Introduction to Quantum Computing With IBM Quantum and Qiskit

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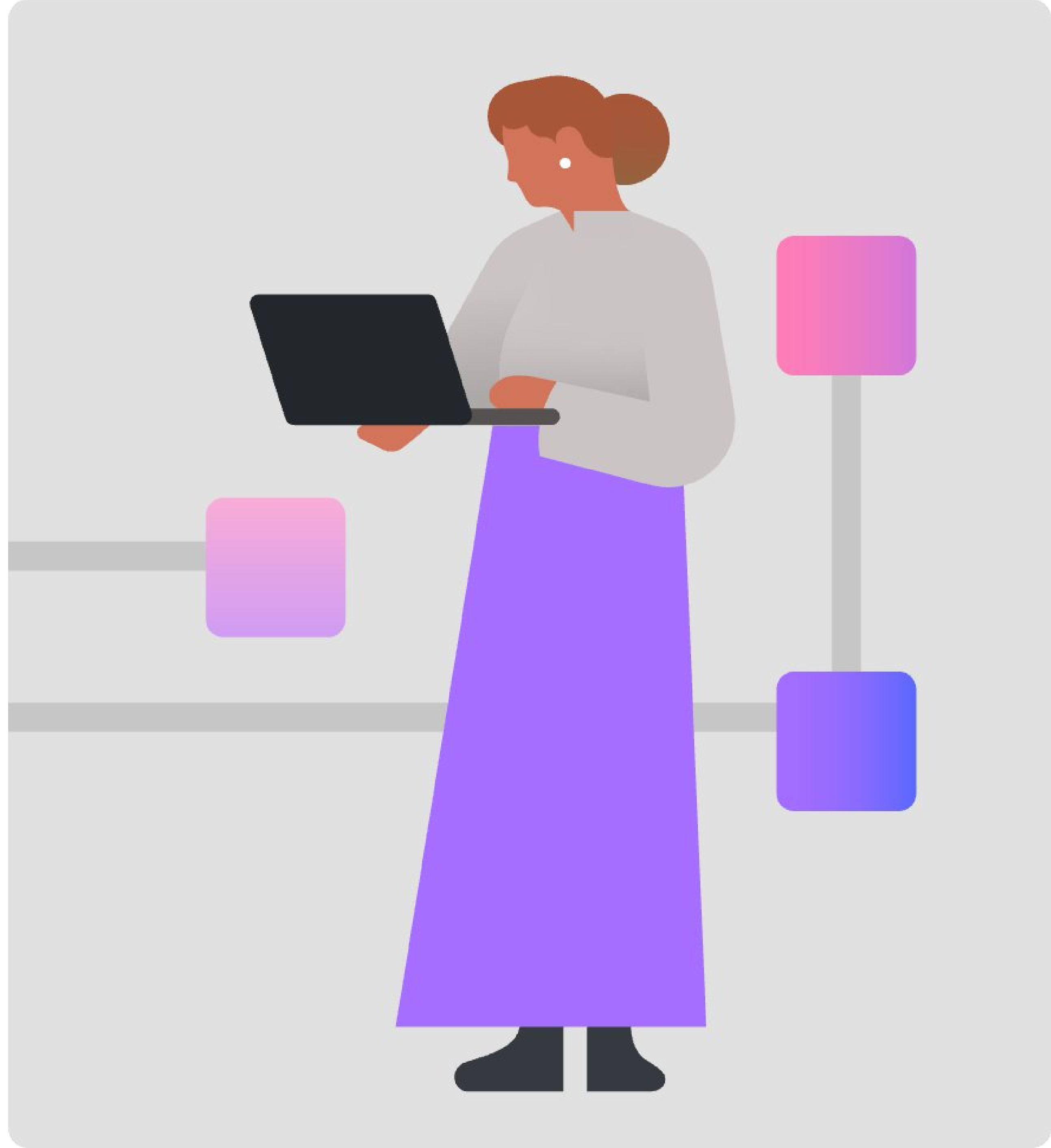
IBM Quantum

IBM

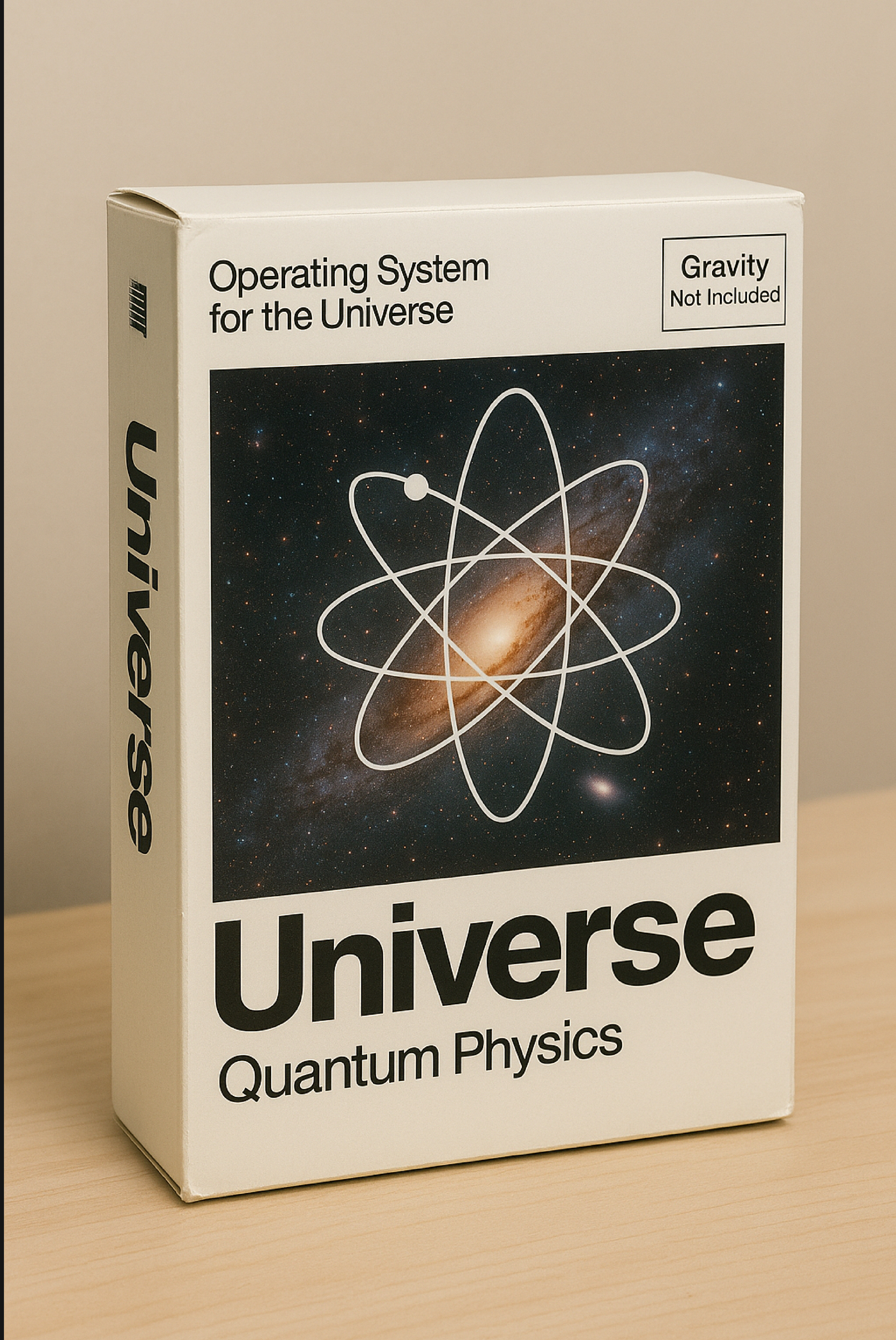
Qiskit Fall Fest 2025



Nature is quantum.

↓

You need quantum to simulate nature.



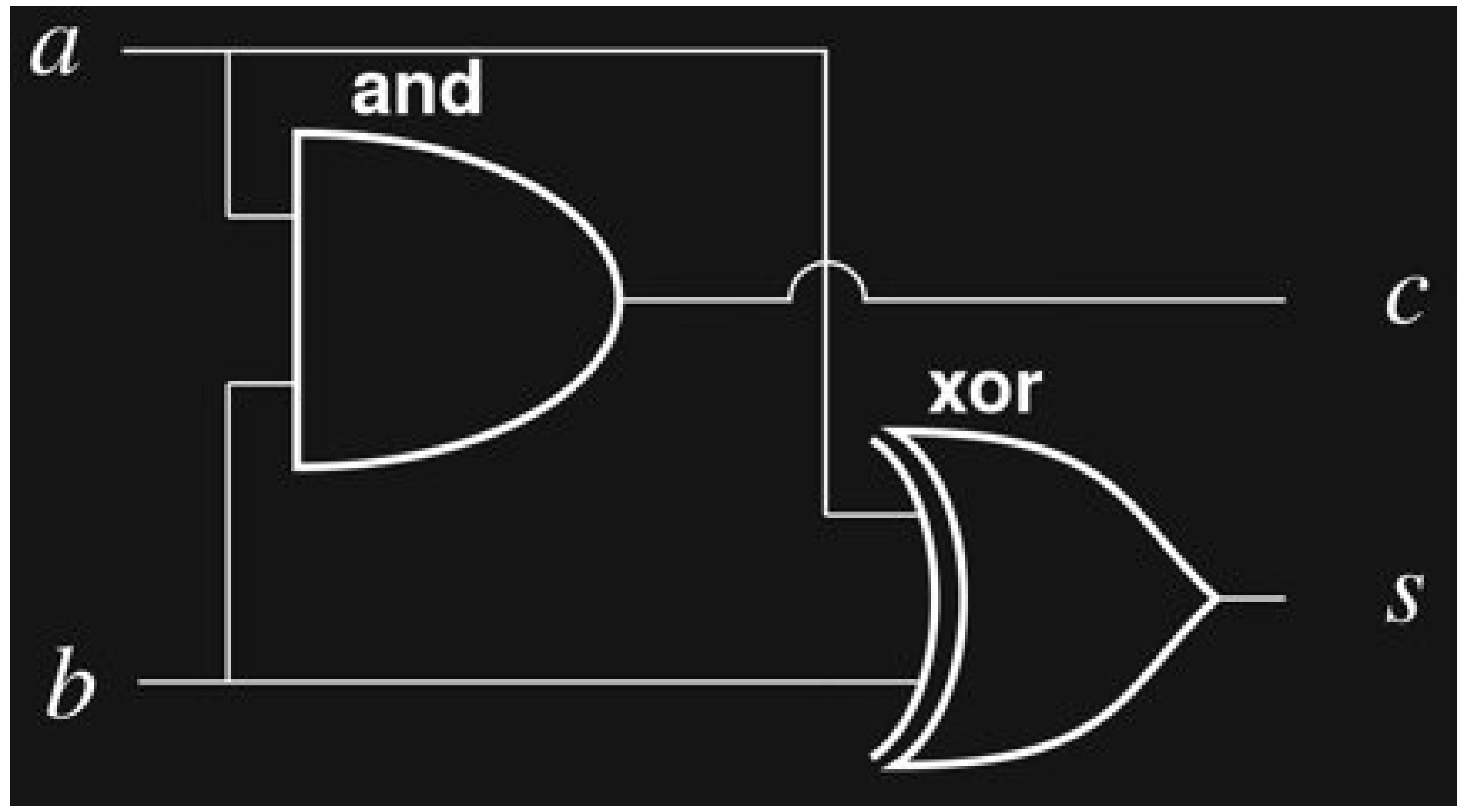
What is quantum computing?

Bits and classical logic circuits

0

1

A bit is a controllable classical object that is the unit of information



A classical logic circuit is a set of gate operations on bits and is the unit of computation

The limit of bits

For decades we've been simplifying nature into **1**s and **0**s because that was the only way we could **manage** to create a useful and scalable system of computation.

0010011011100100100010010010011001001110010111001111100101001000111000100010010100010010010101001001010101011100100110111001001000100100100110010011100101110011111001010010001110001000100101000100100101010100101010111011100111001010111110

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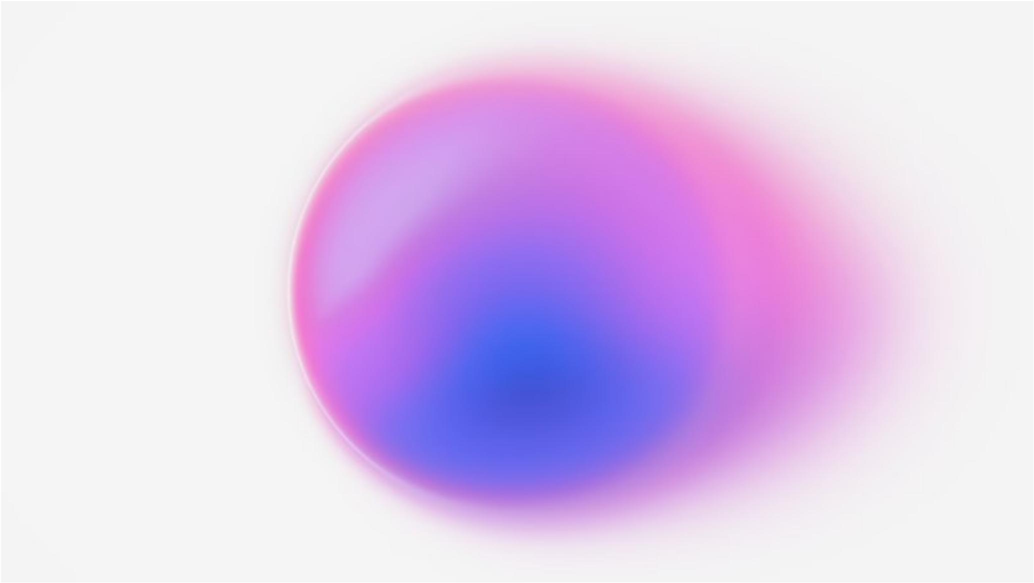
0010011011100100100010010010011001001110 01
01110011111001010010001110001000100101 0001
0010010101010010101011100100110111001001 00
01001001001100100111001011100111110010 1001
00011100010001001010001001001010101001 0101
01110111001110010101 1110

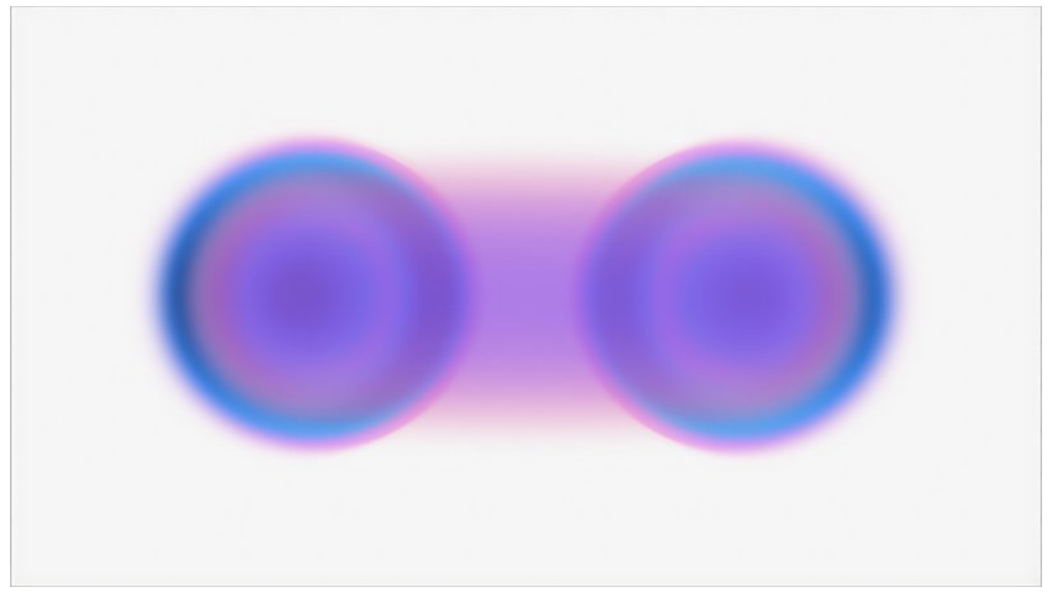
But the future isn't just **1**s and **0**s.

Uniquely quantum

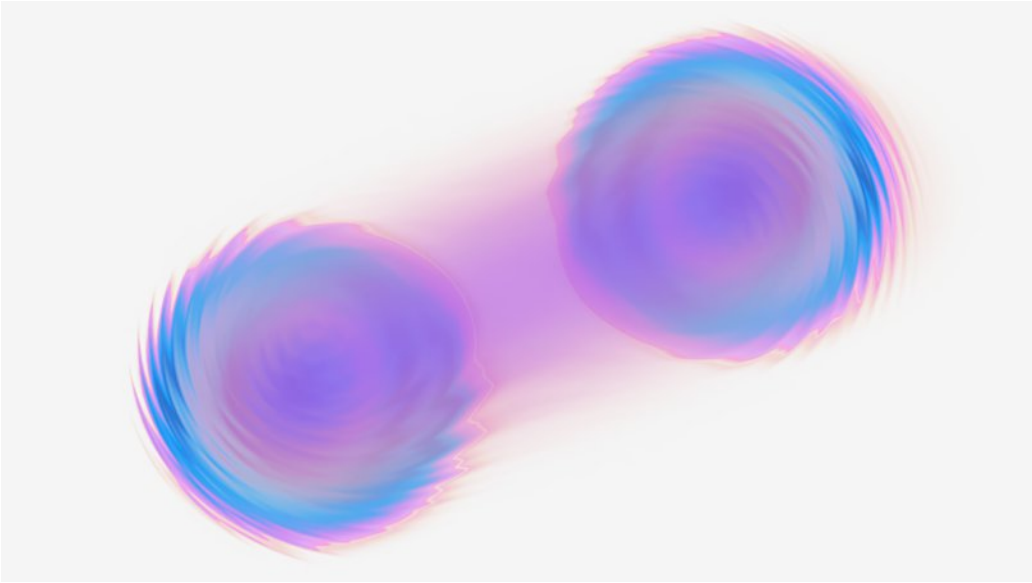
Some problems are classically intractable and will never be solvable with traditional computers



Superposition
A quantum system existing in a complex linear combination of two states until it is measured



Entanglement
Information shared jointly between entangled pairs or groups



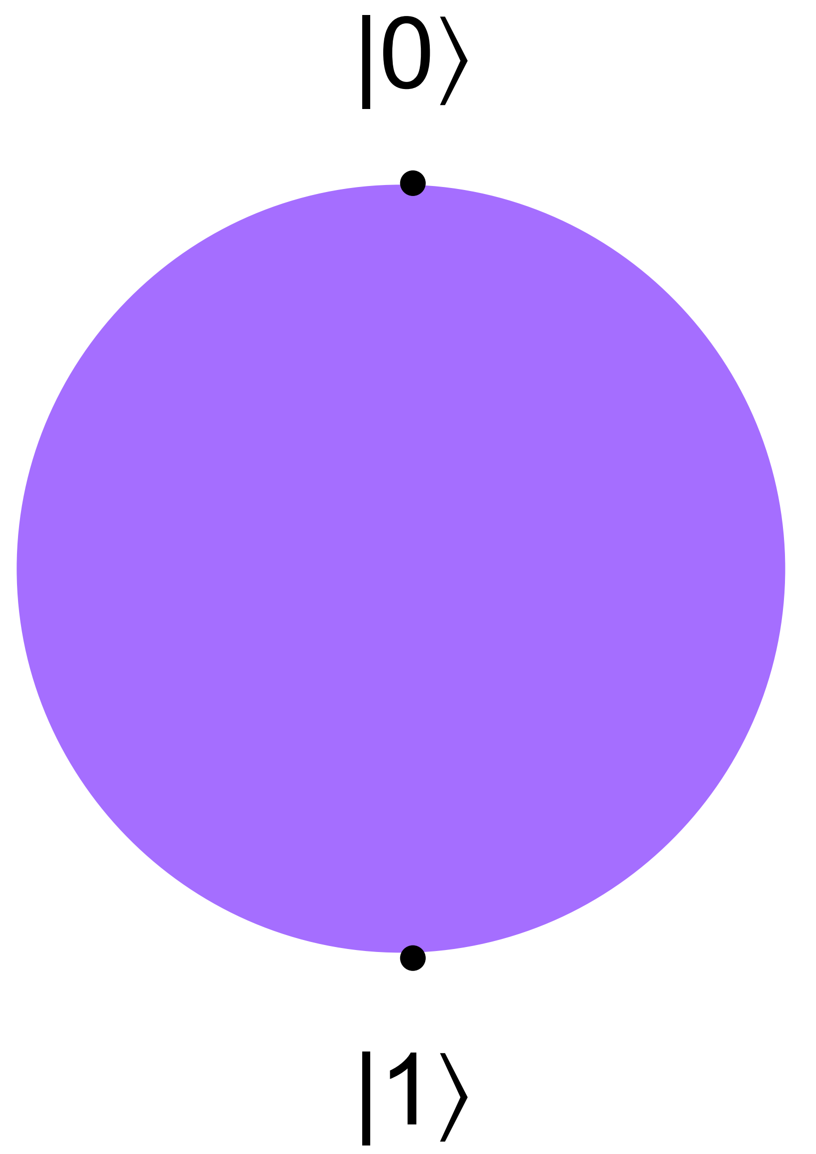
Interference
Interaction that affects likelihood of solutions

These Quantum concepts can reduce the number of computational steps required for certain algorithms
&
At a ~100 qubit scale, with sufficient circuit depth and complexity, classical computers can no longer simulate exactly

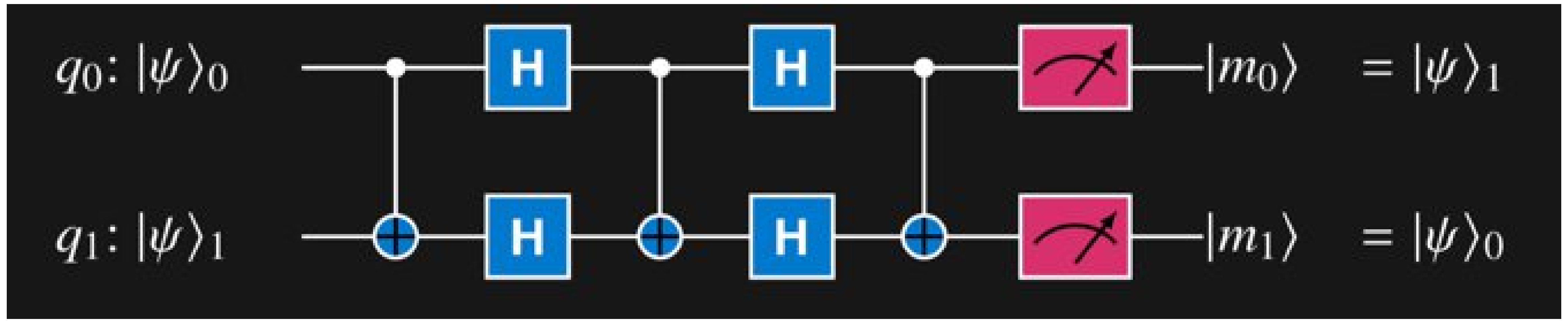
Moore's law: the number of transistors in a classical integrated circuit doubles about every two years
… but we are approaching the end due to physical limitations

[Approaching the physical limit: IBM created the world's first 2 nm node chip in 2021, with transistors as small as 10 silicon atoms]

Quantum bits (qubits) and quantum circuits



A quantum bit or qubit is a controllable quantum object that is the unit of information



A quantum circuit is a set of quantum gate operations on qubits and is the unit of computation

Quantum computing uses essential ideas from quantum mechanics

Superposition

$|0\rangle$ and $|1\rangle$ are vectors in the two-dimensional complex vector space $\mathbf{C}^2$:

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

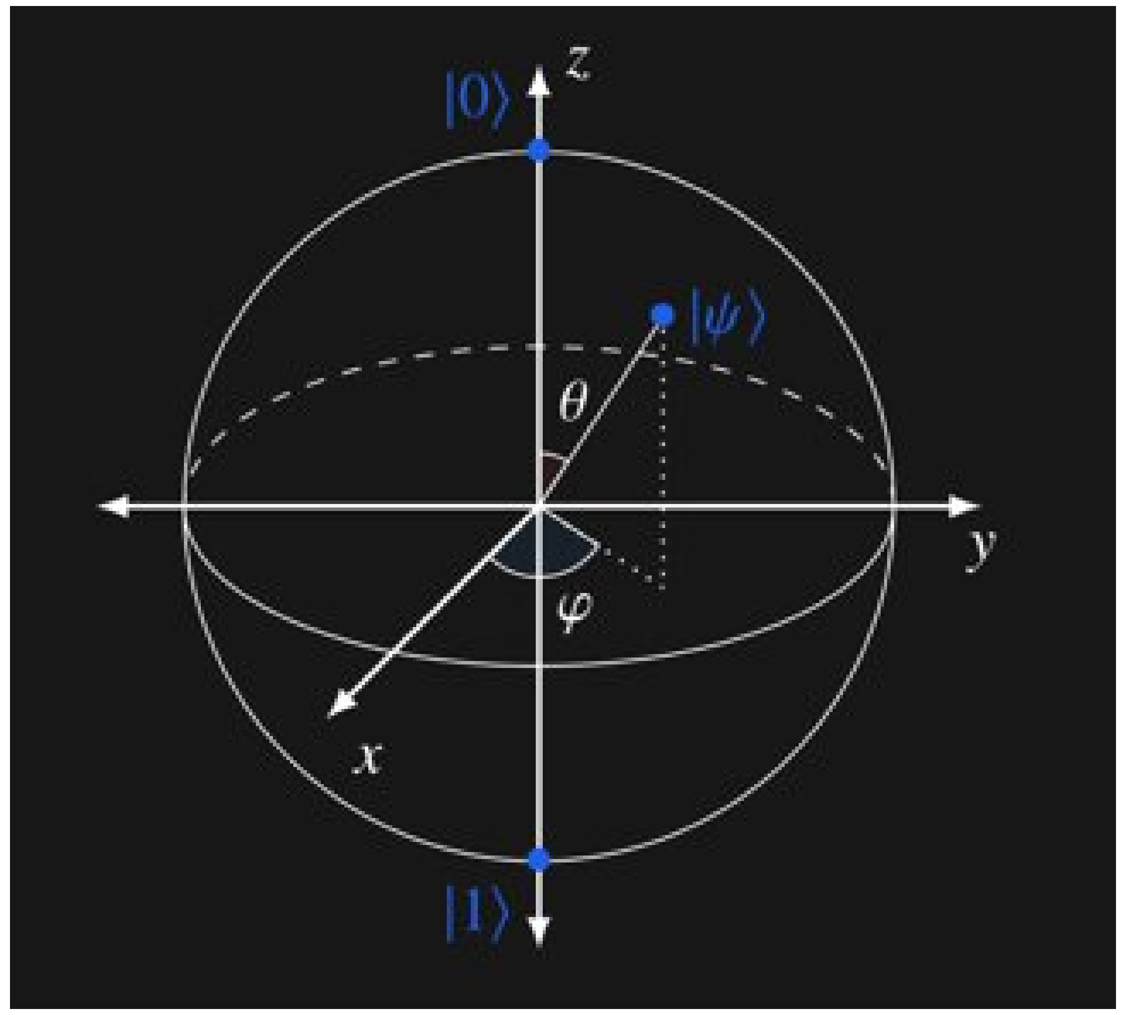
So we can write any vector in $\mathbf{C}^2$ as

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

We pronounce $|0\rangle$ and $|1\rangle$ as “ket zero” and “ket one.” These are called the *computational basis*.

Quantum computing uses essential ideas from quantum mechanics

Superposition



Superposition is creating a quantum state that is a combination of $|0\rangle$ and $|1\rangle$

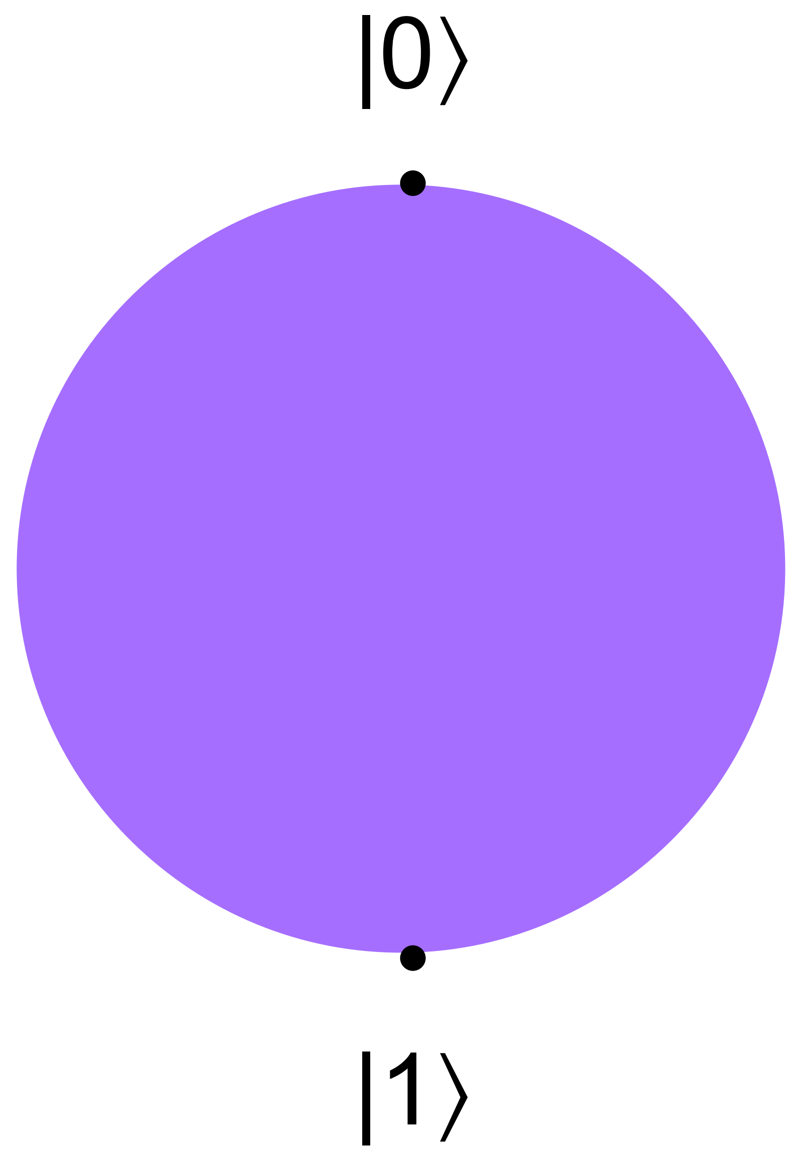
$$a\,|0\rangle + b\,|1\rangle$$

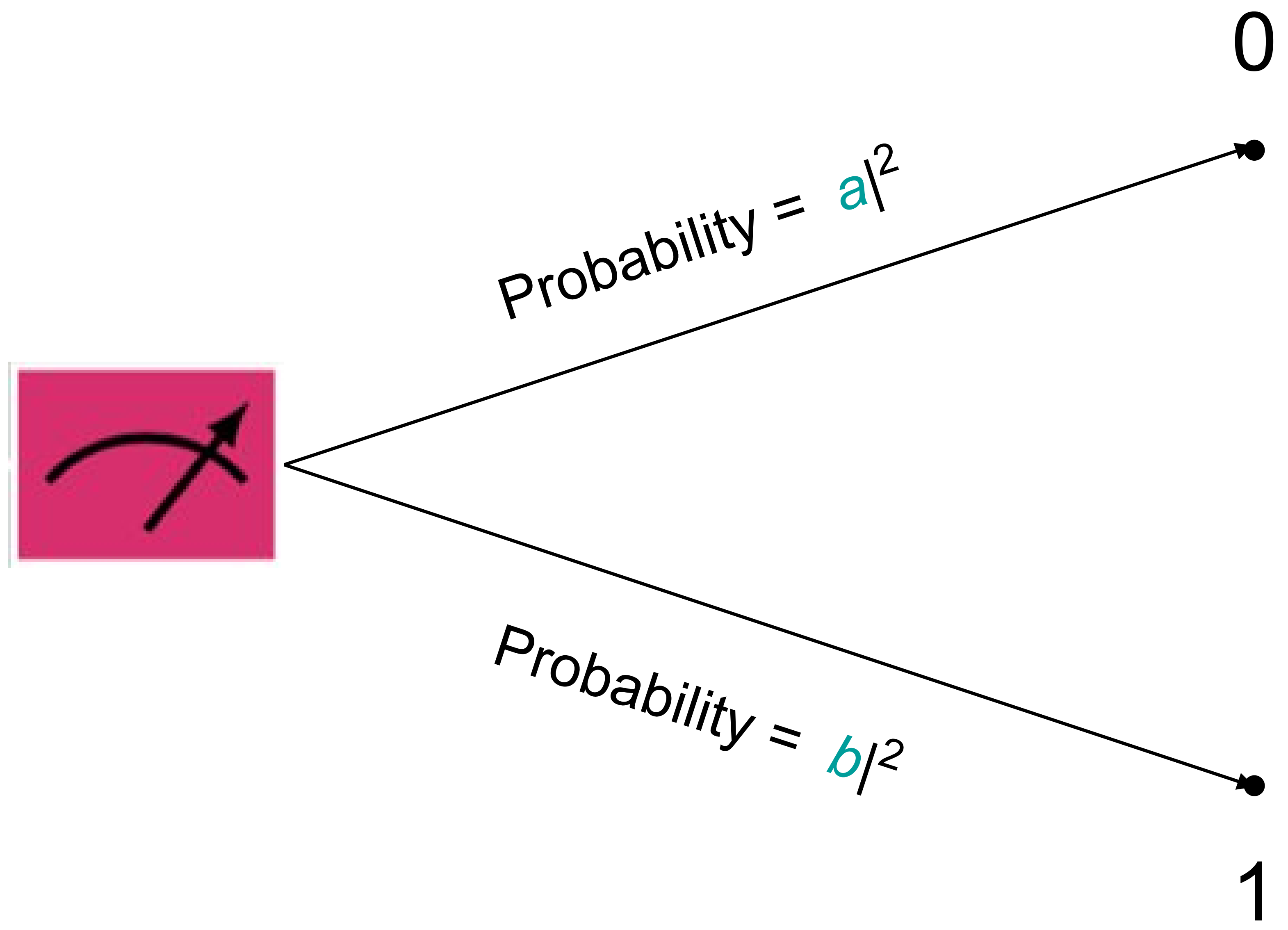
These conditions allow us to map the qubit onto the *Bloch Sphere*.

Note that if a and b are non-zero, then the qubit's state contains both $|0\rangle$ and $|1\rangle$.

This is what people mean when they say that a qubit can be "0 and 1 at the same time."

Bits and qubits





A qubit's state is a combination of |0⟩ and |1⟩:

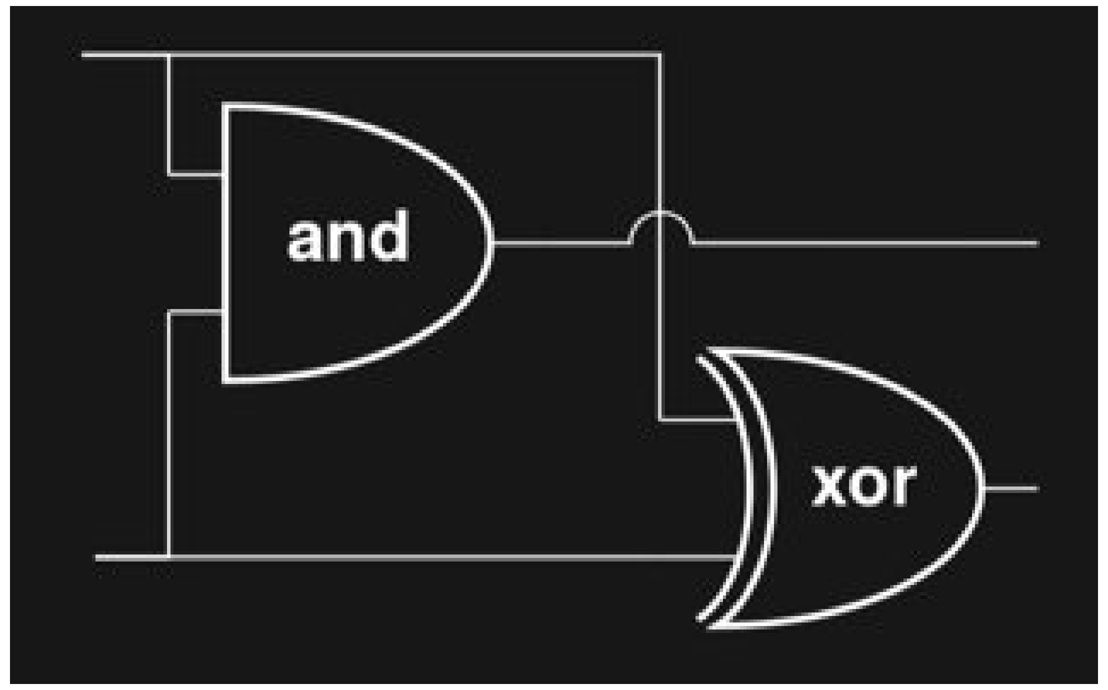
$$a\,|0\rangle + b\,|1\rangle$$

This means that a single qubit contains two pieces of information.

When we measure a qubit, it becomes **0** or **1** based on probability.

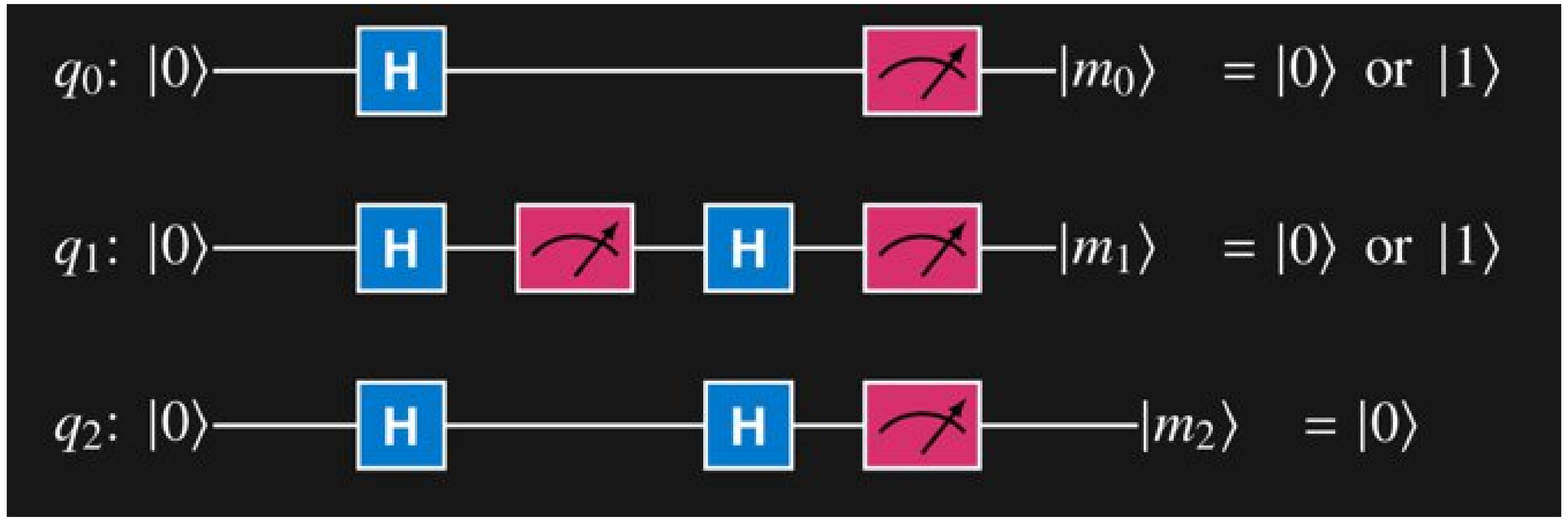
Quantum computing uses essential ideas from quantum mechanics

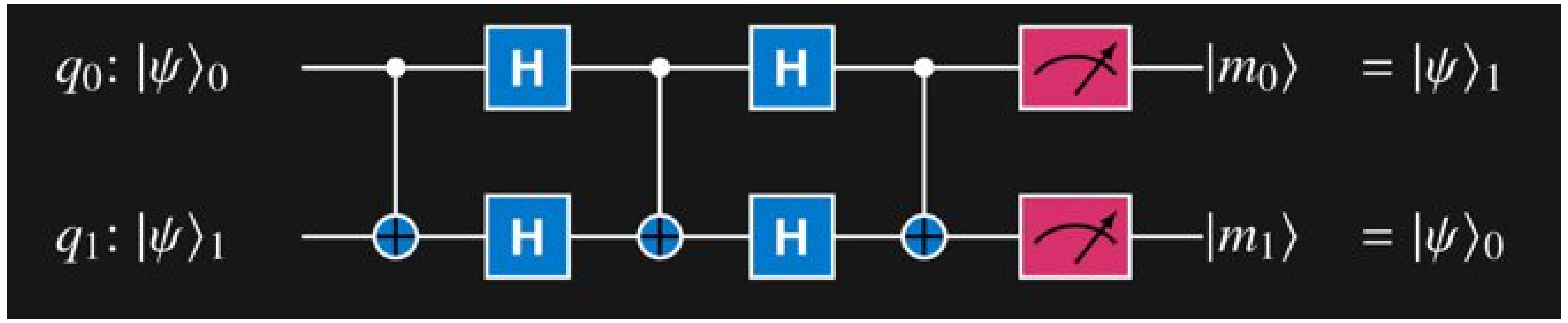
Gates / operations



Classical logical circuits use operations like and, or, not, nand, and xor. We also call these gates.

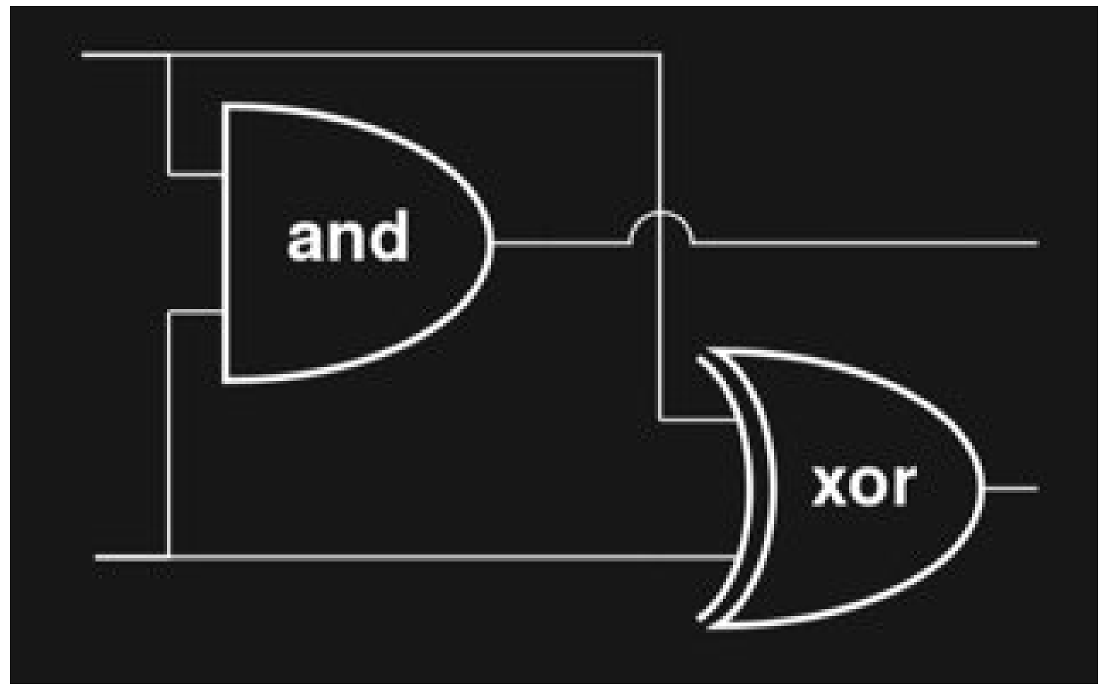
Quantum circuits use reversible gates that change the quantum states of one, two , or more qubits.





Quantum computing uses essential ideas from quantum mechanics

Gates / operations



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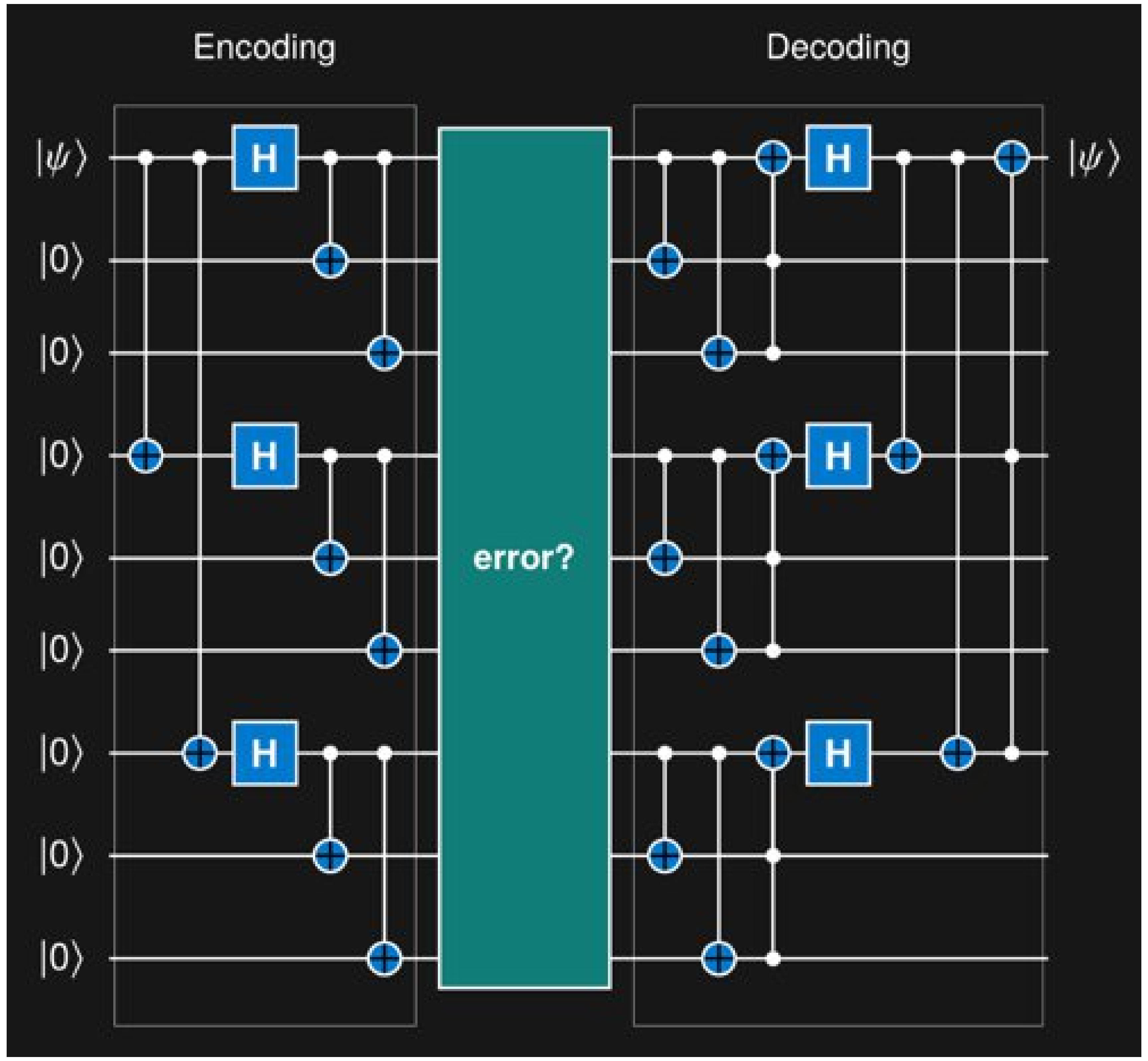
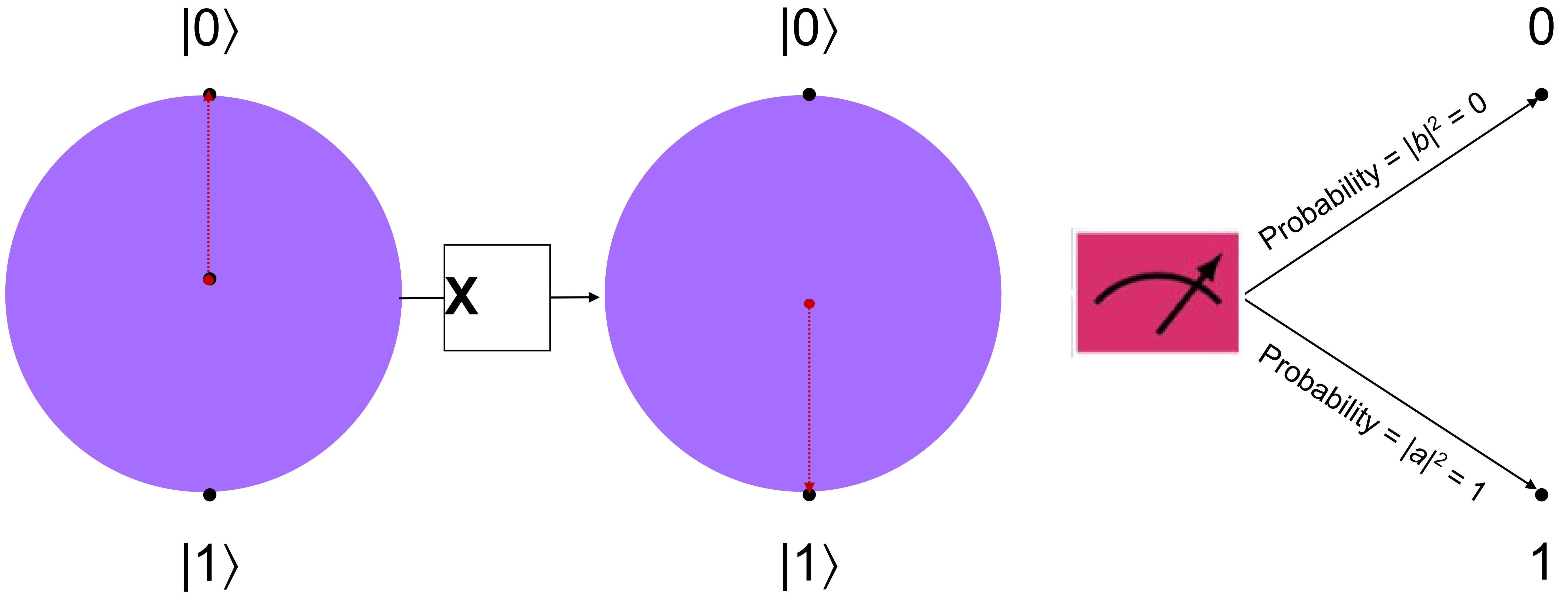


Bits and qubits: the effect of the **X** gate on $|0\rangle$



The **X** gate reverses $|0\rangle$ and $|1\rangle$:

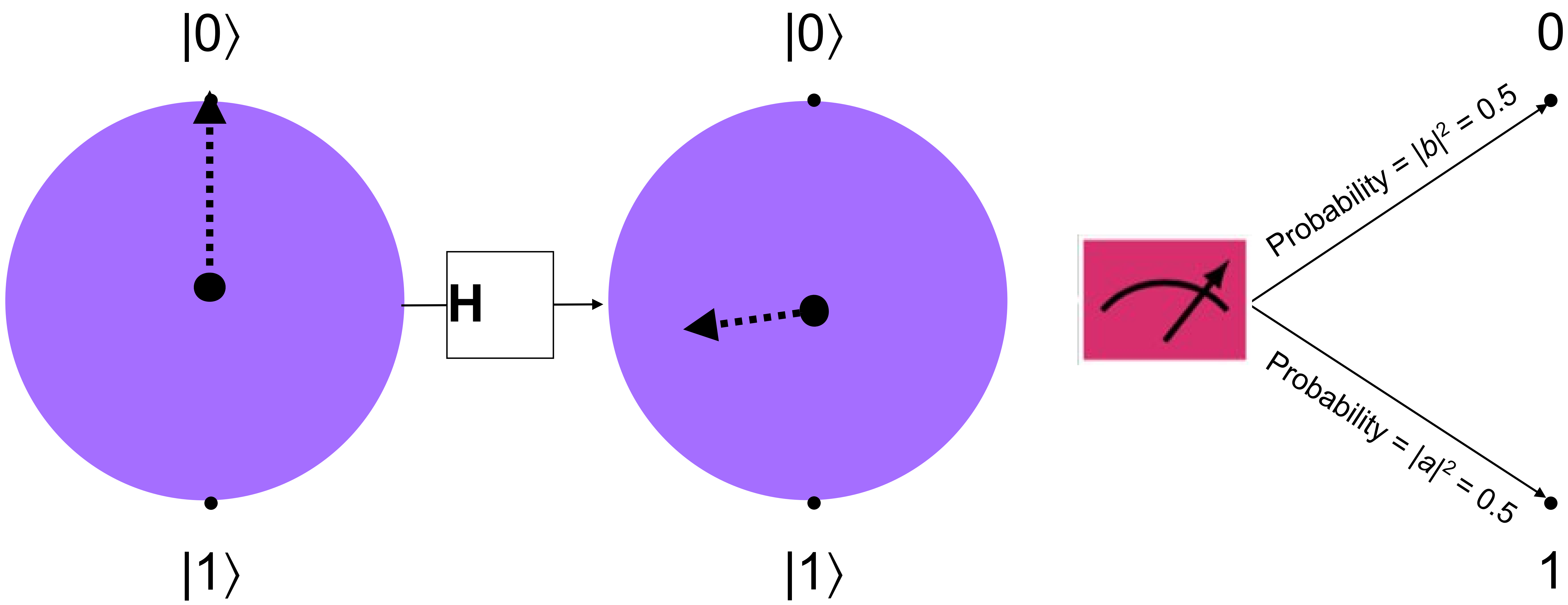
$$a\,|0\rangle + b\,|1\rangle \;\mapsto\; b\,|0\rangle + a\,|1\rangle$$

$a = 1$ and $b = 0$, so $|0\rangle$ is mapped to $|1\rangle$.

When measured, the result is **1** with 100% probability.

Bits and qubits: the effect of the **H** gate on $|0\rangle$

IBM **Quantum**



The **H** gate maps $|0\rangle$ via

$$|0\rangle \mapsto (1/\sqrt{2})\,|0\rangle + (1/\sqrt{2})\,|1\rangle = a\,|0\rangle + b\,|1\rangle$$

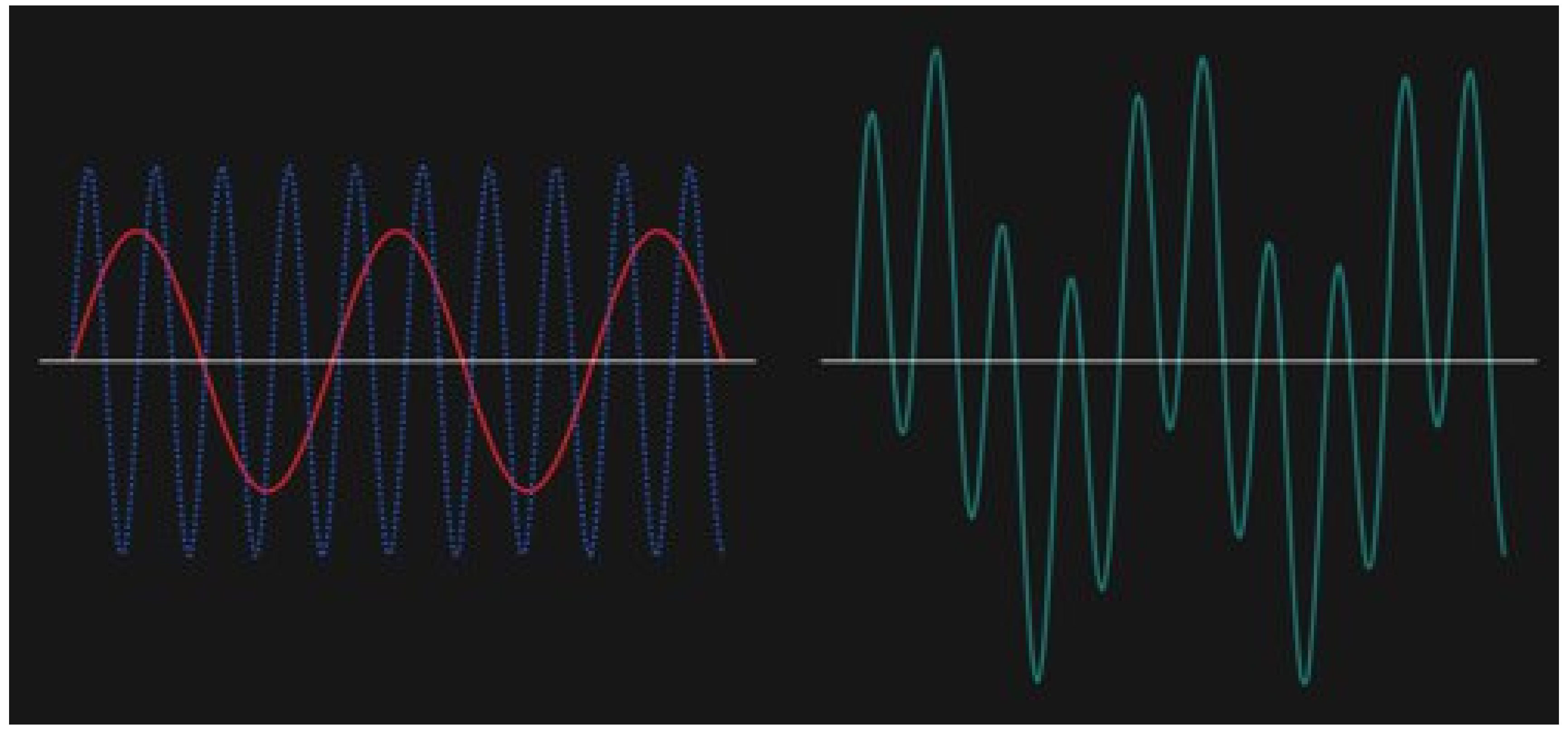
Since $a = b = 1/\sqrt{2}$, $|a|^2 = |b|^2 = ½$.

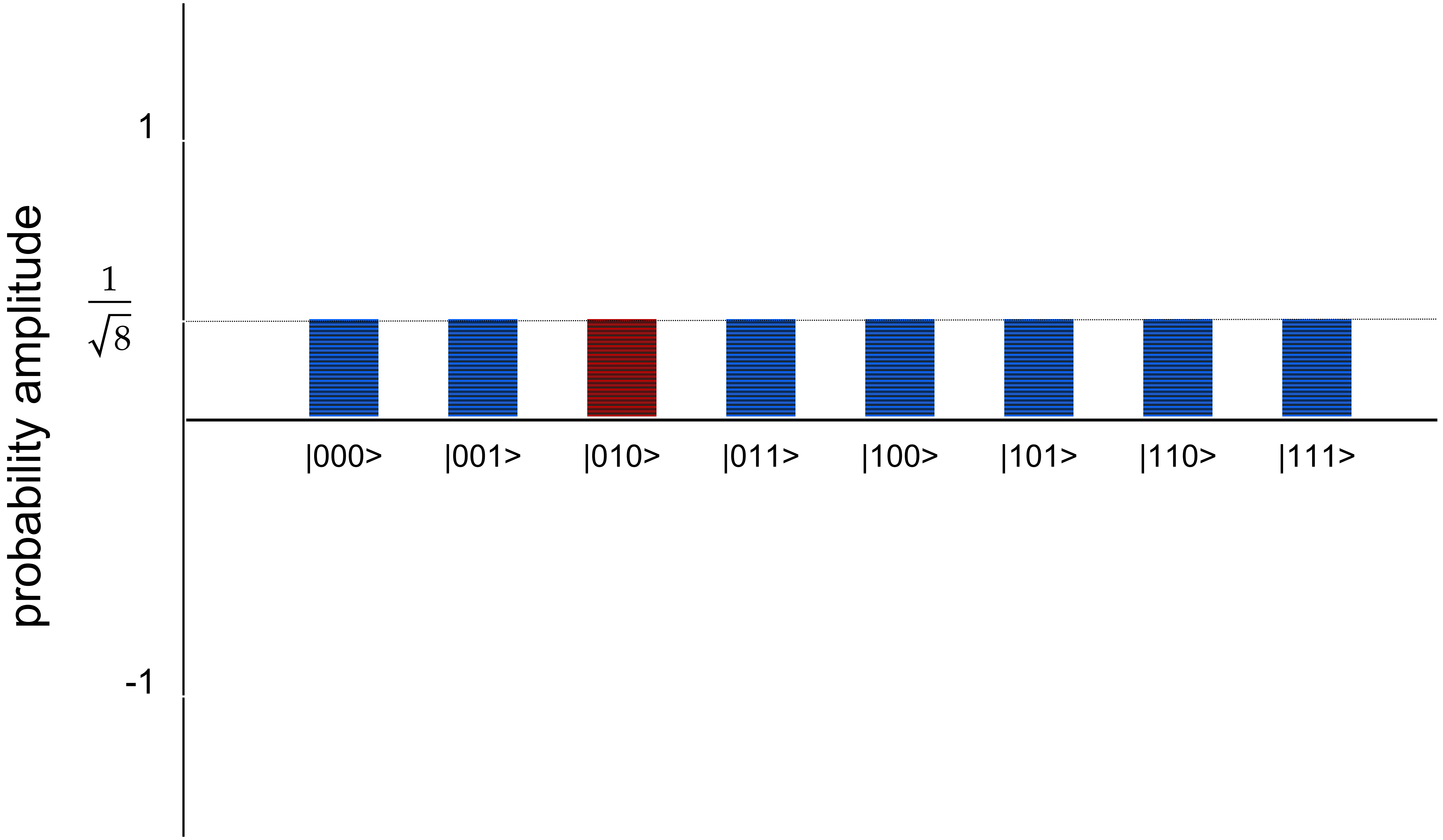
When measured, the probability of getting **0** or **1** is the same, 0.5.
Quantum randomness!

Quantum computing uses essential ideas from quantum mechanics

Interference allows us to increase the probability of getting the right answer and decrease the chance of getting the wrong one.

Interference





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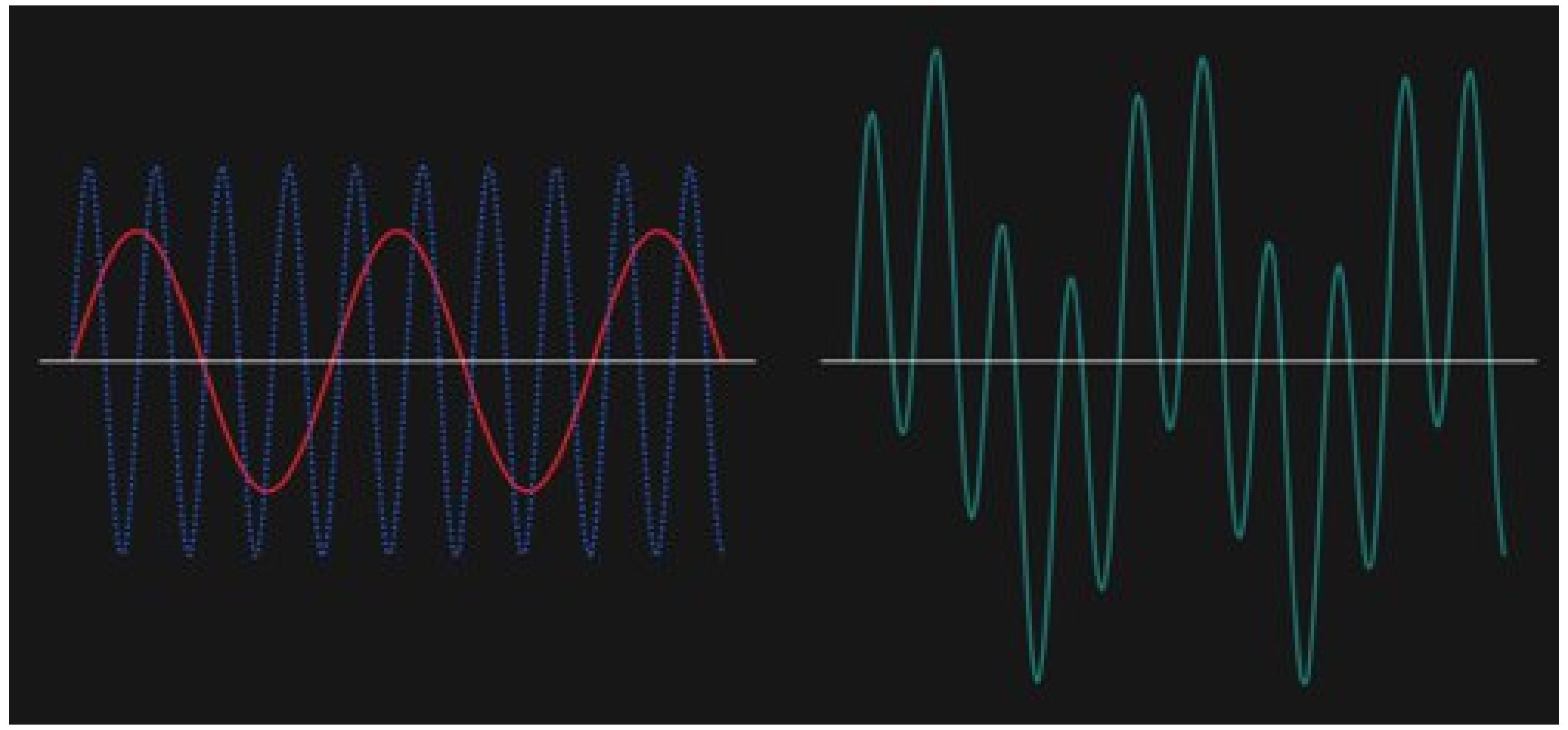

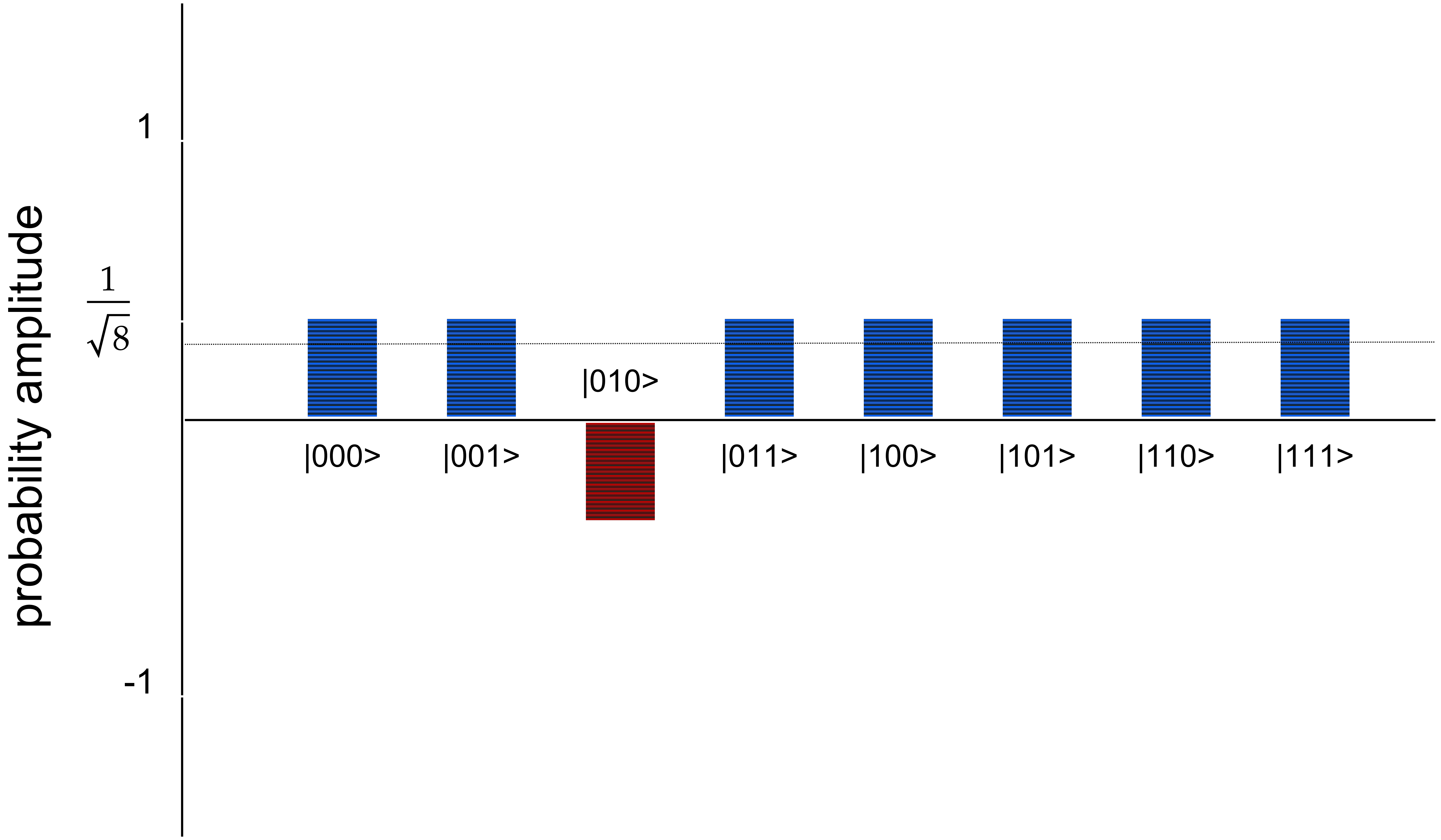

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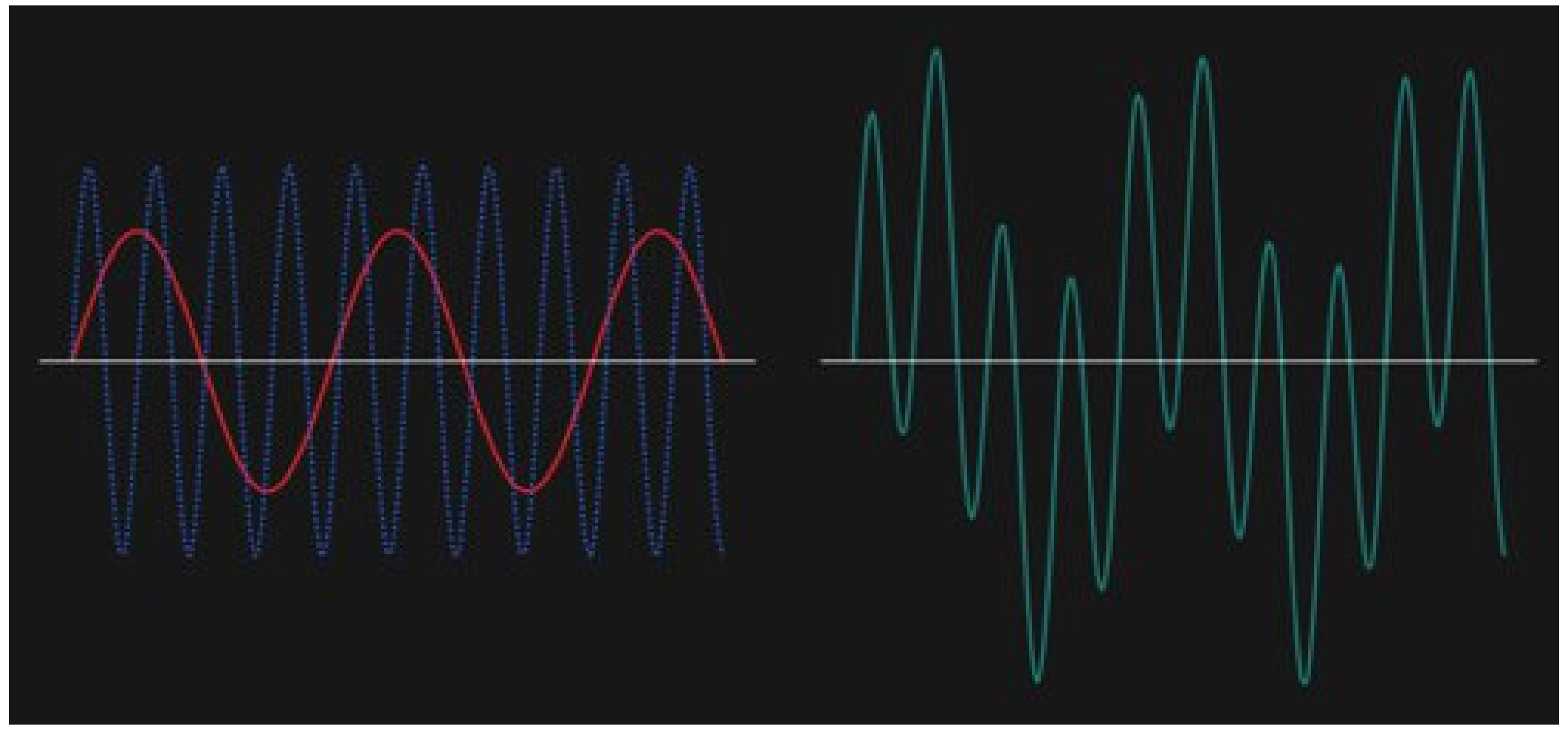
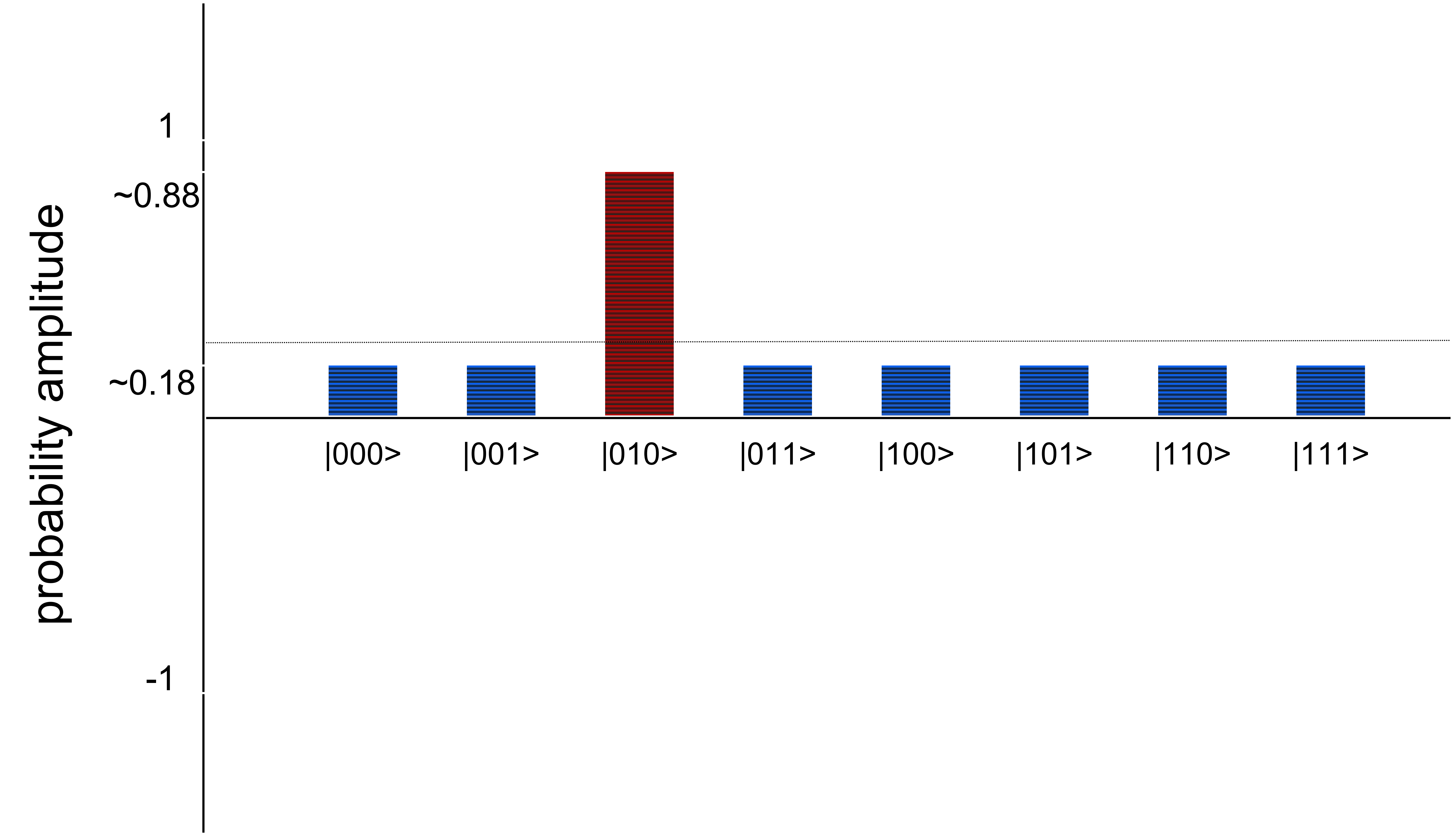
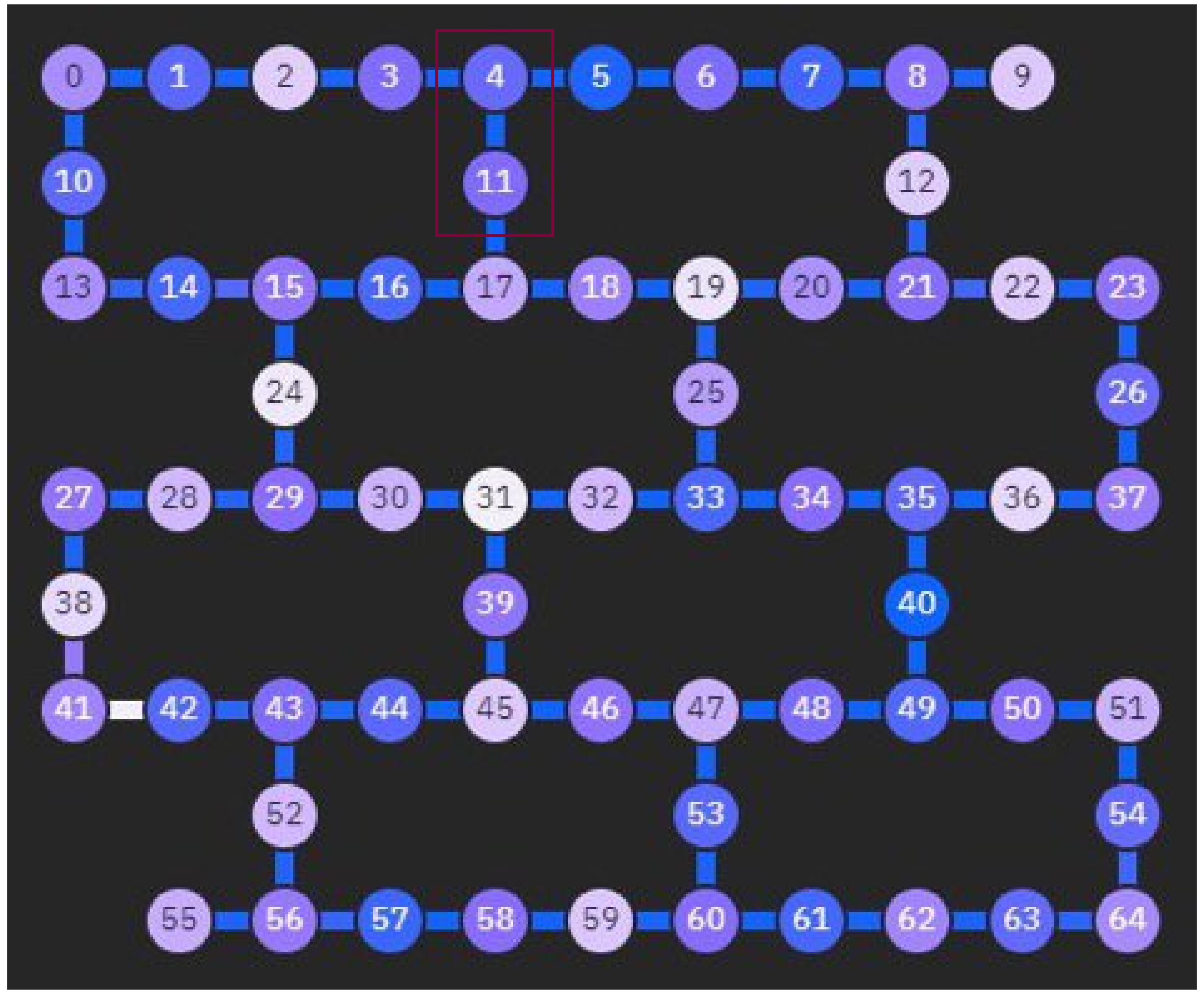




Quantum computing uses essential ideas from quantum mechanics

Entanglement



With two qubits we get combinations like

$$a\,|00\rangle + b\,|01\rangle + c\,|10\rangle + d\,|11\rangle$$

where

$|01\rangle$ means the first qubit is $|0\rangle$ and the second is $|1\rangle$

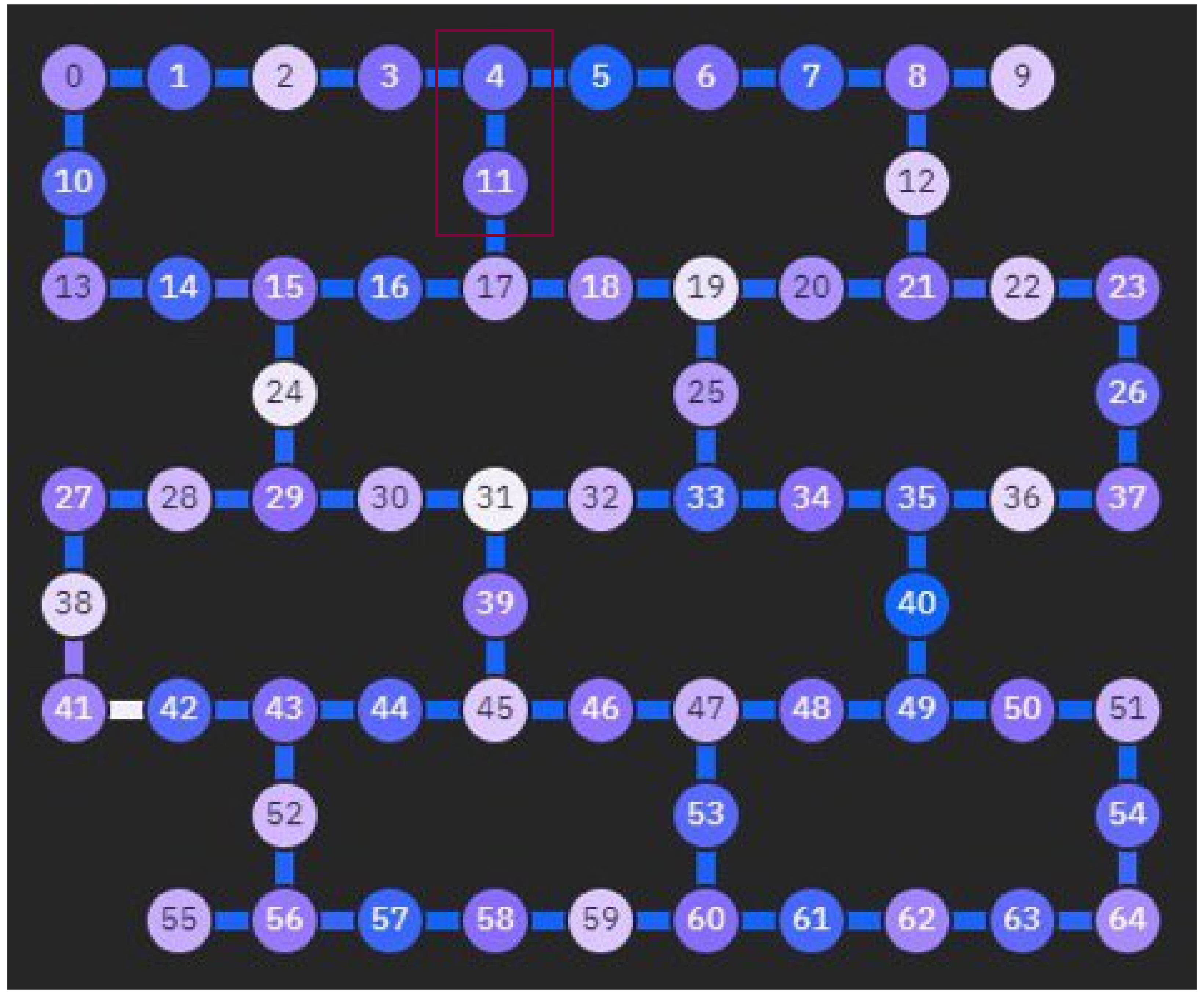
a, b, c and d are complex numbers and

$$|a|^2 + |b|^2 + |c|^2 + |d|^2 = 1$$

If two or more of the a, b, c, and d are non-zero, and we cannot separate the qubits, they are entangled with perfect correlation and are no longer independent.

Quantum computing uses essential ideas from quantum mechanics

Entanglement



For example,

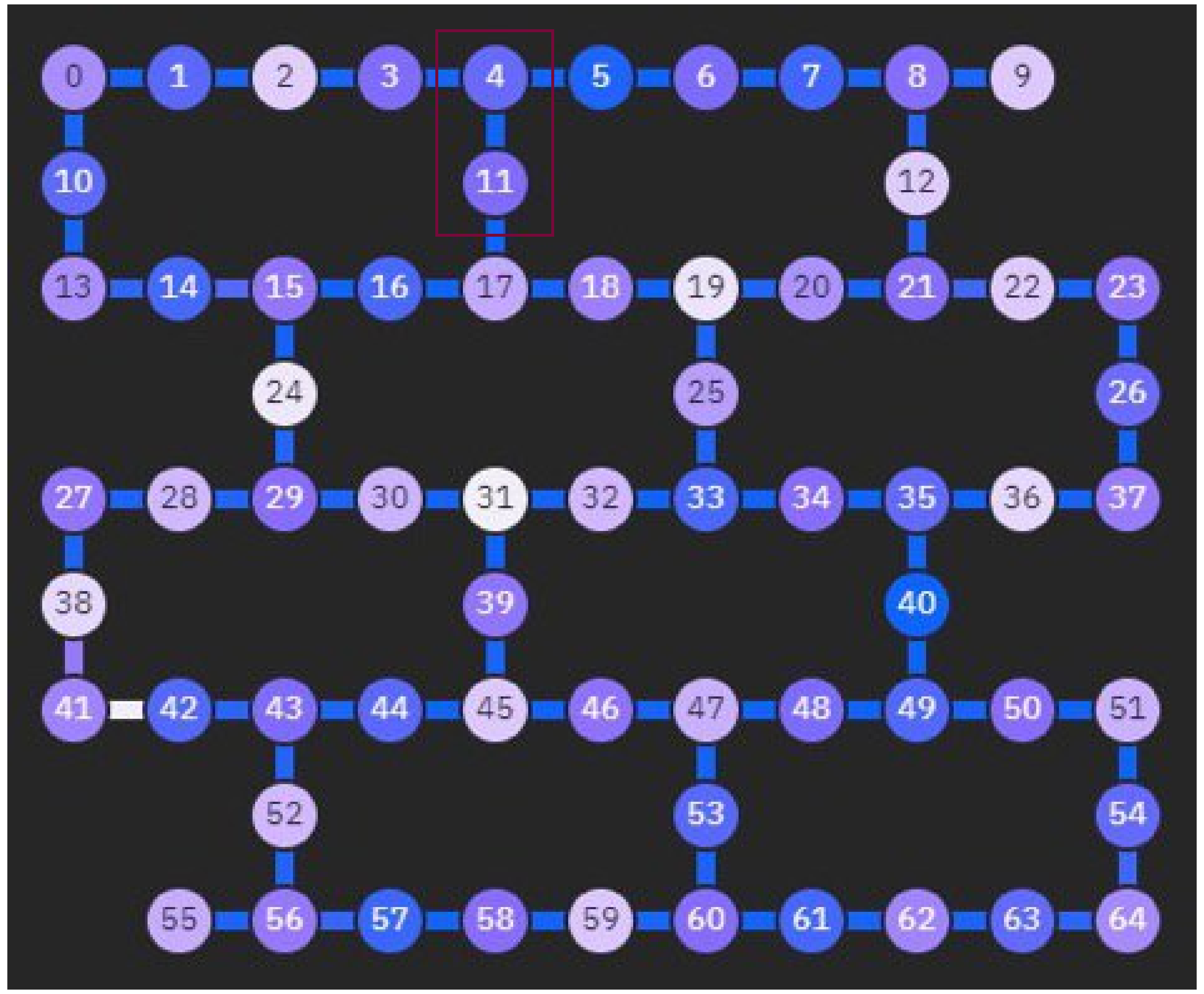
$\frac{\sqrt{2}}{2}|00\rangle + \frac{\sqrt{2}}{2}|01\rangle$ not entangled

$\frac{\sqrt{2}}{2}|01\rangle - \frac{\sqrt{2}}{2}|10\rangle$ entangled

$\frac{\sqrt{2}}{2}|00\rangle + \frac{\sqrt{2}}{2}|11\rangle$ entangled

Quantum computing uses essential ideas from quantum mechanics

Entanglement



We can write

$$\frac{\sqrt{2}}{2}\,|00\rangle + \frac{\sqrt{2}}{2}|01\rangle$$

as

$$|0\rangle\,(\frac{\sqrt{2}}{2}\,|0\rangle + \frac{\sqrt{2}}{2}|1\rangle)$$

but we cannot write

$$\frac{\sqrt{2}}{2}\,|00\rangle + \frac{\sqrt{2}}{2}|11\rangle$$

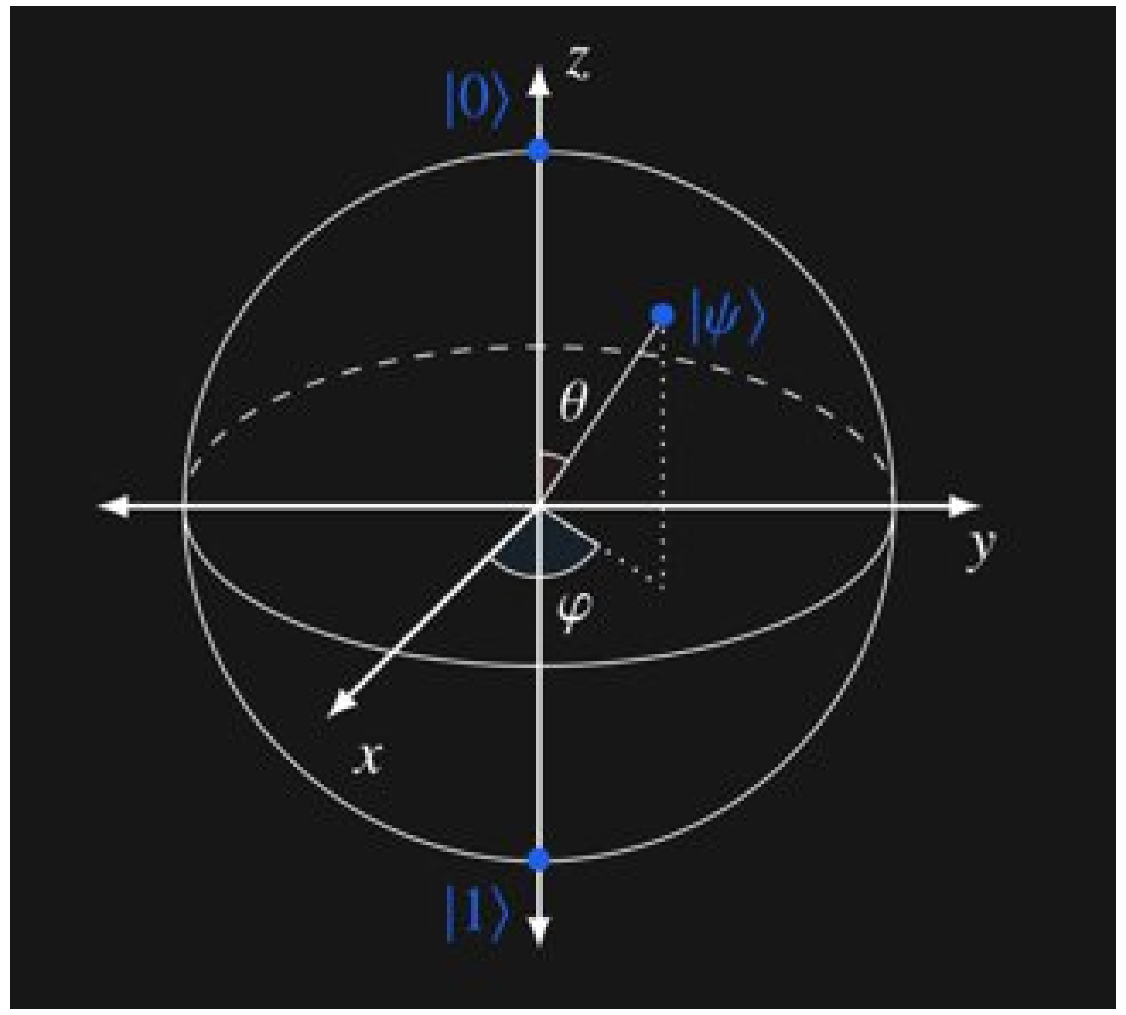
as the “product” of two single qubit states.

They are entangled!

Once you measure the first qubit, the second is uniquely determined.

Quantum computing uses essential ideas from quantum mechanics

Measurement



Measurement is forcing the qubit's state

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

to $|0\rangle$ or $|1\rangle$ by observing it, where

- $|a|^2$ is the probability we will get $|0\rangle$ when we measure
- $|b|^2$ is the probability we will get $|1\rangle$ when we measure

For example,

$$\frac{\sqrt{2}}{2}\,|0\rangle + \frac{\sqrt{2}}{2}\,|1\rangle$$

has an equal probability of becoming $|0\rangle$ or $|1\rangle$, and

$$\frac{\sqrt{3}}{2}\,|0\rangle - \frac{1}{2}\,i\,|1\rangle$$

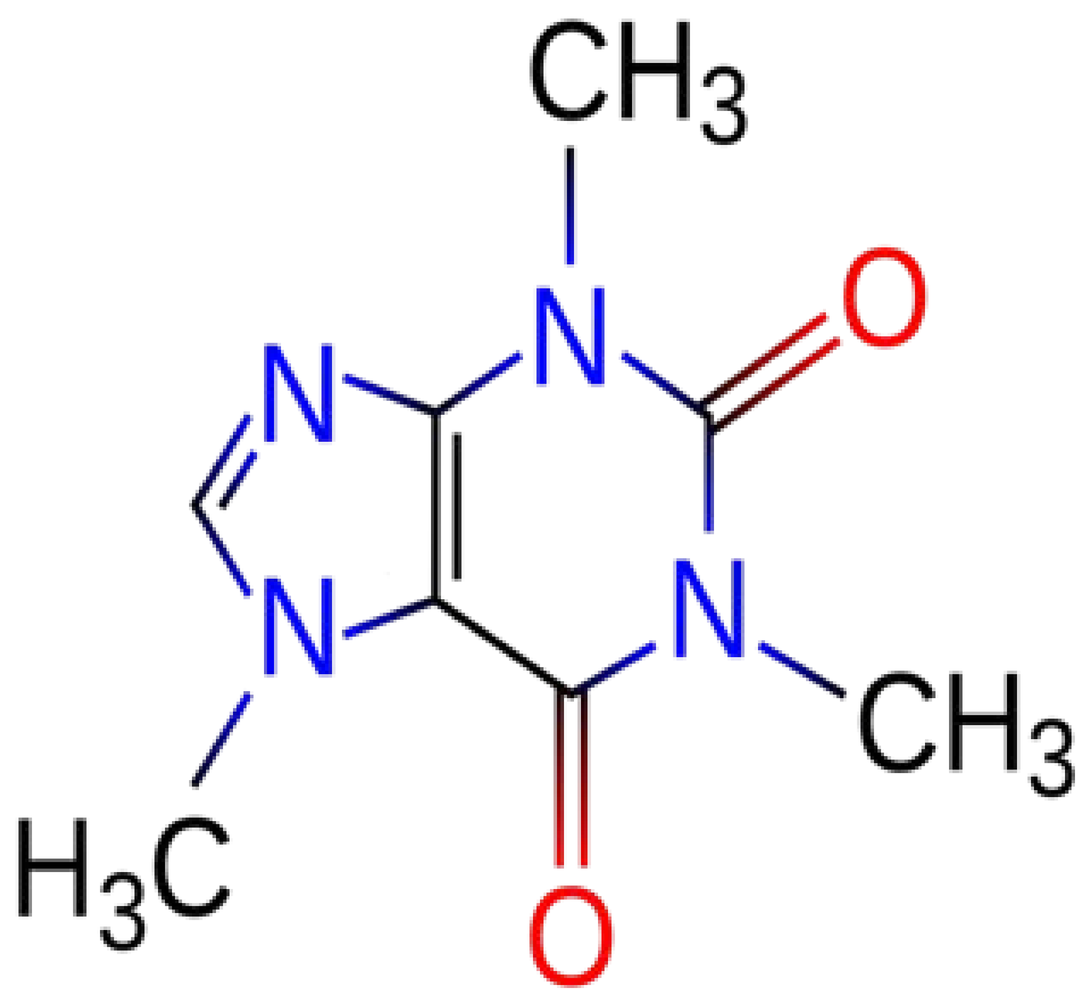
has a 75% chance of becoming $|0\rangle$.

Computing with caffeine

If our best classical computers are so powerful, shouldn’t we be able to perfectly simulate molecules and chemical reactions?

This would allow us to accelerate discovery of new compounds and processes for healthcare, materials, alloys, and sustainable energy creation.

Let’s consider caffeine …



Computing with caffeine

We would need approximately 10^{48} bits to represent the energy configuration of a single caffeine molecule at a single instant in a classical computer.

This is 1 to 10% of the total number of atoms in the Earth.

10^{48} = 1,000,000,000,000,000,
000,000,000,000,000,000,
000,000,000,000,000

Computing with caffeine

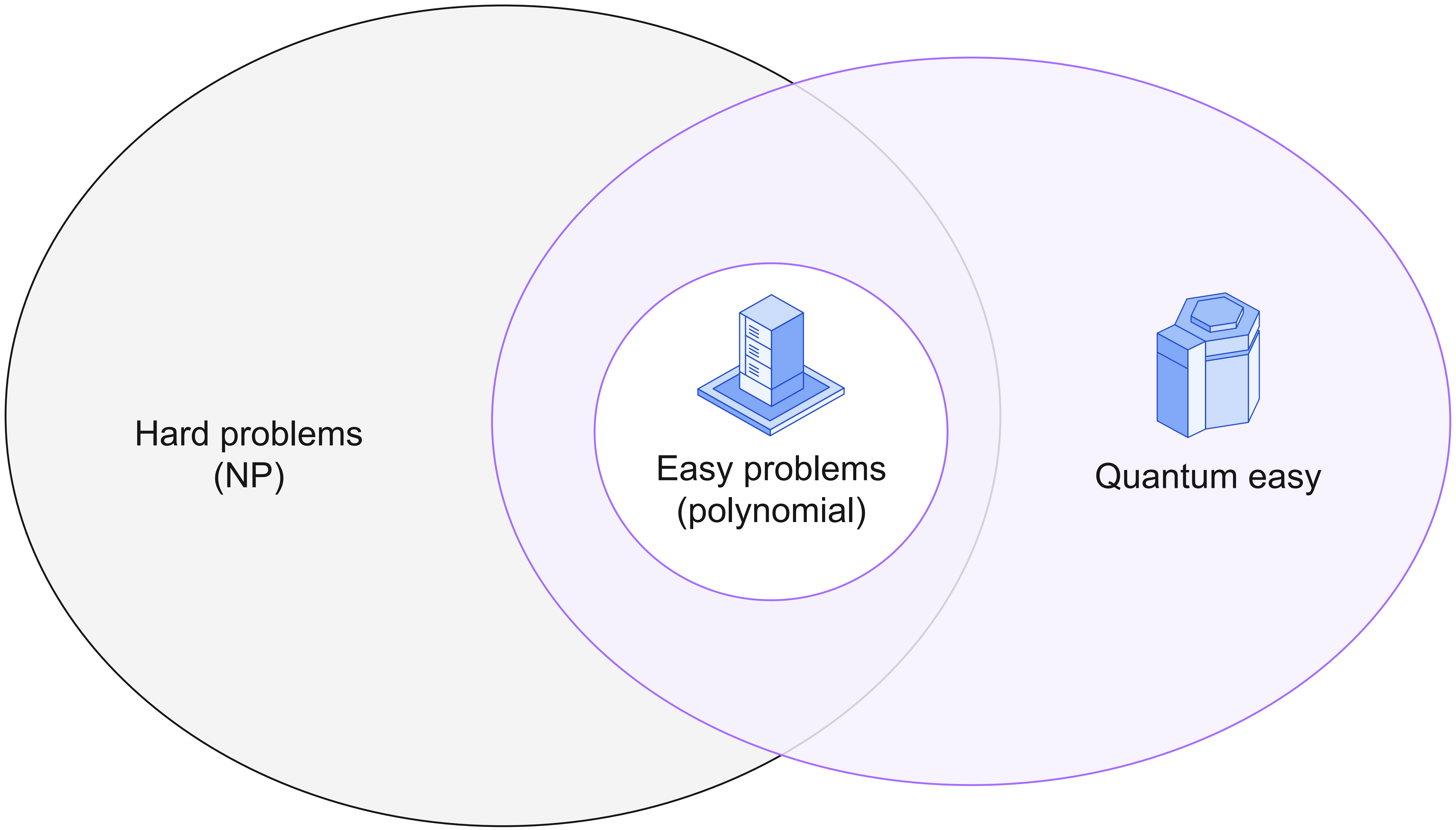
Although it's impossible to completely represent the molecular configuration of caffeine on today's most powerful super computers, we could represent it using 160 logical qubits.

IBM Quantum mission

Bring useful quantum computing to the world

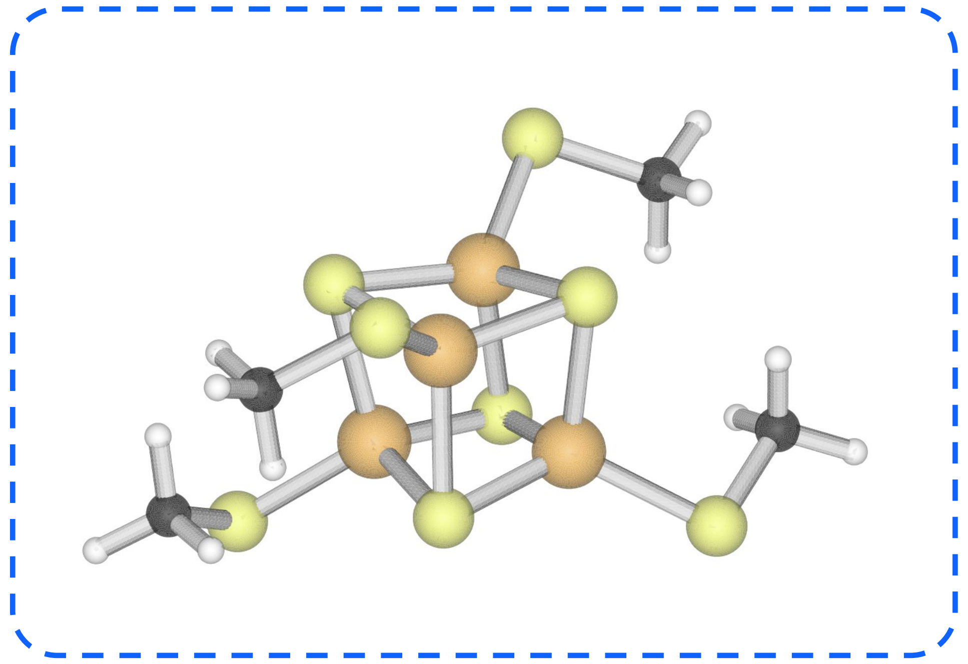
There is a rich seam of problems that cannot be solved by classical and AI supercomputing, and never will.

These are the trillion-dollar problems that quantum computing was designed to solve.

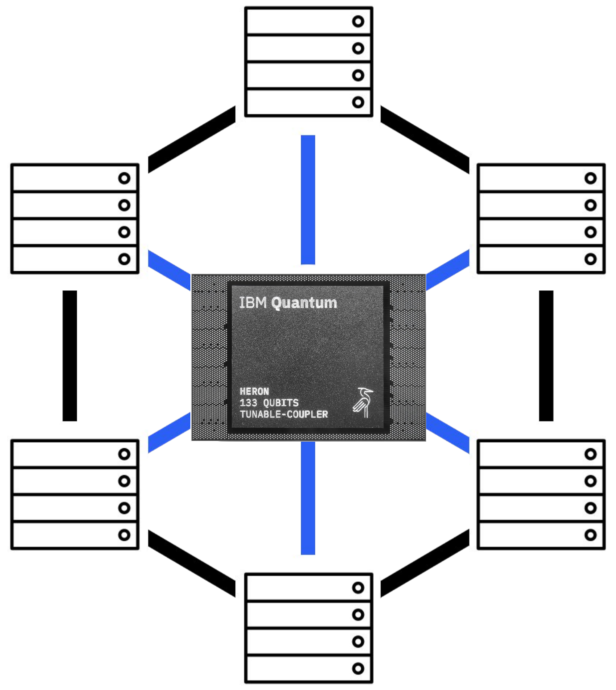


What are these problems?

Modeling molecules, atoms, electrons, and quarks with unprecedented accuracy



[4Fe-4S] using an active space of 54 electrons in 36 orbitals from the TZP-DKH basis set



$$H\Psi = E\Psi$$

Classical exact method	63 PiB of memory[1]
Classical approximate method (DMRG)	8 hours[2,3]
Quantum method (QCSC)	12 min using 77 qubits + 1.5 hours supercomputer time[1]

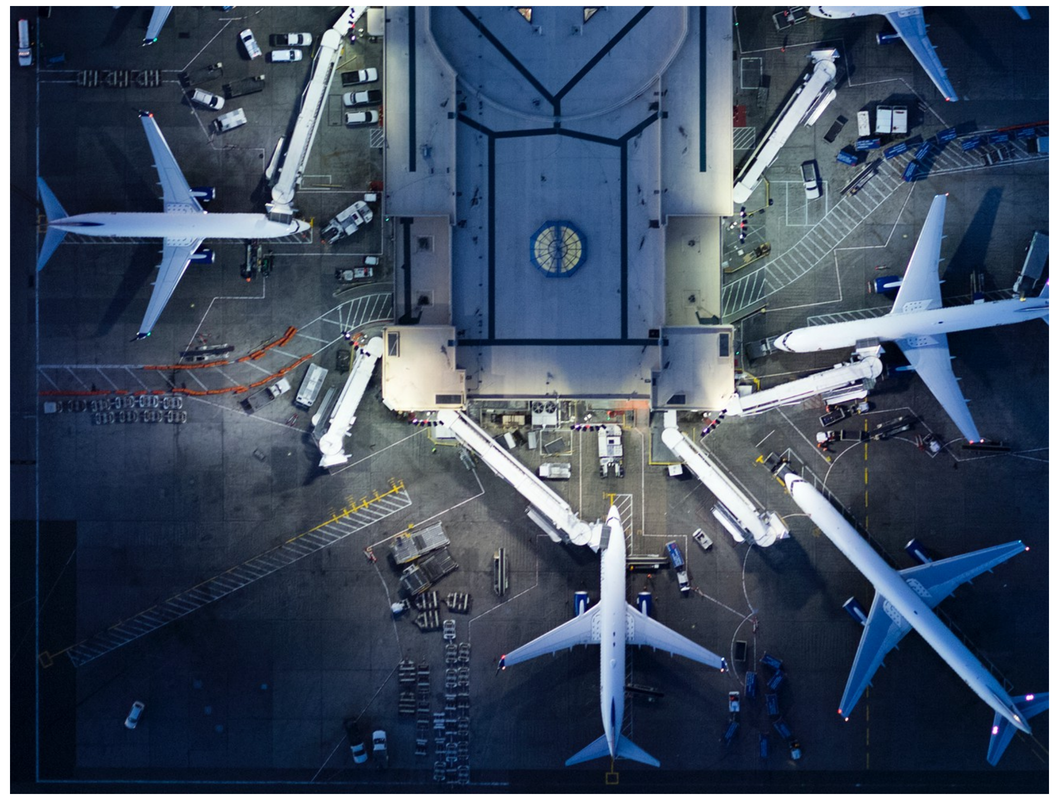
We are already using quantum (Heron, 77 qubits) and HPC (Supercomputer Fugaku) to achieve results comparable with the best classical approximate methods (DMRG) in accuracy and timing

1. Science Advances vol. 11, no. 25 (2025)
2. J. Chem. Theory Comp. 20 (2024): 775–786
3. J. Chem. Phys. 159, 234801 (2023)

What are these problems?

Modeling molecules, atoms, electrons, and quarks with unprecedented accuracy

Developing lighter, longer-lasting batteries for electric vehicles, electronics, and energy grid storage



Designing lighter, stronger materials to allow planes to be more efficient and to need less maintenance

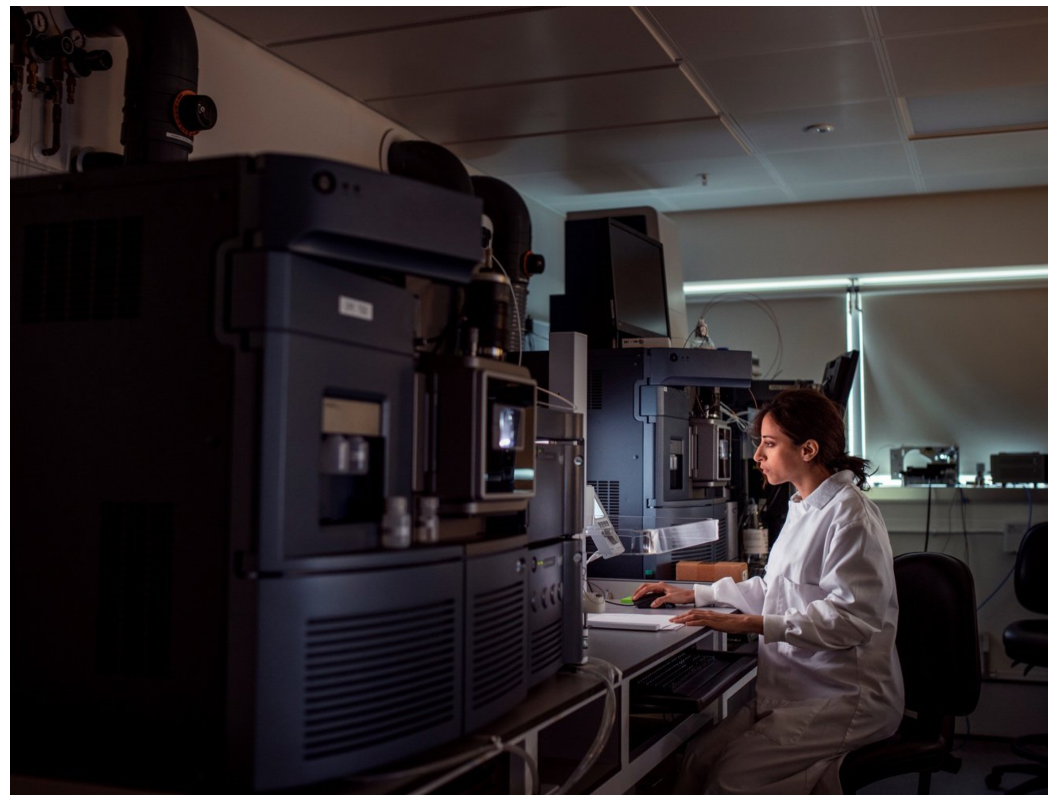
Discovering new classes of antibiotics to counter the emergence of multidrug-resistant bacterial strains

Designing optimal superconductors for MRI, electromobility, and renewable energies

What are these problems?

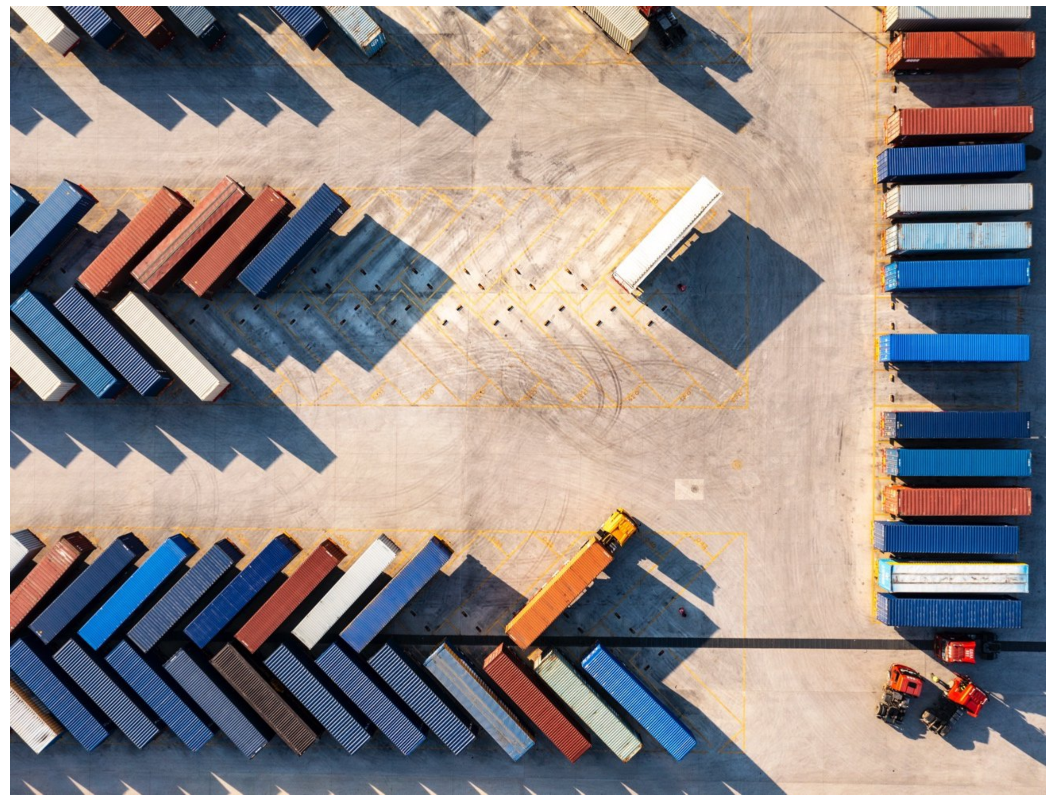
Solving algebra in [exponential] spaces.
Finding hidden patterns in structured problems.

Improving anomaly detection, as for rare events detection and fraud detection



Improving patient outcomes by designing optimal cell-centric therapeutics

Strengthening risk management through better time series and sequence prediction



Optimizing vehicle routing and scheduling for large-scale logistics networks

And we know there are other problems with a structure that quantum can exploit.

↳ So we're also looking for value in problems that are hard classically, like optimization.

State of the technology

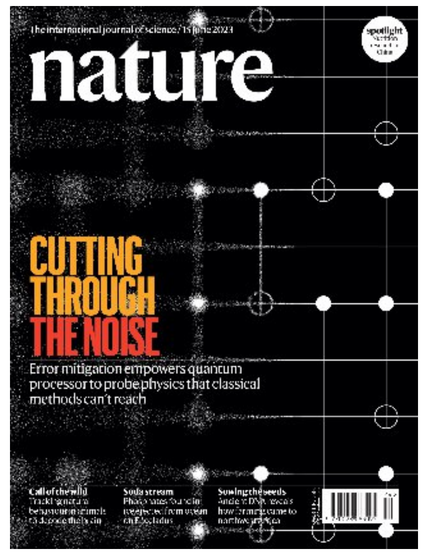
Quantum Utility

Gates ⇨ 3K 5K 100M

PRE-UTILITY | ERROR MITIGATION | ERROR CORRECTION

Year ⇨ 2023 2024 2029

All circuits can be brute force run on classical hardware



Only approximate solutions exists and is the regime for exploring quantum advantage

Well in the error correction regime where today’s known quantum algorithms exist


```
for _ in loop:
    qc,matrix,… = do_classical(param)
    A,… = SGESVD(matrix)
    job = sampler.run([qc])
    do_classical(job.result(), A, …)
    …
```

Thesis

The future of computing is mapping all problems to tensors and circuits

What is quantum advantage?

Performing an information processing task more efficiently, cost-effectively, or accurately using quantum computers than is known to be possible with classical computers alone

There are two important nuances to this →

1

We must establish trust in the outputs of a real and noisy quantum device.

A scientific experiment is only as good as confidence in methods.

2

Quantum advantage is not something that will happen at a singular moment in time.

It is a hypothesis that is subject to falsification.

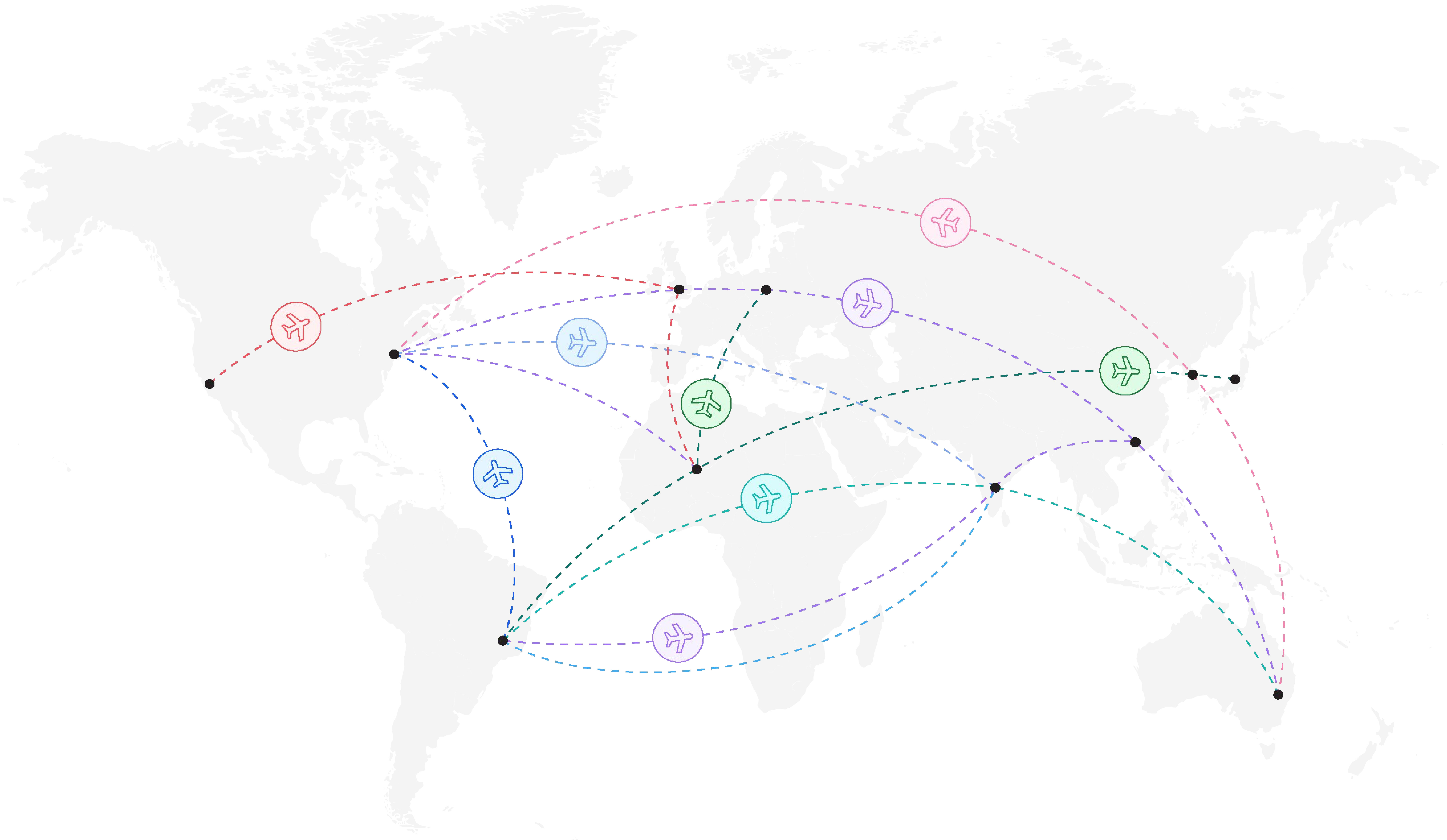
Quantum computing

The new wave of computing

Potential to **Unlock** previously unsolvable problems with quantum computing, cutting computing time **from years to hours.**

A new paradigm of thinking launches inventors into previously unnavigated discovery territories with **new use cases.**

Accelerate discovery through a **powerful** hybrid quantum-classical approach.



The new wave of computing

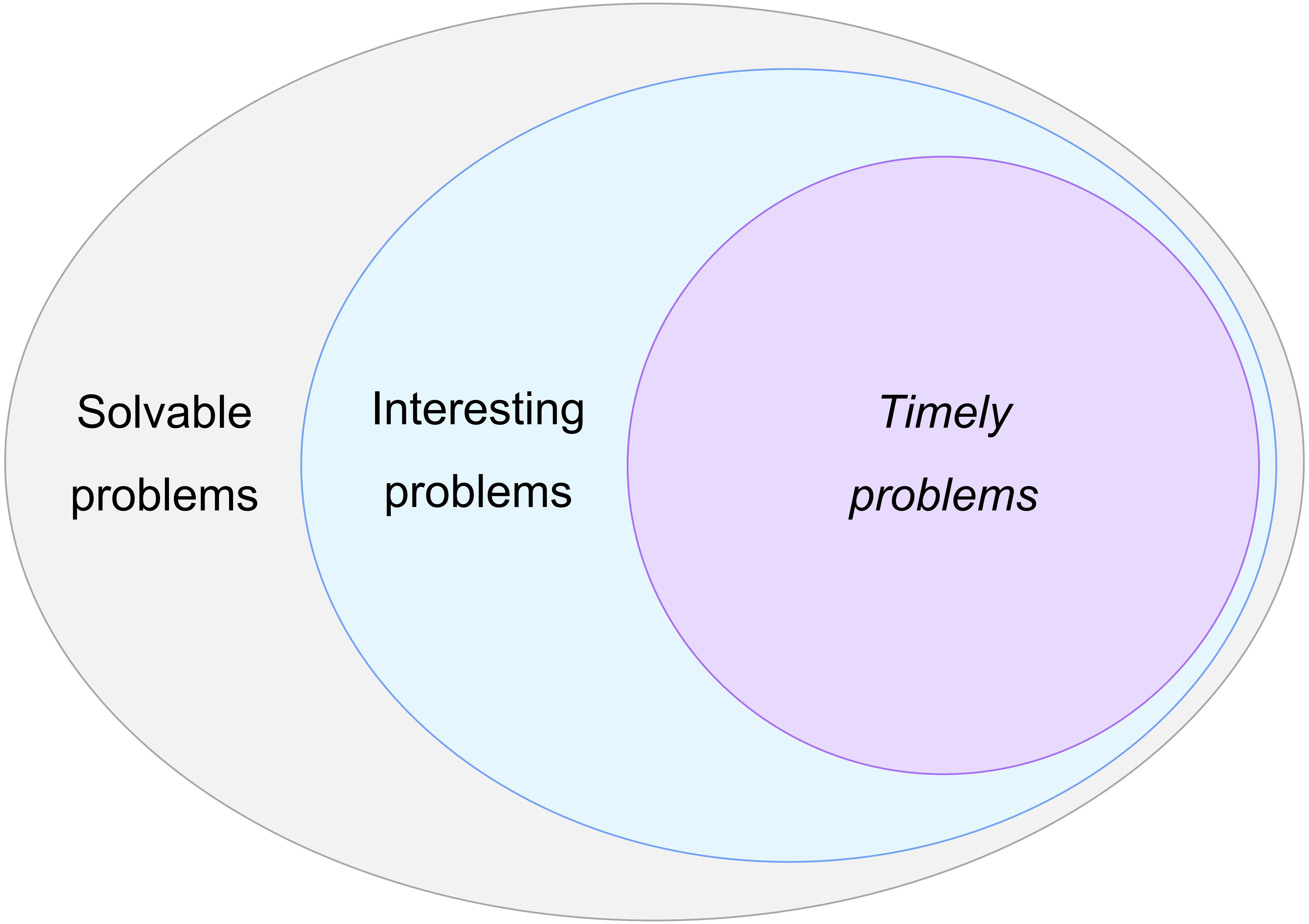
Classical computer
Well suited for many problems

Quantum computer
Unlock classically intractable problems

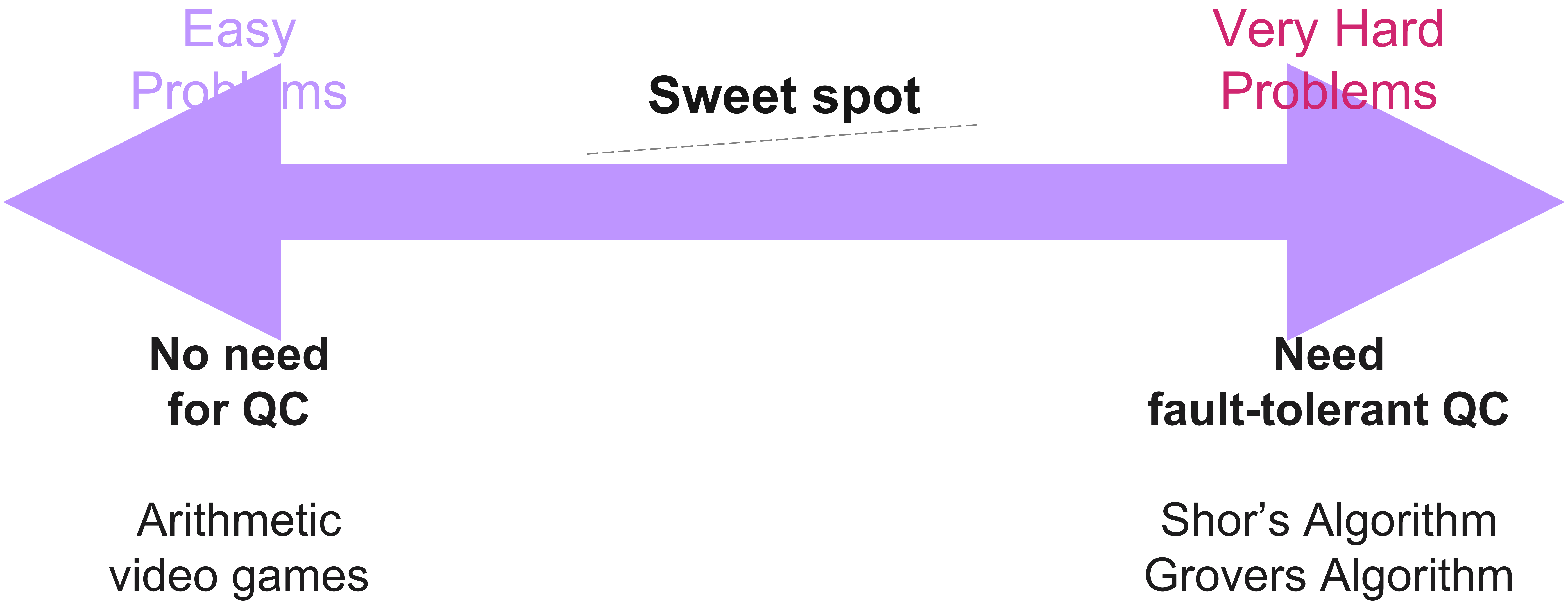
Problem hierarchy

Quantum computers are valuable for solving many different types of problems. However, not all problems are equally relevant.

The success of the field depends on showing value beyond what classical capabilities alone can achieve.



When to use a quantum computer



See [Quantum Computing in Practice](#) | [Which Problems Are Quantum Computers Good For?](#) for additional discussion and insights

Quantum computing is expected to have impact across industries

Example use cases

Nearer Term

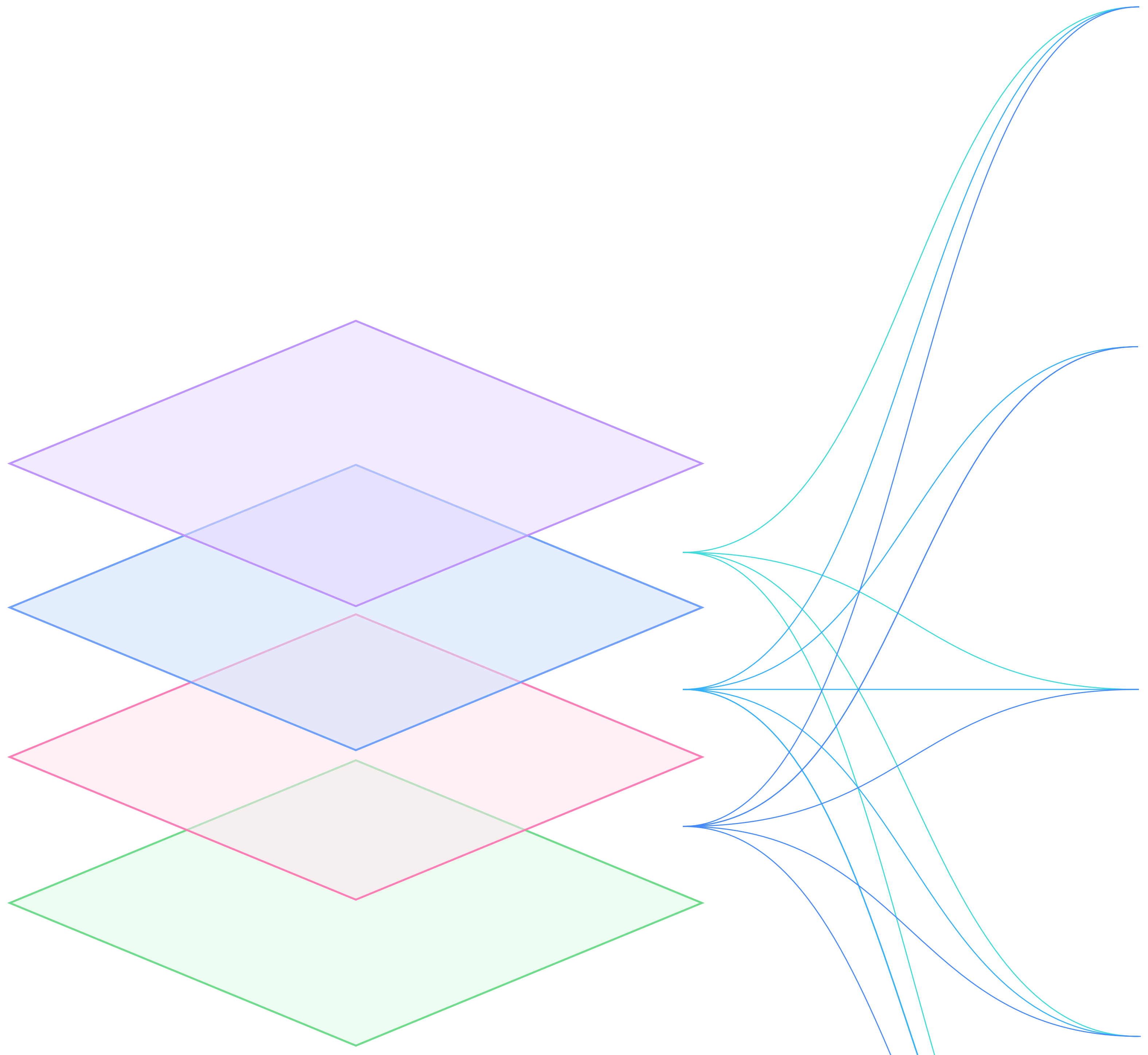
Longer Term

Chemistry & materials

Optimization & Search

Machine Learning/AI

Numerical simulation



Aerospace
- High strength-to-weight materials development
- Wing ply-composite design optimization
- Aircraft computational fluid dynamics

Automotive
- Advanced batteries
- Multi-objective vehicle routing optimization
- Auto design and simulation

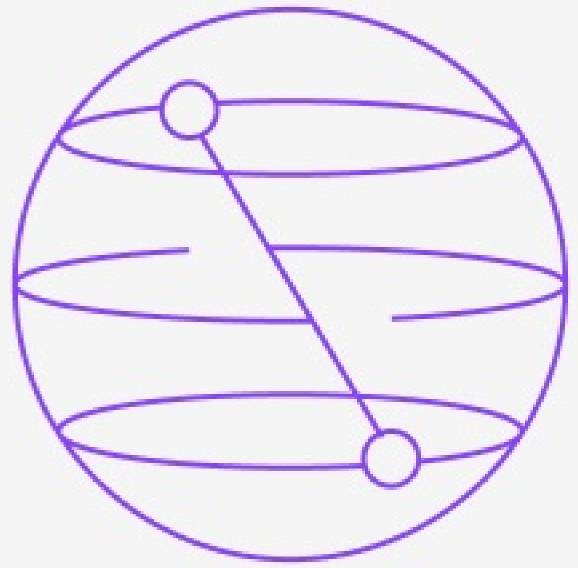
Chemicals
- Lower energy fertilizer manufacturing
- Efficient Catalysts
- Accelerated product development

Electronics & semiconductors
- Placement and routing optimization
- Deposition/etch process modeling
- Multi-domain simulation

Energy
- Grid management
- Grid optimization with EV's
- Carbon Sequestration

Financial Services
- Portfolio optimization
- Derivatives/options pricing
- Antti-Money laundering

Health Care & Life Sciences
- Drug discovery and drug design optimization
- mRNA & protein structure predictions
- Disease target & biomarker discovery



Qiskit

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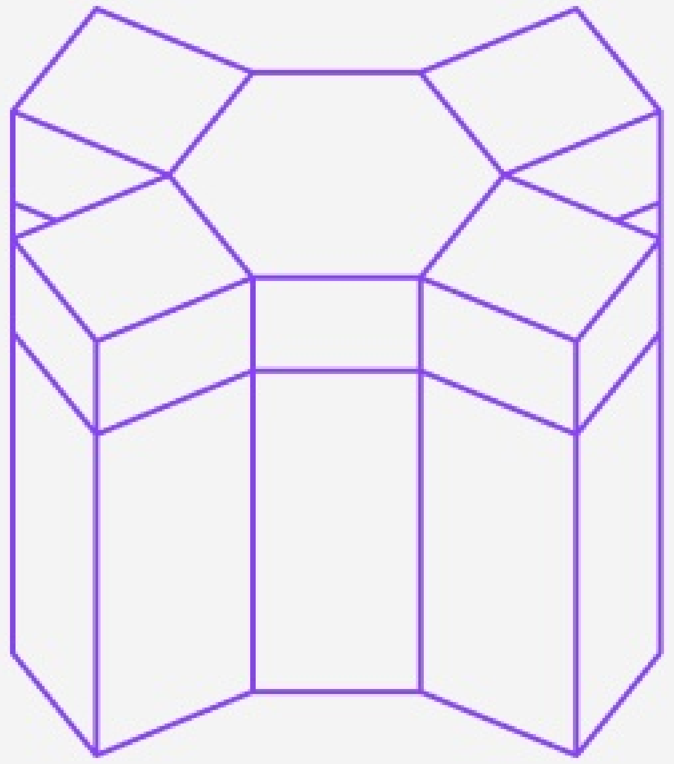

IBM QPUs

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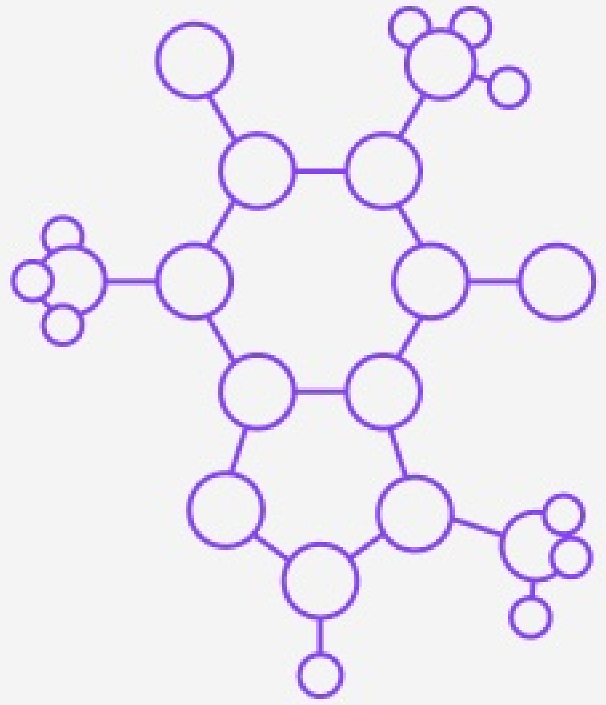
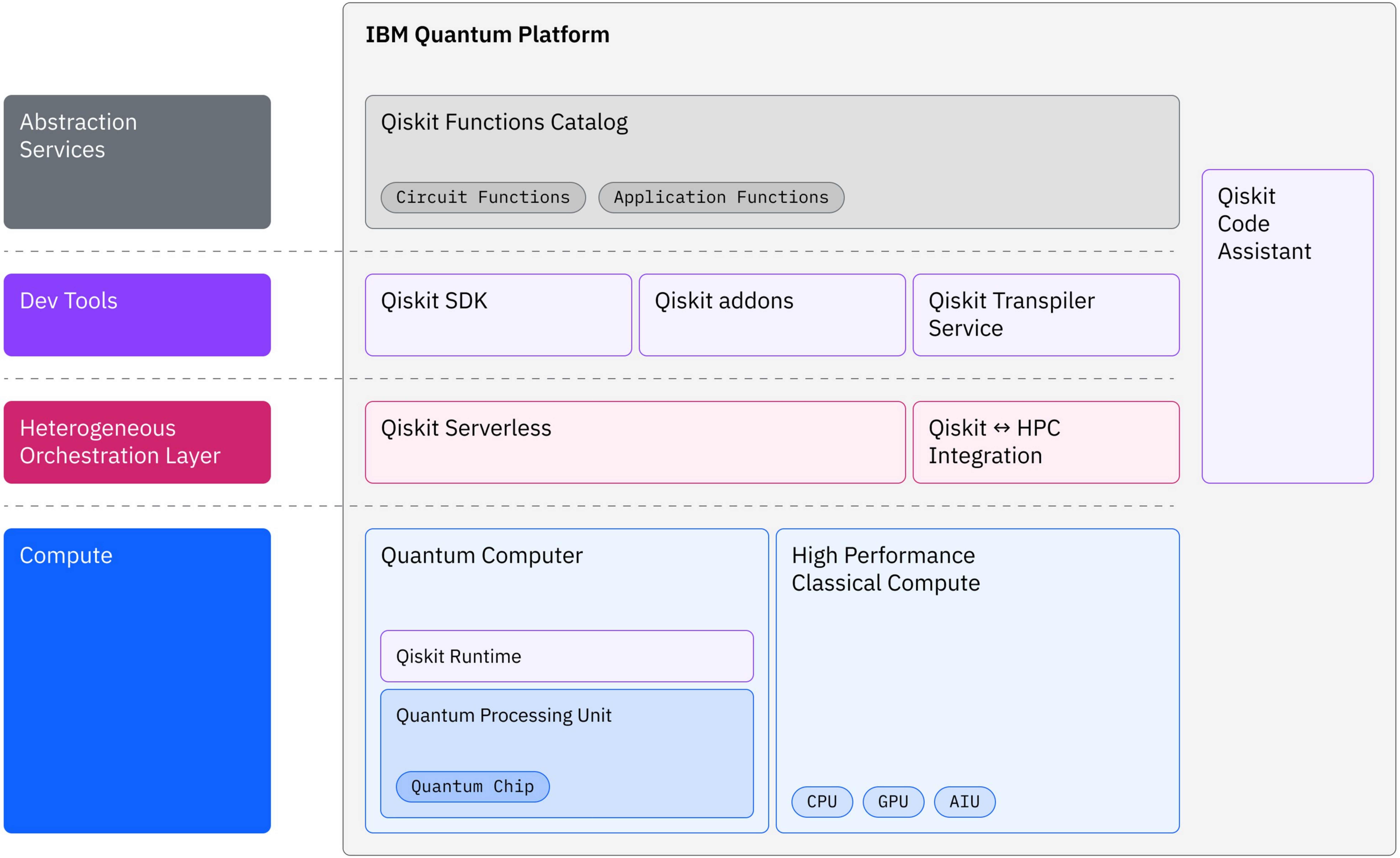


Utility Scale Work

Quantum must be
performant

Quantum must be
easy-to-use



IBM Quantum Platform
Abstraction Services
Qiskit Functions Catalog
Circuit Functions
Application Functions
Qiskit Code Assistant
Dev Tools
Qiskit SDK
Qiskit addons
Qiskit Transpiler Service
Heterogeneous Orchestration Layer
Qiskit Serverless
Qiskit ↔ HPC Integration
Compute
Quantum Computer
Qiskit Runtime
Quantum Processing Unit
Quantum Chip
High Performance Classical Compute
CPU
GPU
AIU

Qiskit SDK

It’s simple…

If it needs a circuit, it needs Qiskit

Qiskit SDK

arXiv:2405.08810

The lingua franca of quantum computing; write once and execute quantum circuits on **10+** different hardware providers

IBM Quantum
AQT
IQM
Azure Quantum
Alice & Bob
IonQ
Amazon Braket
Superstaq
Quantinuum
Rigetti

Quantum SDK Preferred
(2024 Unitary Fund Survey)

74%

Qiskit contributors that are external to IBM

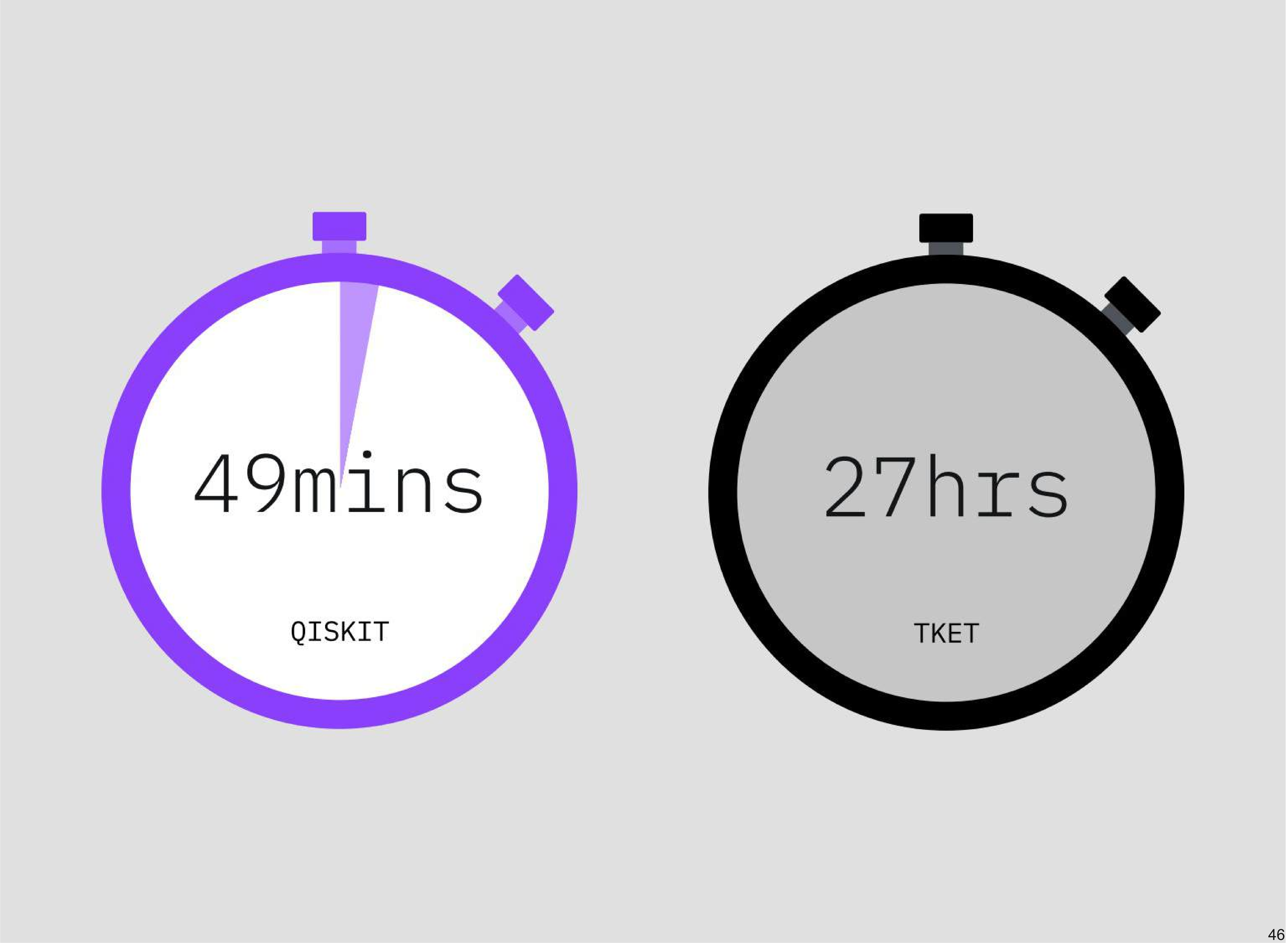
75%

Dependent Qiskit Projects

5185

Speed: Overall Time to Complete

Speed measures how long it takes an SDK to create and manipulate circuits, as well as how long it takes to synthesize and transpile.

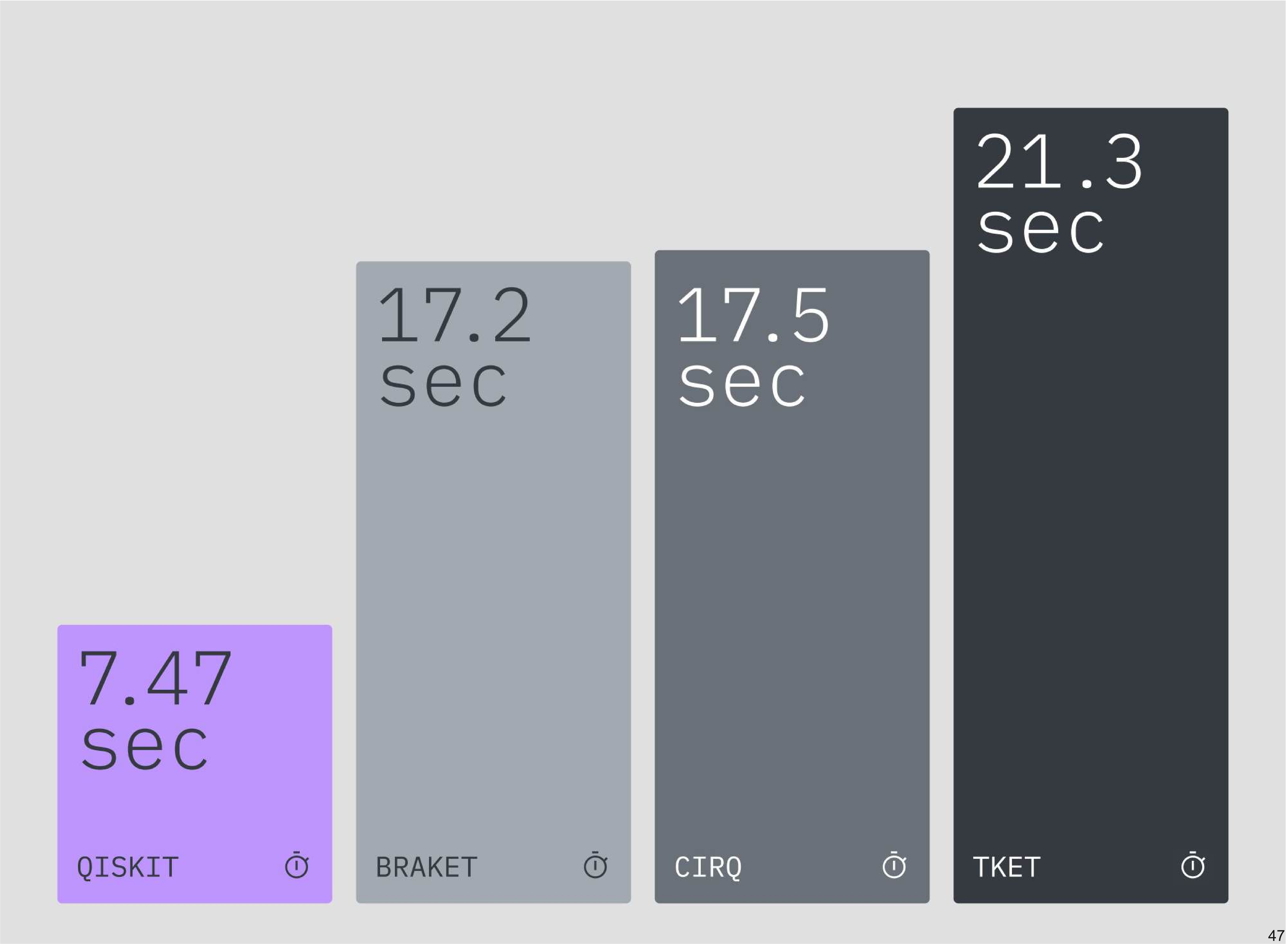


Not included due to insufficient test results: Braket, Cirq, CUDA & Staq

*Timing measured using only completed tests

Data based on arXiv:2409.08844 paper published 2024.SEP.13

Speed: Build & Manipulate Time to Complete



Not included due to insufficient test results: CUDA & Staq

*Timing measured using only completed tests

Data based on arXiv:2409.08844 paper published 2024.SEP.13

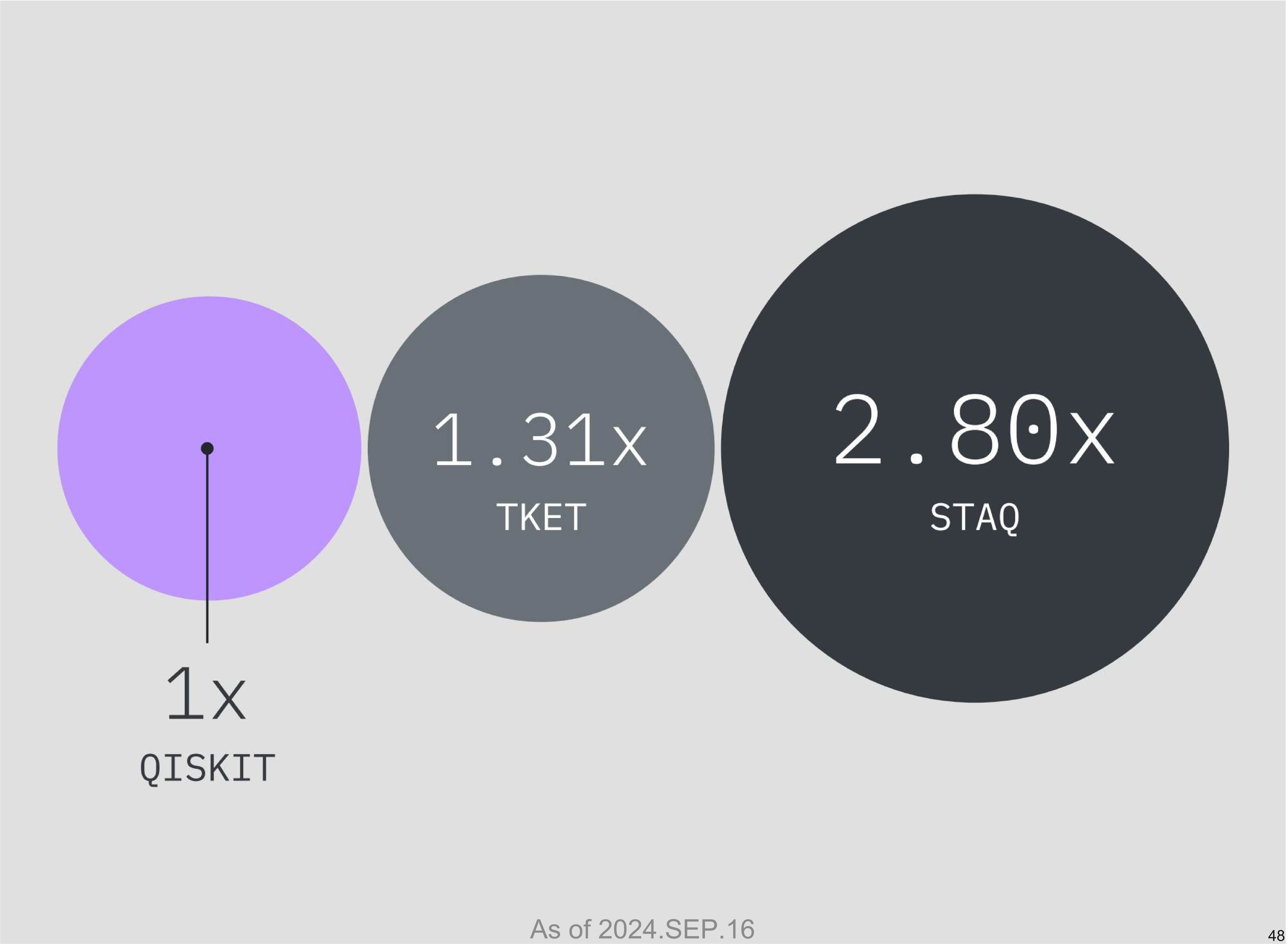
Quality:
Ratio of 2Q Gates

Quality measures the number of two-qubit gates in a transpiled circuit. Fewer operations means less noise and better results.

Not included due to insufficient test results:
Braket, Cirq & CUDA

*Quality measured using only completed tests

Data based on arXiv:2409.08844 paper published 2024.SEP.13



Qiskit Pattern:
The anatomy of a quantum algorithm

01
Map problem instance to quantum circuits and operators

02
Optimize for target hardware execution

03
Execute via Qiskit Runtime

04
Result processing

Map

Optimize

Execute

Post-Process

Qiskit SDK sets the foundation

Qiskit SDK gives us a base layer of building blocks for building and running quantum algorithms

Qiskit Circuit Library	Transpiler	Primitives	Quantum Info
Input: Domain inputs	Input: Circuits, observable	Input: ISA circuit, observable	Input: Expectation value/samples
Output: Circuits, observable	Output: ISA circuit, observable	Output: Expectation value/samples	Output: Data objects/visualizations
Map	Optimize	Execute	Post-Process

Qiskit addons build on the Qiskit SDK

A collection of research capabilities developed as modular tools that can plug into a workflow to design new algorithms at the utility scale

Starting with multi-product formulas (MPF), approximate quantum compilation (AQC-Tensor), operator backpropagation (OBP), and sample-based quantum diagonalization (SQD).

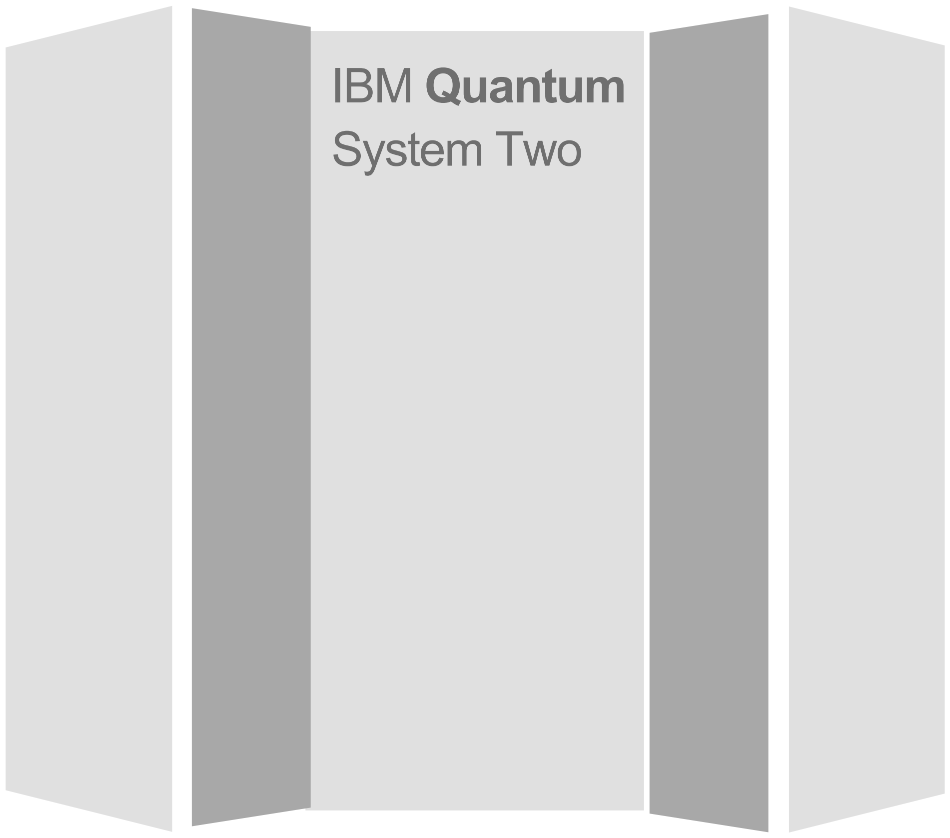
AQC-Tensor	OBP		SQD
MPF	Circuit cutting		M3
Qiskit Circuit Library	Transpiler	Primitives	Quantum Info
Input: Domain inputs	Input: Circuits, observable	Input: ISA circuit, observable	Input: Expectation value/samples
Output: Circuits, observable	Output: ISA circuit, observable	Output: Expectation value/samples	Output: Data objects/visualizations
Map	Optimize	Execute	Post-Process

Quantum Software
(powered by Qiskit Addons and Qiskit Functions)

+

Qiskit

+



QPUs

=

Useful Work

The IBM Quantum platform unlocks research with quantum

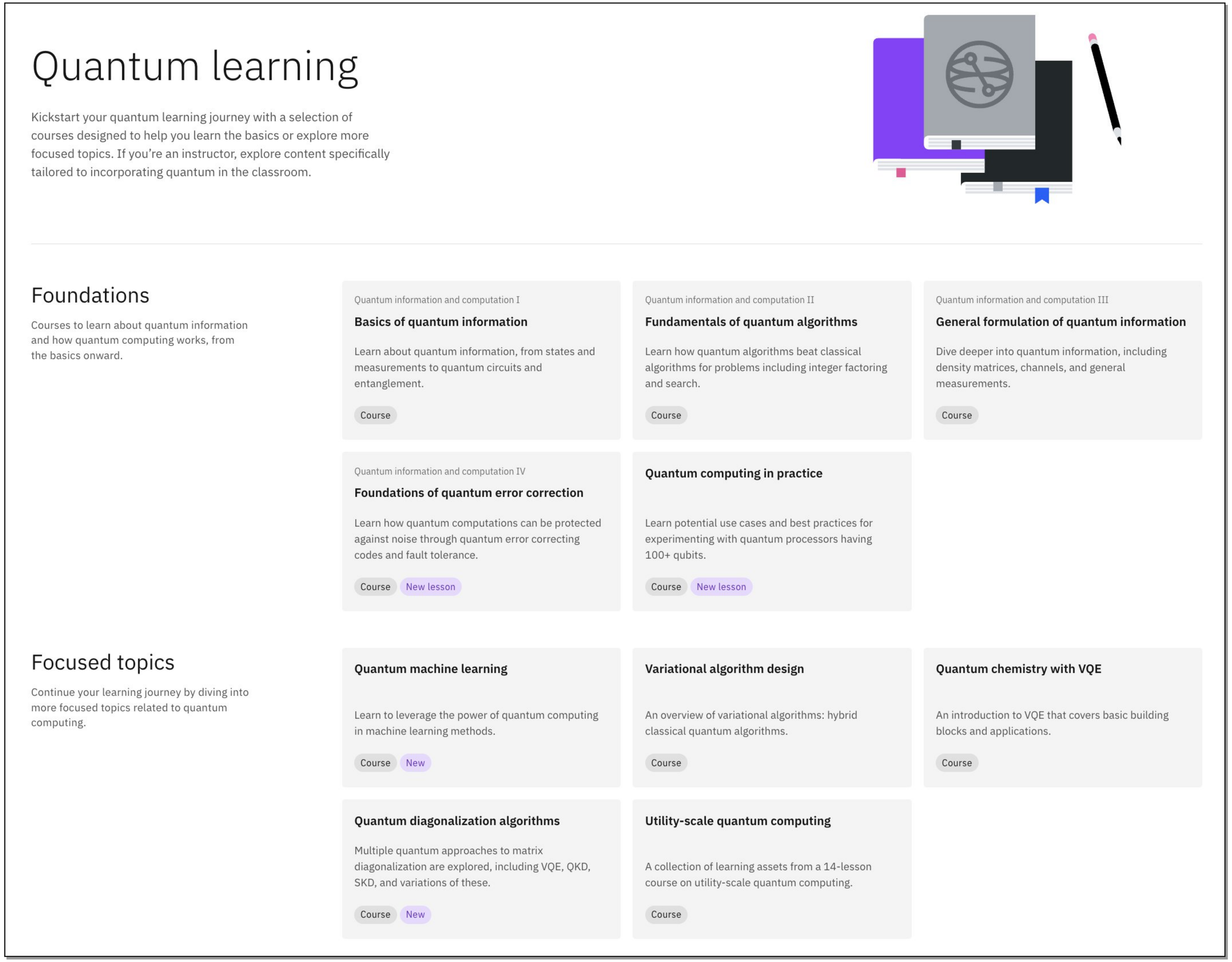
Optional: Hands-on Notebooks (Speaker to show in tutorial format)

Next steps!

IBM Quantum Learning

Learn the basics of quantum computing and how to solve real-world problems with IBM Quantum services and systems

Courses, tutorials, and educational resources by leading quantum experts.

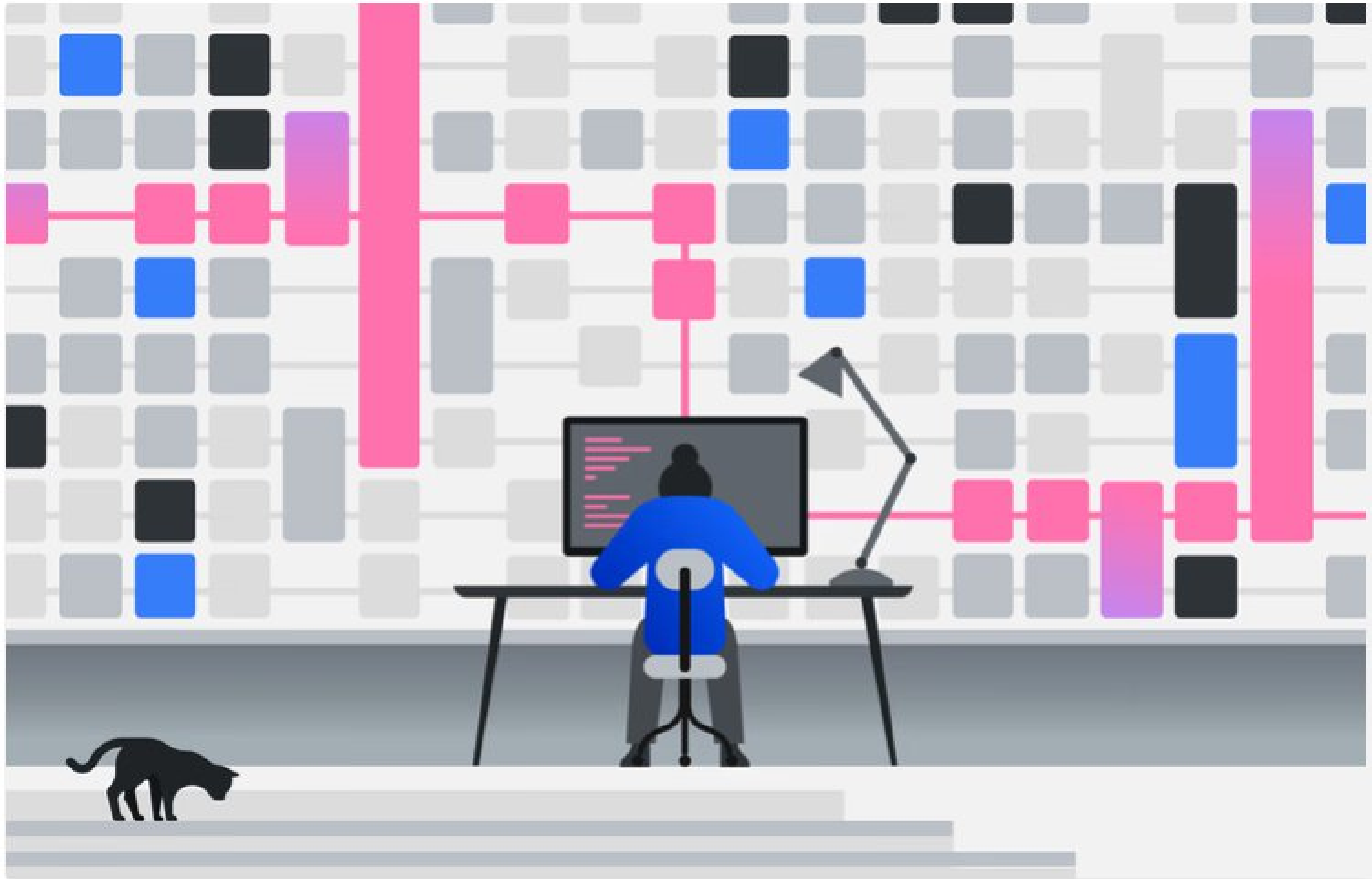


IBM Quantum Learning

Learn the basics of quantum computing, and how to use IBM Quantum services and systems to solve real-world problems.

IBM Quantum Challenge 2024 starts June 5th

Register today →



Quantum Computing in Practice

New Video

Learn about realistic potential use cases for quantum computing and best practices for experimenting with quantum processors having 100 or more qubits.

Lessons
2

Your progress
N/A

Start course →

IBM Quantum community

IBM Quantum Learning

An online platform for learning the basics of quantum computing, and how to use IBM Quantum services and systems to solve real-world problems.

Qiskit Advocates

A global program that provides support to individuals who actively contribute to the Qiskit community. There are hundreds of Qiskit advocates representing many countries who contribute to the Qiskit community.

Qiskit Global Summer School

An annual event featuring online lectures delivered by various IBM Quantum experts, as well as live Q&A sessions.

Qiskit YouTube channel

The Qiskit YouTube channel hosts hundreds of useful videos on quantum computing.

Qiskit Developer Certification

The world's first ever developer certification for programming a quantum computer, setting the benchmark for quantum developer skills.

Qiskit Global Summer School

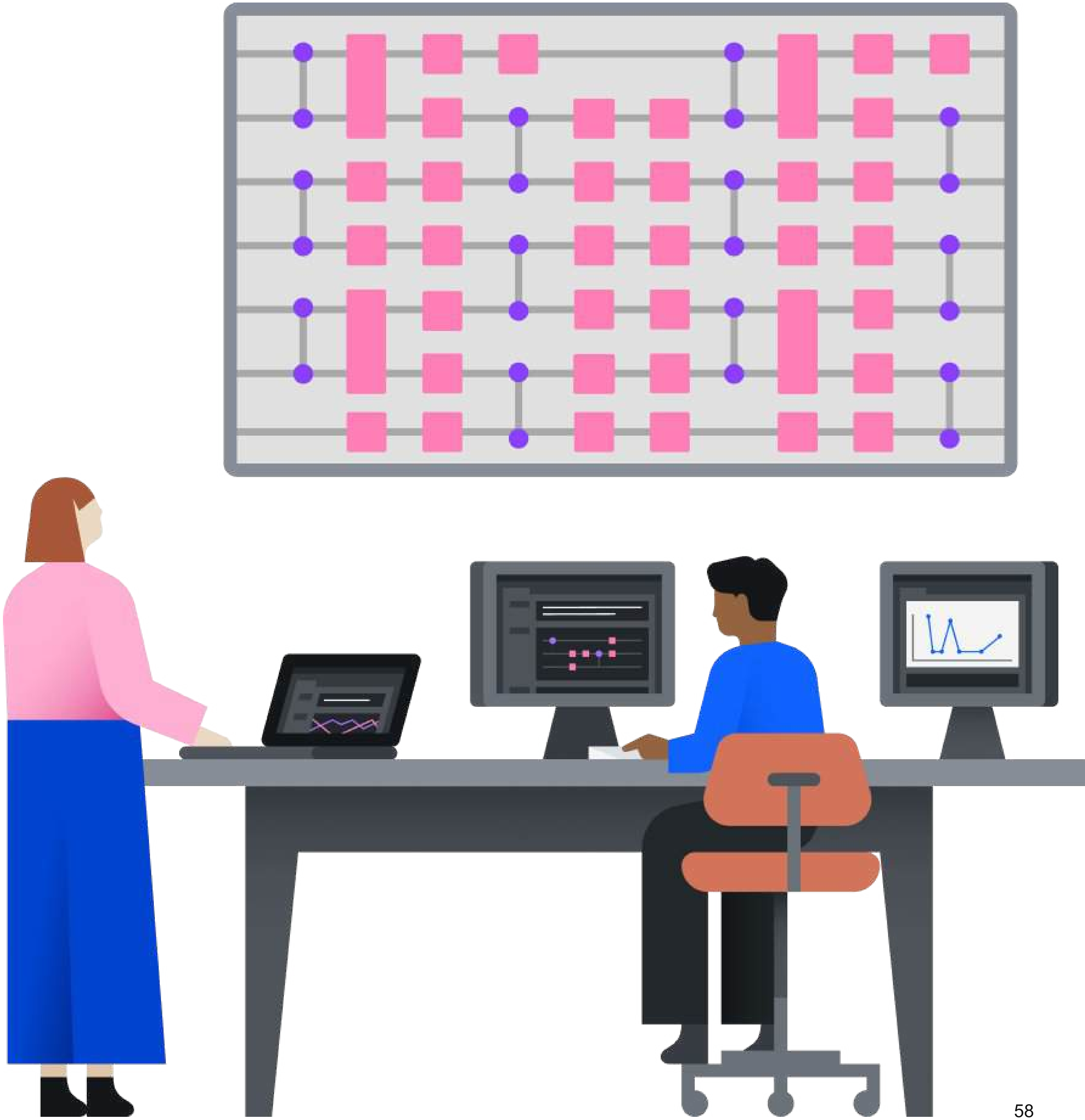
Our largest educational event every year. Two weeks of lectures, labs, Q&As, and community engagement.

Rooted in the IBM Quantum Learning courses, with new content each year.

6,000+ seats sold out in 2024.

Live event featuring badges for completion, extra assignments for partners, and more.

After the event is over, the lecture material becomes available on YouTube.



Qiskit Fall Fest

Student-led quantum computing events on campus
↳ Crafted by student leaders, supported by IBM

Working with the student leaders of today to shape the industry leaders of tomorrow

Organic growth of local communities

Since 2021:

195	28k+
Events	Attendees

(Pictured: 2024 Qiskit Fall Fest event at The University of Ibadan in Nigeria)

IBM Quantum Summer Internship Program

Work across the entire IBM Quantum team, from programming to materials research, on real projects that matter.

Applications open in the fall and continue through winter for different roles globally.

IBM Quantum interns, class of 2023

Qiskit Developer Certification

The Qiskit Developer Certification is the world's first ever developer certification for programming a quantum computer. There are over 1,100+ certified Qiskit developers across the globe. This certificate sets a benchmark for the industry in identifying those with quantum developer skills.

Qiskit Advocates Program

A global cohort of 500+ of the strongest Qiskit Community members who receive support, exclusive opportunities, mentorship, and much more from IBM Quantum

Mentorship

Advocates create long-lasting relationships with IBMers and industry experts via long-term collaborative mentorship projects, contributed to the open source community

Networking

Advocates are invited to join a group of quantum experts, who routinely share opportunities and updates from around the world

Events

Advocates travel to conferences, present at community engagements, host their own events, and mentor others through hackathons and quantum challenges

Recognition

Advocates are seen by many as the strongest members of the field, thanks to the Qiskit Developer Certification, community contributions, and success of the group at large

What is the Qiskit advocate program?

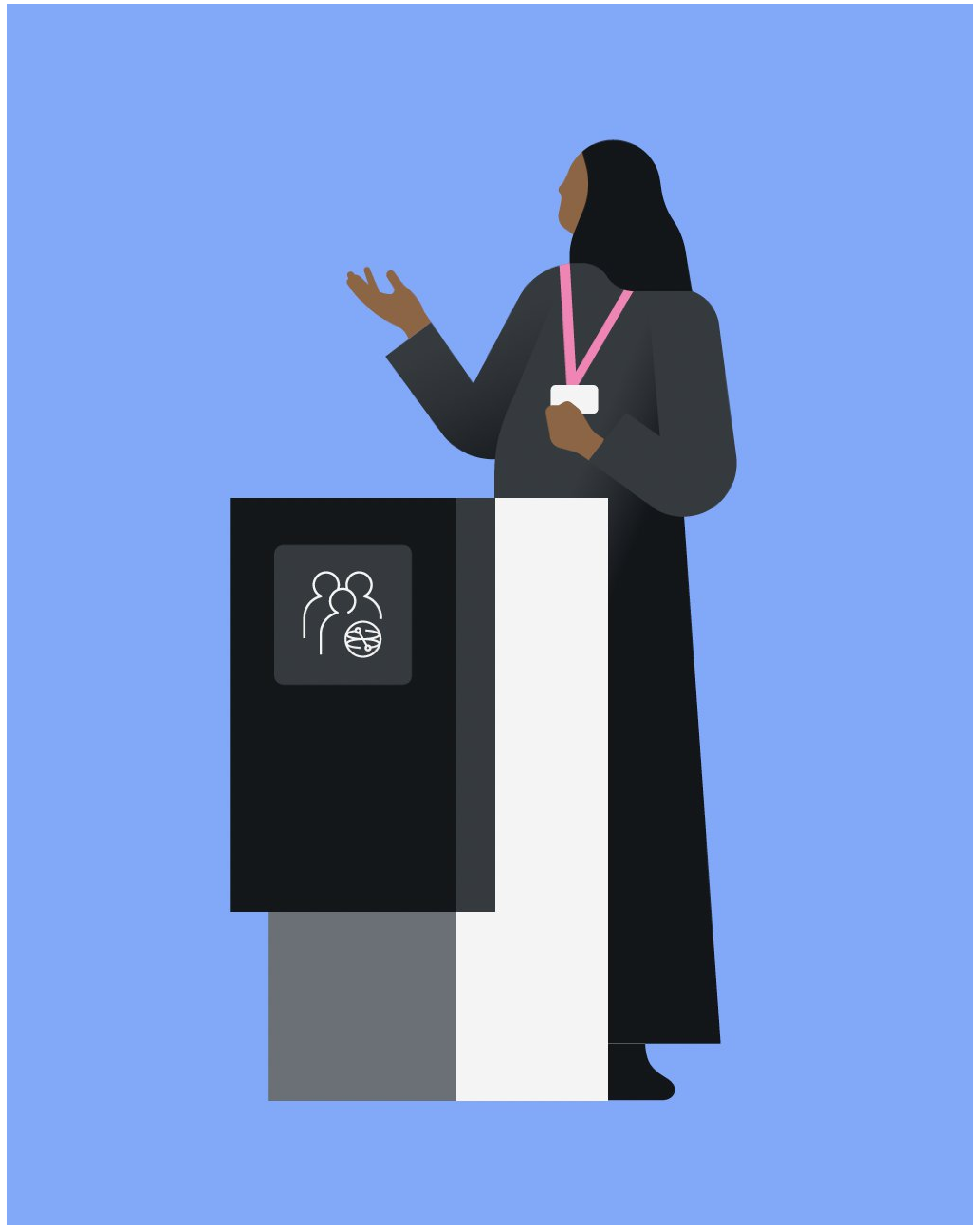
Join 544+ Qiskit Advocates across 50 countries in advancing quantum computing education and community.

The Qiskit advocate program is an external, global initiative that empowers and enables aspiring leaders in the Qiskit open-source community.

Qiskit advocates enhance their professional growth by:

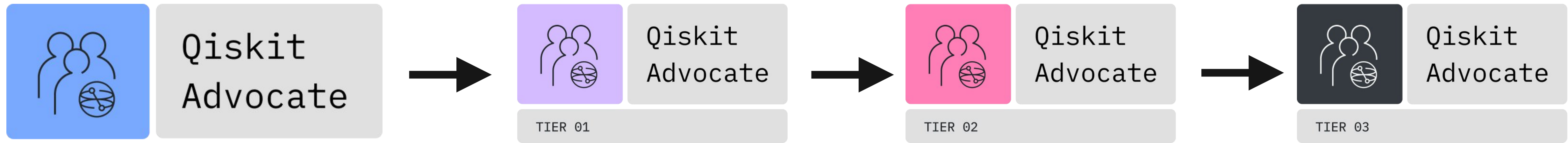
- Building meaningful connections with quantum experts and peers
- Gaining exclusive access to Qiskit education and events
- Getting unique opportunities to contribute to quantum computing advancement
- Making open-source contributions and sharing knowledge through mentorship
- Participating in Qiskit events, networking, and quantum research and so much more.

Perfect for: Students, software developers, quantum researchers, educators, and anyone looking to upskill and advance their career in quantum computing.



What do Qiskit advocates do?

Activities:
- Give talks and presentations on Qiskit at events and conferences
- Contribute to the Qiskit SDK and Qiskit Ecosystem projects
- Mentor participants in flagship events and host events in your local community
- Provide feedback on Qiskit and IBM Quantum tools as active users
- Collaborate with advocates globally
- Earn points through community contributions to advance through program tiers



For more information, see:
ibm.com/quantum/community#advocates

Ready to get started?

Applications open mid-year. Register your interest in applying to the program here:

Eligibility & How to Join:
- Open to quantum enthusiasts worldwide*
- Strongly recommended to complete: Basics of Quantum Information and Quantum Computing in Practice courses offered for free by IBM
- Register above to stay updated with eligibility criteria and hear when applications open

If you are an existing advocate:
- Find an invitation to the new program in your email
- OR if you have not received this email, get back in contact via ibm.com/quantum/community#advocates

* Applicants must also be at least 18 years of age and not usually residing in any of the unavailable countries as listed at quantum.ibm.com/terms

IBM **Quantum**