Qiskit Fall Fest 2025

Indian Institute of Science, Bengaluru

Quantum Computing at IBM Quantum and Qiskit 101

Century of Quantum

Janani A
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IBM Quantum mission

Bring useful quantum computing to the world

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What is quantum computing?

Bits and classical logic circuits

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0

1

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

Mathematics is Boolean Algebra

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

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Quantum bits (qubits) and quantum circuits

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

Mathematics is Linear Algebra

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

IBM Quantum © 2024 IBM Corporation

Bits and qubits

IBM **Quantum**

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.

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

IBM **Quantum**

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.

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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!

IBM Quantum © 2024 IBM Corporation

Quantum computing uses essential ideas from quantum mechanics

Superposition

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

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

So we can write any vector in $\mathbb{C}^2$ 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*.

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Quantum computing uses essential ideas from quantum mechanics

Superposition

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

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

where

a and b are complex numbers

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

Two quantum states are equivalent if they differ only by a constant multiple u where $|u| = 1$.

This is because

$$|a|^2 + |b|^2 = |au|^2 + |bu|^2 = 1$$

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Quantum computing uses essential ideas from quantum mechanics

Superposition

Superposition is creating a quantum state that is a combination of |0⟩ and |1⟩

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

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⟩ and |1⟩.

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

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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 $|0\rangle$.

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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.

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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

IBM Quantum © 2024 IBM Corporation

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

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

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.

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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.

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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

IBM Quantum © 2024 IBM Corporation

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.

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Quantum computing uses essential ideas from quantum mechanics

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Interference

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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

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Roadmap

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Demonstrate quantum advantage before fault tolerance via quantum centric supercomputing

2026

First large-scale, fault tolerant quantum computer

2029

	2016–2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2033+
Development Roadmap ↓	Ran quantum circuits on IBM Quantum Platform	Released multi-dimensional roadmap publicly with initial focus on scaling	Enhanced quantum execution speed by 100x with Qiskit Runtime	Brought dynamic circuits to unlock more computations	Enhanced quantum execution speed by 5x with Quantum Serverless and execution modes	Demonstrated accurate execution of a quantum circuit at a scale beyond exact classical simulation (5K gates on 156 qubits)	Deliver quantum + HPC tools that will leverage Nighthawk, a new higher-connectivity quantum processor able to execute more complex circuits	Enable the first examples of quantum advantage using a quantum computer with HPC	Improve quantum circuit quality to allow 10K gates	Improve quantum circuit quality to allow 15K gates	Deliver a fault-tolerant quantum computer with the ability to run 100M gates on 200 logical qubits	Beyond 2033, quantum computers will run circuits comprising a billion gates on up to 2000 logical qubits, unlocking the full power of quantum computing
						Code assistant						
Applying algorithms to applications						Functions		Use case benchmarking toolkit	Computation libraries			
Discovering new algorithms for advantage						Advanced classical transpilation tools	Advanced classical mitigation tools	Utility mapping tools			Circuit libraries	
Orchestrating workloads for quantum + HPC					Resource Management							
					Qiskit Serverless	Plugins for HPC	C API	Profiling tools		Workflow accelerators		
					Execution modes							
Accurately and efficiently executing on quantum computers			Qiskit Runtime									
	IBM Quantum Experience		OpenQASM 3	Dynamic Circuits	Error mitigation	200K CLOPS	Utility-scale dynamic circuits				Fault-tolerant ISA	
Innovation Roadmap ↓	Early Canary 5 qubits Albatross 16 qubits Penguin 20 qubits Prototype 53 qubits	Falcon Benchmarking 27 qubits		Eagle Benchmarking 127 qubits		Heron (5K) Error mitigation 5K gates | 133 qubits	Nighthawk (5K) Error mitigation 5K gates | 120 qubits	Nighthawk (7.5K) Error mitigation 7.5K gates | 120 qubits Up to 120x3 = 360 qubits	Nighthawk (10K) Error mitigation 10K gates | 120 qubits Up to 120x9 = 1080 qubits	Nighthawk (15K) Error mitigation 15K gates | 120 qubits Up to 120x9 = 1080 qubits	Starling (100M) Fault-tolerant 100M gates 200 logical qubits	Blue Jay (1B) Fault-tolerant 1B gates 2000 logical qubits
Software innovation	IBM Quantum Experience Qiskit Open-source SDK for building and compiling circuits for quantum hardware	Application modules Modules for domain specific application and algorithm workflows	Qiskit Runtime Performance and abstraction through primitives	Quantum Serverless Demonstrate concepts of managing quantum and cloud classical compute for an end to end workflow	AI-enhanced quantum Prototype demonstrations of AI-enhanced circuit transpilation	HPC-Quantum integration Realize an integration of classical HPC and a quantum computer at utility scale	Advantage candidates Define problem types for advantage in 2026	Error correction decoder Demonstrate a real-time error correction decoder	Workflow accelerator Demonstrate a workflow accelerator that streamlines execution for a known advantage workflow	Fault-tolerant ISA Demonstrate a complete instruction set architecture including magic state distillation for FTQC		
Hardware innovation	Early Canary 5 qubits Albatross 16 qubits Penguin 20 qubits Prototype 53 qubits	Falcon Demonstrate scaling with I/O routing with bump bonds	Hummingbird Demonstrate scaling with multiplexing readout	Eagle Demonstrate scaling with MLW and TSV	Osprey Enabling scaling with high density signal delivery	Condor Single-system scaling and fridge capacity	Flamingo Demonstrate scaling with l-couplers	Loon Demonstrate c-couplers and next-generation packaging for FTQC	Kookaburra Demonstrate a complete module consisting of a logical processing unit and quantum memory	Cockatoo Demonstrate entanglement of modules using a universal adapter	Starling Demonstrate multiple modules and magic state distillation	
			Egret Tunable coupler demonstration		Heron Architecture based on tunable-couplers	Crossbill Demonstrate m-couplers						

Completed

On target

IBM **Quantum**

As part of our commitment to transparent quantum development, our roadmap is split into two parts:

Development Roadmap

Tracks the release of production hardware, software, and services delivered to users.

Innovation Roadmap

Charts the scientific breakthroughs and internal releases that underpin development milestones. Some items will remain internal proofs-of-concept, while others may evolve into future external releases.

IBM Quantum / © 2025 IBM Corporation

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Orchestrating workloads for quantum + HPC					Resource Management							
					Qiskit Serverless	Plugins for HPC	C API	Profiling tools		Workflow accelerators		
					Execution modes							
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Completed

On target

IBM **Quantum**

IBM Quantum mission

Bring useful quantum computing to the world

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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.

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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.

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When to use a quantum computer

Easy Problems

Sweet spot

Very Hard Problems

No need for QC

Arithmetic
video games

Need fault-tolerant QC

Shor's Algorithm
Grovers Algorithm

See Quantum Computing in Practice | Which Problems Are Quantum Computers Good For? for additional discussion and insights

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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

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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

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What are these problems?

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

Groups encode symmetries and transformations of data.

$$f(g\mathbf{b}) = f(g) \qquad \forall\, \mathbf{b} \in B$$

$$\frac{1}{\sqrt{|G|}} \sum_{g \in G} |f(g)\rangle |g\rangle$$

$$= \sqrt{\frac{|B|}{|G|}} \sum_{g_0 \in G/B} |f(g_0)\rangle \frac{1}{\sqrt{|B|}} \sum_{\mathbf{b} \in B} |g_0 \mathbf{b}\rangle$$

Quantum computers speak the mathematics of group theory and work in the large spaces needed to answer difficult computational problems inaccessible to classical methods.

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

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Nature is quantum.

↓

You need quantum to simulate nature.

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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.

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“I like to say if you're not using 100+ qubits, you're not doing quantum.”

Jay Gambetta, Director, IBM Research, *IBM Quantum Summit on December 4th, 2023*

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Qiskit

+

IBM QPUs

=

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

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Qiskit Pattern:
The anatomy of a quantum algorithm

01

Map problem instance to quantum circuits and operators

Map

02

Optimize for target hardware execution

Optimize

03

Execute via Qiskit Runtime

Execute

04

Result processing

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).

Map	Optimize	Execute	Post-Process
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

Quantum Software
(powered by Qiskit Addons and Qiskit Functions)

+

Qiskit

+

QPUs

=

Useful Work

The IBM Quantum platform unlocks research with quantum

How can you be a part of this journey?

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.

Quantum learning

Kickstart your quantum learning journey with a selection of courses designed to help you learn the basics or explore more focused topics. If you're an instructor, explore content specifically tailored to incorporating quantum in the classroom.

Foundations

Courses to learn about quantum information and how quantum computing works, from the basics onward.

Quantum information and computation I
Basics of quantum information
Learn about quantum information, from states and measurements to quantum circuits and entanglement.
Course

Quantum information and computation II
Fundamentals of quantum algorithms
Learn how quantum algorithms beat classical algorithms for problems including integer factoring and search.
Course

Quantum information and computation III
General formulation of quantum information
Dive deeper into quantum information, including density matrices, channels, and general measurements.
Course

Quantum information and computation IV
Foundations of quantum error correction
Learn how quantum computations can be protected against noise through quantum error correcting codes and fault tolerance.
Course New lesson

Quantum computing in practice
Learn potential use cases and best practices for experimenting with quantum processors having 100+ qubits.
Course New lesson

Focused topics

Continue your learning journey by diving into more focused topics related to quantum computing.

Quantum machine learning
Learn to leverage the power of quantum computing in machine learning methods.
Course New

Variational algorithm design
An overview of variational algorithms: hybrid classical quantum algorithms.
Course

Quantum chemistry with VQE
An introduction to VQE that covers basic building blocks and applications.
Course

Quantum diagonalization algorithms
Multiple quantum approaches to matrix diagonalization are explored, including VQE, QKD, SKD, and variations of these.
Course New

Utility-scale quantum computing
A collection of learning assets from a 14-lesson course on utility-scale quantum computing.
Course

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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	Your progress
2	N/A

Start course →

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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.

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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.

Applications for 2026 IBM Quantum Internship Program are open now!

IBM Quantum interns, class of 2025

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Qiskit Live Coding Session