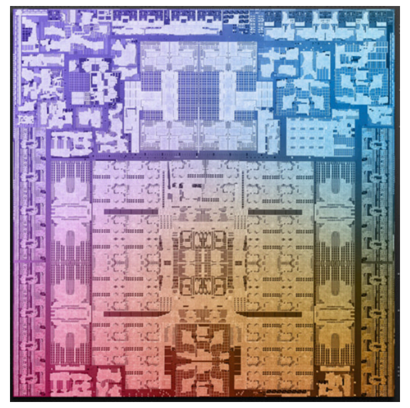
"Understanding electronic structure and molecular dynamics using the Schrödinger equations are central topics in quantum chemistry."



(1925)

(Source: Wikipedia)

2. How does it work ?

	Classical computing	Quantum computing
High level language	python	python
Software packages	PyTorch	Qiskit
Algorithms	Fourier transform, sorting algorithms, balanced search trees, Hash tables, minimum spanning trees, linear programming, Maximum flow / minimum cut, … (Algorithms - Princeton part 1, part 2)	Quantum Fourier transform, quantum phase estimation algorithm, Shor's algorithm, Grover's algorithm, quantum optimization algorithms, Eigensolver, … (Qiskit Algorithms)
Compilers		
Machine code		
Assembler		
Circuits		
Gates		
Processor	 (Source: Apple)	 Source: IBM

Classical mechanics | Quantum mechanics

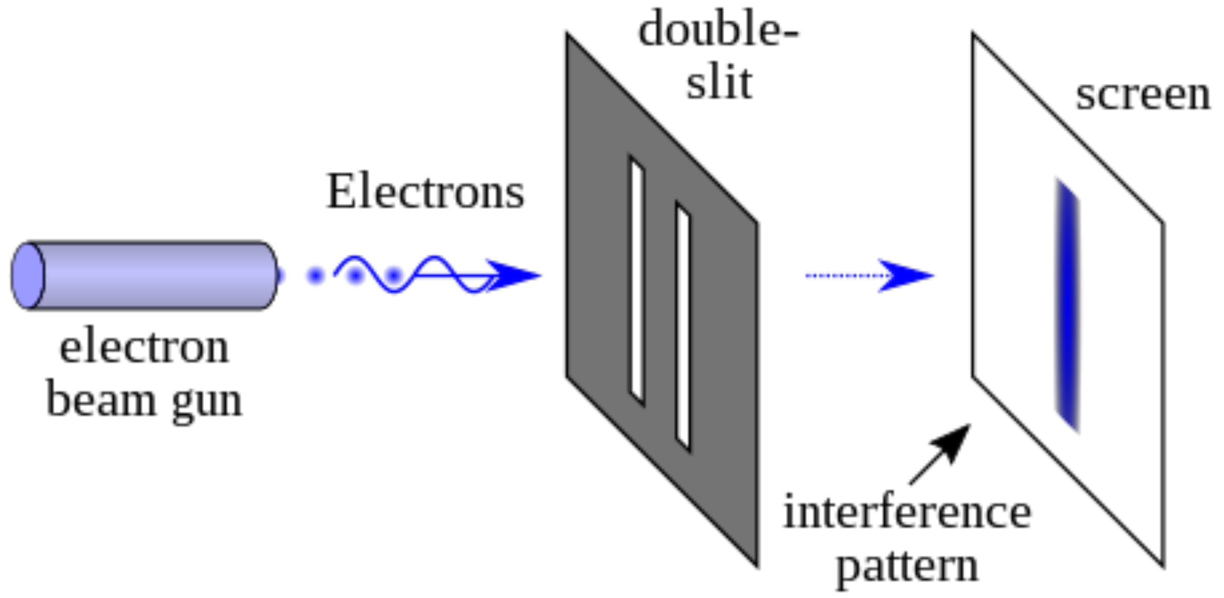
	Classical	Quantum
Scale	Applies to *macroscopic* objects (planets and everyday objects)	Applies to *microscopic* objects (atoms and subatomic particles)
Math framework	Newton's equations, *deterministic*, position, velocity, acceleration	Schroedinger's equation, wave function, *ß* distribution
Behaviour	Particles have definite properties (position, momentum) *Deterministic*, position, trajectories can be predicted precisely.	*Wave-particle duality*. Behaviour *probabilistic*. Impossible to know both position and momentum.
Measurement	Precise and not disturbing system being measured	Affect system being measured. Exact state cannot be measured.
Energy levels	Energy levels are continuous, can have any values	Energy is quantized. Can only have certain values.
Superposition	Objects can only be in one place (state) at a given time	Objects can be in multiple states at once.
Entanglement	Non existent	Objects properties (states) can be correlated even when far away

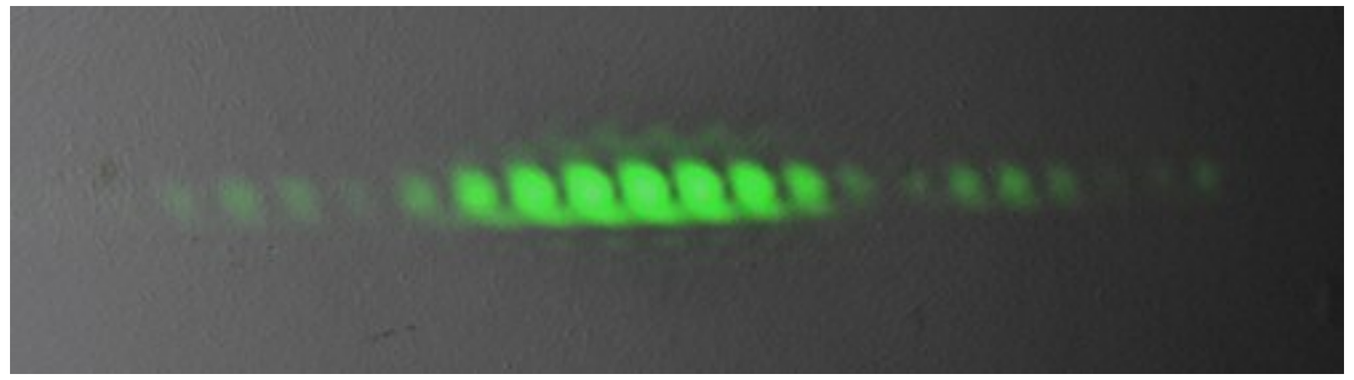
Theories in physics that describe the behaviour of **matter and energy**

Wave particle duality

cmc.edu

Double-slit experiment





(Source: wikipedia)

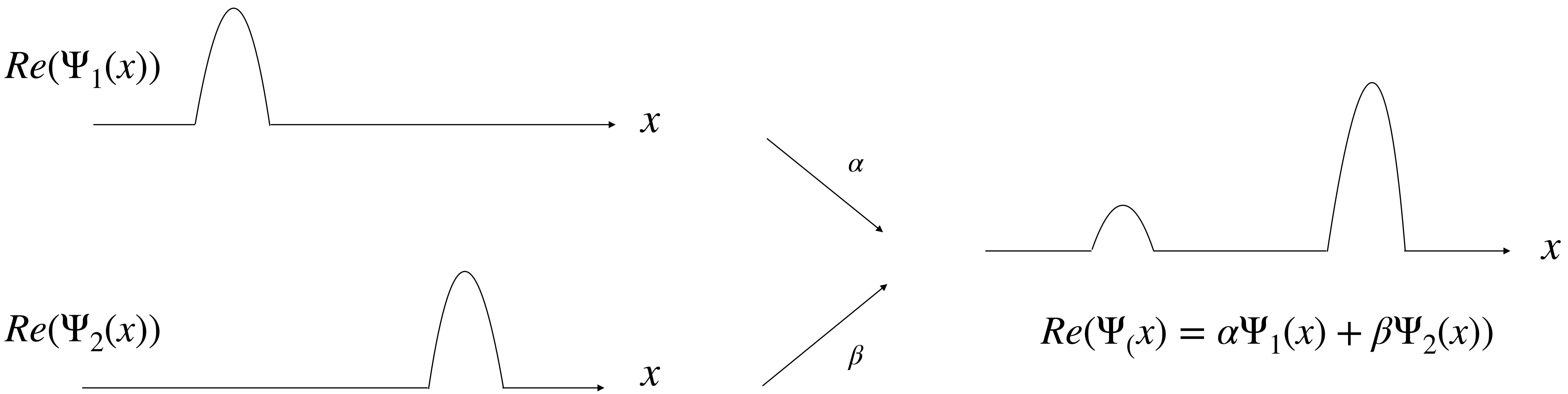
	is	behaves
An electron e^-	not a particle	like a particle
	not a wave	like a wave

(Also applies photons, atoms and molecules)

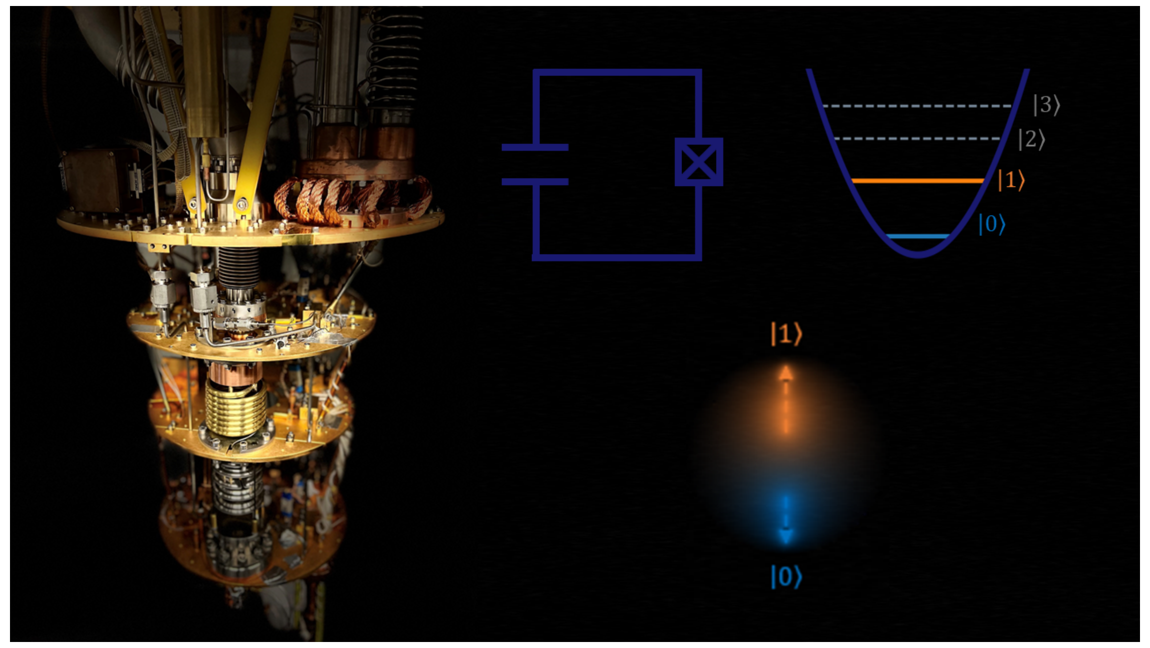
1. Configuration of a quantum object is described by a complex wave function $\Psi(x)$

2. $|\Psi(x)|^2$ is the probability density of finding the object at position x

3. Superposition principle: given $\Psi_1(x)$ and $\Psi_2(x)$, it is possible to have $\Psi(x) = \alpha\Psi_1(x) + \beta\Psi_2(x)$

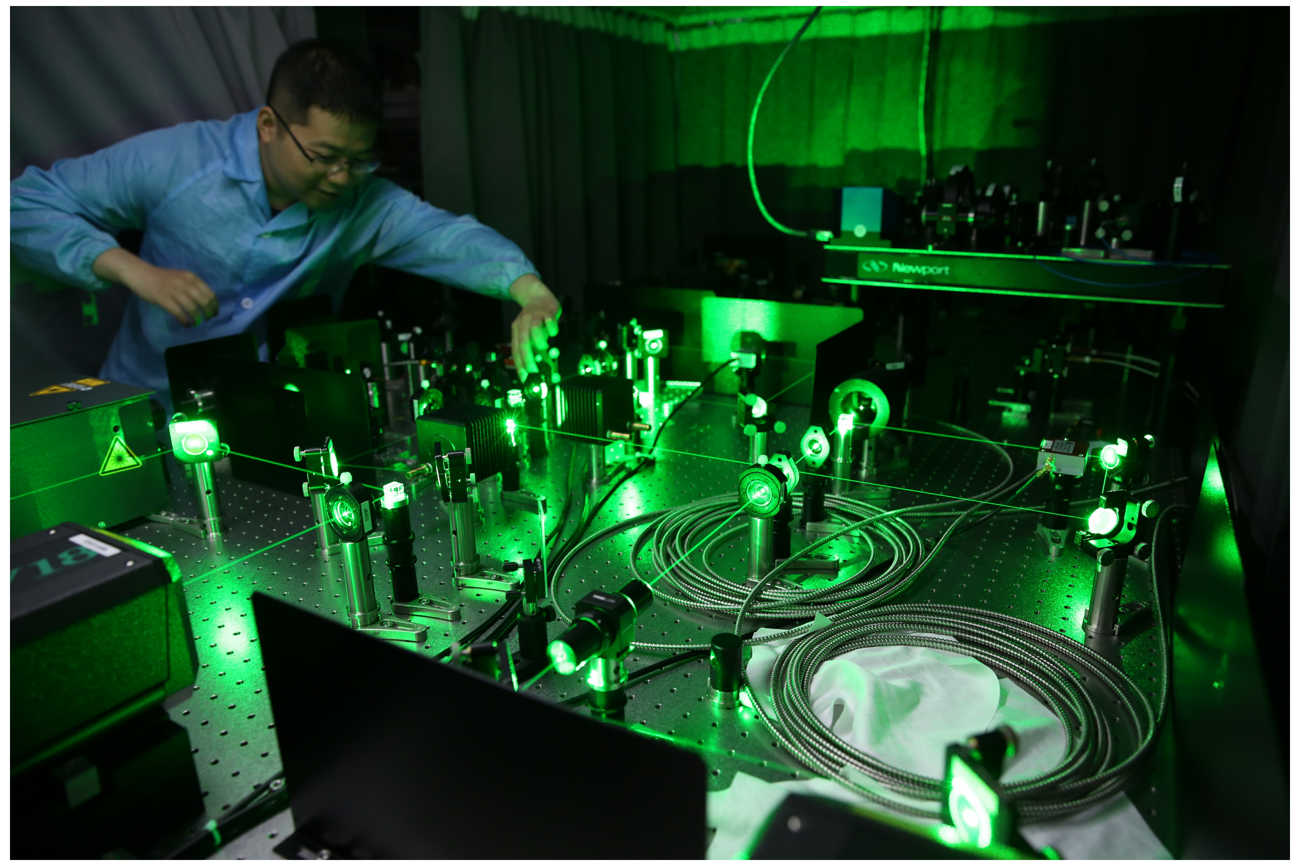


Superconductor



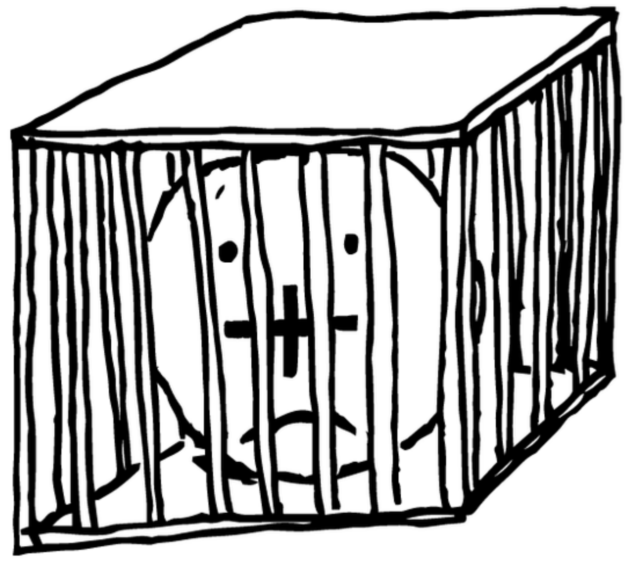
Source: QST @ Naples

Photons

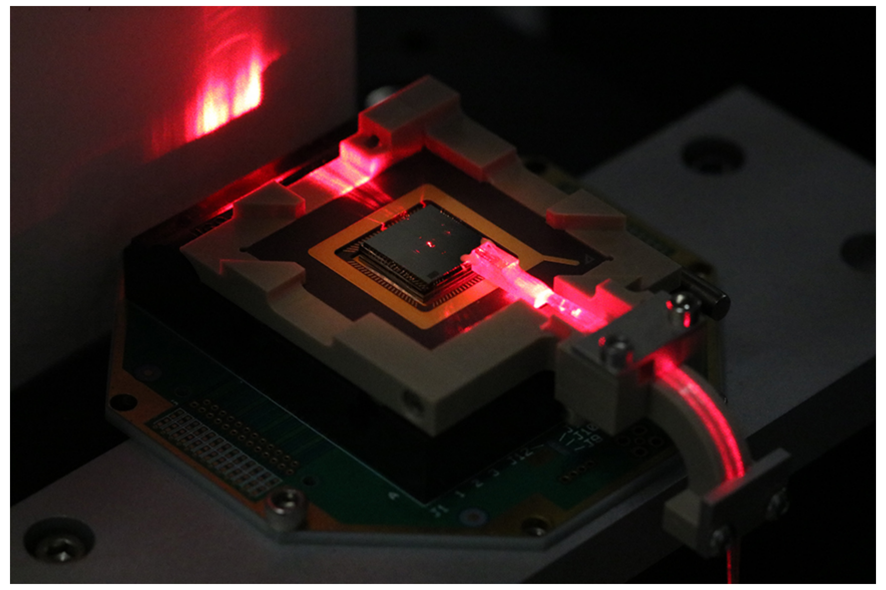


Source: CAS-Alibaba Quantum Computing Laboratory

Trapped ions



Source: U. Chicago



Source: MIT News

Head or Tail

Spinning coin

Classical bit (binary digit) vs Quantum bit (qubit)

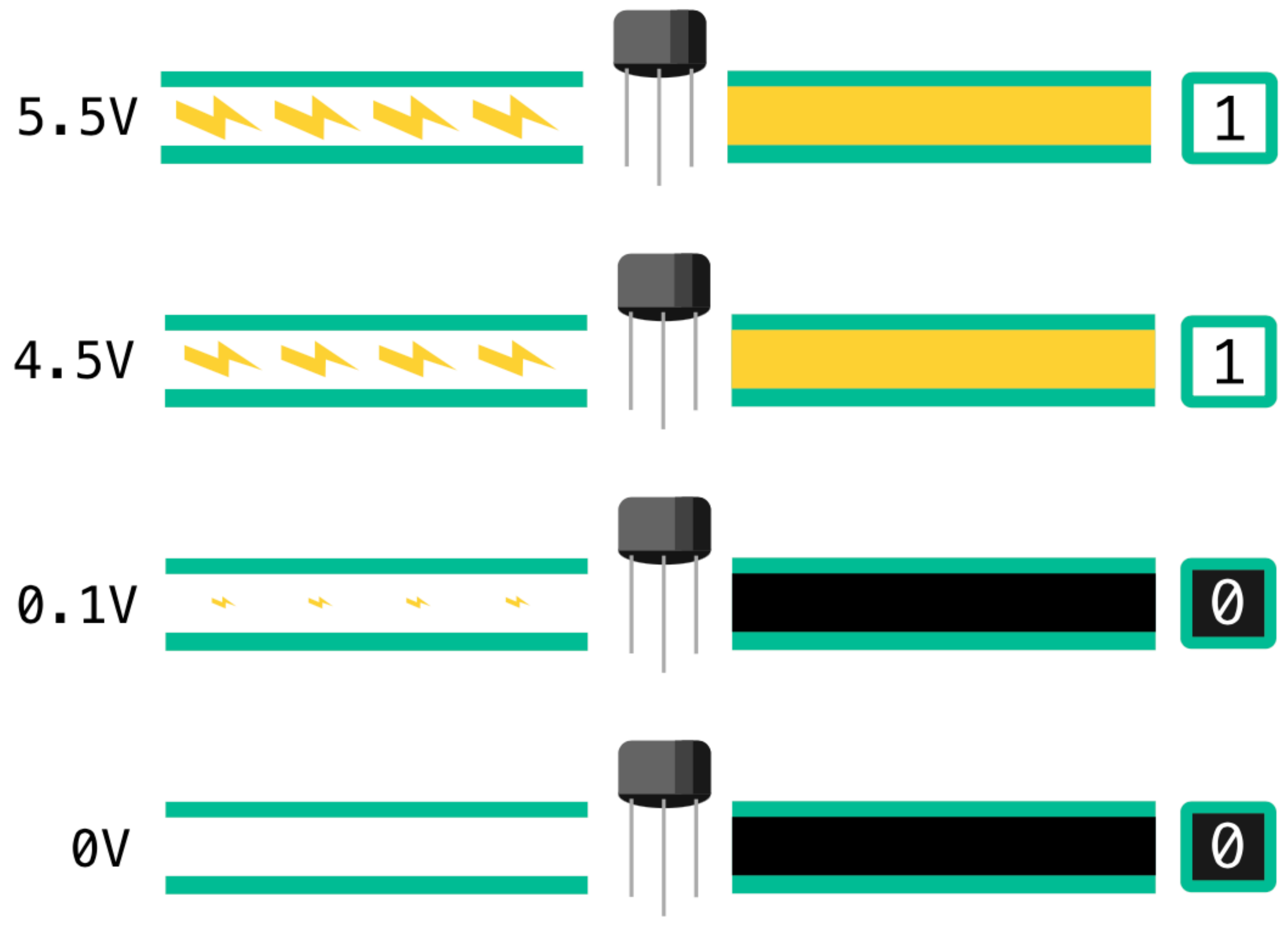
Bit

0 (1) dimension - 2 discrete values

Two distinct values: 0 or 1

Can be represented as two different voltage levels

Show voltage diagram



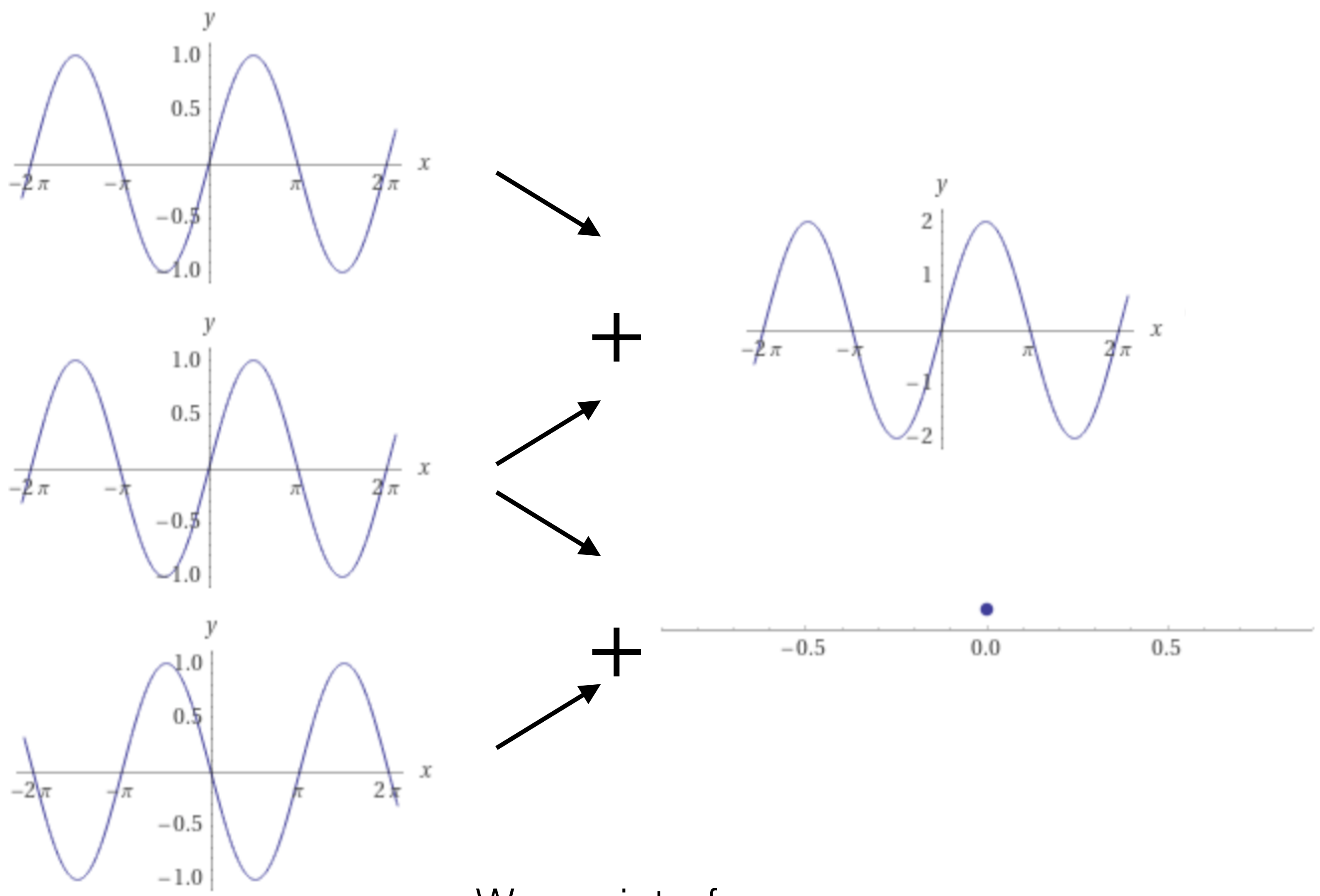
Source: KhanAcademy.org

Qubit

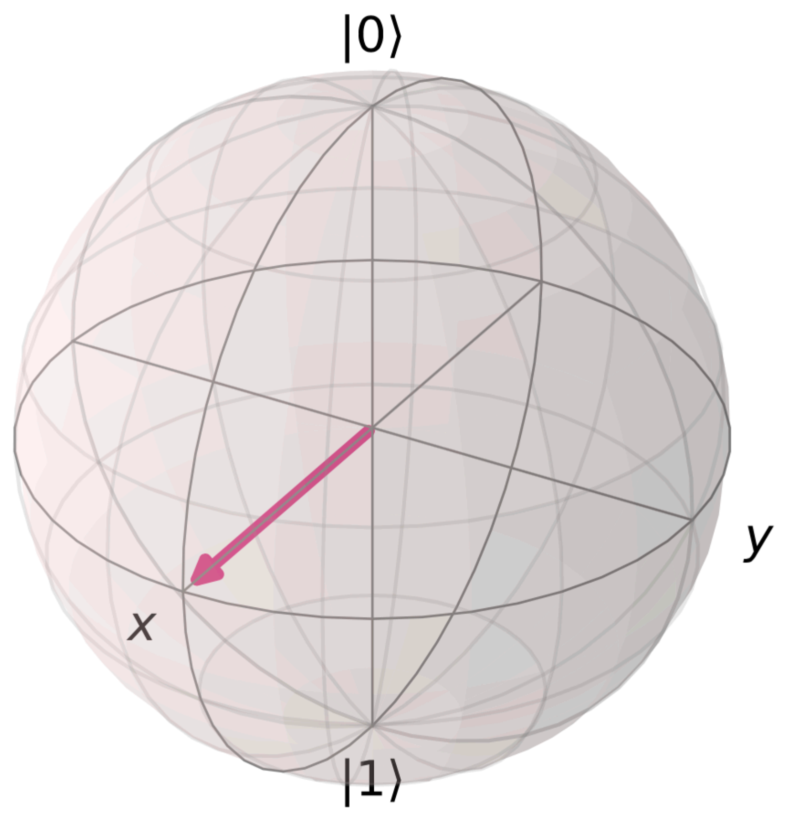
Unobservable: **2 dimensions - complex continuous values**

Observable: Either 0 or 1 (classical bit)

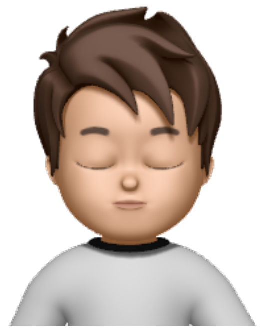
Particle / wave duality



Waves interference



Bloch sphere

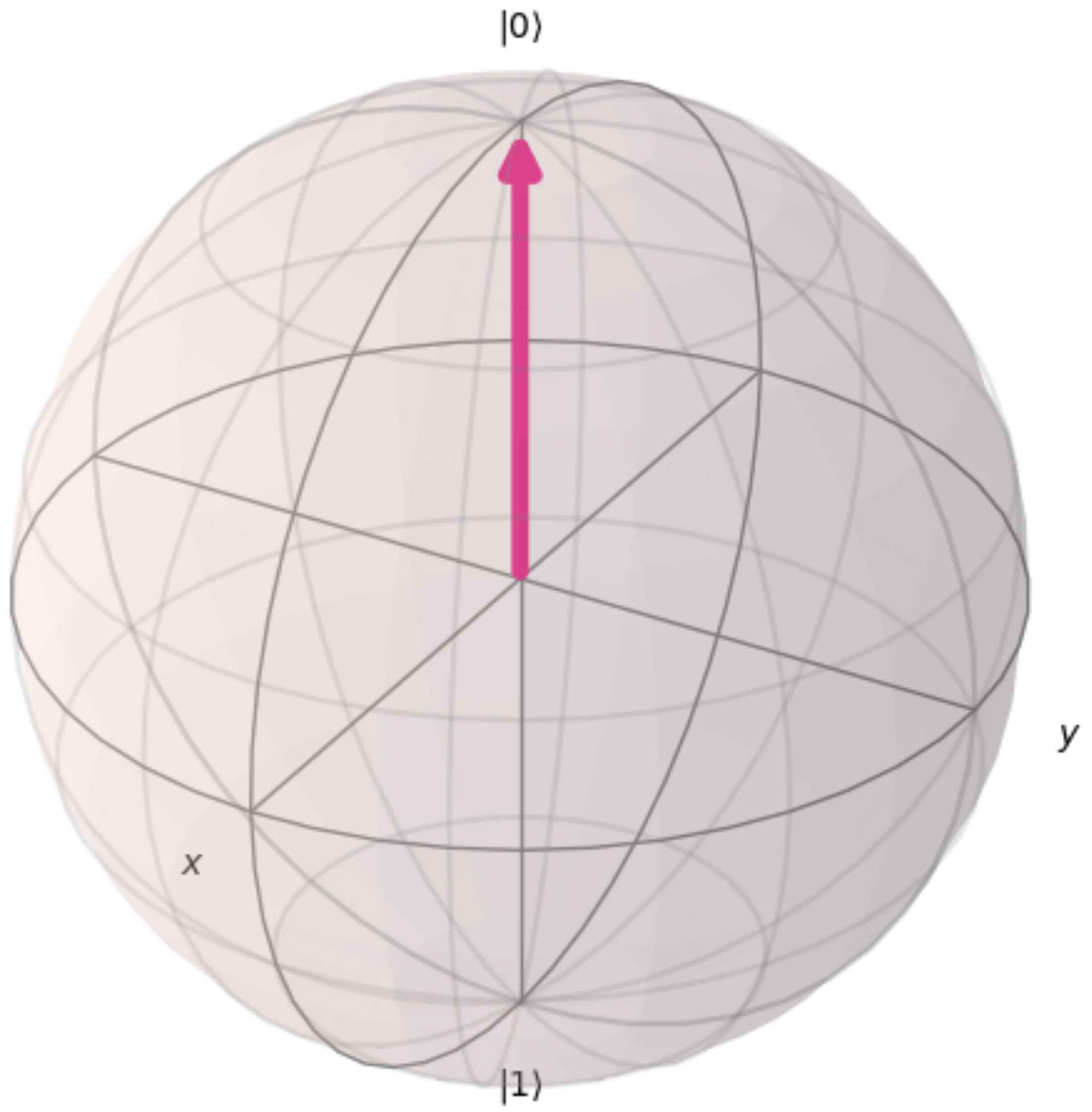


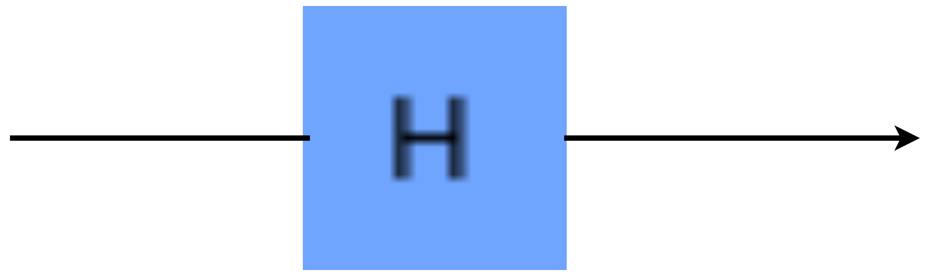
Unobservable (quantum)

"Schrödinger's cat"

Observable (classical)

Initial (zero) state

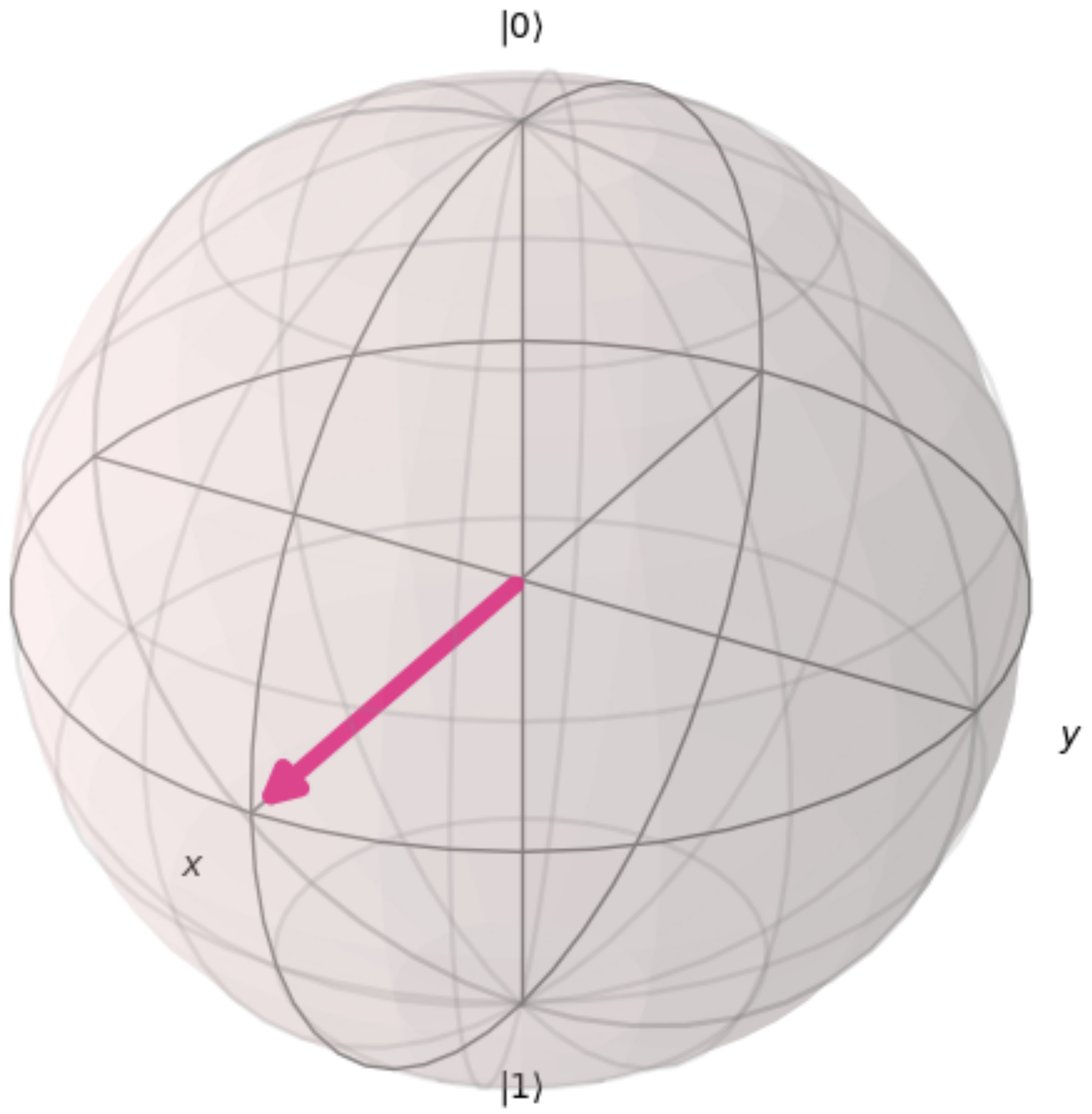


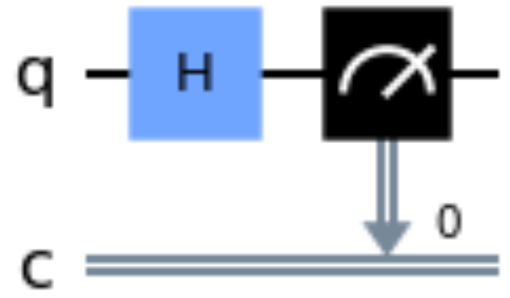


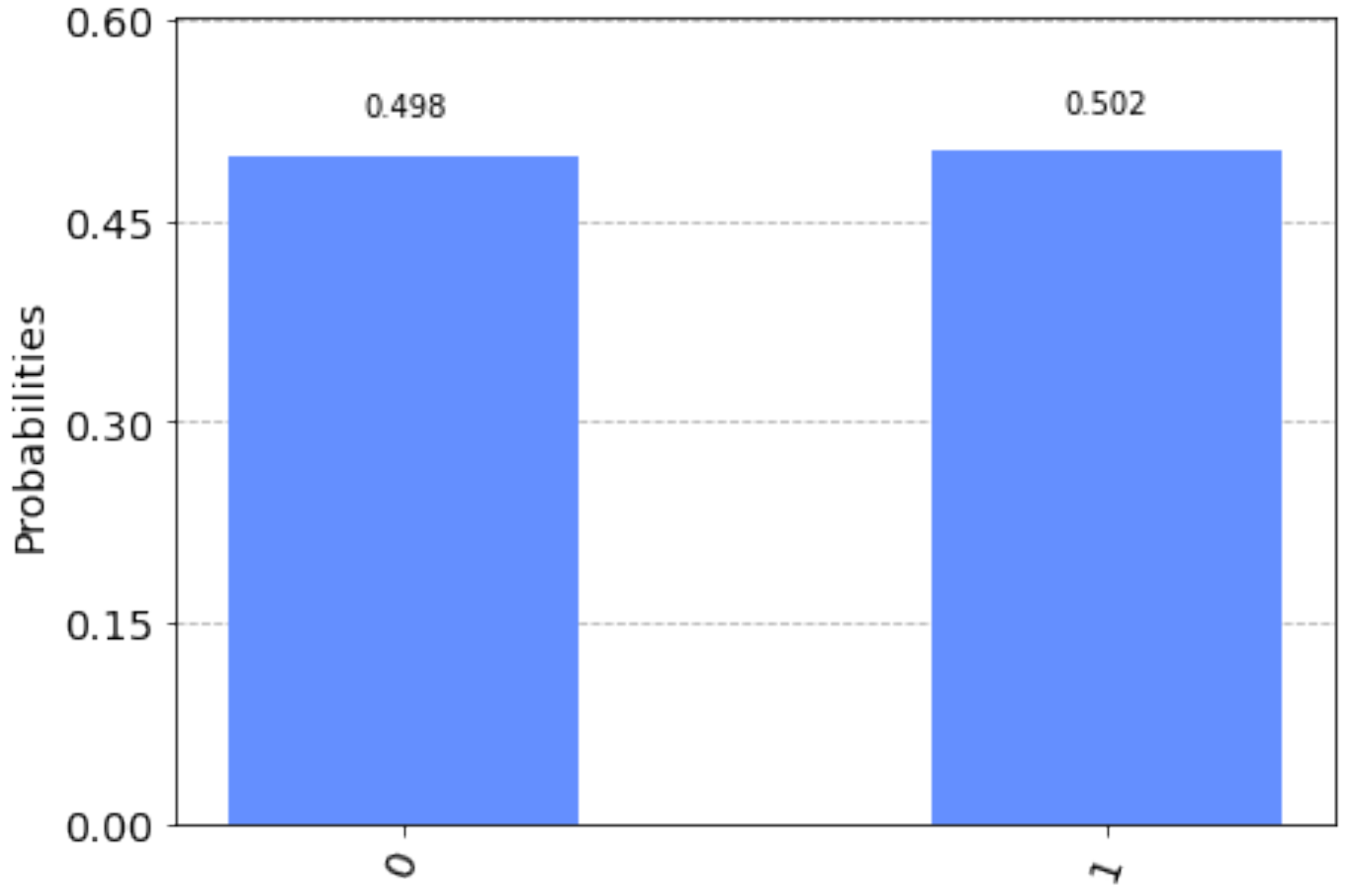
Hadamard gate

Applying electromagnetic fields

Initial (superposition) state





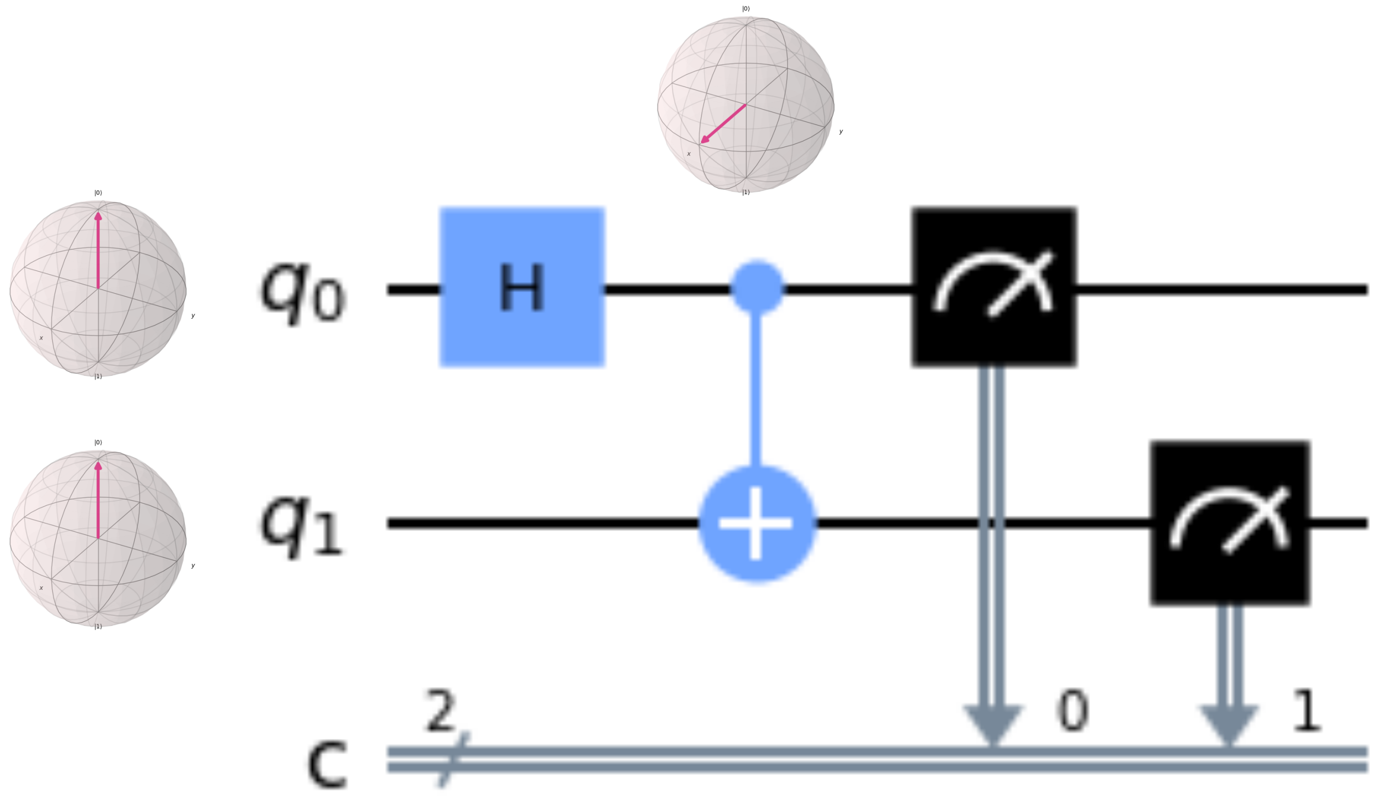


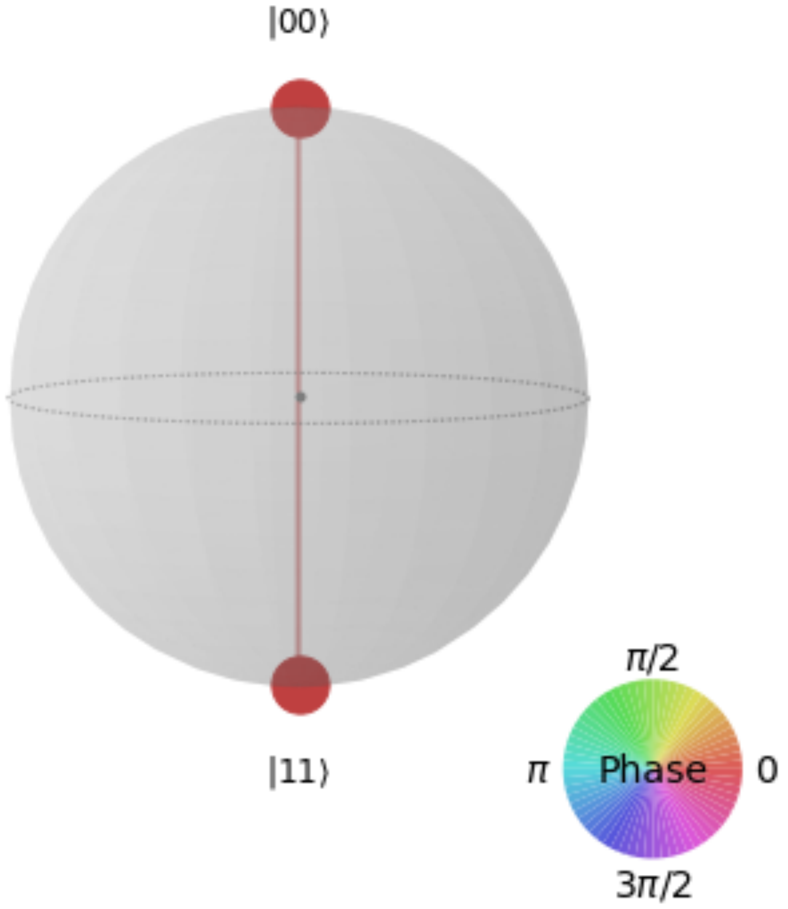
$$\begin{pmatrix} 1 \\ 0 \end{pmatrix} \begin{matrix} |0> \\ |1> \end{matrix}$$

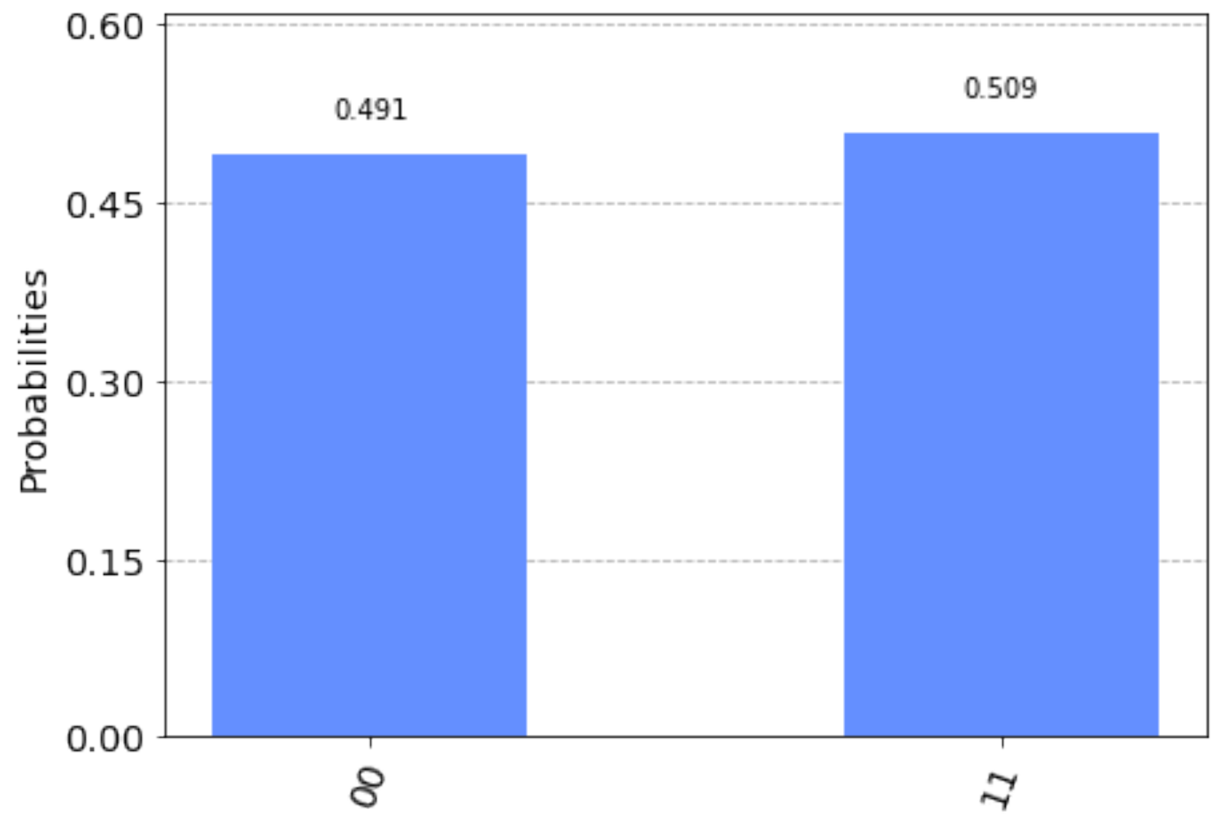
$$H = \begin{pmatrix} \frac{1}{\sqrt(2)} & \frac{1}{\sqrt(2)} \\ \frac{1}{\sqrt(2)} & -\frac{1}{\sqrt(2)} \end{pmatrix}$$

$$\begin{pmatrix} \frac{1}{\sqrt(2)} \\ \frac{1}{\sqrt(2)} \end{pmatrix} \begin{matrix} |0> \\ |1> \end{matrix}$$

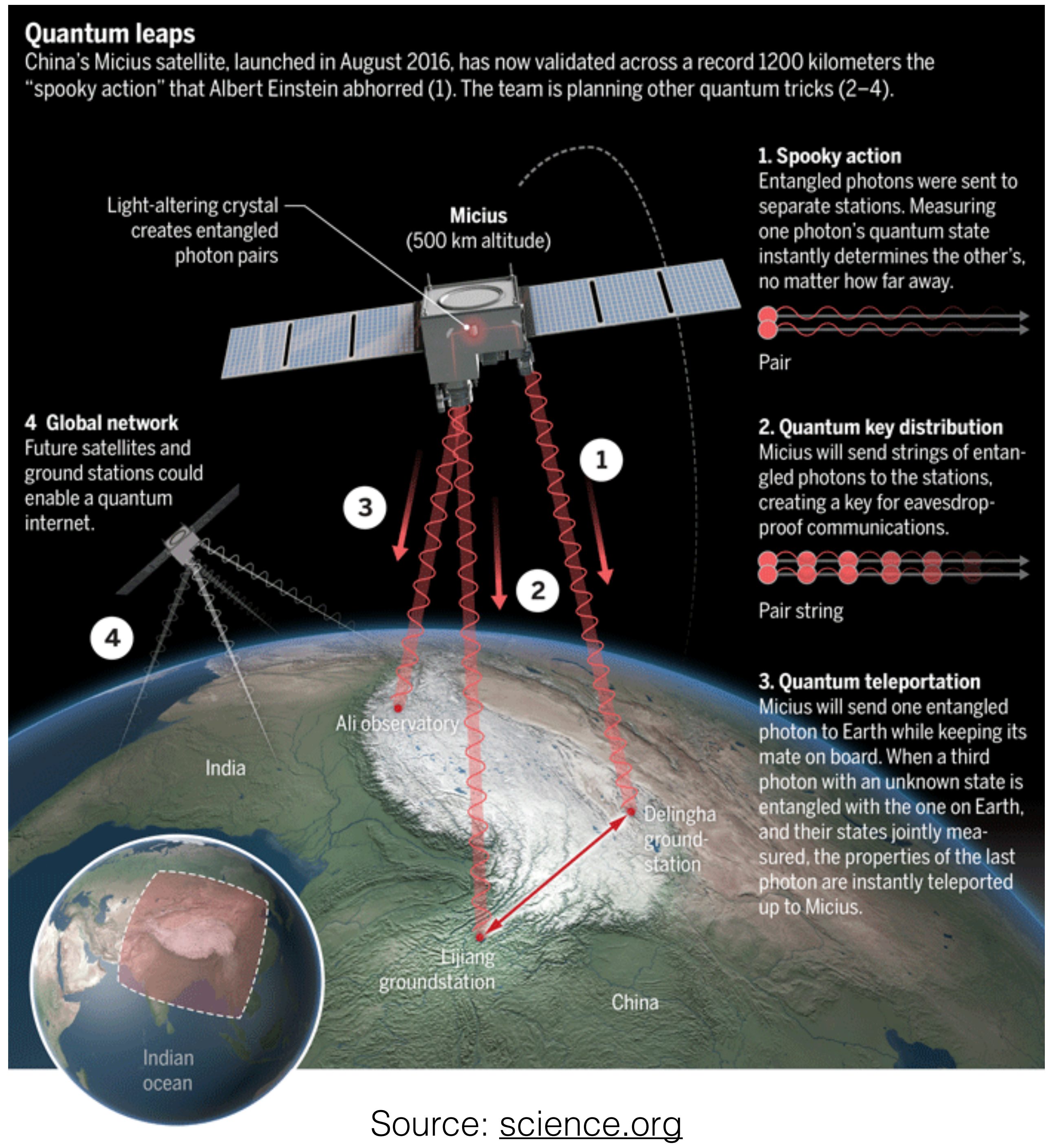
Superposition = “we have no clue what is going on … superposition is really weird, but true” (MIT Quantum Physics 8.04)







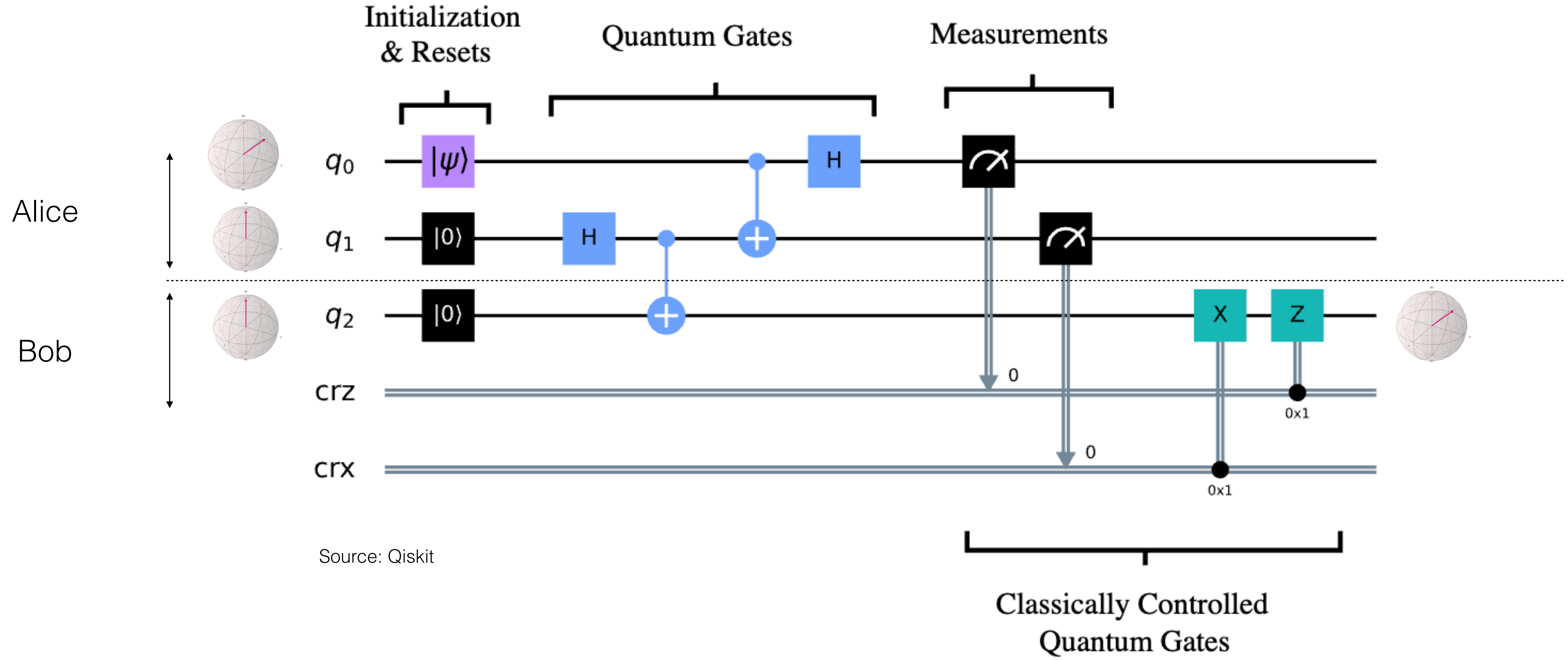
$$C\left(H\begin{pmatrix}1\\0\end{pmatrix}\otimes\begin{pmatrix}1\\0\end{pmatrix}\right) = C\left(\begin{pmatrix}\frac{1}{\sqrt{(2)}}\\\frac{1}{\sqrt{(2)}}\end{pmatrix}\otimes\begin{pmatrix}1\\0\end{pmatrix}\right) = \begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{pmatrix}\begin{pmatrix}\frac{1}{\sqrt{(2)}}\\0\\\frac{1}{\sqrt{(2)}}\\0\end{pmatrix} = \begin{pmatrix}\frac{1}{\sqrt{(2)}}\\0\\0\\\frac{1}{\sqrt{(2)}}\end{pmatrix}\begin{matrix}|00>\\|01>\\|10>\\|11>\end{matrix}$$



Source: science.org

“Spooky action at a distance” Einstein (source: Wikipedia)

Quantum teleportation



Source: Qiskit

Code: quantum teleportation Qiskit tutorial (lecture video)

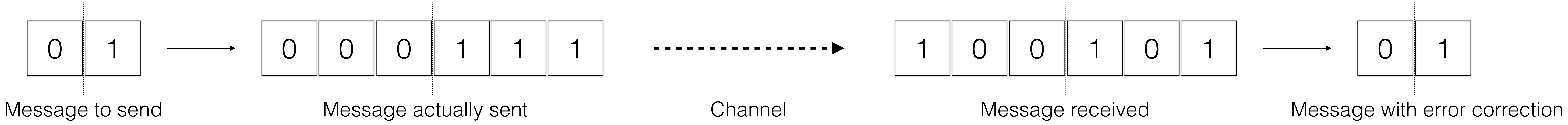
3. What are the problems ?

Problems

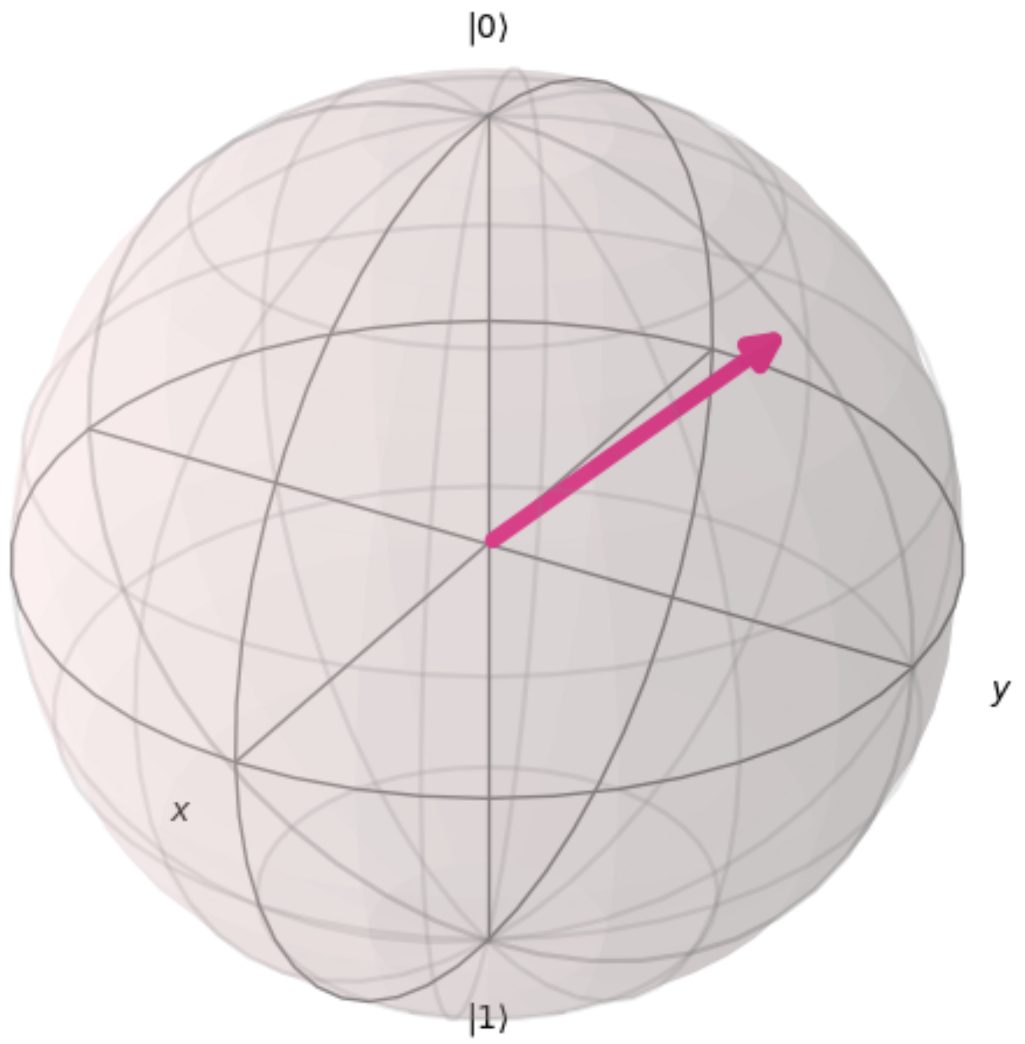
1. Noise (need for error correction)
2. Quantum decoherence
3. Scaling up

Classical computing (classical bit)

Basic error correction scheme: *3* physical bits sent for *1* logical bit of information



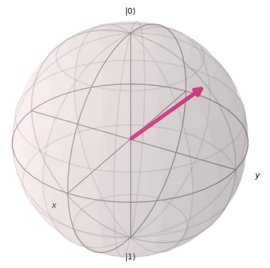
Quantum computing (quantum bit)



Vector of 2 complex values

Currently approx. *1,000* physical qubits for *1* logical qubit

Need for: Work on error correction schemes



Issue

After a very short time (milli to micro-seconds in a superconducting processor), qubits *lose* their coherence (*state*).

Impact

Circuits can only have a *limited number of gates* for a computation to remain meaningful

Find algorithms that require less gates.

Limit use of complex gates that need to be expressed (compiled into) multiple basis gates.

Need for

Limiting external noise (cryogenics / low temperature physics)

Limiting noise among qubits

…

3. Scaling up

Issue / fact

Today's quantum processors have in the order of *100* qubits

Factoring a 2,048 bit integer (Shor's algorithm / RSA cryptosystem) requires 4,000 logical (perfect) qubits,
Or approximately *4,000,000* of today's noisy (imperfect) physical qubits.

Each qubit adds noise for the other qubits

Each qubit is controlled by a co-axial cable (electromagnetic field)

Need for

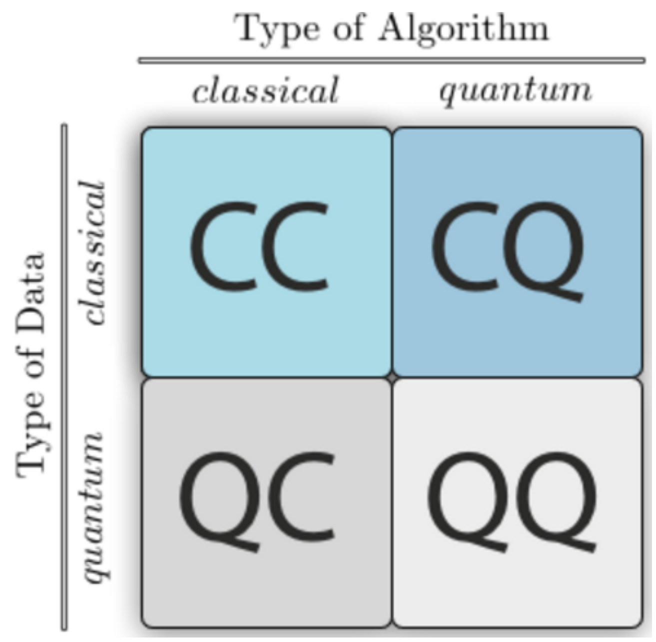
Work on quantum error correction (needing less physical qubits to implement a logical qubit)

Architecture (how to arrange the qubits), limit noise from neighbouring qubits

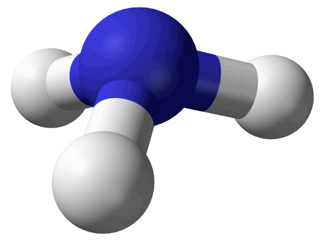
…

4. Potential future applications

1. Cryptography: breaking encryption schemes (unlikely), quantum key distribution, …
2. Chemistry & material science: simulating molecule behaviours, new drugs, materials, cheaper process for ammonia
3. Optimization: logistics, finance
4. Machine learning
5. Energy production



Source: Wikipedia


Source: Wikipedia

Government of Canada Gouvernement du Canada

Applied Quantum Computing Challenge program

Algorithms and simulations: advanced materials, biological systems, …

Enabling technologies: efficient use and scaling, error correction, compiling, …

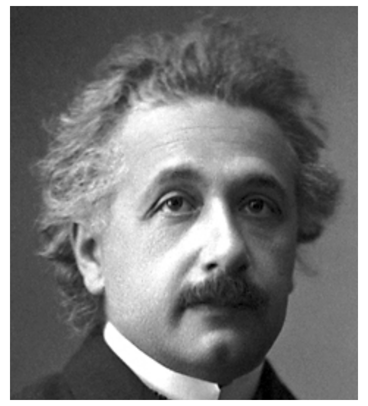
Canada’s National Quantum Strategy: research, talent, commercialization

5. People / organizations involved ?

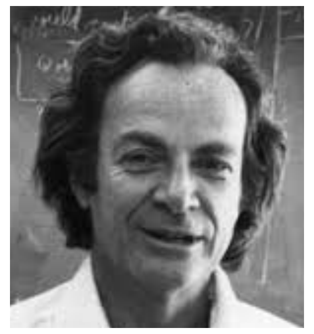
People involved in Quantum Computing

Theory

Theoretical physicist



Albert Einstein



Richard Feynman

Hardware

Quantum experimentalists

Cryogenics

Photonics

Superconductor

Engineer

Software

Computer scientist

Compiler, software packages

Domain expert (e.g. chemistry)

Algorithm development

Applied Mathematics

Peter Shor

All groups are working in parallel…

Canadian Universities

- Université de Sherbrooke — Institut Quantique
- Université de Montréal — Computer Science and Operations Research
- McGill University — Cryptography and quantum information laboratory
- University of Waterloo — Institute for quantum computing
- University of Toronto — Center for Quantum Information and Quantum Control
- University of Calgary — Institute for quantum science and technology
- Simon Fraser University — Silicon Quantum Technology Lab
- The University of British Columbia — Quantum Information Theory

…

Canadian Companies

Companies involved in various aspects of quantum computing or proposing classical solutions to prepare for potential "quantum threat".

1QBit | AbaQus | ANYON | Artiste-qb.net | BOXCAT | CogniFrame® The Hybrid Machine Learning Company

D-Wave The Quantum Computing Company™ | evolution Q | GOOD CHEMISTRY COMPANY | INFINITY|Q⟩ | ISARA

Nord Quantique | photonic | ProteinQure | QEYnet | quantropi®

⟨q|b⟩ quantum benchmark | Quantum Bridge | softwareQ | SolidStateAI | XANADU

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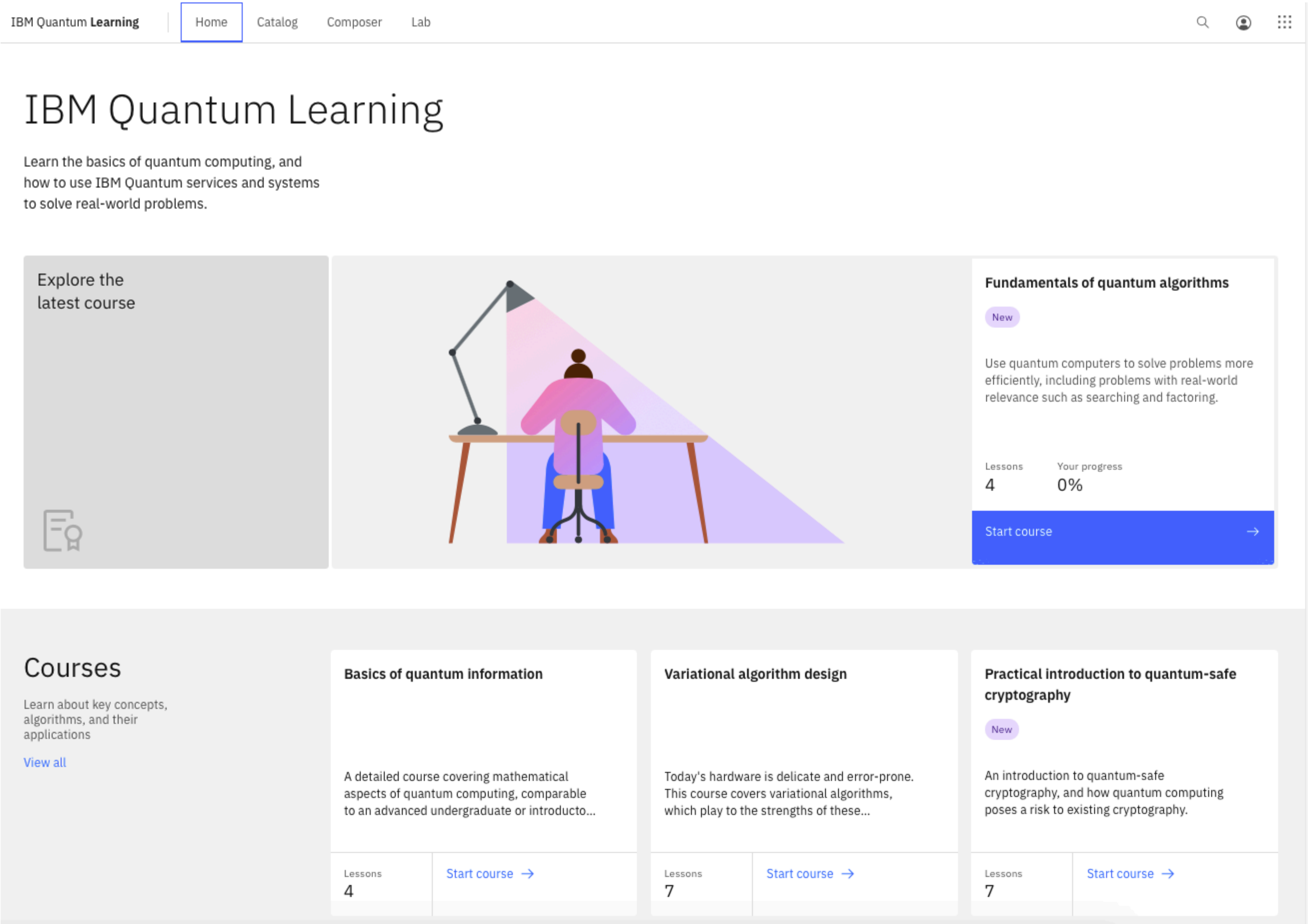
State Of Canada Quantum Computing [2022]

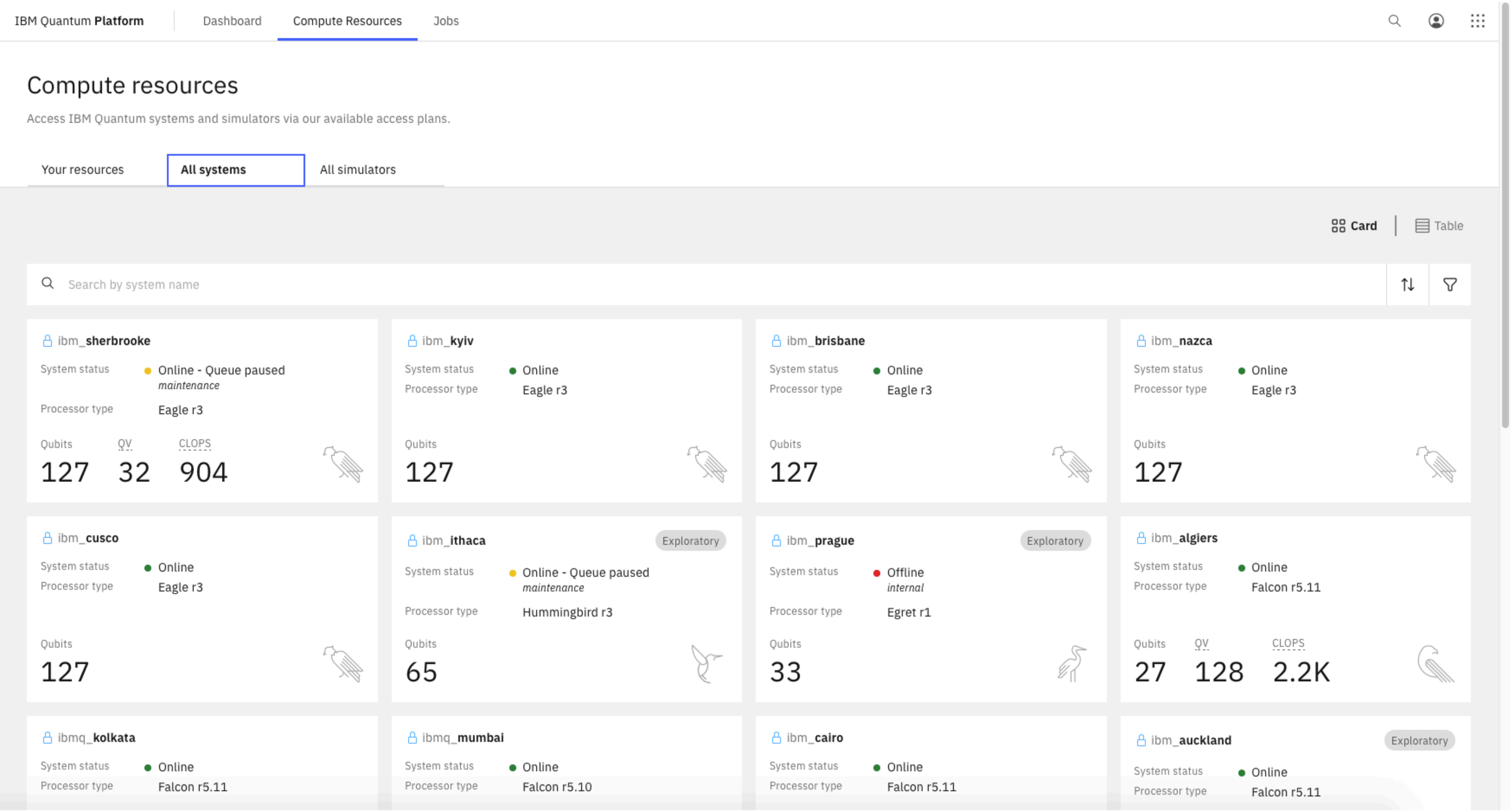
6. Coding, playing, learning…

IBM Quantum Platform: learning, coding, testing

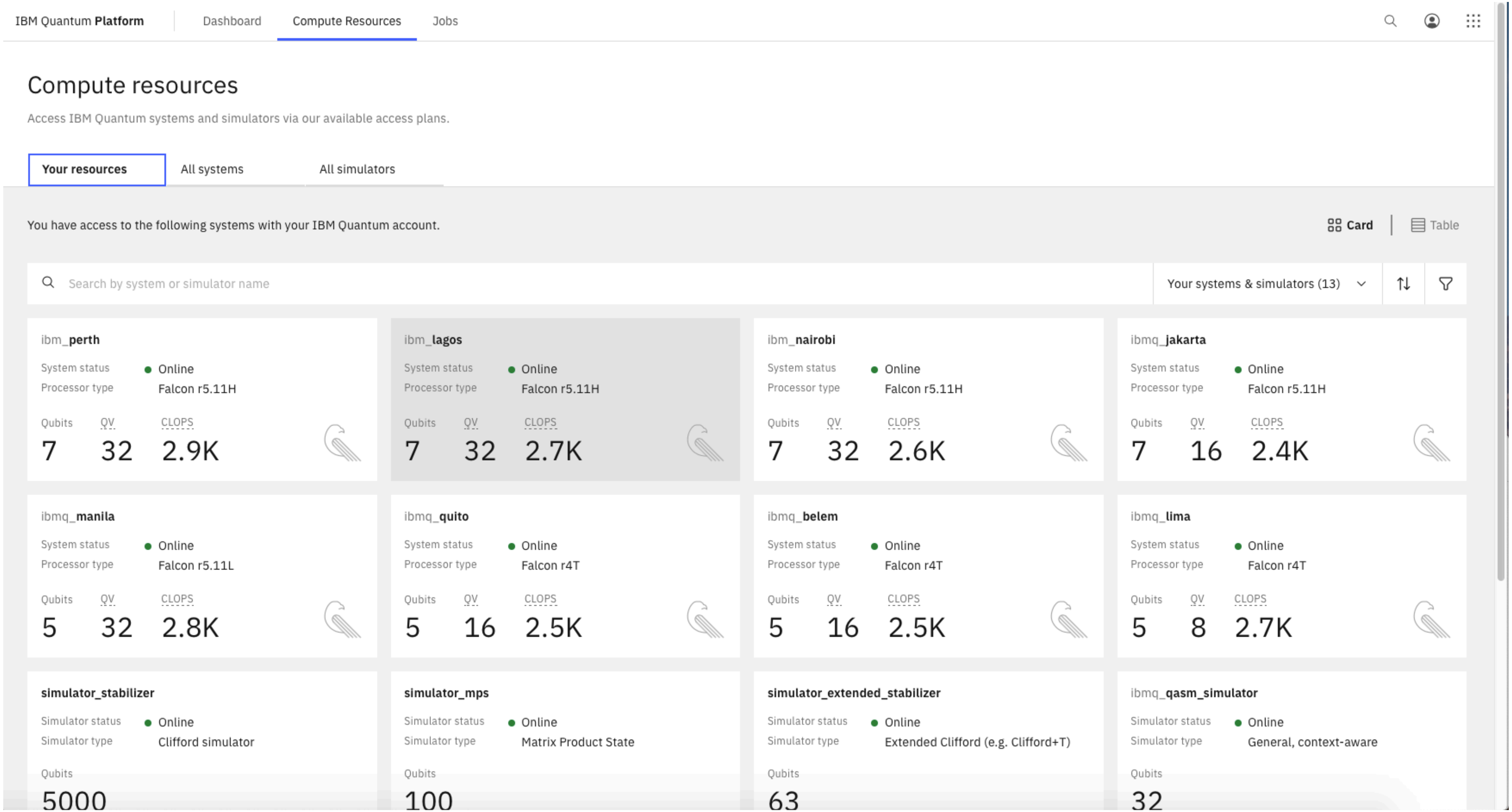


https://learning.quantum-computing.ibm.com

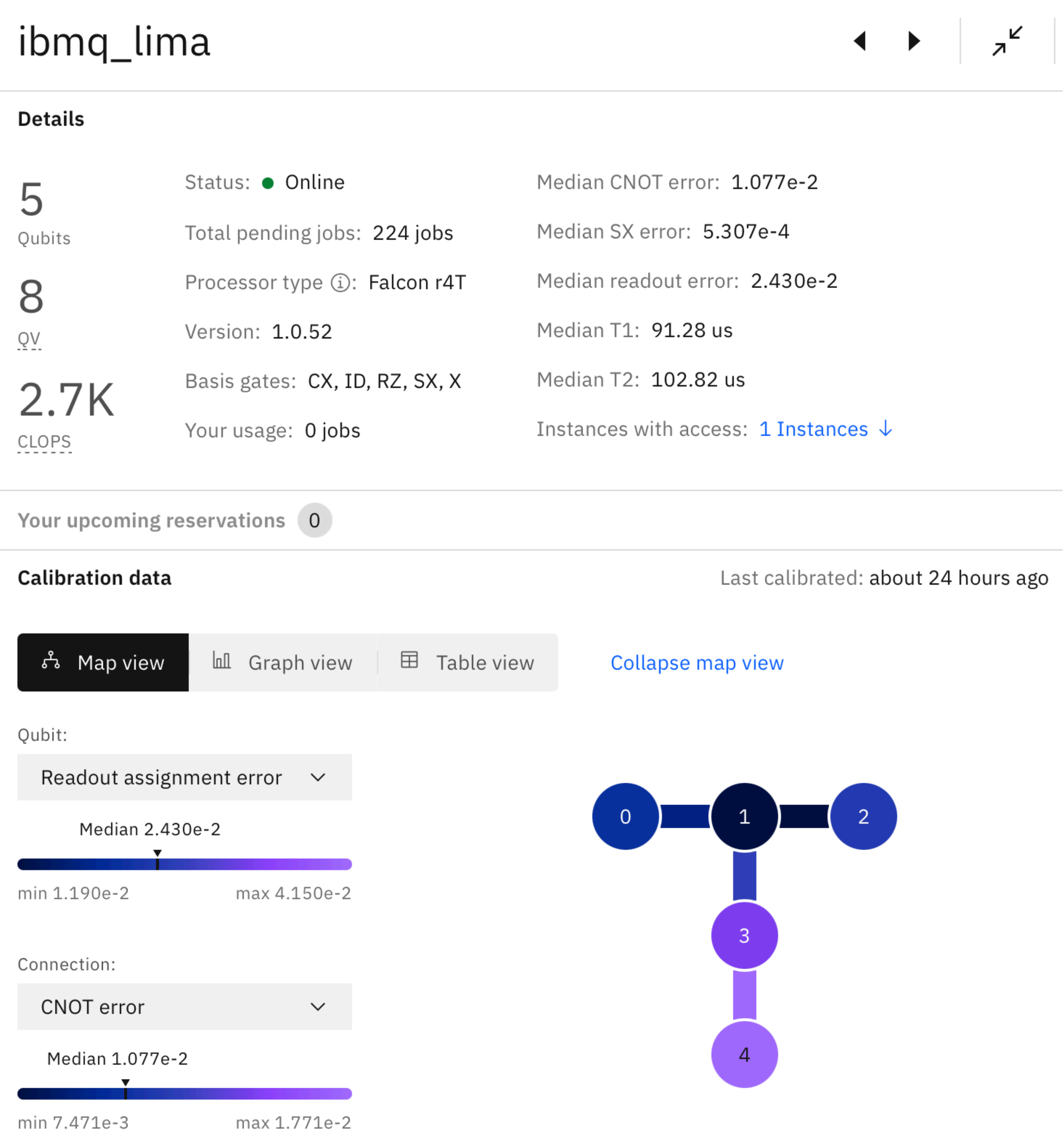
IBM Quantum Platform - Compute Resources



IBM Quantum Platform - Free compute resources



IBM quantum machines



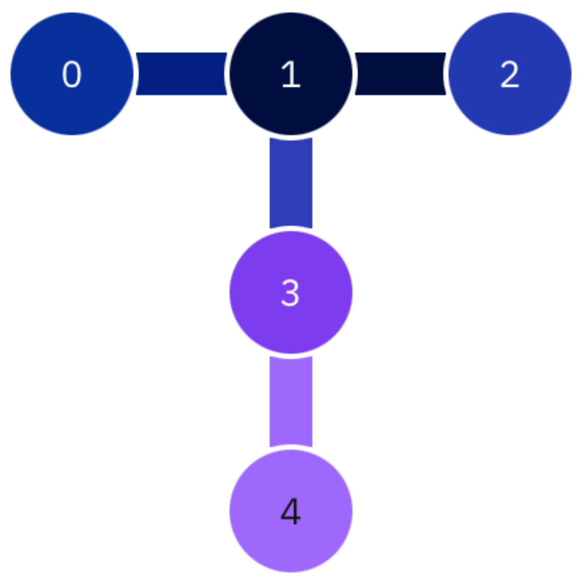
Available systems

- 7-qubit and 5-qubit QPUs
- Simulators

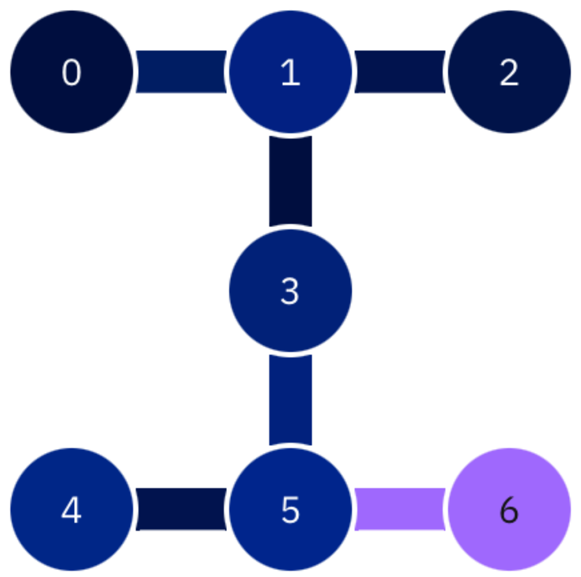
Available systems

- 433-qubit Osprey systems (coming soon)
- 127-qubit Eagle systems
- 27-qubit Falcon systems
- Exploratory systems
- Simulators

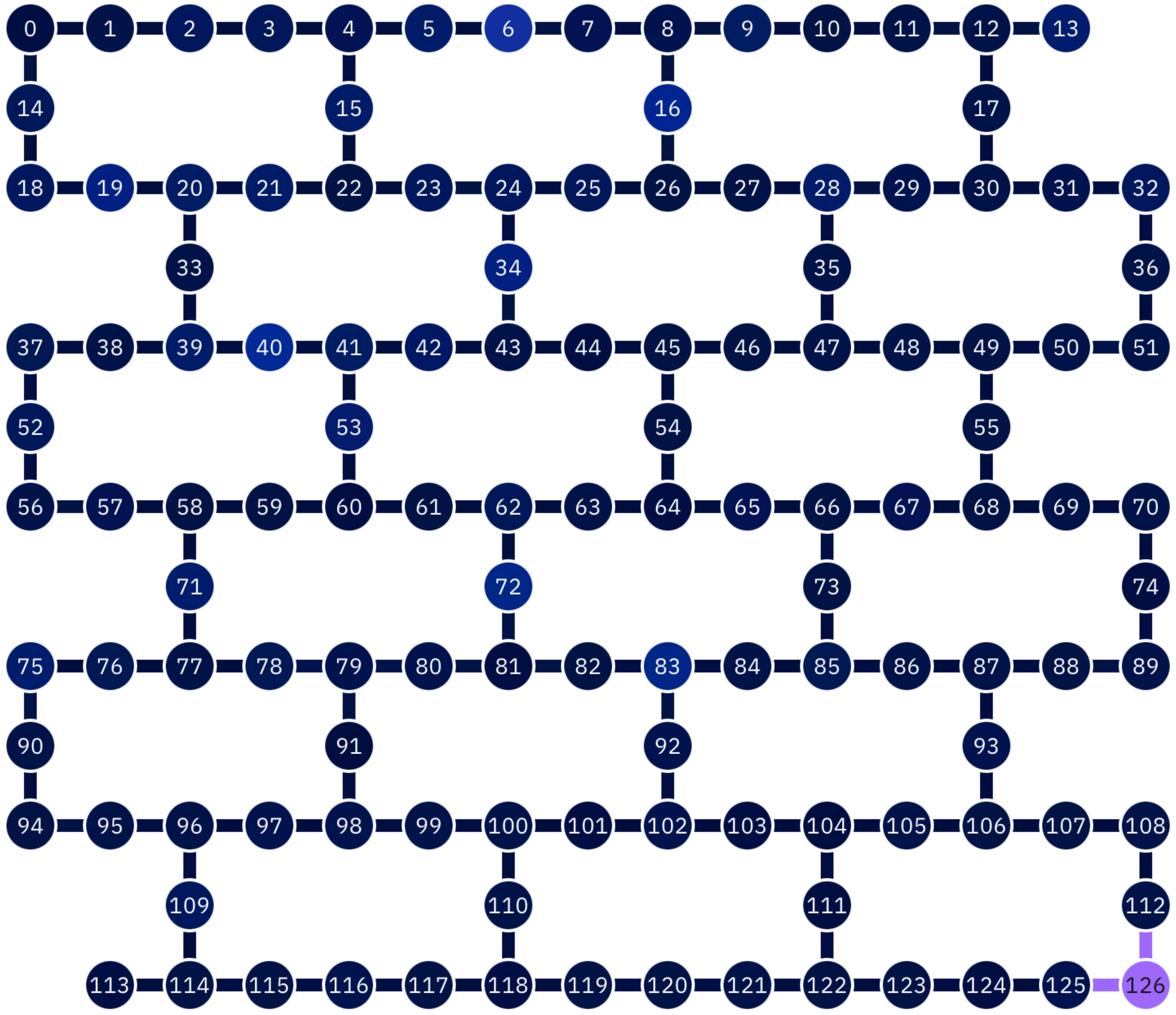
ibm_lima (5 qubits)



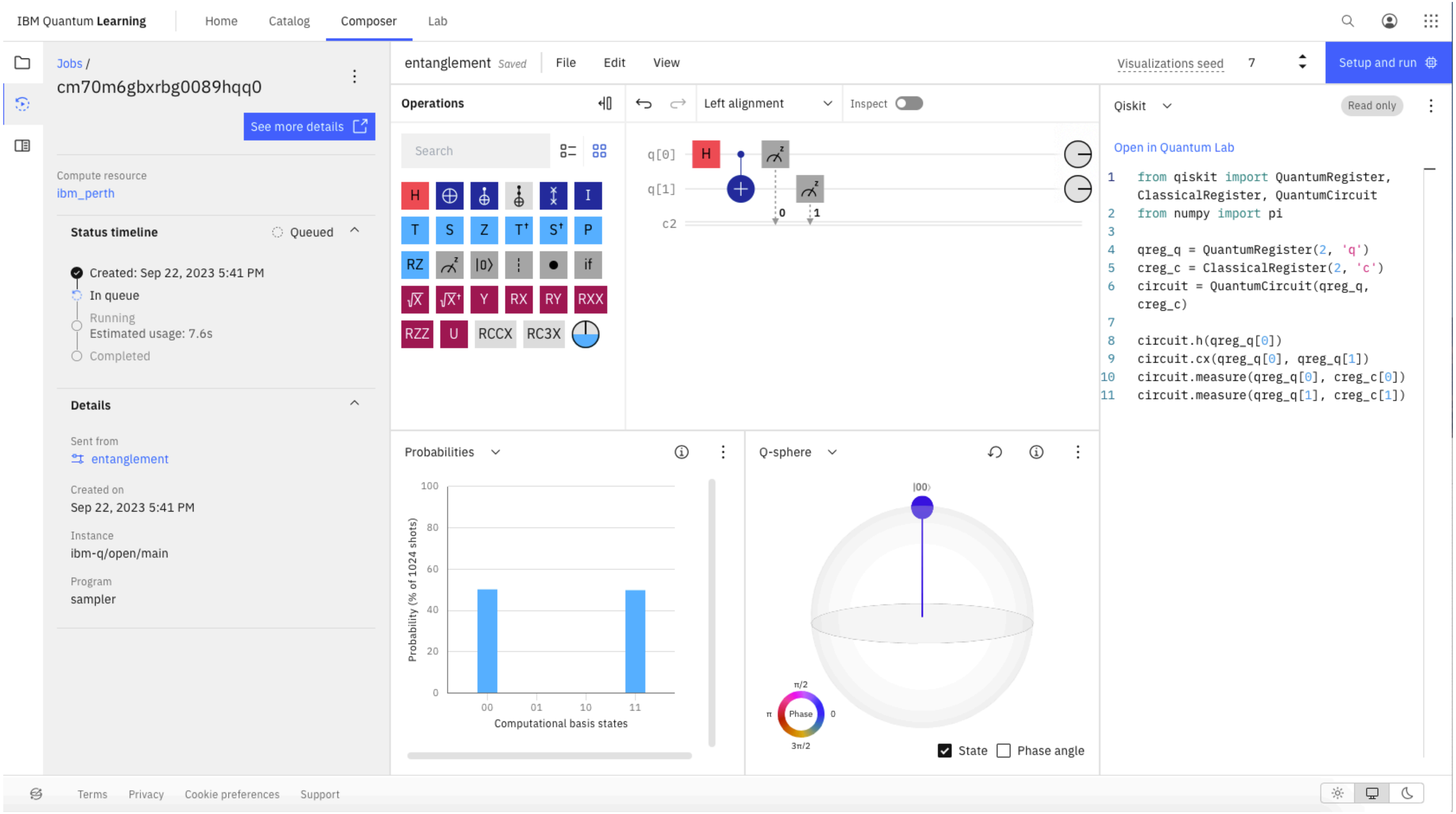
ibm_lagos (7 qubits)



ibm_sherbrooke (127 qubits)



Sending jobs on a real quantum processor



Experiment sent to ibm_perth

ibm_perth
OpenQASM 3

32 QV

2.9K CLOPS

Processor type: Falcon r5.11H

Version: 1.2.8

Basis gates: CX, ID, RZ, SX, X

Your usage: 1 job

Median readout error: 2.770e-2

Median T1: 154.74 us

Median T2: 112.25 us

Instances with access: 1 Instances

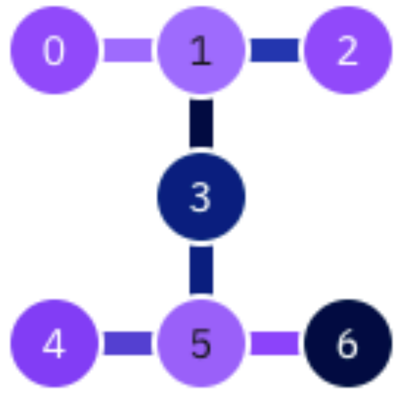
Your upcoming reservations 0

Calibration data — Last calibrated: 30 minutes ago

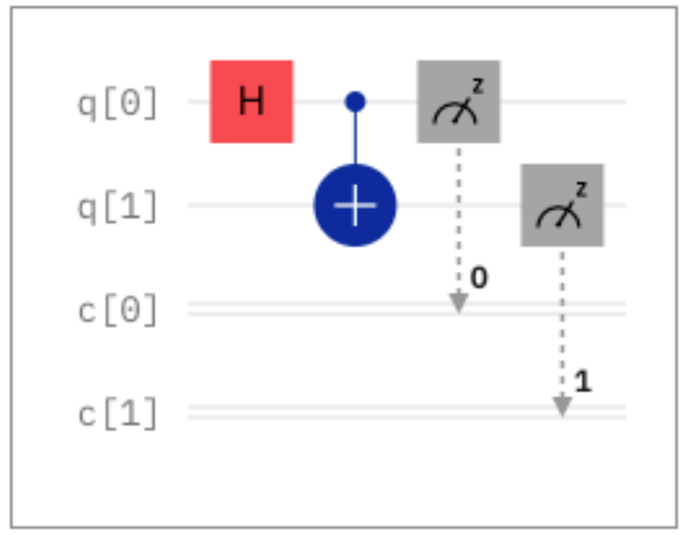
Map view | Graph view | Table view | Expand map view

Qubit: Readout assignment error — Median 2.770e-2 — min 1.300e-2, max 3.120e-2

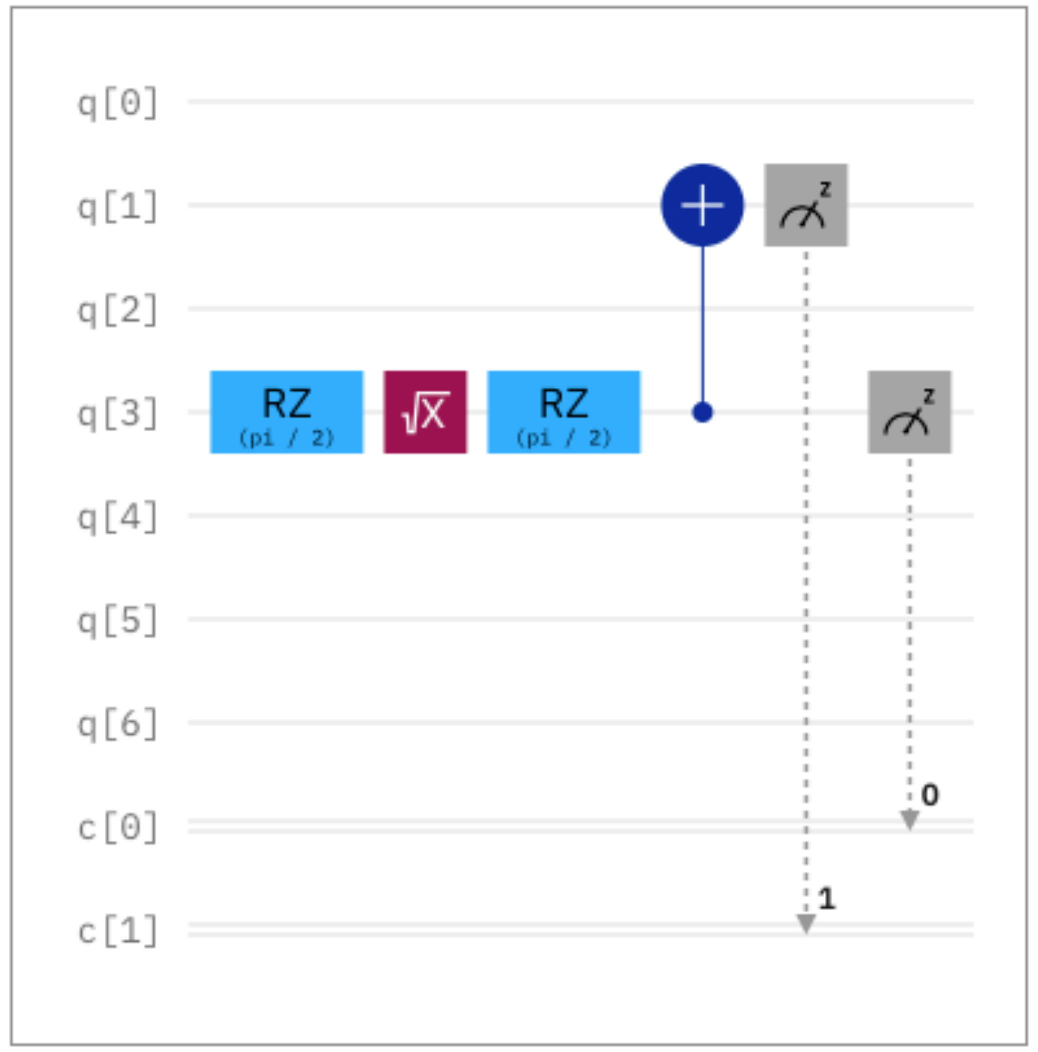
Connection: CNOT error — Median 1.151e-2 — min 4.424e-3, max 1.857e-2



Original circuit



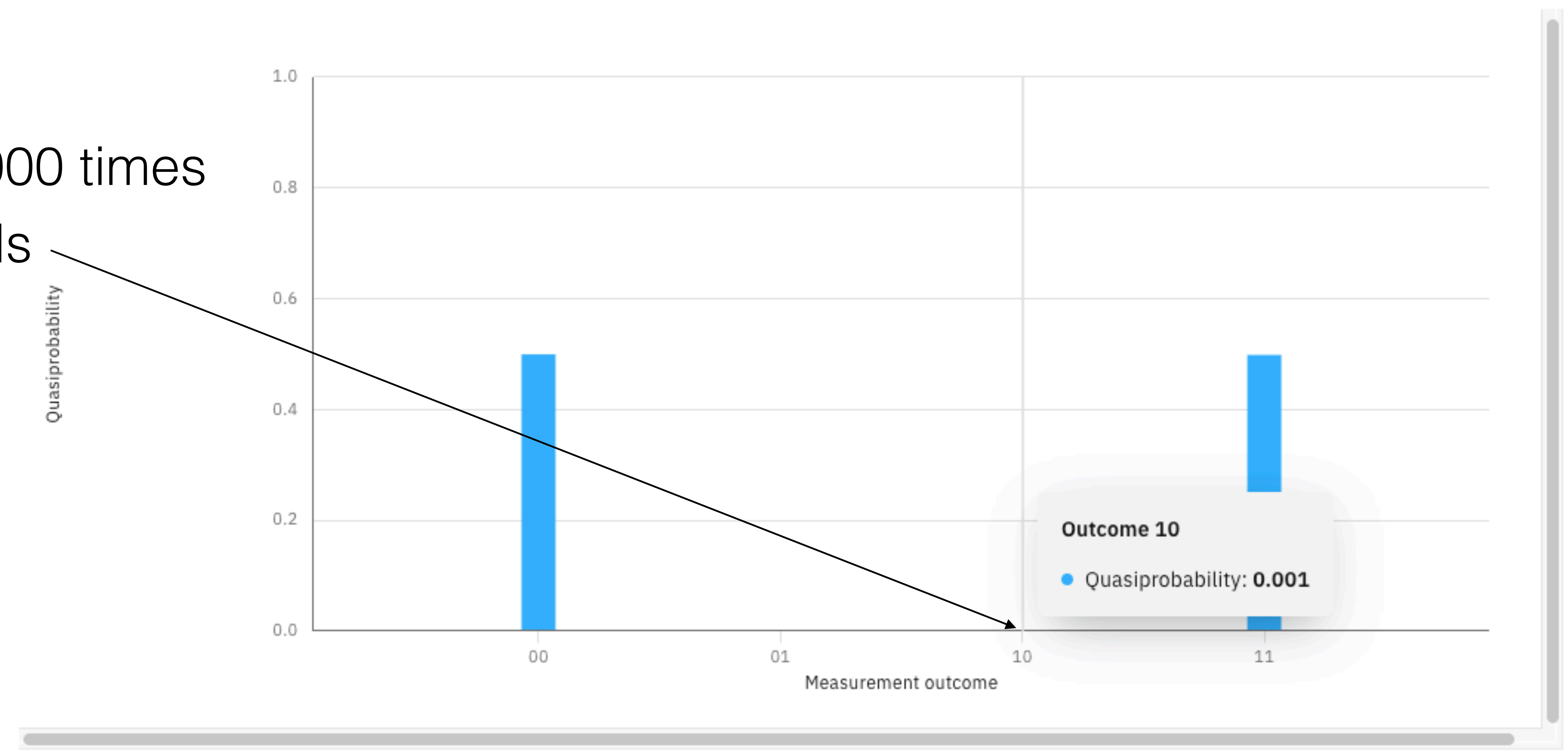
Transpiled circuit



Experiment (circuit) run 1,000 times

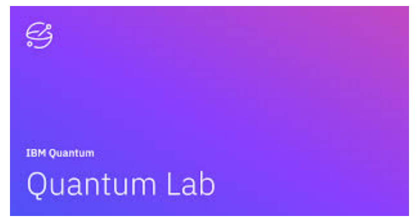
1 error out of 1,000 trials

Quasiprobability distribution



7. Where can I learn more ?

Learning…



IBM Quantum Learning Courses, tutorials, videos (YouTube channel), summer schools, challenges, … IBM Quantum **Platform**

Qiskit “open-source software development kit (SDK) for working with quantum computers” (wikipedia) Cirq

MIT OPENCOURSEWARE MASSACHUSETTS INSTITUTE OF TECHNOLOGY Quantum physics I (8.04)

QUBIT X QUBIT 1 year quantum course for high school students & above (course created by researchers @ Berkeley, MIT, Oxford)

Q-munity “nonprofit striving to connect and teach young individuals about quantum computing”

edX coursera Numerous university courses from Stanford, UofT, UBC, Purdue, EPFL, X, …

Looking Glass Universe (Youtube channel)

Quantum Computing Expert Explains One Concept in 5 Levels of Difficulty

Summary

A quantum processor will *never* replace a classical computer

“any computational problem that can be solved by a quantum computer can also be solved by a classical computer” (IBM)

“*might* provide *faster* solutions to *some* computational problems” (IBM); e.g. modelling molecules (quantum chemistry)

Still very early stage… quantum mechanics (100 years old), idea to build a quantum processor (40 years old)

Governments are preparing: education, research, commercialization

Preparing for quantum resistant encryption algorithms (just in case, better be prepared than sorry)

Large companies, banks, governments are experimenting / learning on potential use cases with current error prone quantum processors

Notation, varia, …

Advantages of quantum processors

IBM fundamentals of quantum computing

“might provide *faster* solutions to some computational problems”

“may allow us to solve certain computational problems that classical computers are too slow to solve”

“any computational problem that can be solved by a quantum computer can also be solved by a classical computer”

States of a classical bit

X: system being considered e.g. a bit

$\Sigma = \{0,1\}$ possible states assumed by the bit

Probabilistic state: Assume we believe X is in state 0 with probability 3/4 (resp. in state 1 with prob. 1/4)

$$\begin{pmatrix} \frac{3}{4} \\ \frac{1}{4} \end{pmatrix} \begin{matrix} 0 \\ 1 \end{matrix}$$

Measuring probabilistic states

“we can never "see" a system in a probabilistic state” (source: IBM Quantum learning)

“a measurement will yield exactly one of the allowed classical states” (source: IBM Quantum learning)

We see either state 0 and state 1 (standard basis vector)

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \qquad \begin{pmatrix} \frac{3}{4} \\ \frac{1}{4} \end{pmatrix} = \frac{3}{4}|0\rangle + \frac{1}{4}|1\rangle$$

Flip of a fair coin

Example: a flip of a fair coin has equal probability to fall on heads and tails

Original probabilistic state: $\begin{pmatrix} \frac{1}{2} \\ \frac{1}{2} \end{pmatrix} = \frac{1}{2} \;\; heads\rangle + \frac{1}{2} \;\; tails\rangle$

State set of a coin: $\Sigma = \{heads, tails\}$

Observed state: either $heads\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ or $tails\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

Quantum systems behave in an analogous way: observed states are one of the basic states (not a combination)

Deterministic operations (matrix vector multiplication)

Deterministic operations on probabilistic states can be represented as a *matrix vector multiplication*.

E.g. NOT operation: $\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$ If applied on state $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$ Results in $\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

Bra notation: $\langle a$ for **row vectors**

$\langle a$ is the row vector having a 1 in entry corresponding to a and 0 elsewhere

For $\Sigma = \{0,1\}$, we have $\langle 0 = (1\ \ 0)$ and $\langle 1 = (0\ \ 1)$

Ket notation: $a\rangle$ for **column vectors**

$a\rangle$ is the column vector having a 1 in entry corresponding to a and 0 elsewhere

For $\Sigma = \{0,1\}$, we have $0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and $1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

Quantum information

Quantum state vectors

Indices label the classical states of the system; e.g. for 3-bit system:

$$\begin{pmatrix} \alpha_0 \\ \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \\ \alpha_7 \end{pmatrix} \begin{matrix} 000 \\ 001 \\ 010 \\ 011 \\ 100 \\ 101 \\ 110 \\ 111 \end{matrix}$$

1. **The entries α_i are complex numbers**

2. The sum of absolute values squared of entries α_i equals 1: $\Sigma_i \;\; \alpha_i \;\; ^2 = 1$

Quantum state vectors are unit vectors (Euclidean norm of 1.0)

Example of a qubit state

$$\psi\rangle = \begin{pmatrix} \frac{1+2i}{3} \\ \frac{-2}{3} \end{pmatrix} = \frac{1+2i}{3} \;\; 0\rangle - \frac{2}{3} \;\; 1\rangle$$

Measuring quantum states (*standard basis* measurement)

"measurements act as the interface between quantum and classical information" (source: IBM learning)

each classical state results with probability equal to absolute value squared of the entry

E.g. a 3 bit quantum state: the classical state 010 appears with probability $\alpha_2 \; ^2$

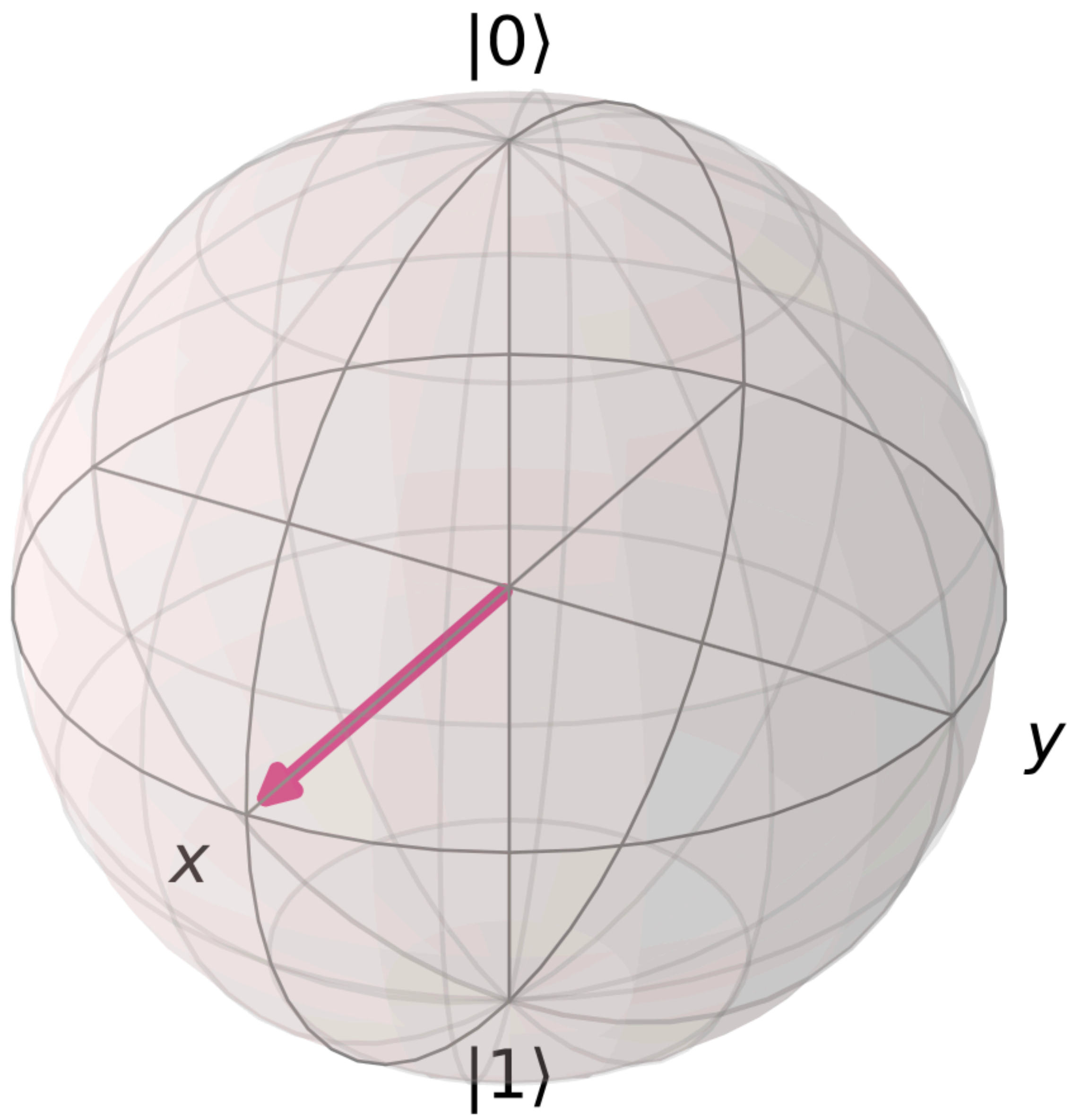
$$\psi = \begin{pmatrix} \alpha_0 \\ \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \\ \alpha_7 \end{pmatrix} \begin{array}{l} 000 \\ 001 \\ 010 \\ 011 \\ 100 \\ 101 \\ 110 \\ 111 \end{array}$$

Unitary matrix operations (reversible) on a single qubit

Pauli operations

$$I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \sigma_x/X = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \sigma_y/Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \sigma_z/Z = \begin{pmatrix} 1 & 0 \\ 0 & -i \end{pmatrix}$$

identity — NOT (bit flip) — phase flip



Hadamard operation

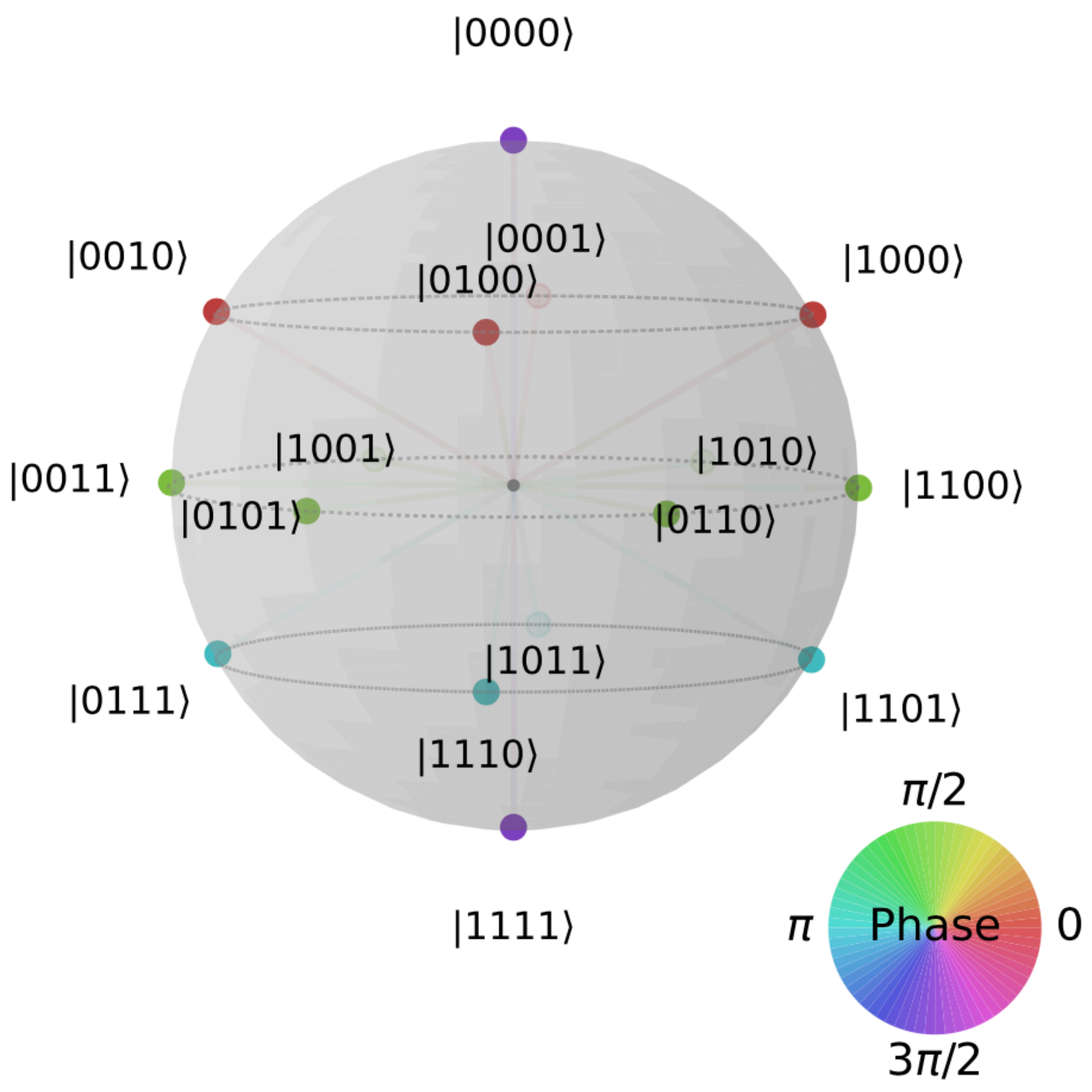
$$H = \begin{pmatrix} \frac{1}{\sqrt(2)} & \frac{1}{\sqrt(2)} \\ \frac{1}{\sqrt(2)} & -\frac{1}{\sqrt(2)} \end{pmatrix}$$

Phase operations

$$P_\theta = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\theta} \end{pmatrix}$$

e.g. $S = P_{\pi/2} = \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$ $T = P_{\pi/4} = \begin{pmatrix} 1 & 0 \\ 0 & \frac{1+i}{\sqrt(2)} \end{pmatrix}$

Representation of multi qubit states using Bloch sphere



A tautology, obviously true, proved with logic and integers

$$N(A,\bar{B}) + N(B,\bar{C}) \geq N(A,\bar{C})$$

$$N(A,\bar{B},C) + N(A,\bar{B},\bar{C}) \; + \; N(A,B,\bar{C}) + N(\bar{A},B,\bar{C}) \quad \geq \quad N(A,B,\bar{C}) + N(A,\bar{B},\bar{C})$$