Quantum Computing:

An Introduction for the perplexed

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IBM Distinguished Engineer

Master Inventor, Visiting Professor, FBCS

IBM Quantum Ambassador leader for UK

Our mission

Bring useful quantum computing to the world

Make the world quantum safe

Our mission

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Make the world quantum safe

Our modern digital world depends on public key *cryptography*

This is now a problem

The problem with quantum computers

Shor's algorithm (1994) shows a quantum computer can factor large numbers—at least 2048 bits long (that's 617 decimal digits).

On a classical computer, this would take millions of years.

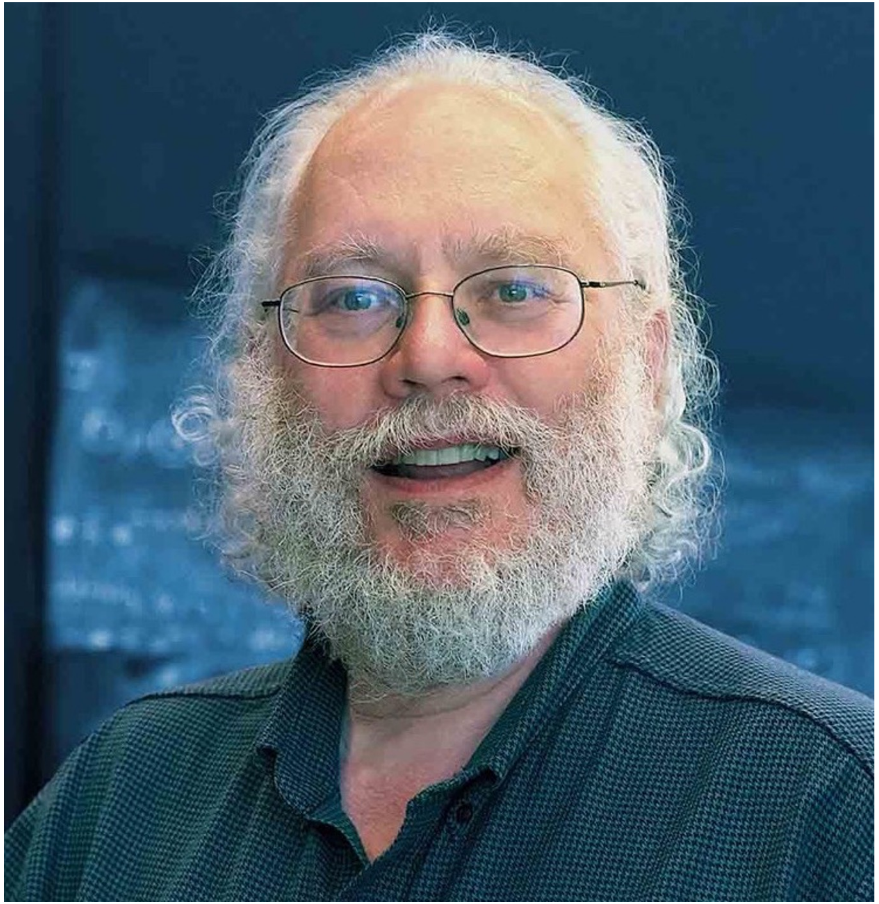
On a *cryptographically relevant quantum computer,* this would take a few hours.

Shor's algorithm breaks RSA and other public-key cryptosystems, where security is based on the difficulty of mathematical **trapdoor** functions (factoring large numbers or taking discrete logarithms).[1]

Grover's algorithm (1996) theoretically affects AES, but probably won't in our lifetimes.[2]

1. "Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer," 25 January 1996.

2. "A fast quantum mechanical algorithm for database search" 29 May 1996



Peter Shor of Bell Labs and MIT delivered the 2017 Viterbi Lecture, "Capacities for Quantum Communication Channels"
Photo: Ming Hsieh, Department of Electrical and Computer Engineering at the University of Southern California.

Today’s classical security protocols will be obsolete tomorrow

Prime factors

= p x q

2048-bit composite integer

```
2519590847565789349402718324004839857142928212620403
2027777137836043662020707595556264018525880784406918
2906412495150821892985591491761845028084891200728449
9268739280728777673597141834727026189637501497182469
1165077613379859095700097330459748808428401797429100
6424586918171951187461215151726546322822168699875491
8242243363725908514186546204357679842338718477444792
0739934236584823824281198163815010674810451660377306
0562016196762561338441436038339044149526344321901146
5754445417842402092461651572335077870774981712577246
7962926386356373289912154831438167899885040445364023
527381951378636564391212010397122822120720357
```

Expected computation time

The most powerful computer today:

Millions of years

Shor’s quantum algorithm:

Hours

Public key encryption • Digital signatures • Key exchange algorithms

RSA • DSA • ECC • ECDSA • DH

Journey to Quantum Safe

U.S. National Institute of Standards and Technology announced the first quantum-safe cryptography protocol standards for cybersecurity (July 2022), three of which were created by IBM in collaboration with industry and academic partners.

Purpose	Algorithm
Public-key Encryption and Key establishment Algorithms	CRYSTALS-Kyber
Digital Signature Algorithms	CRYSTALS-DILITHIUM
DSA (alternate)	Falcon
DSA (alternate)	SPHINCS+
NIST Selected Algorithms, July 5th 2022. NIST recommended two primary algorithms to be implemented for most use cases: CRYSTALS-KYBER (key-establishment) and CRYSTALS-Dilithium (digital signatures).	NIST National Institute of Standards and Technology U.S. Department of Commerce

US Government

establishes timeline for transition to CNSA 2.0-compliant algorithms

z16

First Quantum-safe platform

GSMA Telco Consortium

Support industry transition to quantum-safe cryptography

vodafone

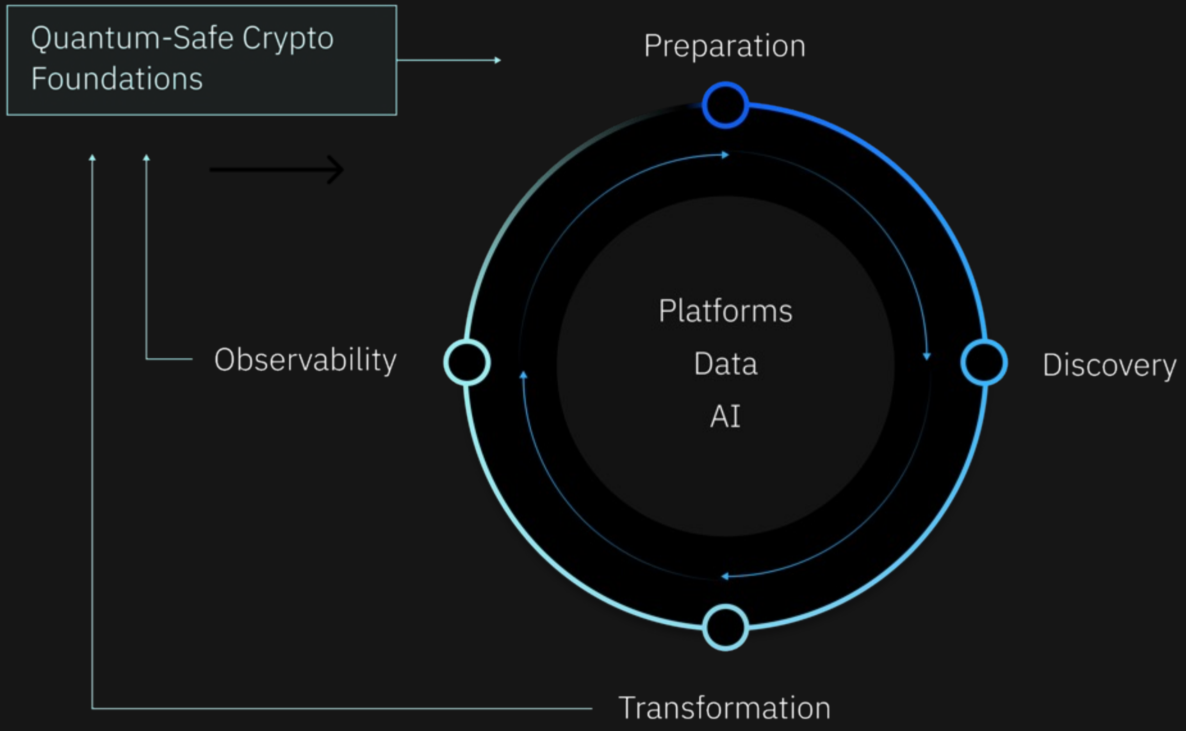
GSMA Taps IBM, Vodafone for Post-Quantum Taskforce

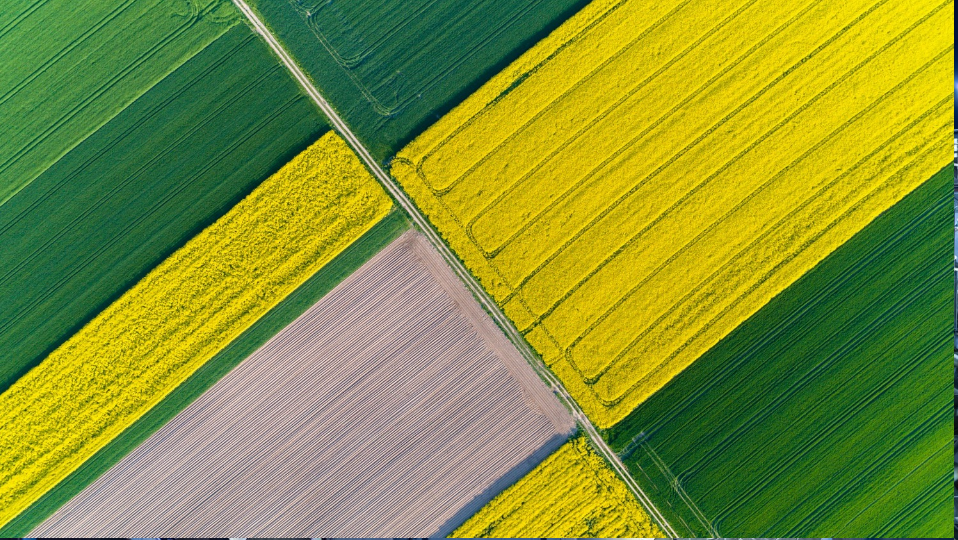
IBM Quantum Safe

Support client transition to quantum-safe cryptography

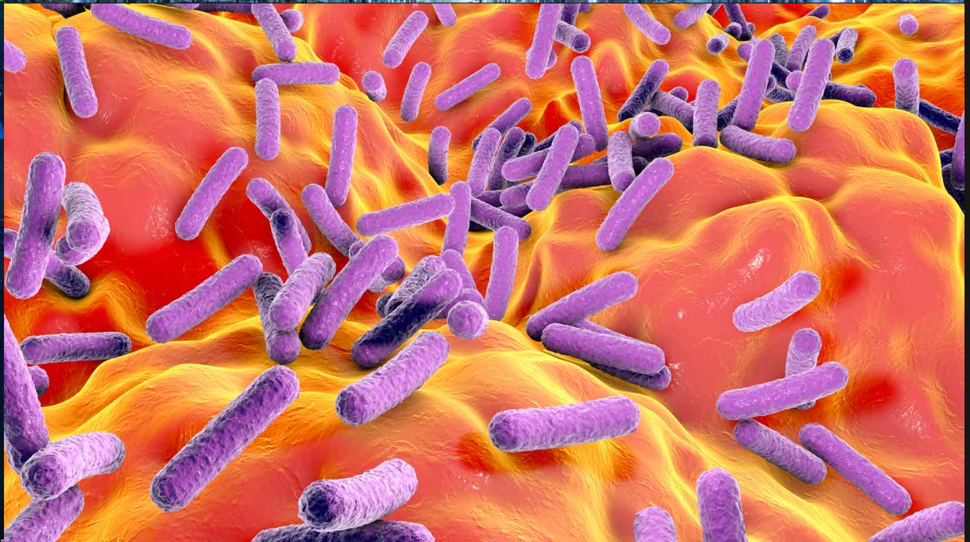
IBM Quantum Safe

- Understand, Prepare & Plan
- Discover & Classify Data
- Create a Crypto Inventory
- Implement with Crypto Agility

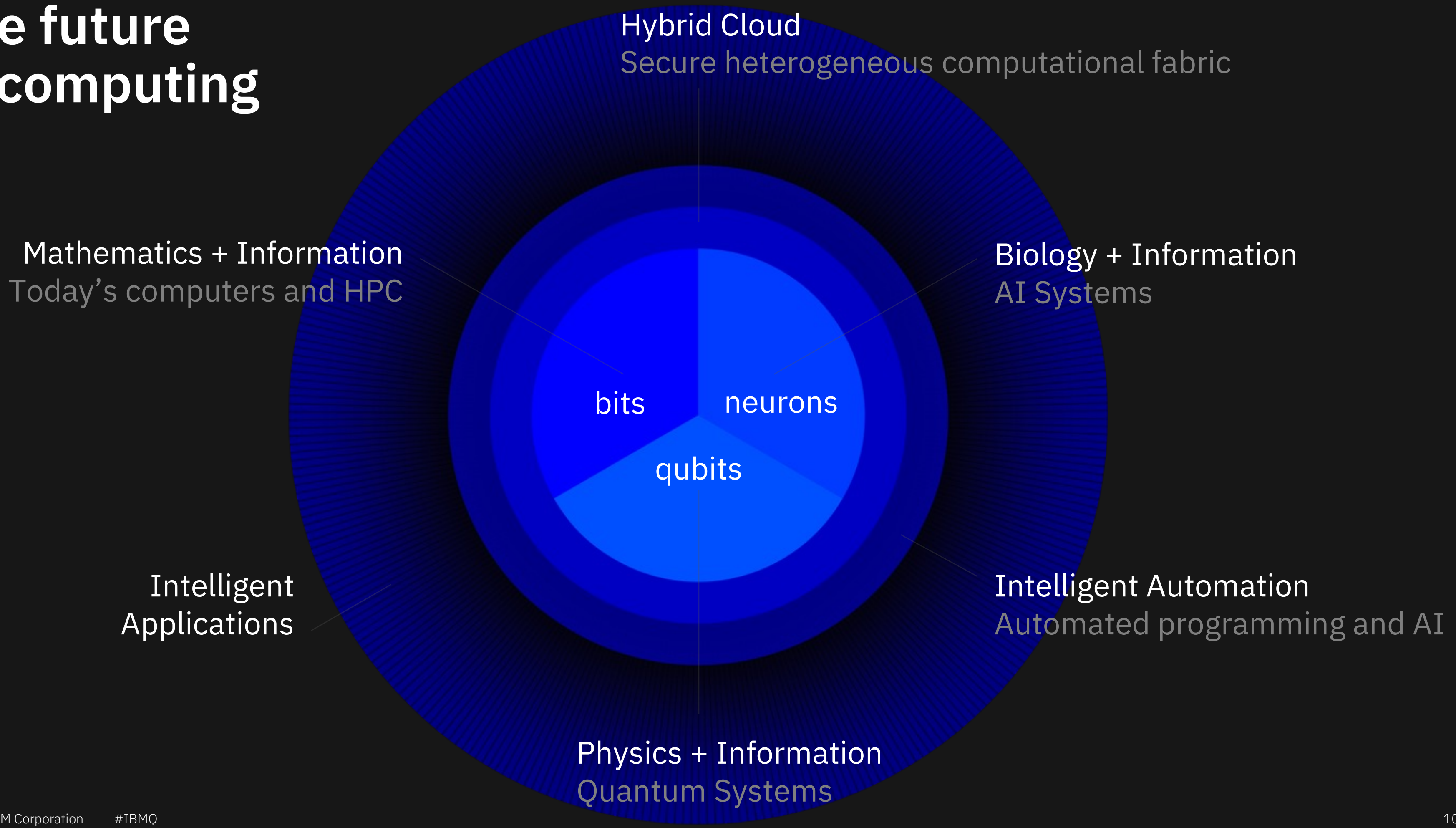





C-2301



The future of computing



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.

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

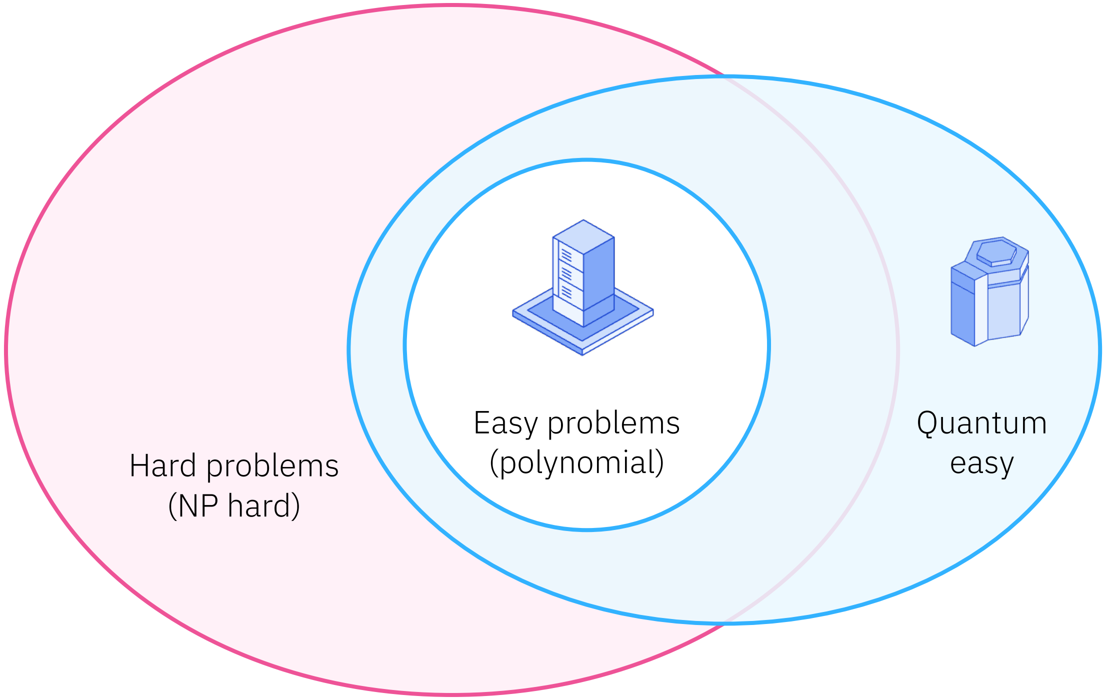
```
001001101110010010001001001001100100111
001011100111110010100100011100010001001
010001001001010101001010101110010011011
100100100010010010011001001110010111001
111100101001000111000100010010100010010
010101010010101011101110011100101011110
```

Quantum computers are the only novel hardware that changes the game

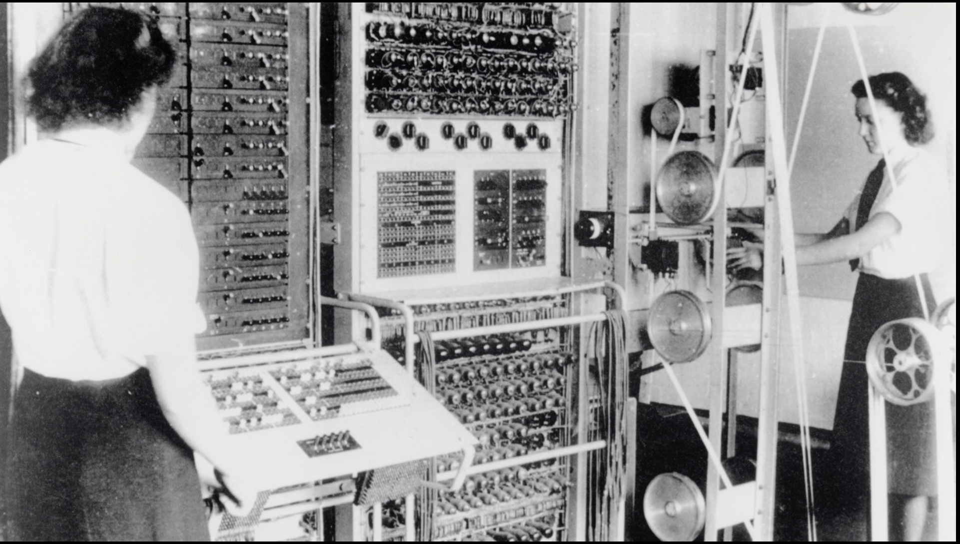
Quantum computing is not just a faster or better version of classical systems. It is an entirely new branch of computing.

Quantum computing follows the laws of nature to represent data in ways that mimic the randomness and unpredictability of the natural world.

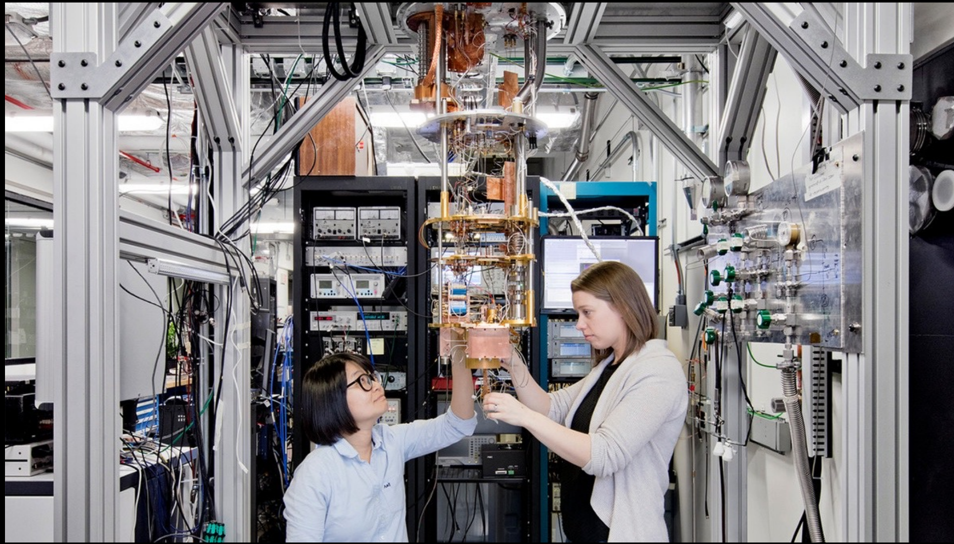
Ultimately, GPUs and classical hardware are not built for this.



We are in the early stages of a rapidly advancing new computing technology



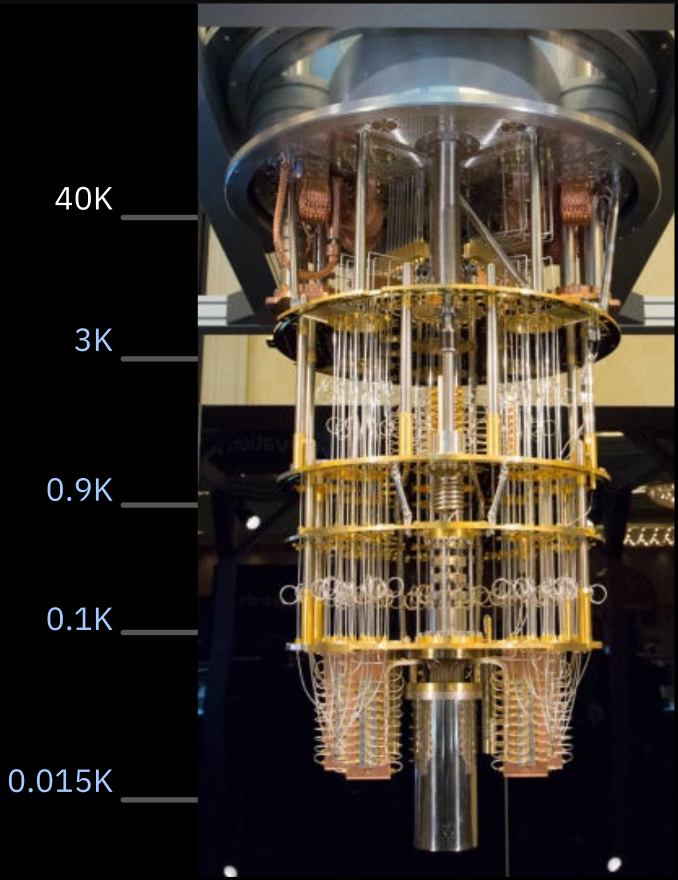
Computer:
1944



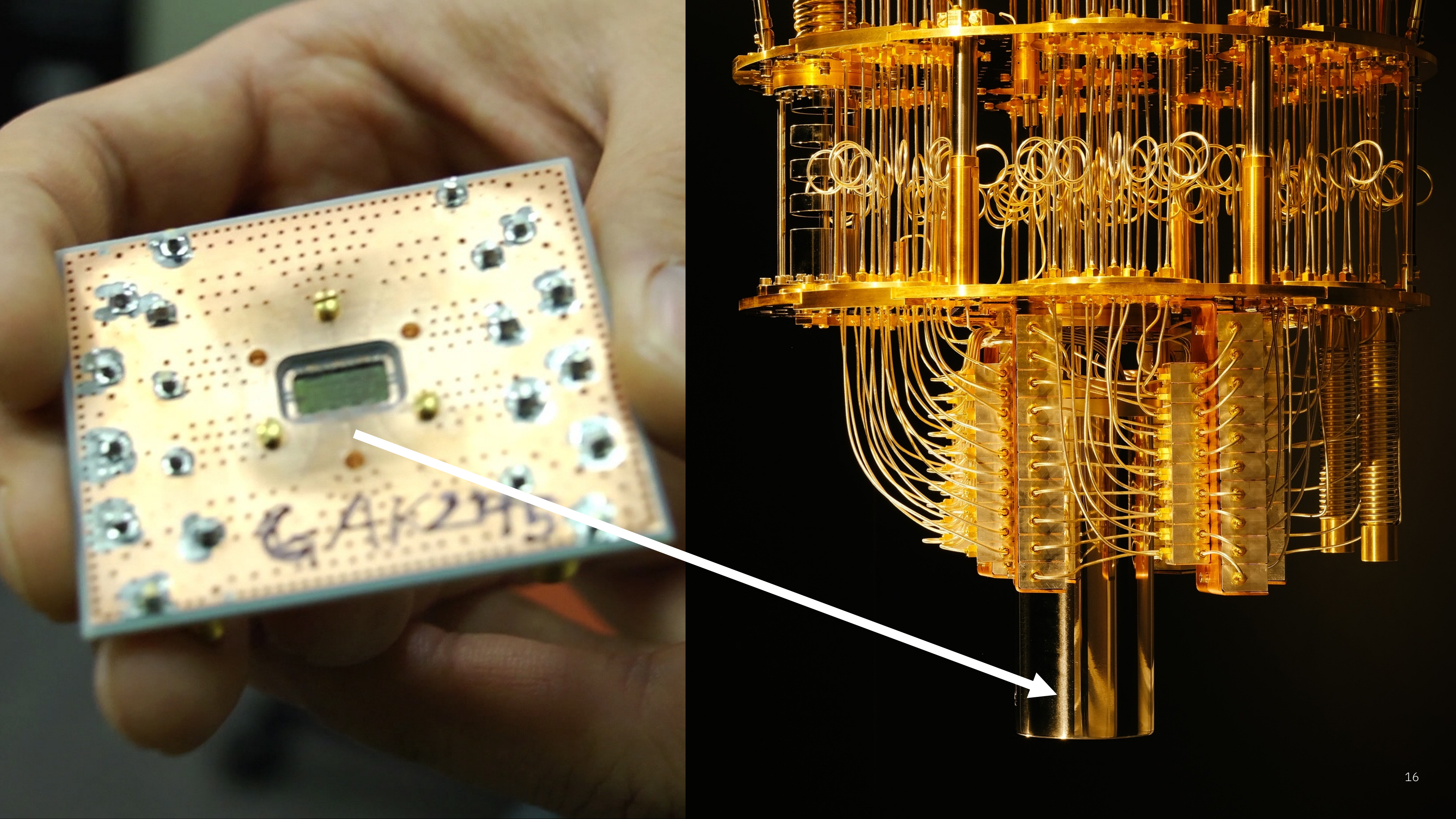
Quantum Computer:
2019

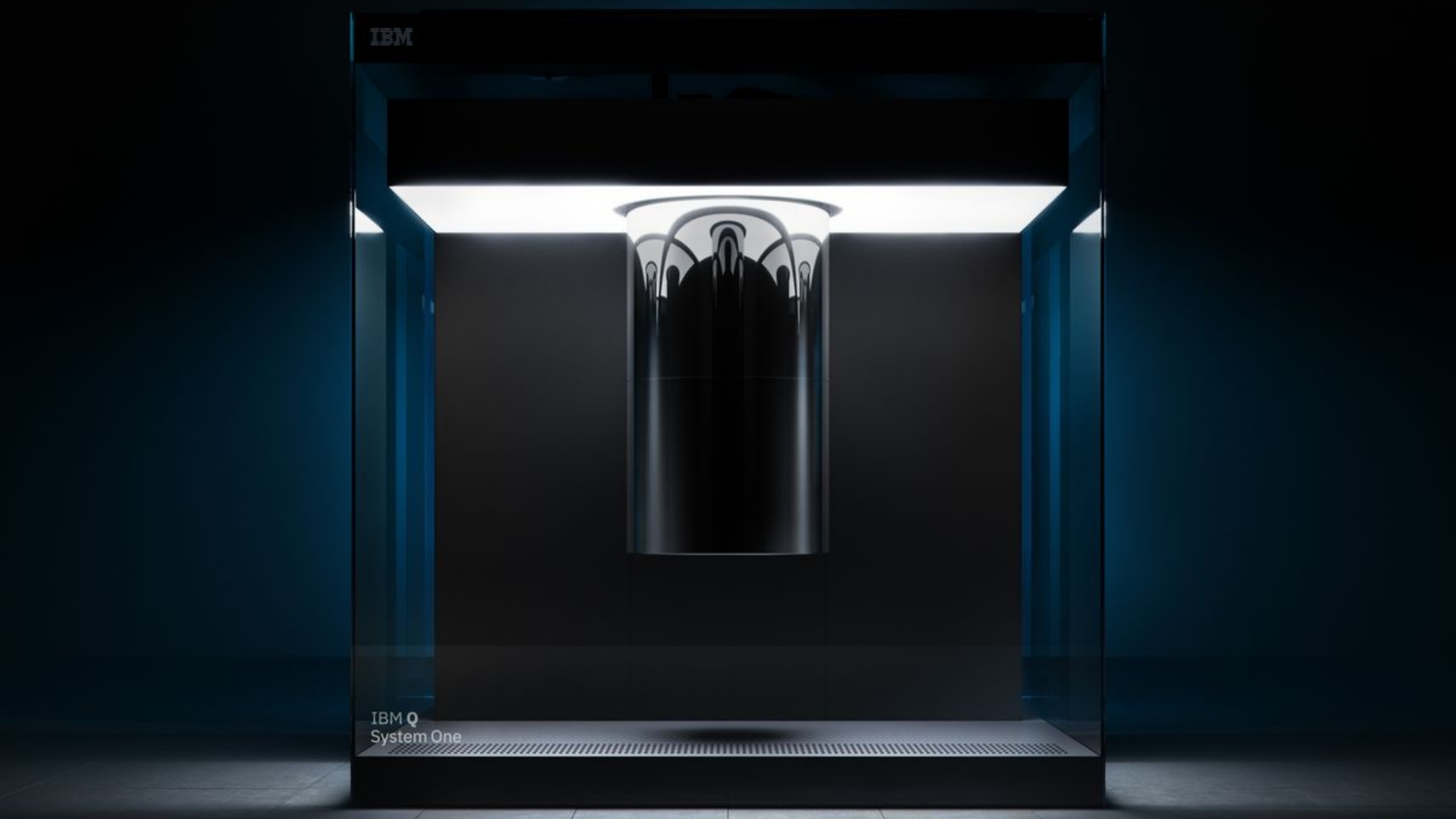

IBM Q
IBM Q

Superconducting qubits need to be really COLD



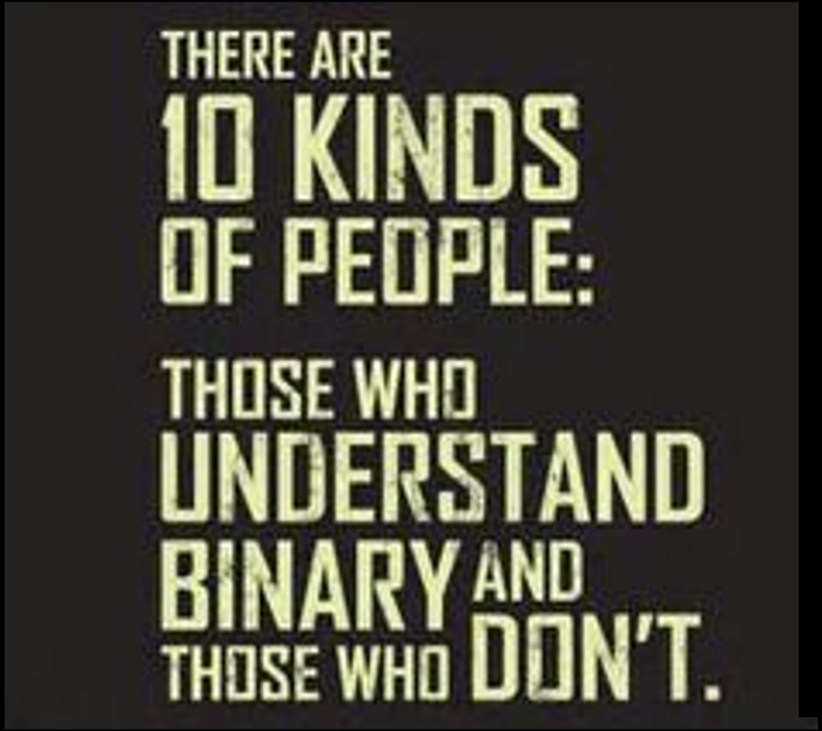
Refrigerator to cool qubits to 10 - 15 mK with a mixture of ^3He and ^4He 0.015 Kelvin – colder than space

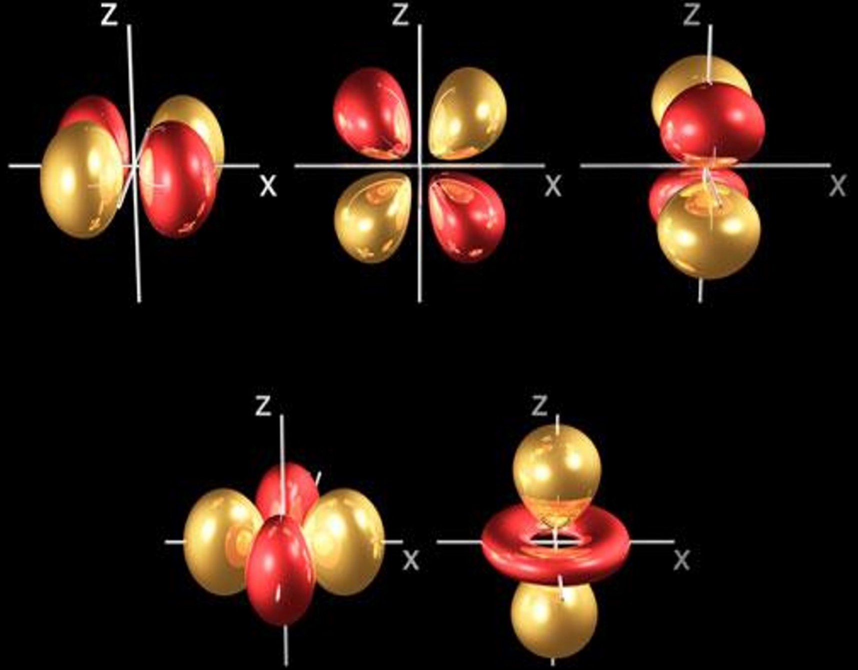



IBM
IBM Q
System One

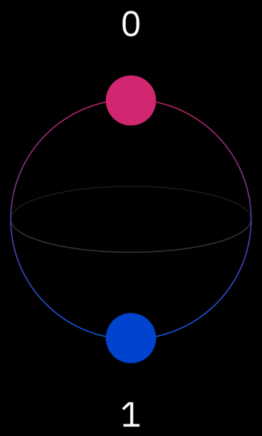

IBM
IBM Quantum
System Two

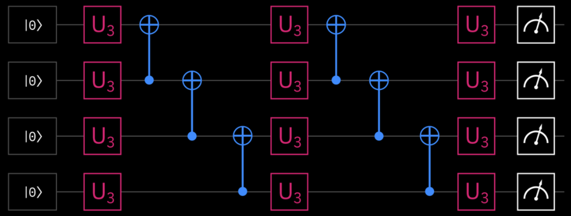
Quantum Particles





Quantum bits and quantum circuits

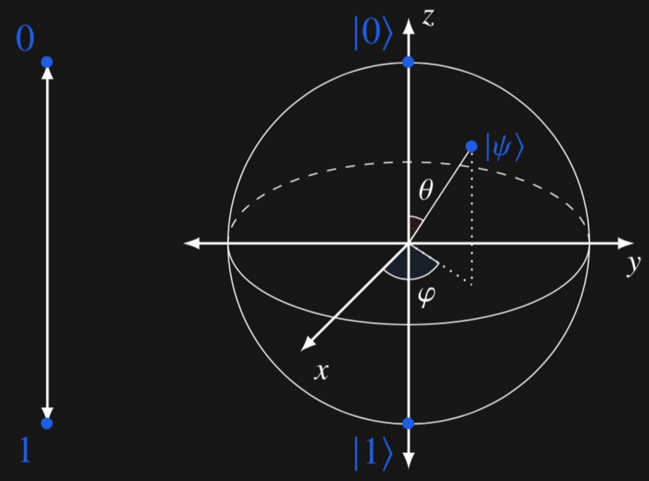




A quantum bit or **qubit** is a controllable quantum object that is the unit of information

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 is creating a quantum state that is a combination of |0> and |1>.

Measurement is an action that forces a qubit to either |0> or |1> based on probability.

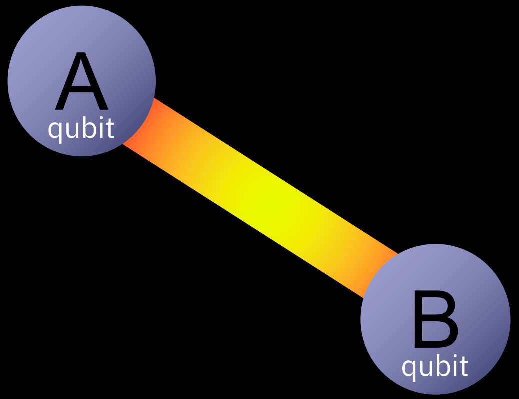
Entanglement strongly connects two or more qubits so that their quantum states are no longer independent.

Quantum gates perform the basic computational operations on qubits (think of as counterparts to classical and, +, and so on).

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

Entanglement: “Spooky action at a distance”

We can also combine qubits to cause a correlation of results when observed.



Is the system observed as 1 or 0 ?

A: 50% of the time the answer is 1
50% of the time the answer is 0

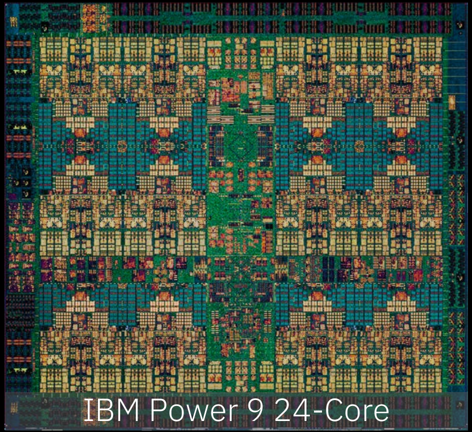
B: Gives the same random answers as qubit A

Yet we can still perform deterministic operations on the two qubits.

The power of quantum computing

Classical Computers

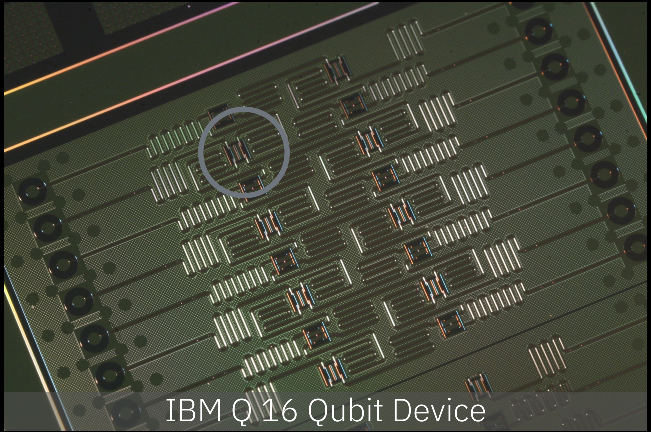
The potential power of a classical computer doubles every time you double the number of transistors.



IBM Power 9 24-Core

Quantum Computers

The potential power of a quantum computer doubles every time you add one additional qubit.



IBM Q 16 Qubit Device

Exponential growth

$$2^n$$

n qubits – 2^n quantum state dimensions.

2^{10} = 1,024

2^{20} = 1,048,576

2^{50} = 1,125,899,906,842,624

2^{65} = 36,893,488,147,419,103,232

2^{127} = 170,141,183,460,469,231,731,
687,303,715,884,105,728

Exponential growth

$$2^{275}$$

275 qubits – more quantum state dimensions than there are atoms in the observable universe.

60,708,402,882,054,033,466,233,184,58
8,234,965,832,575,213,720,379,360,039,
119,137,804,340,758,912,662,765,568

$$\sim 6.1 \times 10^{82}$$

The path to useful quantum computing

Run quantum circuits faster on quantum hardware

Chart a path to develop quantum technology (hardware + software) that runs noise-free estimators of quantum circuits faster than can be done using classical hardware alone.

Map interesting problems to quantum circuits

We need applications that can be solved only with quantum circuits that are known to be difficult to simulate. This must be done in partnership with our clients and users.

The three key metrics for measuring quantum computing performance

IBM **Quantum**

Scale

Measured by **number of qubits** which indicates the amount of information we can encode in the quantum system.

High coherence, high reliability, lower cost

2020	2021	2022
65 qubits	127 qubits	433 qubits

Quality

Measured by **Quantum Volume** which indicates quality of circuits and how faithfully circuits are implemented in hardware.

Need low operation errors, meaning large Quantum Volume

2020	Today	2022
32 QV	512 QV	1024 QV

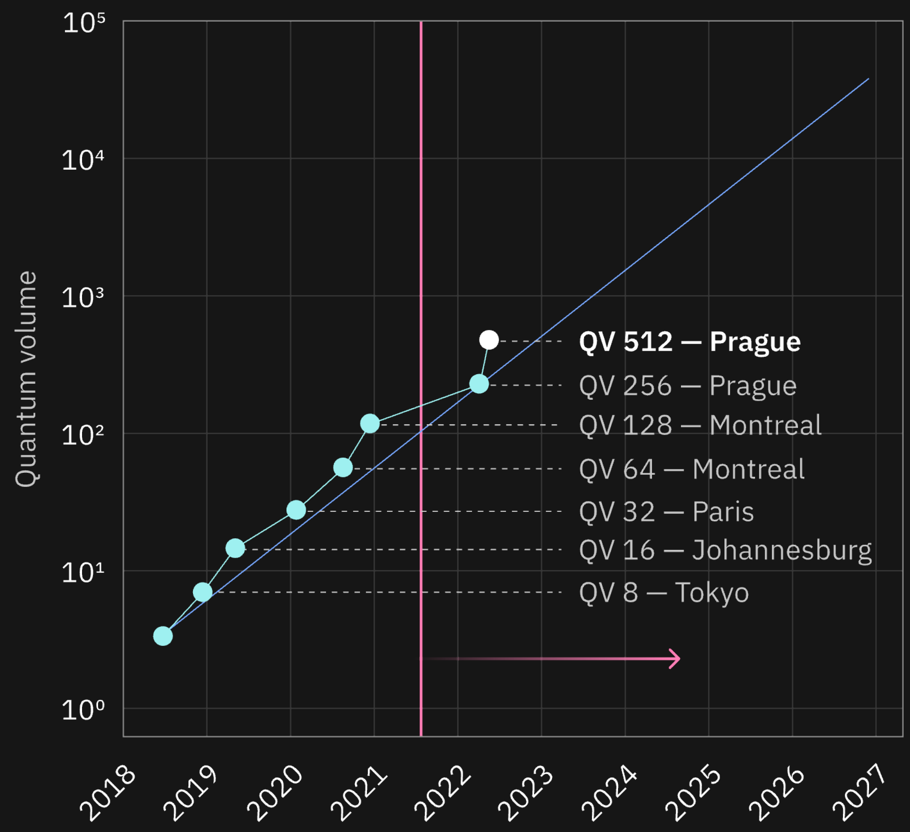
Speed

Measured by **CLOPS (Circuit Layer Operations Per Second)** which indicates how many circuits can run on hardware in a given time.

Seamless synchronization of quantum and classical circuits increases execution rate

2020	Today	2022
200 (Inferred)	1.4K CLOPS	10K CLOPS

Quantum volume

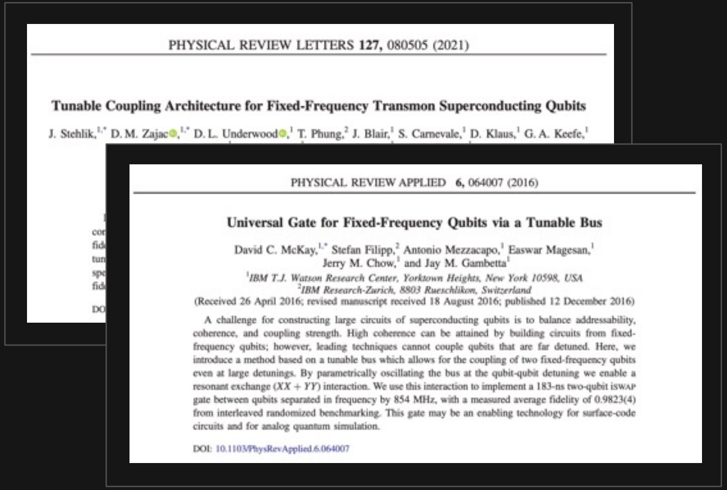


Quality

Coherence

Improved control

New architectures



PHYSICAL REVIEW LETTERS **127,** 080505 (2021)

Tunable Coupling Architecture for Fixed-Frequency Transmon Superconducting Qubits

J. Stehlik,[1,*] D. M. Zajac,[1,*] D. L. Underwood,[1] T. Phung,[2] J. Blair,[1] S. Carnevale,[1] D. Klaus,[1] G. A. Keefe,[1]

PHYSICAL REVIEW APPLIED **6,** 064007 (2016)

Universal Gate for Fixed-Frequency Qubits via a Tunable Bus

David C. McKay,[1,*] Stefan Filipp,[2] Antonio Mezzacapo,[1] Easwar Magesan,[1]
Jerry M. Chow,[1] and Jay M. Gambetta[1]

[1]*IBM T.J. Watson Research Center, Yorktown Heights, New York 10598, USA*
[2]*IBM Research-Zurich, 8803 Rueschlikon, Switzerland*

(Received 26 April 2016; revised manuscript received 18 August 2016; published 12 December 2016)

A challenge for constructing large circuits of superconducting qubits is to balance addressability, coherence, and coupling strength. High coherence can be attained by building circuits from fixed-frequency qubits; however, leading techniques cannot couple qubits that are far detuned. Here, we introduce a method based on a tunable bus which allows for the coupling of two fixed-frequency qubits even at large detunings. By parametrically oscillating the bus at the qubit-qubit detuning we enable a resonant exchange ($XX + YY$) interaction. We use this interaction to implement a 183-ns two-qubit iSWAP gate between qubits separated in frequency by 854 MHz, with a measured average fidelity of 0.9823(4) from interleaved randomized benchmarking. This gate may be an enabling technology for surface-code circuits and for analog quantum simulation.

DOI: 10.1103/PhysRevApplied.6.064007

Development Roadmap

IBM **Quantum**

2016–2019 ✓	2020 ✓	2021 ✓	2022 ✓	2023 ✓	2024	2025	2026	2027	2028	2029	2033+
Run quantum circuits on the IBM Quantum Platform	Release multi-dimensional roadmap publicly with initial aim focused on scaling	Enhancing quantum execution speed by 100x with Qiskit Runtime	Bring dynamic circuits to unlock more computations	Enhancing quantum execution speed by 5x with quantum serverless and Execution modes	Improving quantum circuit quality and speed to allow 5K gates with parametric circuits	Enhancing quantum execution speed and parallelization with partitioning and quantum modularity	Improving quantum circuit quality to allow 7.5K gates	Improving quantum circuit quality to allow 10K gates	Improving quantum circuit quality to allow 15K gates	Improving quantum circuit quality to allow 100M gates	Beyond 2033, quantum-centric supercomputers will include 1000's of logical qubits unlocking the full power of quantum computing

Data Scientist

Platform (2024–2033+)

- Code assistant (2024, on target)
- Functions (2025)
- Mapping Collection (2026)
- Specific Libraries (2027–2029)
- General purpose QC libraries (2033+)

Researchers

Middleware (2023–2033+)

- Quantum Serverless (2023, executed)
- Transpiler Service (2024, on target)
- Resource Management (2025)
- Circuit Knitting x P (2026)
- Intelligent Orchestration (2027–2029)
- Circuit libraries (2033+)

Quantum Physicist

Qiskit Runtime (2021–2033+)

- IBM Quantum Experience (2016–2020, executed)
- QASM3 (2021, executed)
- Dynamic circuits (2022, executed)
- Execution Modes (2023, executed)

Early ✓ (2016–2019)	Canary 5 qubits; Albatross 16 qubits; Penguin 20 qubits; Prototype 53 qubits
Falcon ✓ (2020–2021)	Benchmarking 27 qubits
Eagle ✓ (2022–2023)	Benchmarking 127 qubits
Heron (5K) (2024, on target)	Error Mitigation; 5k gates; 133 qubits; Classical modular; 133x3 = 399 qubits
Flamingo (5K) (2025)	Error Mitigation; 5k gates; 156 qubits; Quantum modular; 156x7 = 1092 qubits
Flamingo (7.5K) (2026)	Error Mitigation; 7.5k gates; 156 qubits; Quantum modular; 156x7 = 1092 qubits
Flamingo (10K) (2027)	Error Mitigation; 10k gates; 156 qubits; Quantum modular; 156x7 = 1092 qubits
Flamingo (15K) (2028)	Error Mitigation; 15k gates; 156 qubits; Quantum modular; 156x7 = 1092 qubits
Starling (100M) (2029)	Error correction; 100M gates; 200 qubits; Error corrected modularity
Blue Jay (1B) (2033+)	Error correction; 1B gates; 2000 qubits; Error corrected modularity

Innovation Roadmap

Software Innovation

2016–2019	IBM Quantum Experience ✓	
2020	Qiskit ✓	Circuit and operator API with compilation to multiple targets
2020	Application modules ✓	Modules for domain specific application and algorithm workflows
2021	Qiskit Runtime ✓	Performance and abstract through Primitives
2022	Serverless ✓	Demonstrate concepts of quantum centric-supercomputing
2023	AI enhanced quantum ✓	Prototype demonstrations of AI enhanced circuit transpilation
2024	Resource management (on target)	System partitioning to enable parallel execution
2025	Scalable circuit knitting	Circuit partitioning with classical reconstruction at HPC scale
2026	Error correction decoder	Demonstration of a quantum system with real-time error correction decoder

Hardware Innovation

2016–2019	Early ✓	Canary 5 qubits; Penguin 20 qubits; Albatross 16 qubits; Prototype 53 qubits
2020	Falcon ✓	Demonstrate scaling with I/O routing with Bump bonds
2020	Hummingbird ✓	Demonstrate scaling with multiplexing readout
2021	Eagle ✓	Demonstrate scaling with MLW and TSV
2022	Osprey ✓	Enabling scaling with high density signal delivery
2023	Condor ✓	Single system scaling and fridge capacity
2023	Heron ✓	Architecture based on tunable-couplers
2024	Flamingo (on target)	Demonstrate scaling with modular connectors
2024	Crossbill (on target)	m- coupler
2025–2026	Kookaburra	Demonstrate scaling with nonlocal c-coupler; Demonstrate path to improved quality with logical memory
2027	Cockatoo	Demonstrate path to improved quality with logical communication
2028	Starling	Demonstrate path to improved quality with logical gates

✓ Executed by IBM

On target

Condor

Pushing the limits of scale & yield

1,121

Superconducting qubits

50%

Increase in qubit density

1 mile +

Of flex cabling

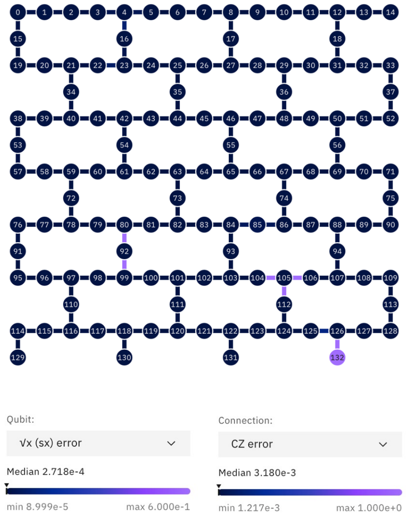
Introducing

Heron

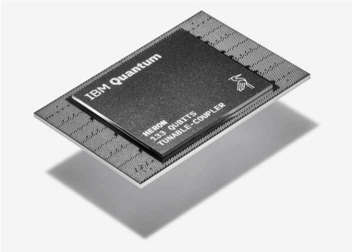
133 qubit systems

Tunable coupler architecture

ibm_montecarlo



	ibm_sherbrooke Eagle	*ibm_montecarlo (Heron)*
Gate Error (best system)	0.6-0.7%	0.3% - **Best ~ 0.1%**
Crosstalk	High (qubit-qubit collisions)	Almost zero!
Gate time	500-600ns	90-100ns

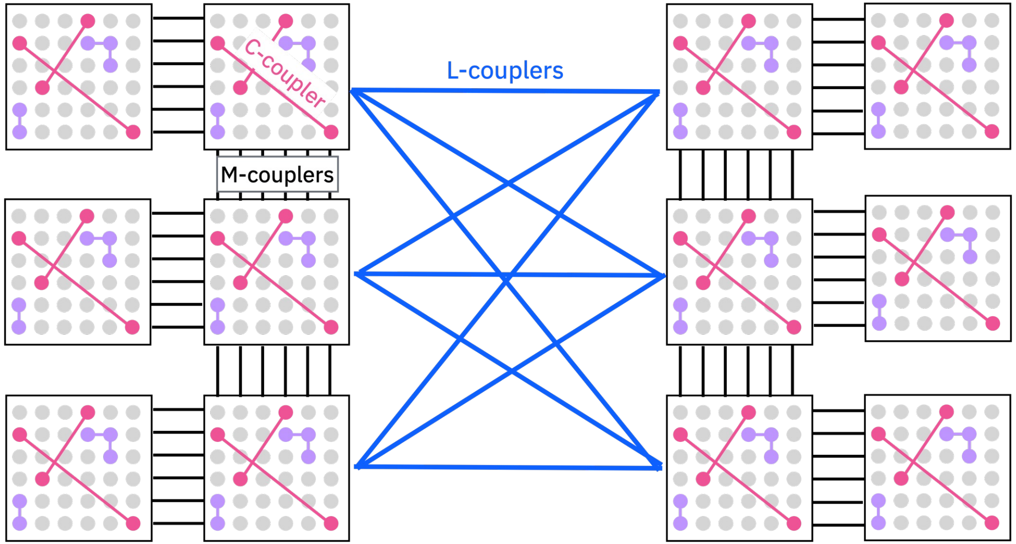


New error correction codes
and system modularity

C-coupler enables long-range on-chip connections for high-rate LDPC codes

L-coupler enables joining multiple logical memories to create large-scale systems

M-coupler enables joining multiple short-range chip-to-chip connections



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Map interesting problems to quantum circuits

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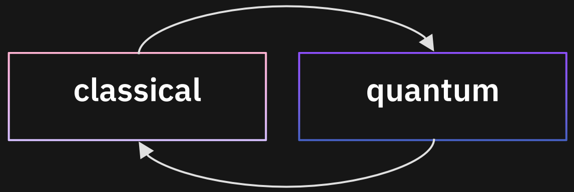
Structure of a typical workload



Real workloads are not purely quantum, but rather require interaction between quantum and classical compute resources.

Quantum applications span three general areas

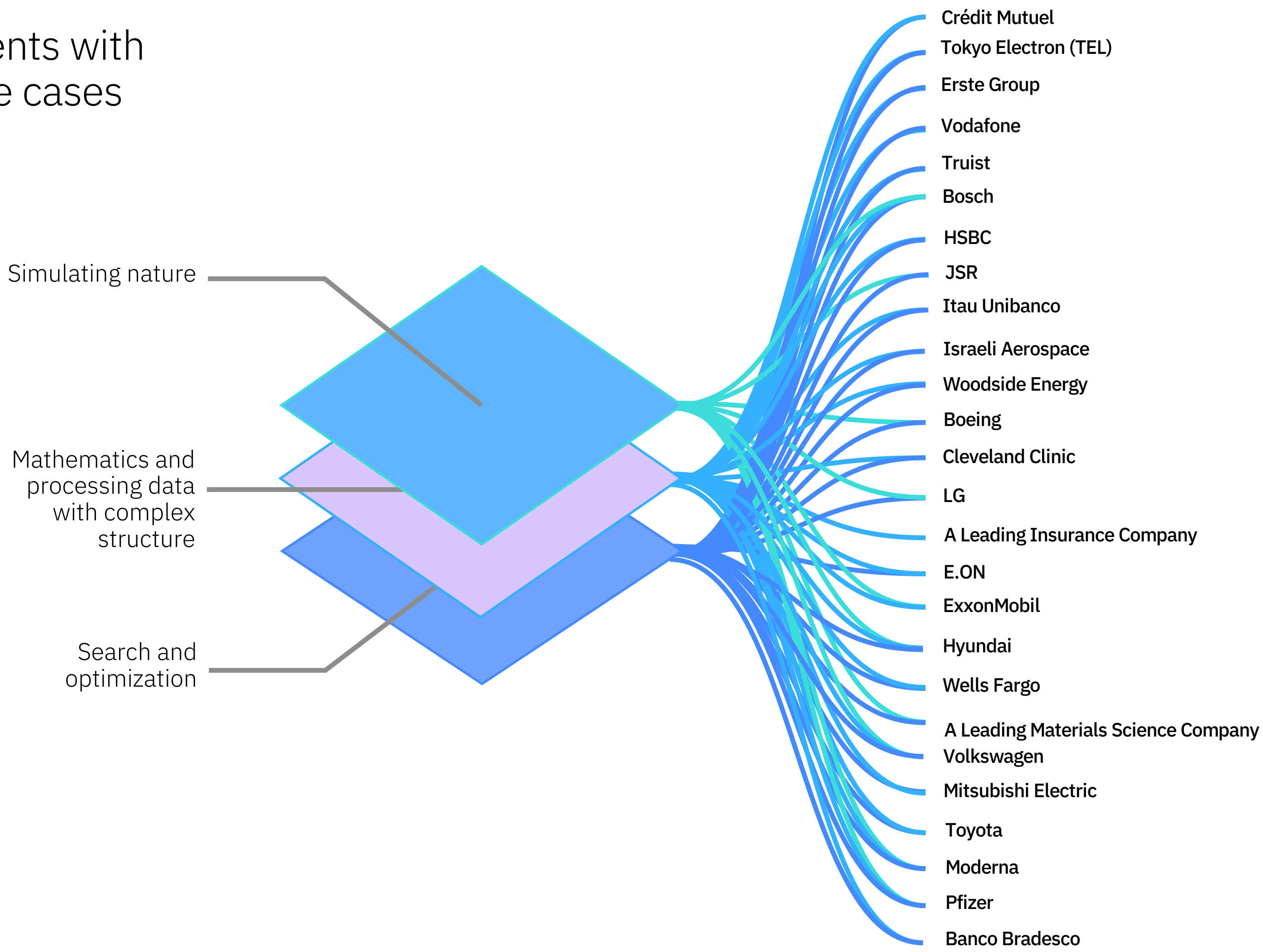
Simulating Quantum Systems	Artificial Intelligence	Optimization / Monte Carlo
Quantum chemistry Material science High energy physics	Better model training Pattern recognition Fraud detection	Portfolio optimization Risk analysis Loans & credit scoring Monte Carlo-like applications

Quantum applications span three general areas

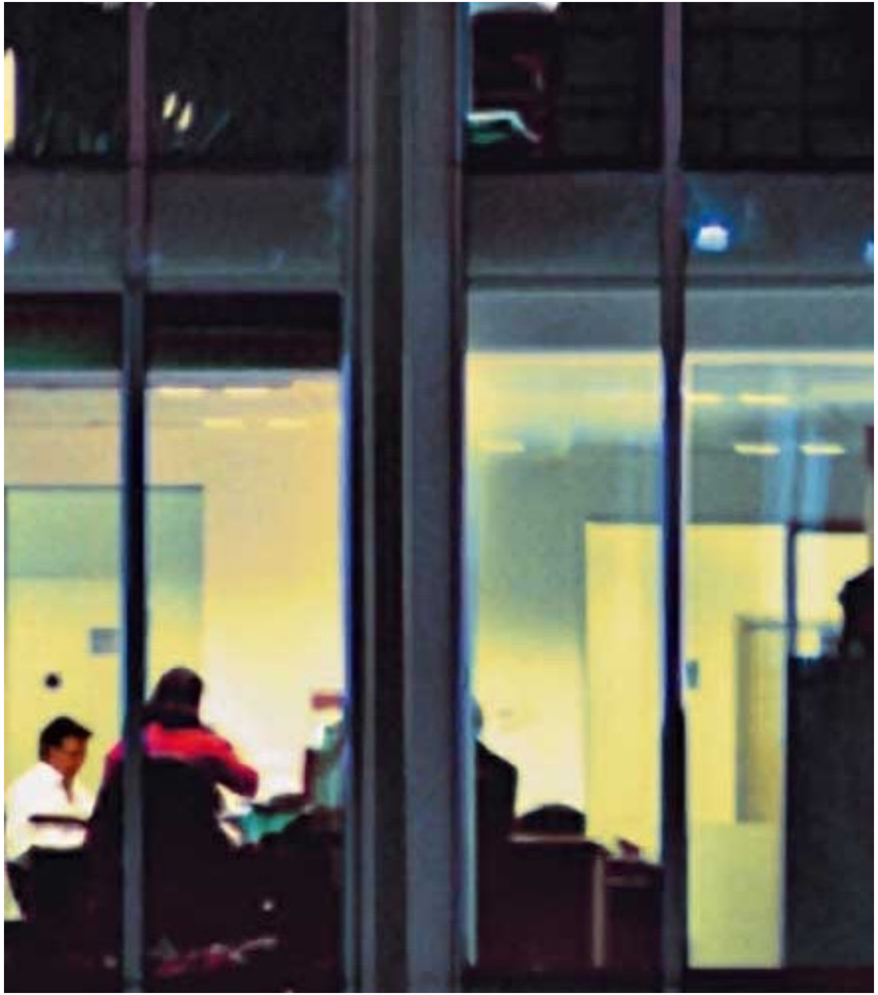
IBM **Quantum**

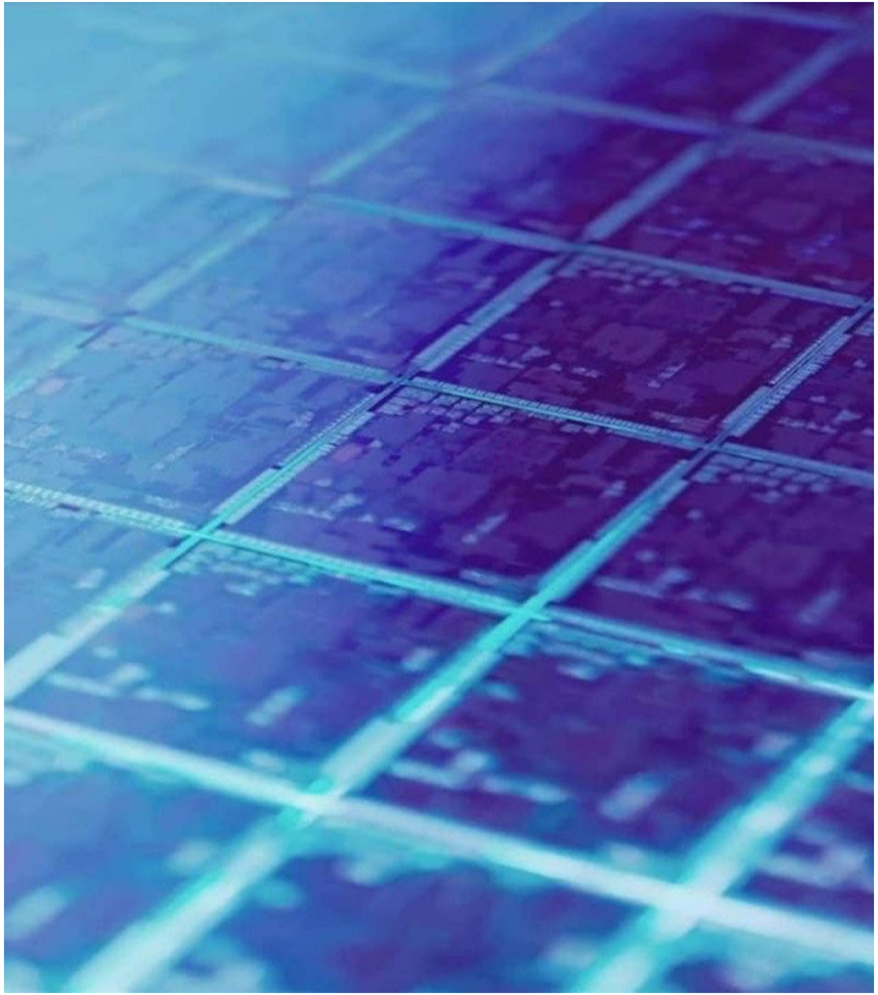
Simulating Quantum Systems		Artificial Intelligence	Optimization / Monte Carlo	
Improved battery materials	Accelerated Diagnosis	Fraud detection	Irregular Operations	Freight Forecasting
Manufacturing defect identification	Genomic Analysis	Risk analysis	Network Optimization	Irregular Operations
Semiconductor materials	Chemical product design	Options pricing	Product Portfolio Optimization Process Planning	Fabrication Optimization
Chemical property prediction	Catalyst discovery	Derivatives Pricing	Quality Control	Manufacturing Supply Chain
Drug Discovery	Chemical process optimization	Investment Risk Analysis	Vehicle Routing	Fluid Dynamics
Protein Structure Predictions	High energy physics classification	Portfolio Management	Raw materials shipping	
Disease Risk Predictions	Transaction classification	Transaction Settlement	Refining Processes	
	Product recommendation	Finance Offer Recommender	Seismic imaging	
		Credit/Asset Scoring	Disruption Management	and many more …
		Airline Scheduling		

Connecting industry clients with quantum computing use cases



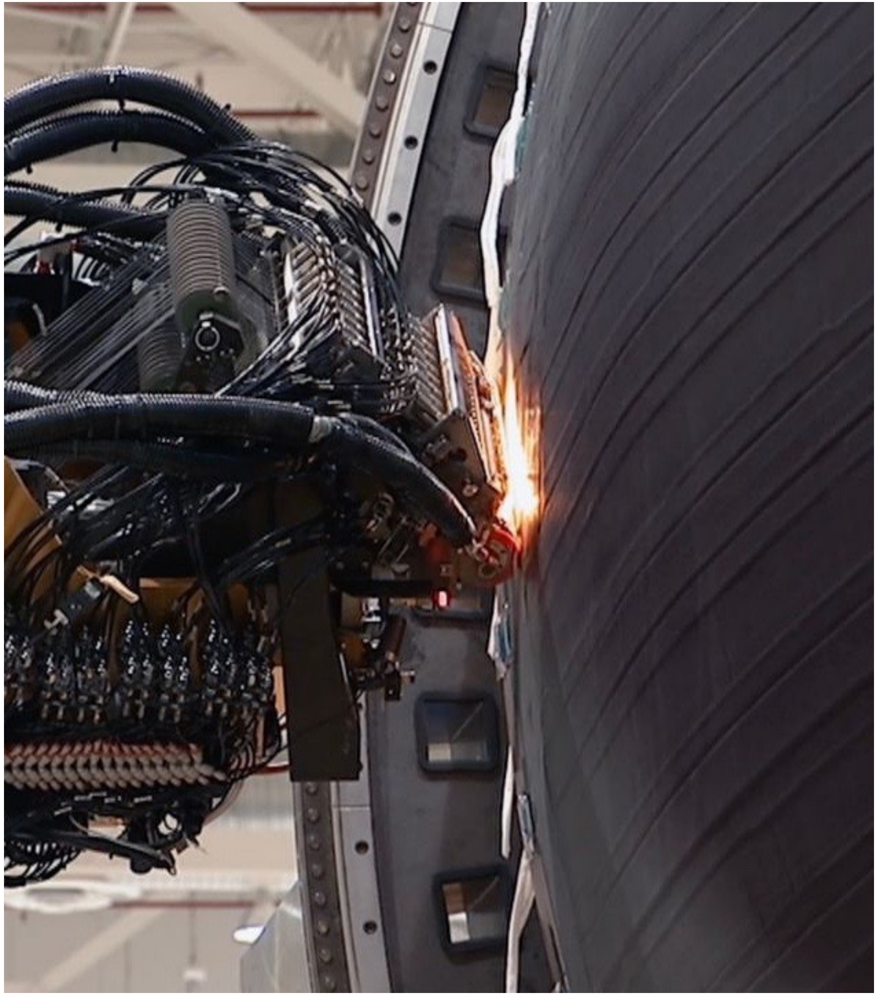
- Wells Fargo + IBM Quantum have published more than 10 quantum research papers in recent years.
- These papers explore new kinds of algorithms and new ways of thinking about problems in the financial services industry.
- Research focus on training quantum systems to mimic the probability distributions seen in the real world, then use that system for predictive modeling.





- JSR + IBM are experimenting with chemical simulations to help improve the development and manufacture of photoresists.
- We've already demonstrated that we can simulate small molecules that mimic parts of the photoresist.
- We hope that simulations like these will help us realize even faster chips.

- Boeing + IBM demonstrated a way to create larger computational spaces for simulating new materials.
- The simulations that the team ran are among the most complex quantum optimizations ever run.
- Boeing hopes these simulations will let them design lighter and stronger materials so planes can fly further with less fuel.



- ExxonMobil + IBM are modeling maritime inventory routing on quantum devices.

- By analyzing different strategies for vehicle and inventory routing they're laying the foundation for constructing practical solutions for their operations.

- More efficient shipping routes could help us transport fuel more efficiently around the globe.

IBM Quantum Network

A collaborative community of discovery

Educate and Train

Accelerate Research

Develop Applications

IBM Quantum Network members worldwide

1Qbit Systems
AIQTECH Inc
Aalto University
Agnostiq Inc
Aliro Quantum
Amgen
Anthem
Applied Quantum Computing
Apply Science
Argonne National Lab
Arizona State University
Assured Information Security
BP
Beit
Blueqat
Boeing
Bosch
Boston University
Bowie State University
Boxcat Inc
Brookhaven National Lab
Bundeswehr University Munich
CERN
CMC Microsystems
Cambridge Quantum Computing
Capgemini SE
Carnegie Mellon Software Engineering Institute
Centrum Wiskunde & Informatica
Chalmers University of Technology
Classiq
Clemson University
Cleveland Clinic Foundation
Cognizant
ColdQuanta
ColibriTD
Consiglio Nazionale delle Ricerche - Istituto di calcolo e reti ad alte prestazioni
Cornell University
Credit Mutuel
DIC Corporation
Daimler
Deloitte
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Fidelity Investments
First Quantum
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Florida State University
Fraunhofer
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General Atomics
Georgia Institute of Technology
Goldman Sachs
HQS Quantum Simulations
HSBC
Hampton University
Hanyang University
Harvard University
Hitachi Ltd
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III Taiwan
Indian Institute of Technology - Madras
IIT
Industrial Technology Research Institute
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JP Morgan Chase
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North Carolina State University
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Opacity
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Quebec PINQ2
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SoftwareQ
Solid State AI
Sony
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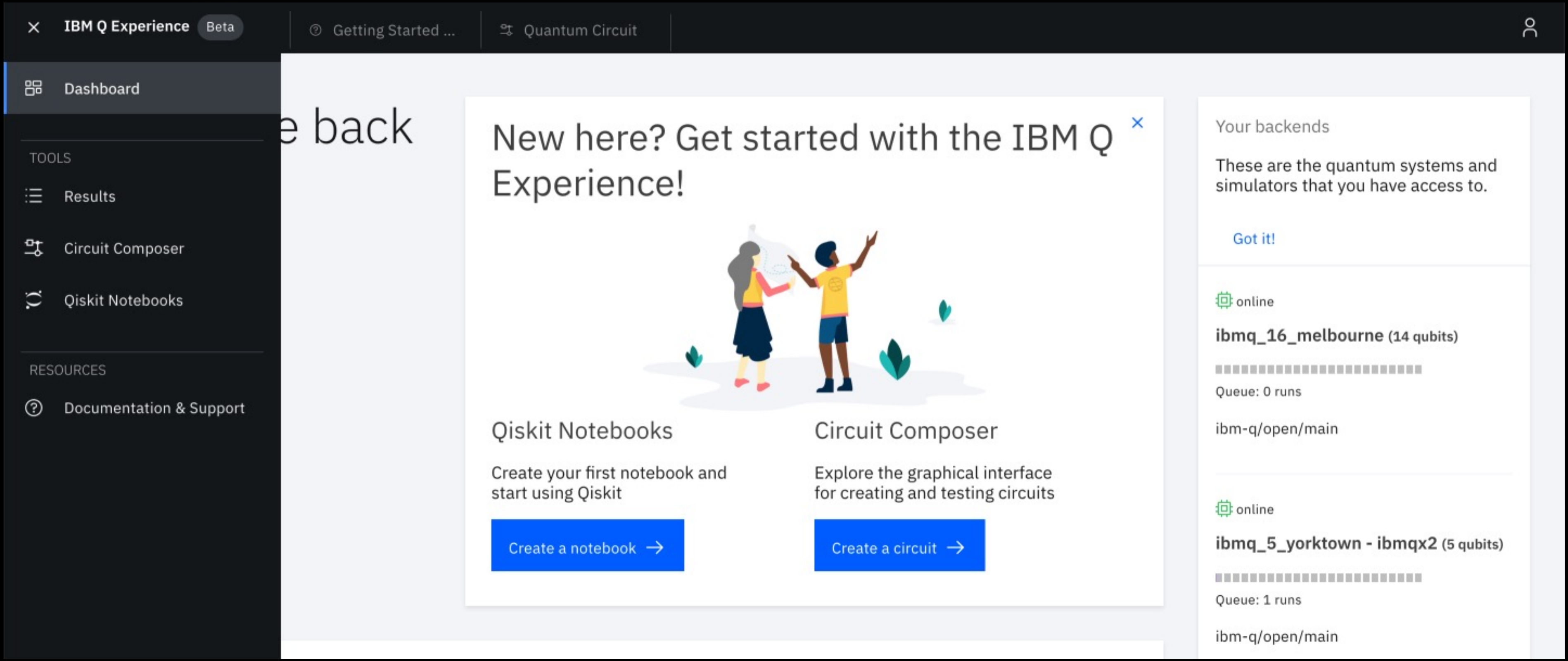

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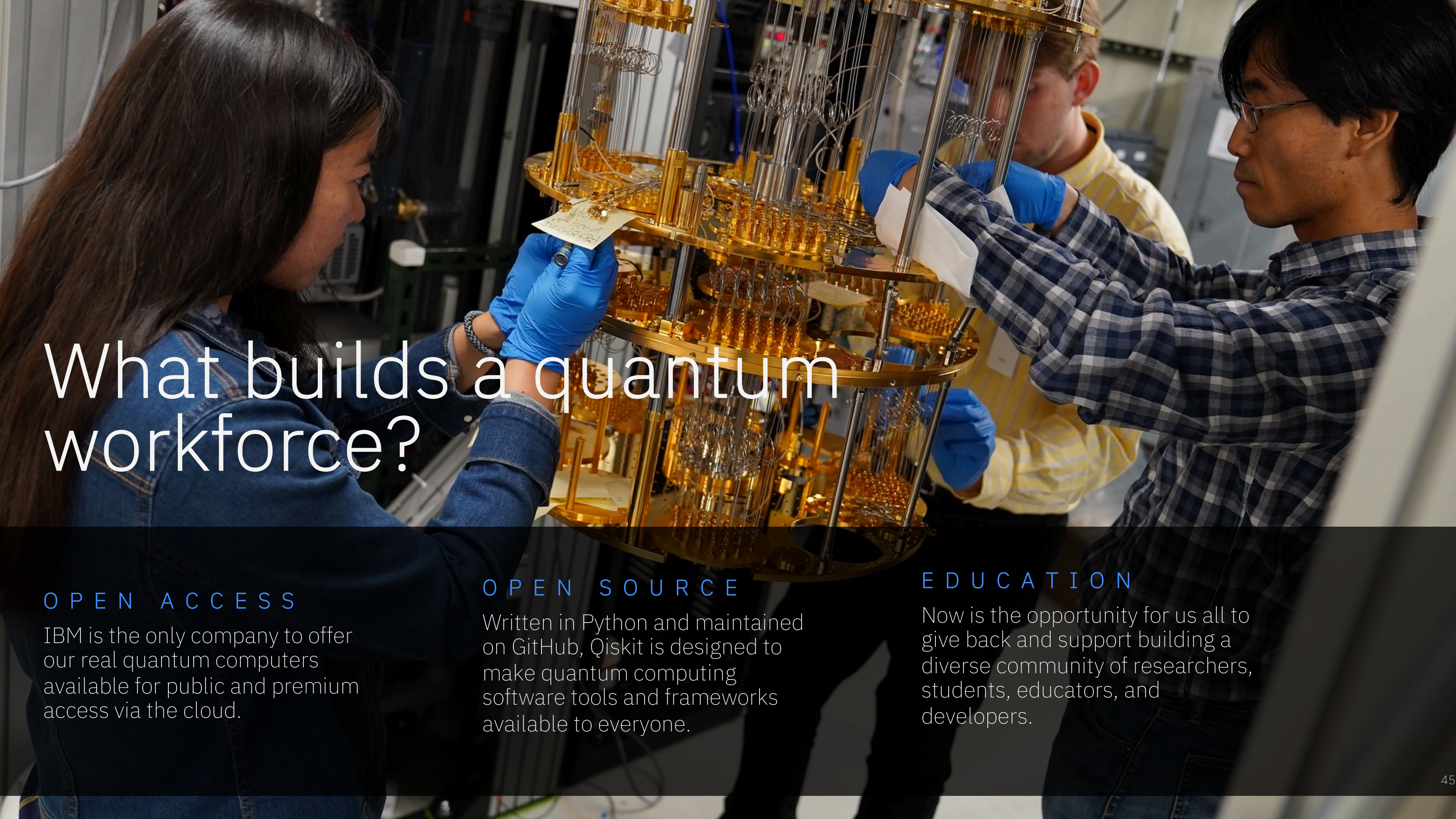


What builds a quantum workforce?

OPEN ACCESS

IBM is the only company to offer our real quantum computers available for public and premium access via the cloud.

OPEN SOURCE

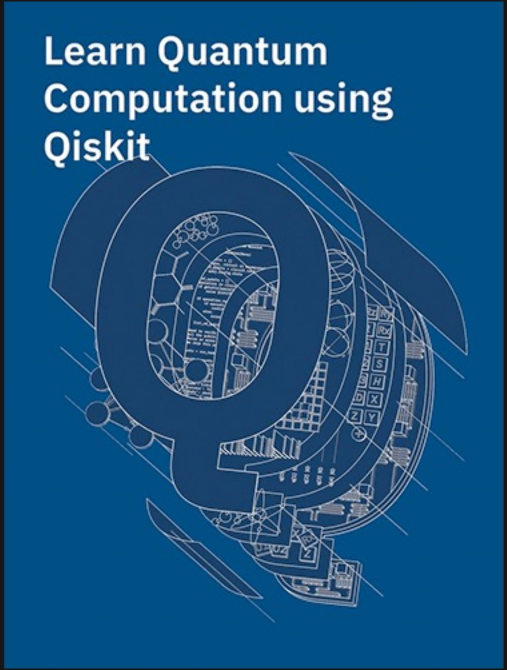
Written in Python and maintained on GitHub, Qiskit is designed to make quantum computing software tools and frameworks available to everyone.

EDUCATION

Now is the opportunity for us all to give back and support building a diverse community of researchers, students, educators, and developers.

Open Source Textbook

community.qiskit.org/textbook



Traditional Quantum Computation Course

Linear Algebra Quantum Mechanics → Quantum Algorithms → Quantum Hardware

Learn Quantum Computation using Qiskit Textbook

Python Qiskit → Quantum Programming → Quantum Algorithms on Today's Hardware

Chapters:

0. Prerequisites
1. Quantum States and Qubits
2. Single Qubits and Multi-Qubit Gates
3. Quantum Algorithms
4. Quantum Algorithms for Applications
5. Investigating Quantum Hardware Using Qiskit
6. Implementations of Recent Quantum Algorithms

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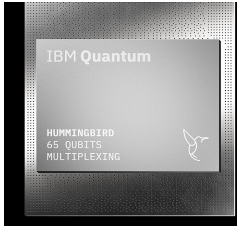
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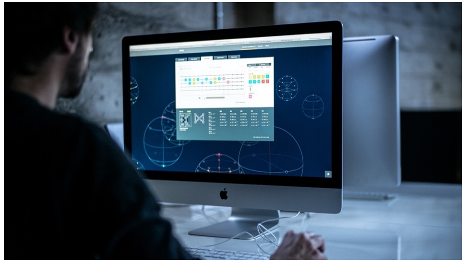



IBM Quantum
EAGLE
127 QUBITS
PACKAGING

2023 → Utility

We have entered the era of Quantum Utility.

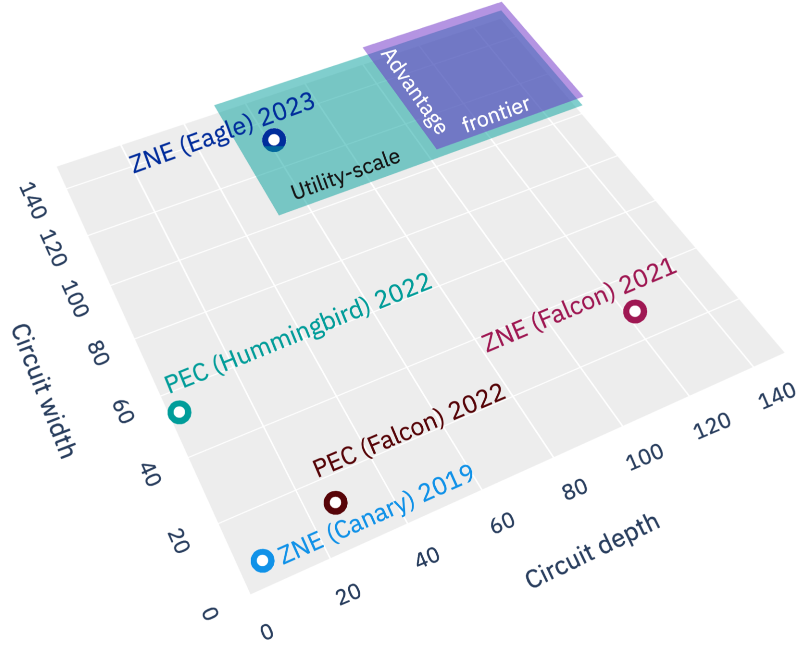
Definition of Quantum Utility

High-fidelity quantum computation outside the reach of exact classical simulation methods

It is the first major milestone on the path to Quantum Advantage.

Useful quantum computation requires utility-scale hardware and co-designed scalable software capabilities.

This means systems larger than 100 qubits, where simulations are not a viable alternative.



If you’re not using 100+ qubits, you’re not doing quantum.

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