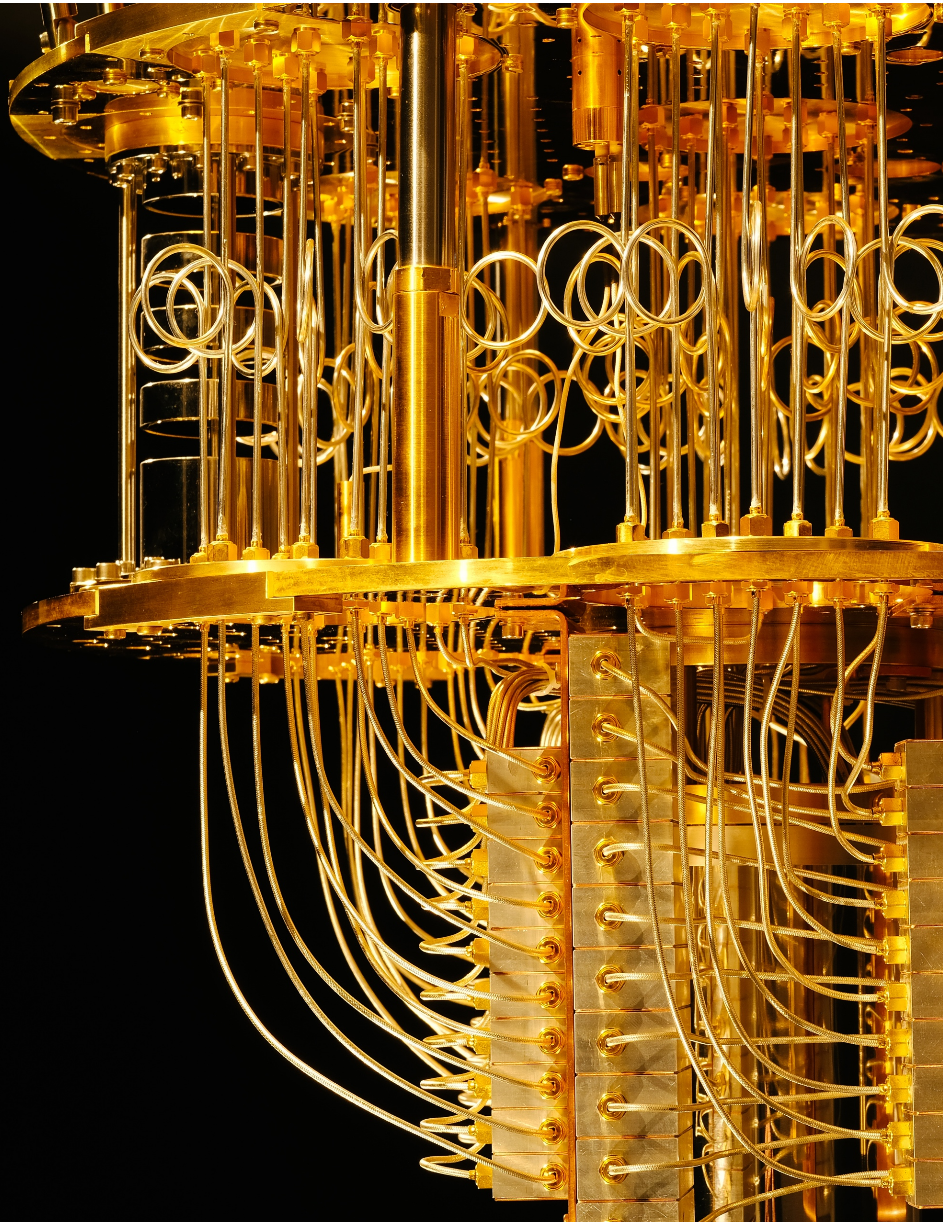
Quantum Computing and IBM Q
An Introduction



Teppo Seesto
IBM Q Ambassador
IBM Nordic

IBM

IBM Research around the world

Six Nobel Laureates

Nine Medals of Technology

Five National Medals of Science

Six Turing Awards

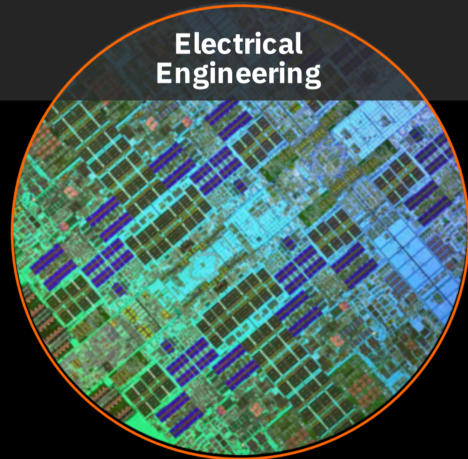
69 Members

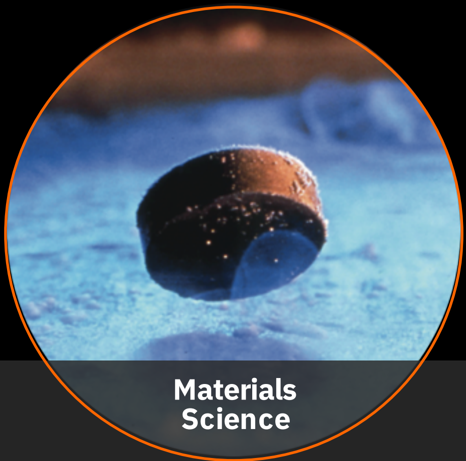
123 IEEE Fellows

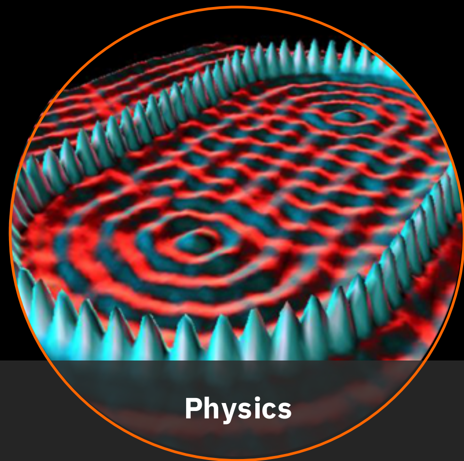
28 ACM Fellows

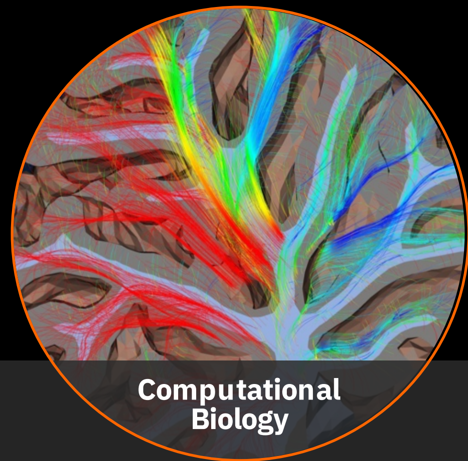
95 IBM Fellows

IBM Research: A diversity of core academic disciplines









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$$H_{eff} = \sum_i (\omega_i - \delta_{i/2}) b_i^+ b_i + \frac{\delta_i}{2} b_i^+ b_i b_i^+ b_i + J_{ij}(b_i^+ b_j + b_i b_j^+)$$

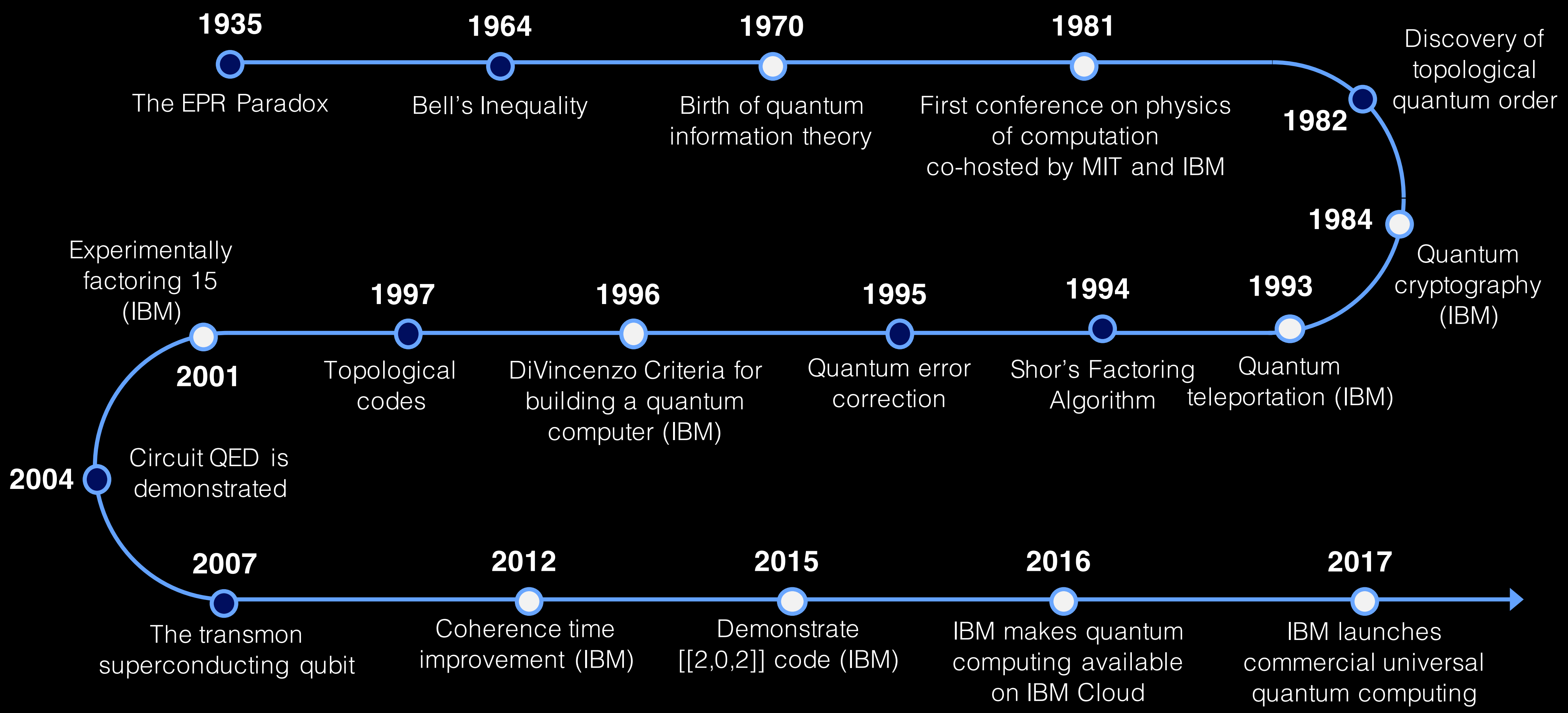
“Anyone who is not shocked by quantum theory has not understood it”

— Niels Bohr

“I think I can safely say that nobody understands quantum mechanics.”

— Richard Feynman

A history of quantum computing



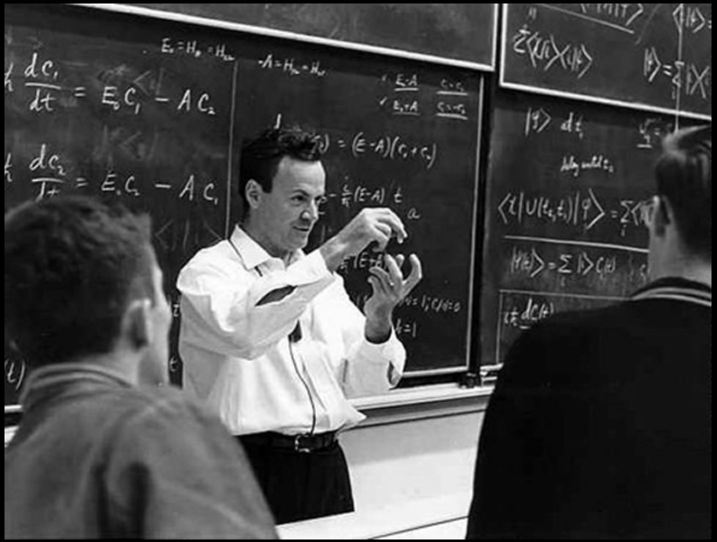
In May of 1981, IBM and MIT hosted the Physics of Computation Conference

I'm not happy with all the analyses that go with just the classical theory, *because nature isn't classical*, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical ...

International Journal of Theoretical Physics, VoL 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman
Department of Physics, California Institute of Technology, Pasadena, California 91107



The Basics of Quantum Computing

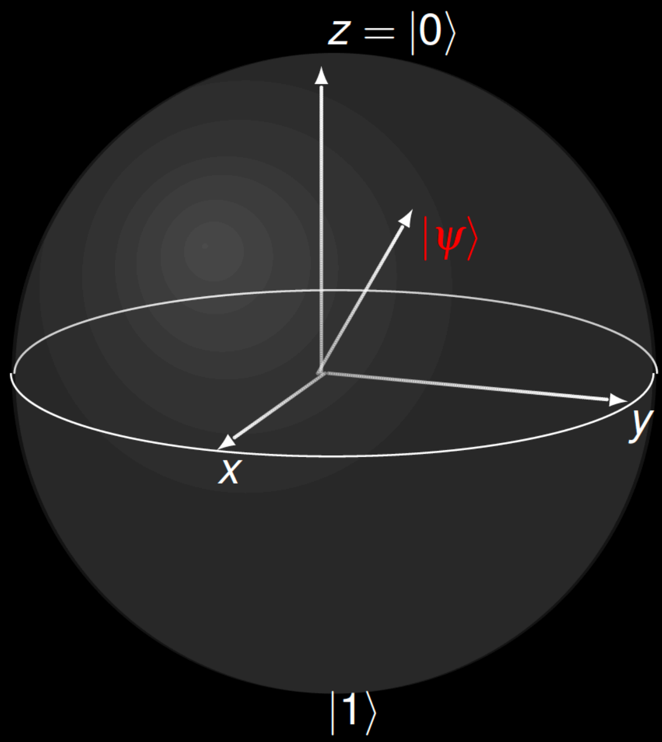
Bit vs. qubit

The bit is the basic unit of information and has two possible states: 0 and 1.

The qubit is the basic quantum unit of information and also is 0 or 1 when you measure, or look at, it.

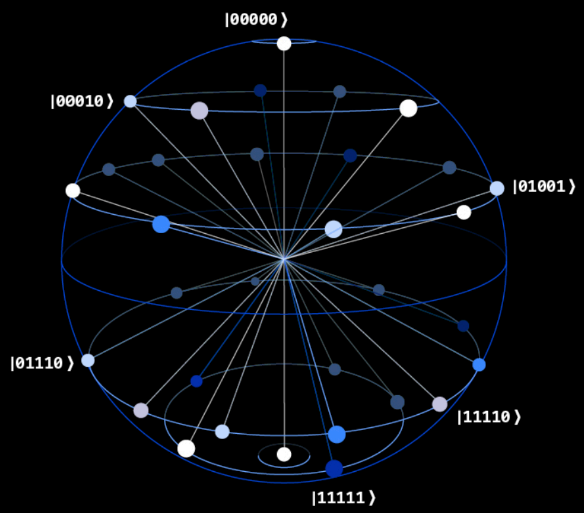
The difference is that the state of a qubit can also be a *superposition*, or combination, of both 0 and 1 while you are using it.

So one qubit can be in two parallel states.



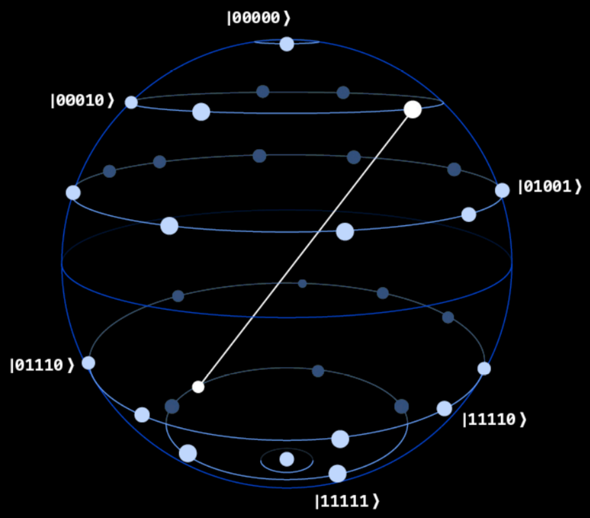
How do universal quantum computers work?

Leverage quantum mechanical properties of superposition and entanglement to create states that scale exponentially with number of qubits, or quantum bits.



Superposition

A single quantum bit can exist in a superposition of 0 and 1, and N qubits allow for a superposition of all possible 2^N combinations.



Entanglement

The states of entangled qubits cannot be described independently of each other.

Two principles of quantum information science

Classical Systems

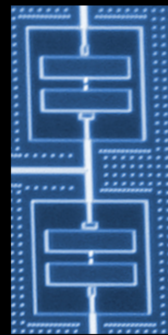
The states are reliably distinguishable, and can be observed without disturbing the system

To specify the joint state of two or more systems, it is sufficient to specify the state of each one separately.

0	0
0	1
1	0
1	1

Quantum Systems

Attempting to observe a state in general disturbs it, while obtaining only partial information about the state (**uncertainty principle**).



Two systems can exist in an **entangled state**, causing them to behave in ways that cannot be explained by supposing that each particle has some state of its own.

The Motivation for Quantum Computing

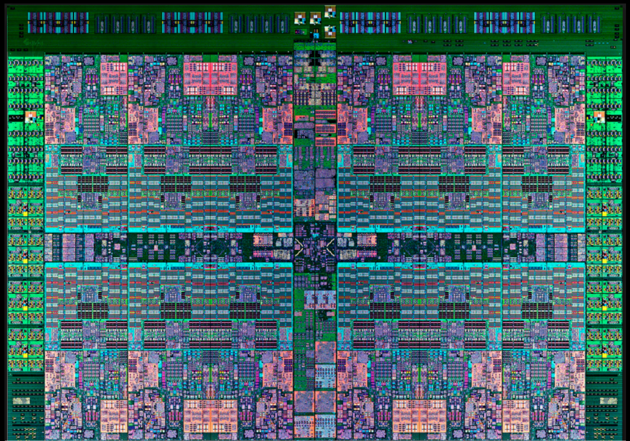
Exponential growth

$$2^n$$

The power of quantum computing

Classical Computers

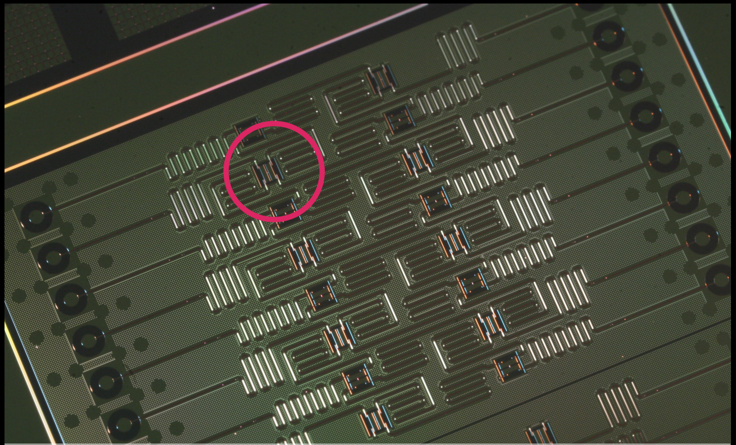
2 x transistors = 2 x compute power



IBM Power 8 Core

Quantum Computers

+ 1 qubit = 2 x compute power



IBM Q 16 Qubit Device

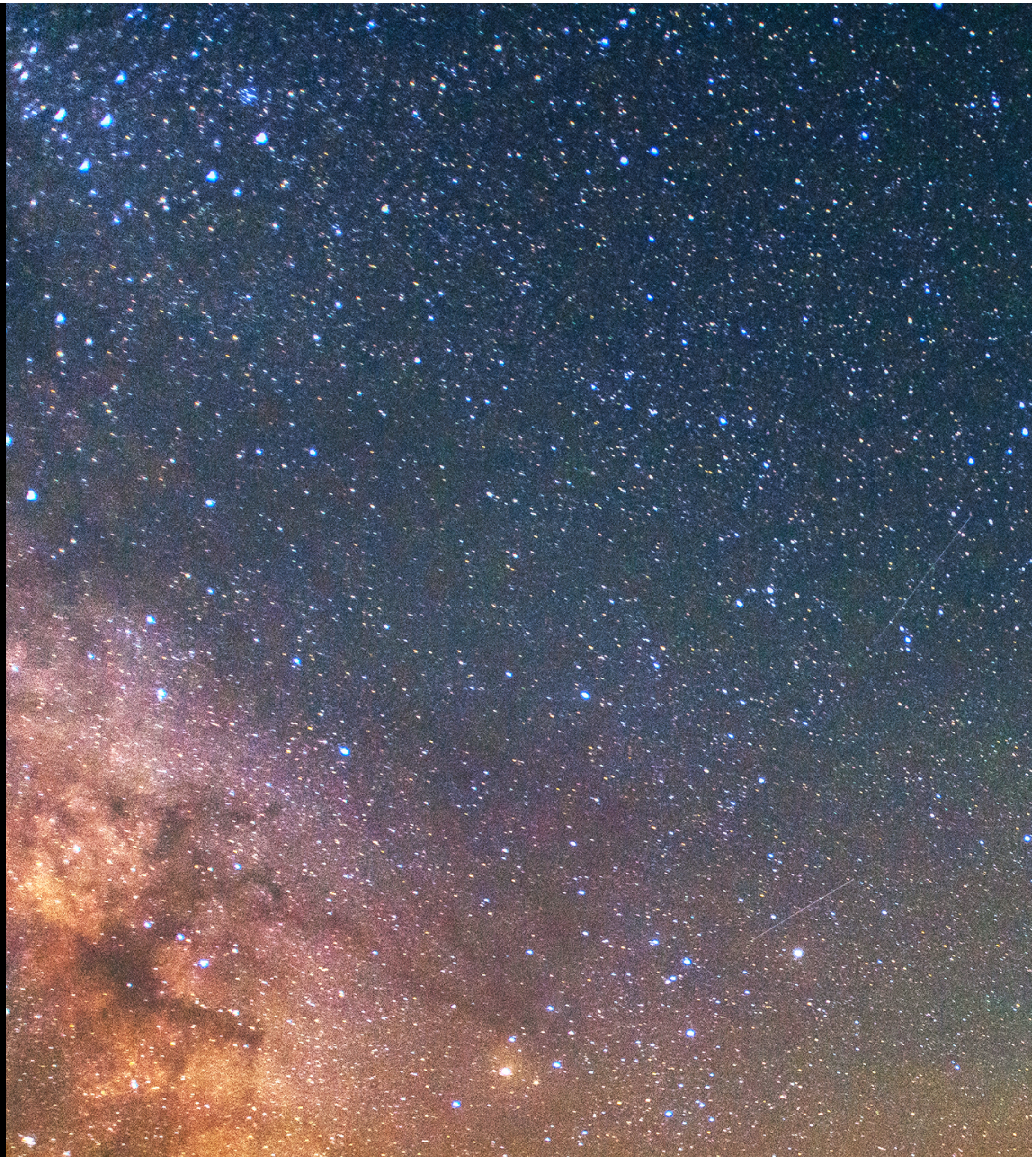
2^{50}

=

# of computational states in prototype IBM **Q** system with 50 qubits

2^{200}

= more computational states than there are atoms in the observable universe



Example: Caffeine

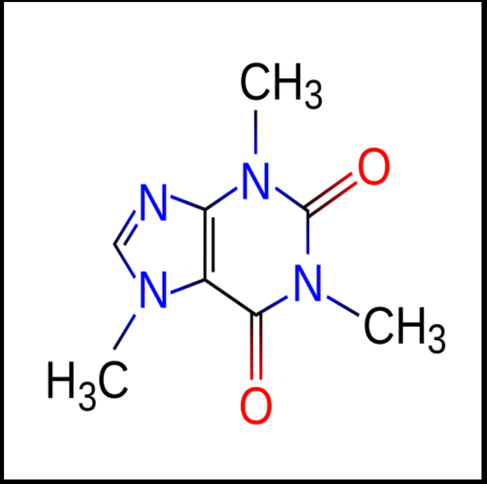
We would would require 10^{48} classical computer bits to represent a single energy state of one molecule:

1000000000000000000000000000000000000000000000000

The number of atoms in our planet is estimated to be between 10^{49} and 10^{50}.

So we would need memory proportional to 1% to 10% of all atoms in the Earth, and this is impossible.

We could represent this using 160 quantum bits, or qubits.



Possible application areas for quantum computing

We believe the following areas might be useful to explore for the early applications of quantum computing:

Chemistry

Material design, oil and gas, drug discovery

Artificial Intelligence

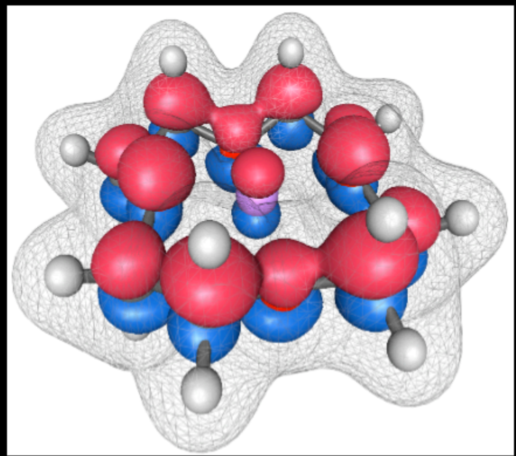
Classification, machine learning, linear algebra

Financial Services

Portfolio optimization, scenario analysis, pricing

Applications and use cases

Initial applications will leverage algorithms that can tolerate or mitigate errors found in approximate quantum computers.



Travelling Salesman

n cities = (*n* – 1)! / 2 options

10 cities ~= 1.8 million routes
20 cities ~= 1 billion billion routes

Optimizations

e.g. customer orders wood in various lengths

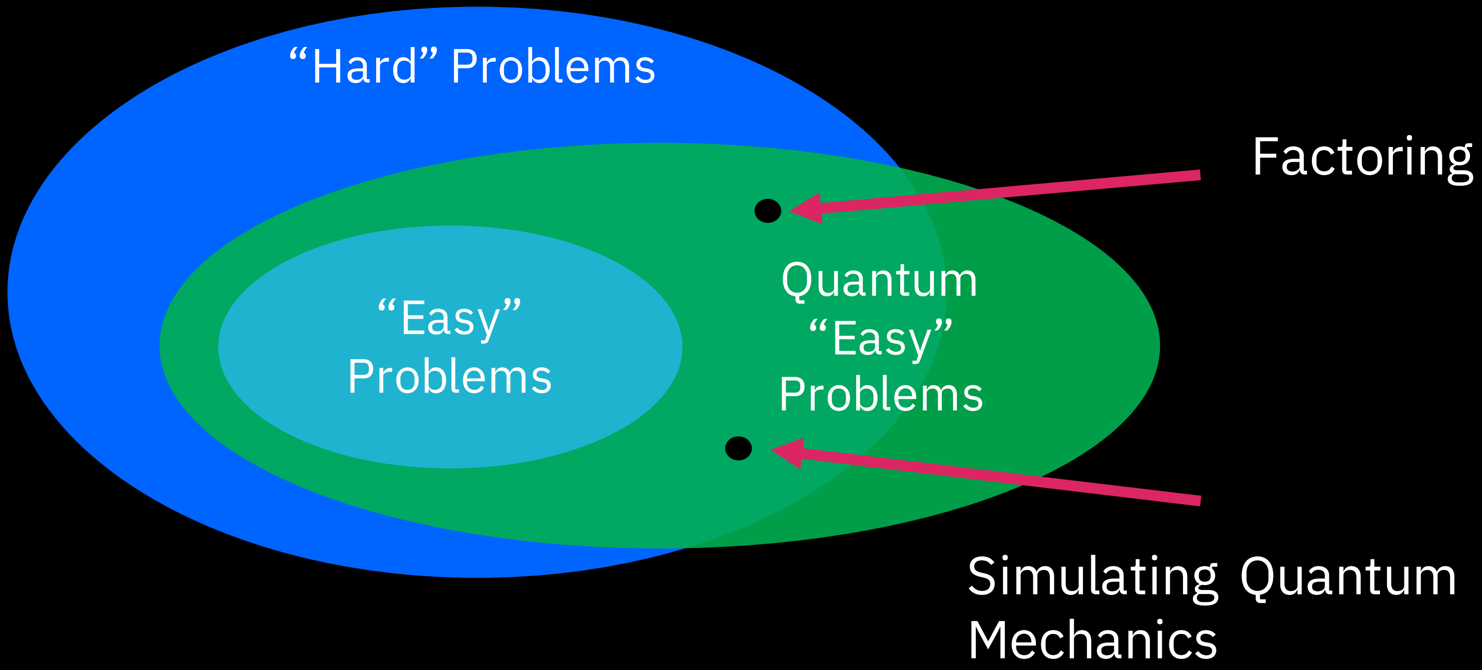
Solution requires starting with a guess and trying all options

Modelling Molecules

Simulate electron interactions

25 electrons ~= laptop sized problem
43 electrons ~= Titan supercomputer

Hard problems and quantum speedups



Quantum computing provides a new path to solve some of the hardest problems in business and science.

Factoring

881 x 409 = 360329 easy

360329 = 881 x 409 hard

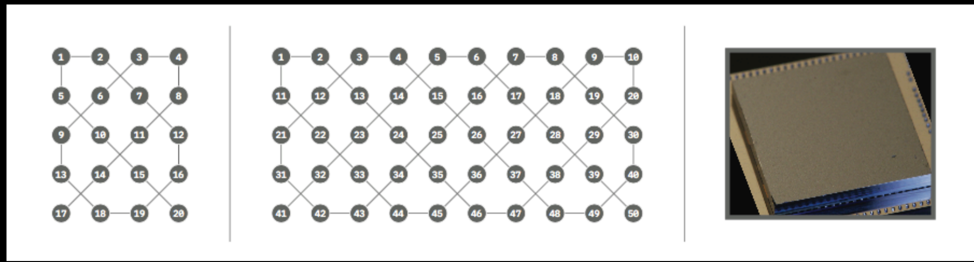
RSA cryptography depends upon this property, e.g. when publishing a public key.

Quantum Computers

There are several kinds of quantum computing

Universal fault-tolerant quantum computer

The holy grail of quantum information science. Allows one to run useful quantum algorithms which achieve exponential speed ups over their classical counterparts. However the over head of quantum error correction estimates **1M-5M qubits**



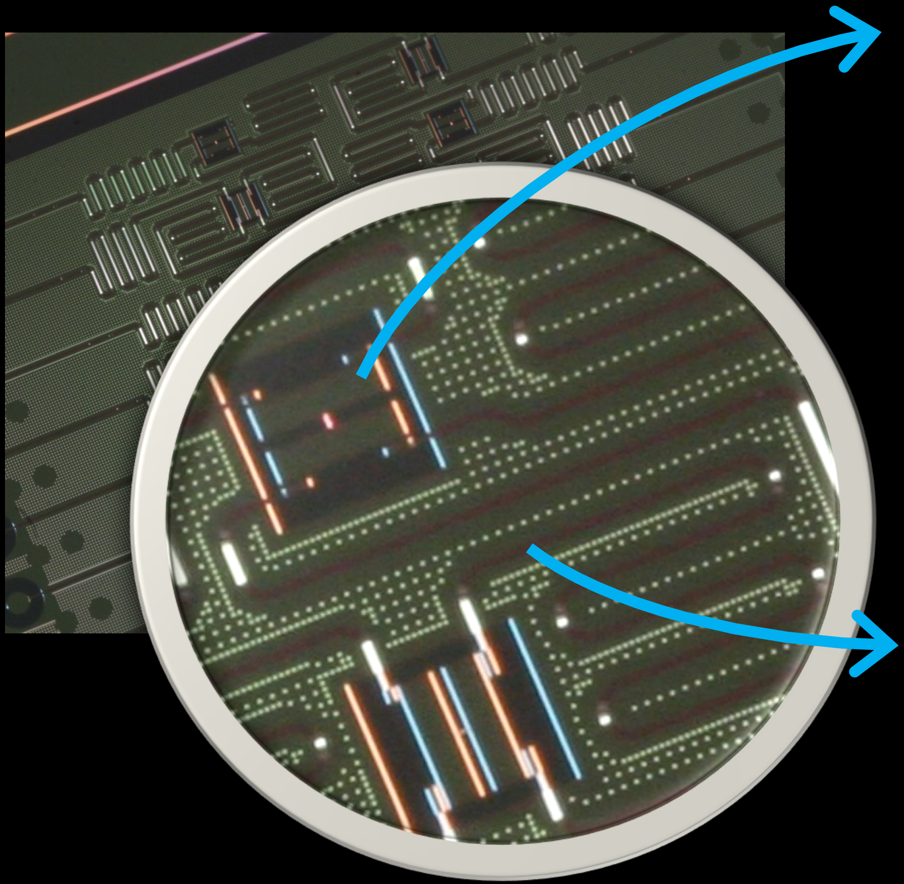
Approximate quantum computer

A quantum device which does not have fault tolerance, with the goal of demonstrating a useful application by interacting with a classical computing system, e.g. quantum chemistry, optimization. **Estimate 1K-5K qubits.**

Analog / quantum-inspired / quantum annealer

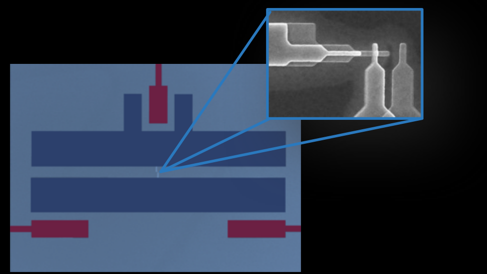
A specially built system which may use quantum effects to solve/emulate a specific problem. It has limited programmability and unclear if and when it will have a speed up over conventional computers using classical algorithms. Among your considerations should be whether software simulations or non-quantum computers can get the same results in roughly the same time.

IBM: Superconducting qubit processor



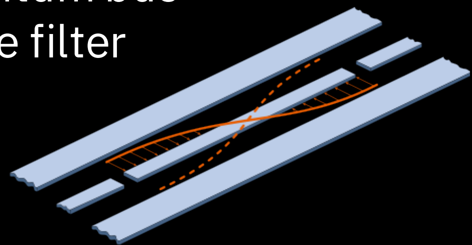
Superconducting qubit

- quantum information carrier



Microwave resonator:

- read-out of qubit states
- quantum bus
- noise filter



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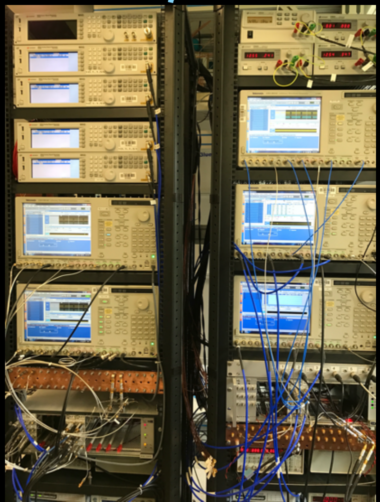
IBM Q structure



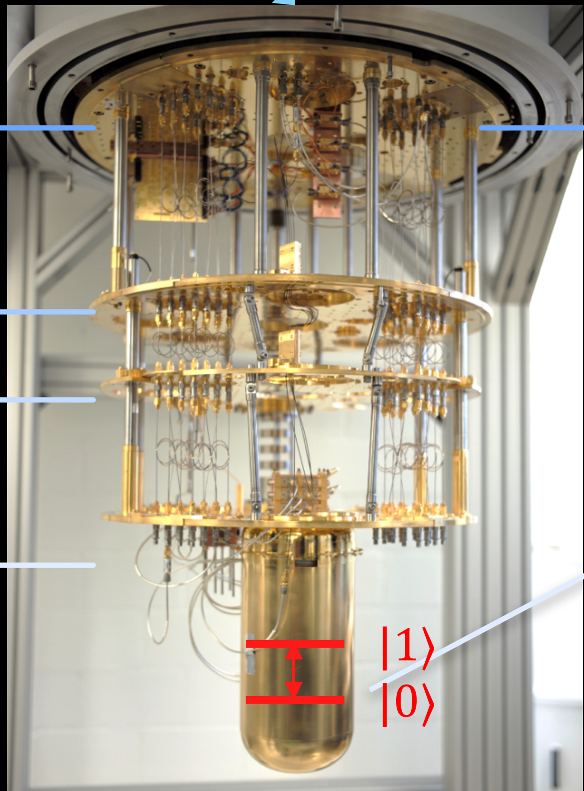
Microwave electronics

2.7K

0.8K

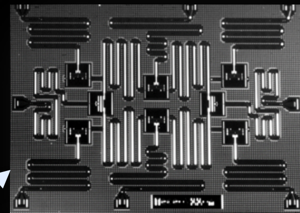
0.1K

0.02K

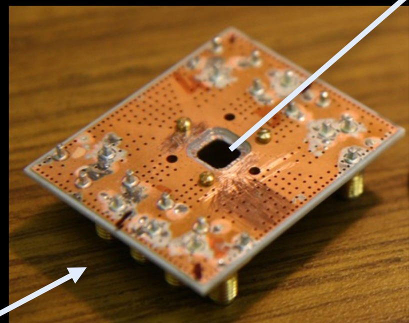


Dilution cryostat

-270°C



Chip with superconducting qubits and resonators



PCB with the qubit chip at 20mK
Protected from the environment
by multiple shields

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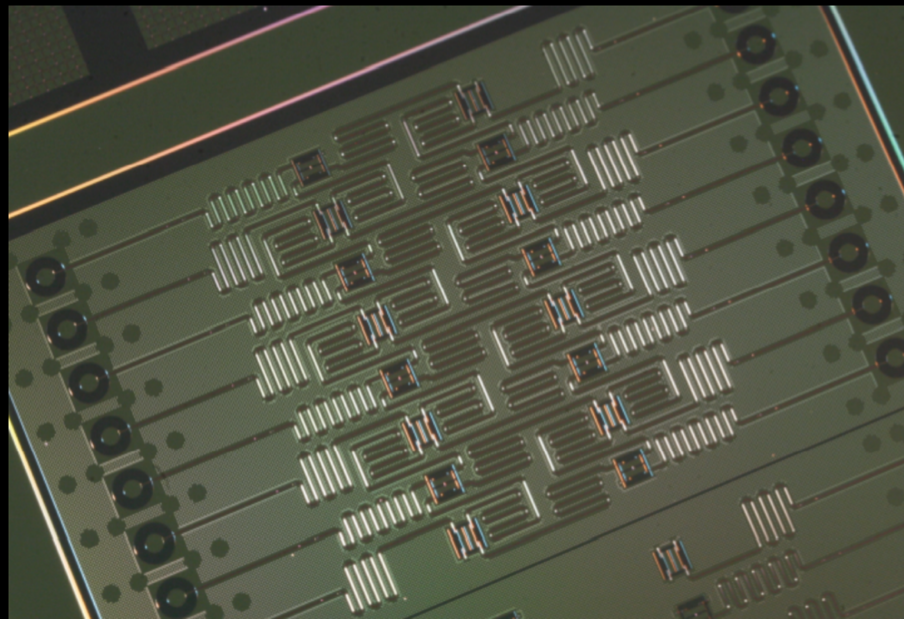
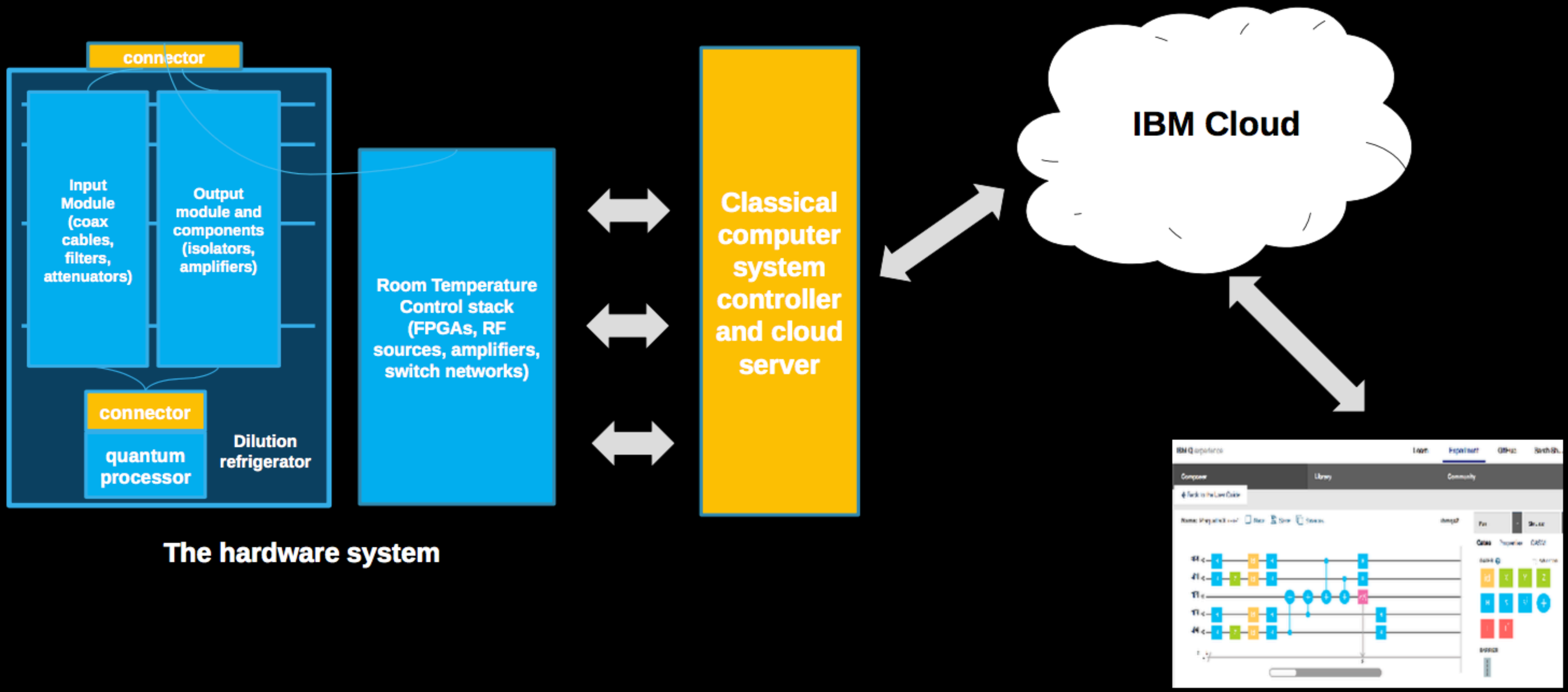
IBM Quantum Computer

Now 50 qubits!

IBM Q is an industry-first initiative to build commercially available universal quantum computers for business and science

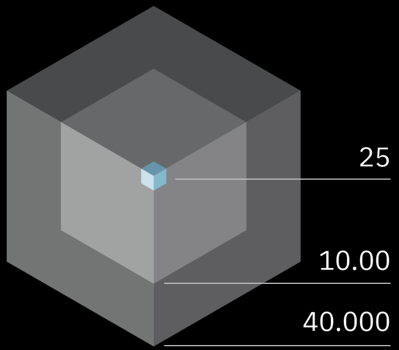


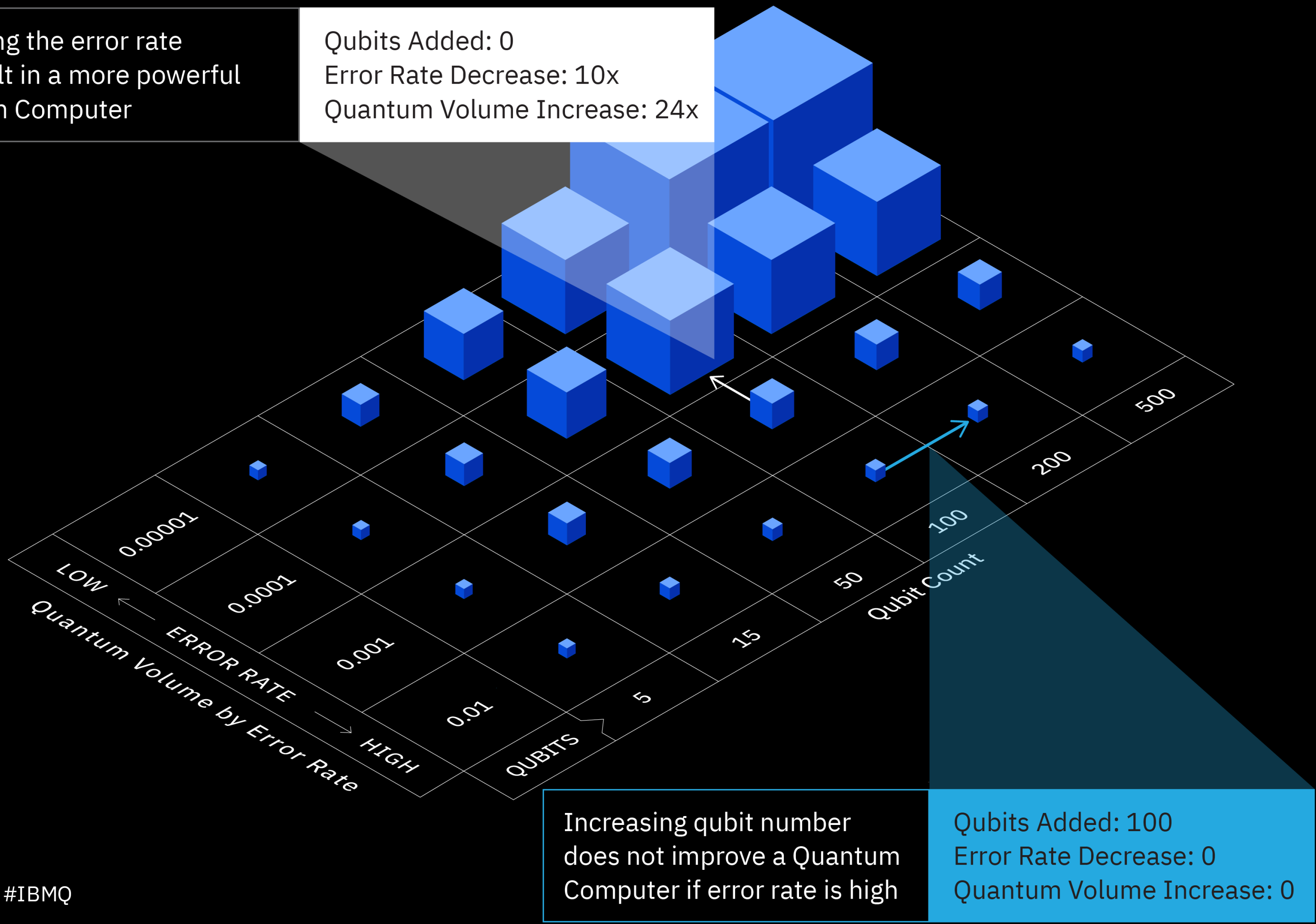
IBM Q Systems



The power of quantum computing is more than the number of qubits

Quantum Volume
Volume of cube proportional to useful quantum computing that can be done





Source: IBM Research

Where are we on the road to Quantum Advantage?

Quantum Science

Fundamentals of quantum information science

Create and scale qubits with increasing coherence

Create error detection and mitigation schemes

Launch of IBM **Q** Experience

Quantum Ready

Core algorithm development

Increase quantum volume

Standardize performance benchmarks

System infrastructure and software enablement

2016

2020s

Quantum Advantage

Demonstrate an advantage to using QC for real problems of interest

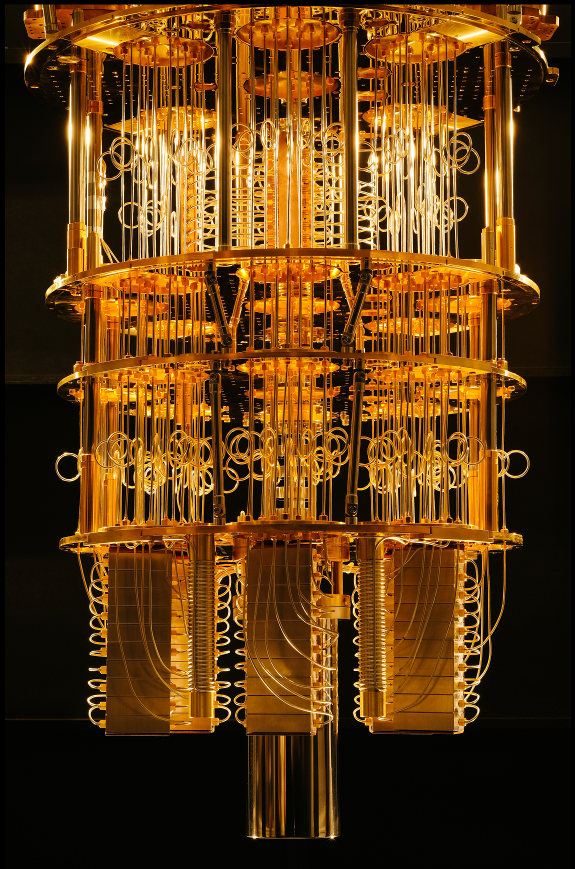
Extract Commercial Value

Enable scientific discovery

~1900

Today

How many qubits are required to see quantum improvement?



Quantum Computing and IBM Q: An Introduction.

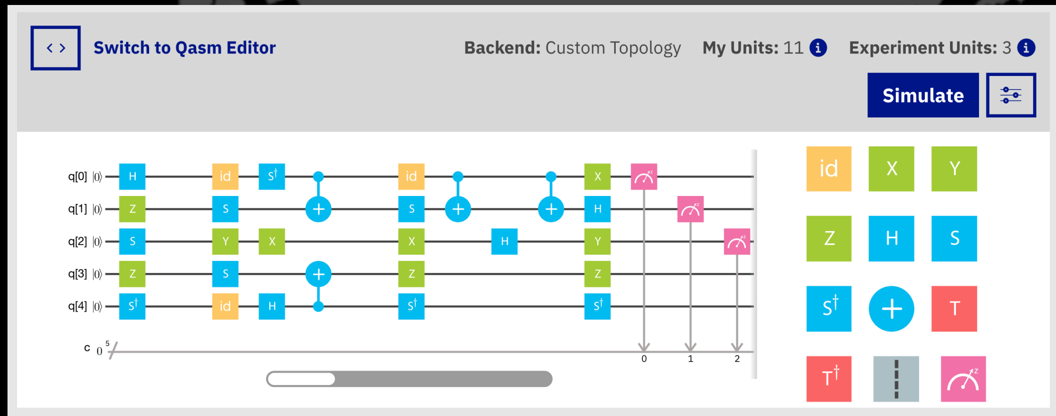
Estimate of the number of “good” qubits required before quantum computing shows advantage over conventional:

Problem	Type of Quantum Computer	# Qubits for advantage (est)	Years to advantage (est)
Quantum Chemistry	NISQ/Approximate QC	$10^2 \sim 10^3$	< 5 ?
Optimization (specific)	NISQ/Approximate QC	$10^2 \sim 10^3$	< 5 ?
Heuristic machine learning	NISQ/Approximate QC	$10^2 \sim 10^3$	< 5 ?
Shor’s algorithm	Universal fault-tolerant QC	$> 10^8$	10~15 if possible
Big Linear Algebra Programs (FEM)	Universal fault-tolerant QC	$> 10^8$	10~15 if possible

The IBM **Q** Experience

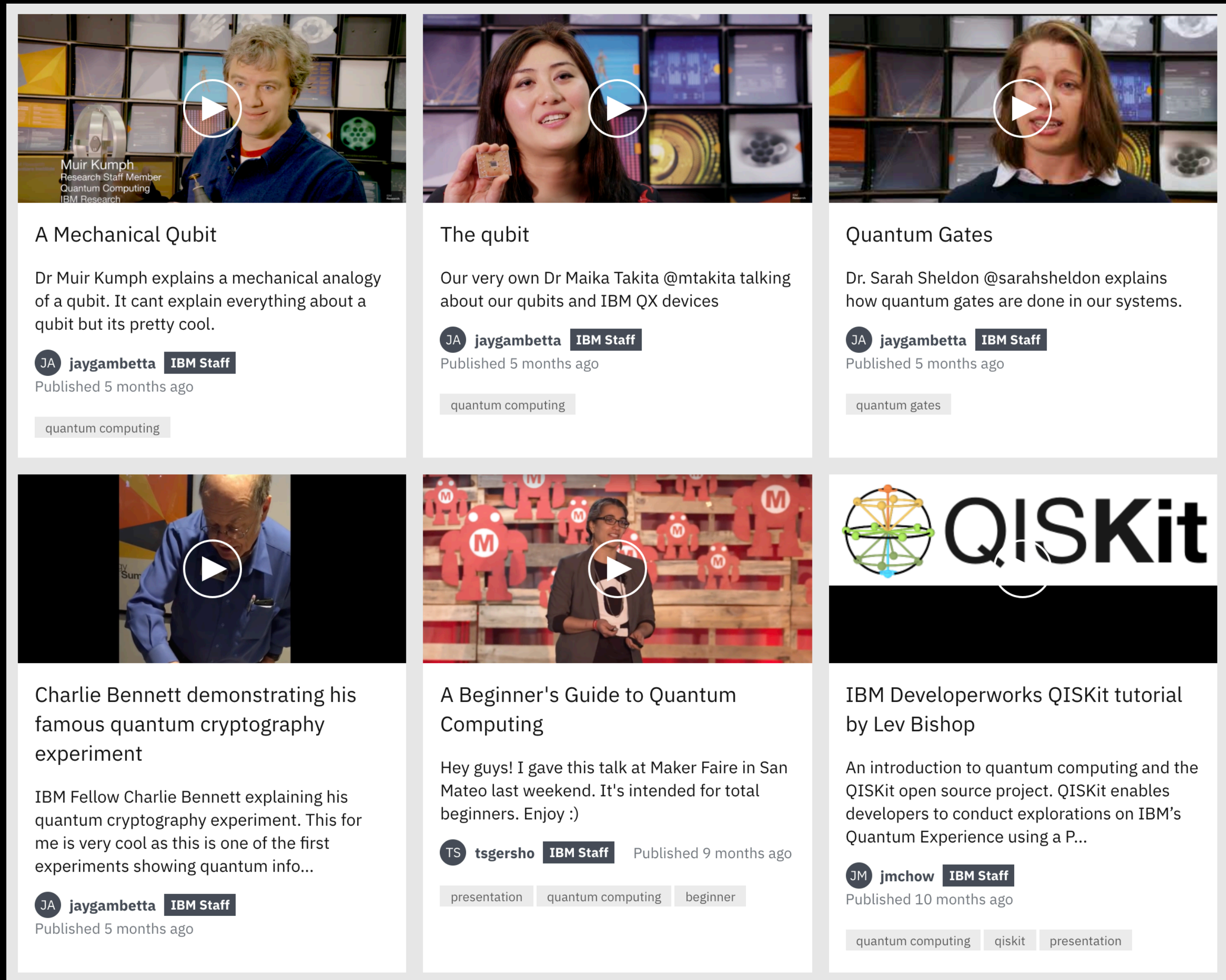
The IBM Q Experience has seen extraordinary adoption

- First quantum computer on the cloud
- > 85,000 users
- All 7 continents
- > 4.4 **Million** experiments run
- > 70 papers
- > 1500 colleges and universities, 300 high schools, 300 private institutions



https://quantumexperience.ng.bluemix.net

The IBM Q Experience offers resources to do real quantum computing today.



QISKit is our open source software development kit and provides libraries, documentation, a simulator, and what you need to connect to IBM Q devices

QISKit

Quantum Information Software Kit

Join our Slack community

Latest version pypi v0.4.7

The Quantum Information Software Kit (QISKit for short) is a software development kit (SDK) for working with OpenQASM and the IBM Q experience (QX).

GitHub

Road map

Learn

Use QISKit to create quantum computing programs, compile them, and execute them on one of several backends (online Real quantum processors, and simulators).

Tutorials

Documentation

IBM Q experience

Run a quantum program

```
[python3] $ pip install qiskit
```

```
from qiskit import QuantumProgram
qp = QuantumProgram()
qr = qp.create_quantum_register('qr',2)
cr = qp.create_classical_register('cr',2)
qc = qp.create_circuit('Bell',[qr],[cr])
qc.h(qr[0])
qc.cx(qr[0], qr[1])
qc.measure(qr[0], cr[0])
qc.measure(qr[1], cr[1])
result = qp.execute('Bell')
print(result.get_counts('Bell'))
```

Python 3.5+ required, see more **in the docs**

QISKit

Getting Started with QISKit SDK

The latest version of this notebook is available on https://github.com/QISKit/qiskit-tutorial.

Contributors

Ismael Faro, Jay Gambetta, Andrew Cross

QISKit (Quantum Information Software developer Kit)

This tutorial aims to explain how to use QISKit. We assume you have installed QISKit if not please look at qiskit.org or the install documentation.

QISKit is a Python software development kit (SDK) that you can use to create your quantum computing programs based on circuits defined through the OpenQASM 2.0 specification, compile them, and execute them on several backends (real quantum processors online, simulators online, and simulators on local). For the online backends, QISKit uses our python API connector to the IBM Q experience project.

In addition to this tutorial, we have other tutorials that introduce you to more complex concepts directly related to quantum computing.

Commercializing Quantum Computing via IBM **Q**

IBM announced in early 2017 that we were building the first universal quantum computers for business and science

News room > News releases >

IBM Announces Advances to IBM Quantum Systems & Ecosystem

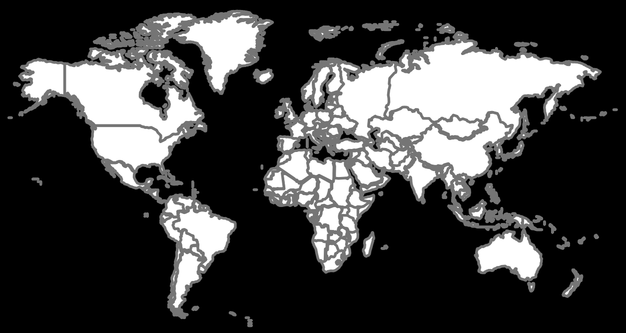
-- Client systems with 20 qubits ready for use; next-generation IBM Q system in development with first working 50 qubit processor
-- IBM expands its open-source quantum software package QISKit; offers the world's most advanced ecosystem for quantum computing

Yorktown Heights, N.Y. - 10 Nov 2017: IBM (NYSE: IBM) announced today two significant quantum processor upgrades for its IBM Q early-access commercial systems. These upgrades represent rapid advances in quantum hardware as IBM continues to drive progress across the entire quantum computing technology stack, with focus on systems, software, applications and enablement.

To augment this ecosystem of quantum researchers and application development, IBM rolled out earlier this year its QISKit (www.qiskit.org) project, an open-source software developer kit to program and run quantum computers. IBM Q scientists have now expanded QISKit to enable users to create quantum computing programs and execute them on one of IBM's real quantum processors or quantum simulators available online. Recent additions to QISKit also include new functionality and visualization tools for studying the state of the quantum system, integration of QISKit with the IBM Data Science Experience, a compiler that maps desired experiments onto the available hardware, and worked examples of quantum applications.

The IBM **Q** Network

In December, 2017, IBM launched the IBM **Q** Network, a collaboration with leading Fortune 500 companies and research institutions with a shared mission to ...



Accelerate Research

Collaborate with the most advanced academic and research organizations to advance quantum computing technology.

Launch Commercial Applications

Engage industry leaders to combine IBM's quantum computing expertise with industry specific expertise to accelerate development of the first commercial use cases.

Educate and Prepare

Expand and train the ecosystem of users, developers, and application specialists that will be essential to the adoption and scaling of quantum computing.

The IBM **Q** Network

IBM Q Network Hubs

Keio University
Japan

Oxford University
UK

Oak Ridge National Laboratory
USA

University of Melbourne
Australia

North Carolina State University
USA

IBM Q Network Partners

JP Morgan Chase
USA

Daimler
Germany

Samsung
South Korea

JSR
Japan

IBM Q Network Members

Barclays
UK

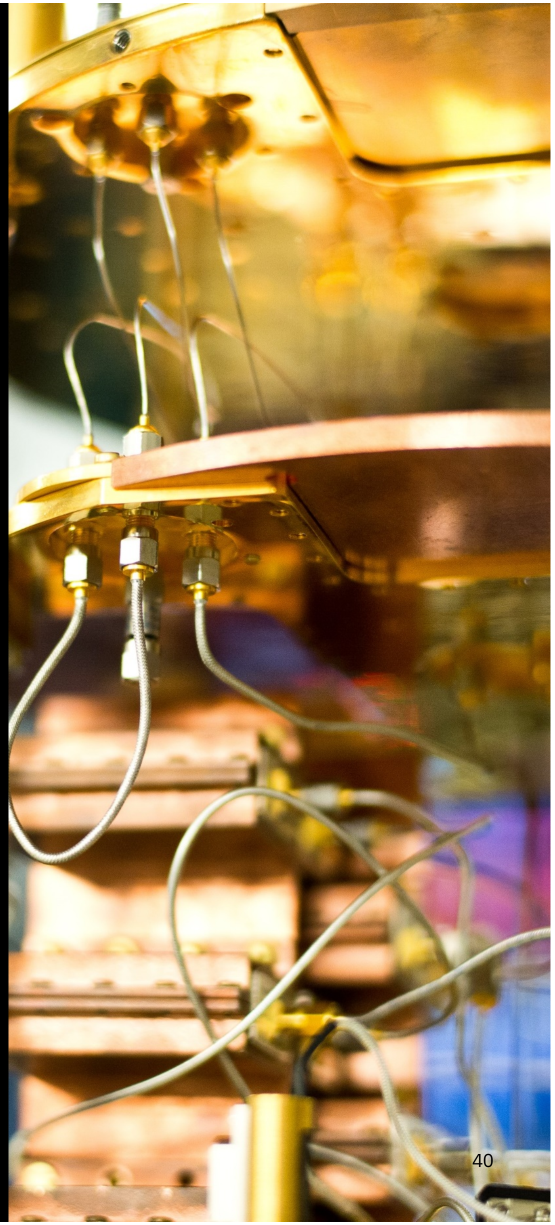
Honda
Japan

Hitachi Metals
Japan

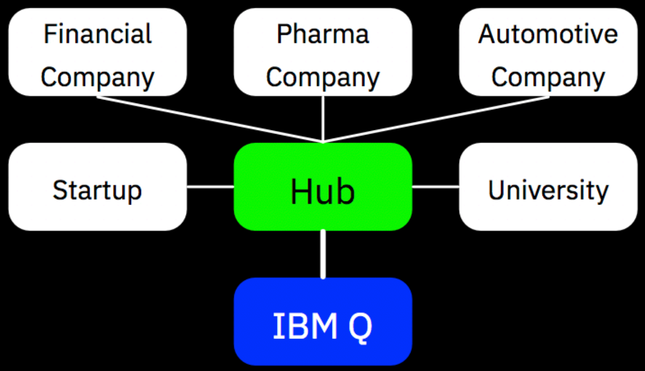
Nagase
Japan

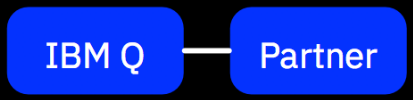
IBM Q Education Partner

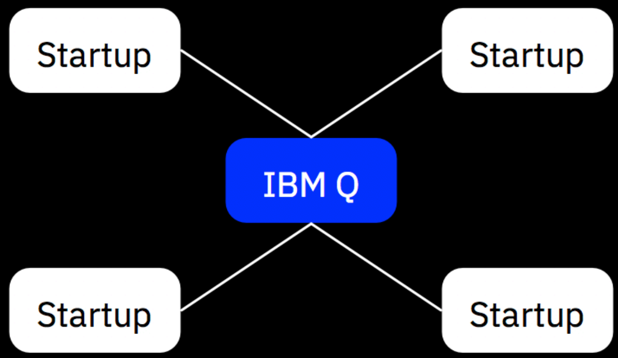
MIT
USA



Types of engagement within the IBM **Q** Network





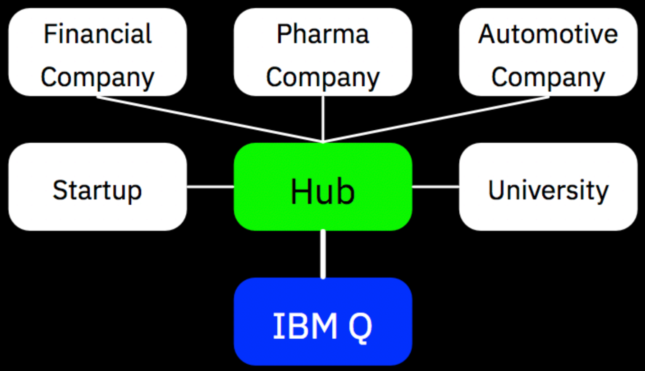


Hubs
Regional centers of quantum computing R&D and ecosystem

Partners
Pioneers of quantum computing in a specific industry or academic field

Startups
Rapidly advance early applications

IBM **Q** Network Hubs



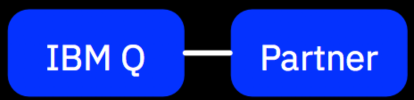
Hubs
Regional centers of quantum computing R&D and ecosystem

IBM **Q** Network Hubs are organizations that are regional centers of quantum computing education, research, development, and commercialization.

Hubs deploy a hub and spoke model of engagement to scale access and enablement to many organizations and create a regional center of excellence in quantum computing.

Hubs provide access to IBM **Q** systems, technical support, educational and training resources, community workshops and events, and opportunities for joint work.

IBM **Q** Network Partners



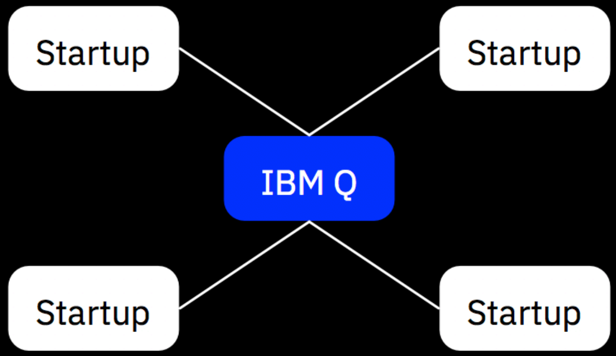
Partners
Pioneers of quantum computing in a specific industry or academic field

IBM **Q** Network Partners are organizations that are pioneers of quantum computing in a specific industry or academic field.

Partners work closely with IBM and select individual collaborators and commit to shape how quantum computing will transform the future of their industry or field.

Partners have direct access to IBM **Q** systems and work closely with IBM on joint development and creation and training of an in-house team of quantum experts within the Partner organization.

IBM **Q** Startup Members



Startups
Rapidly advance early applications

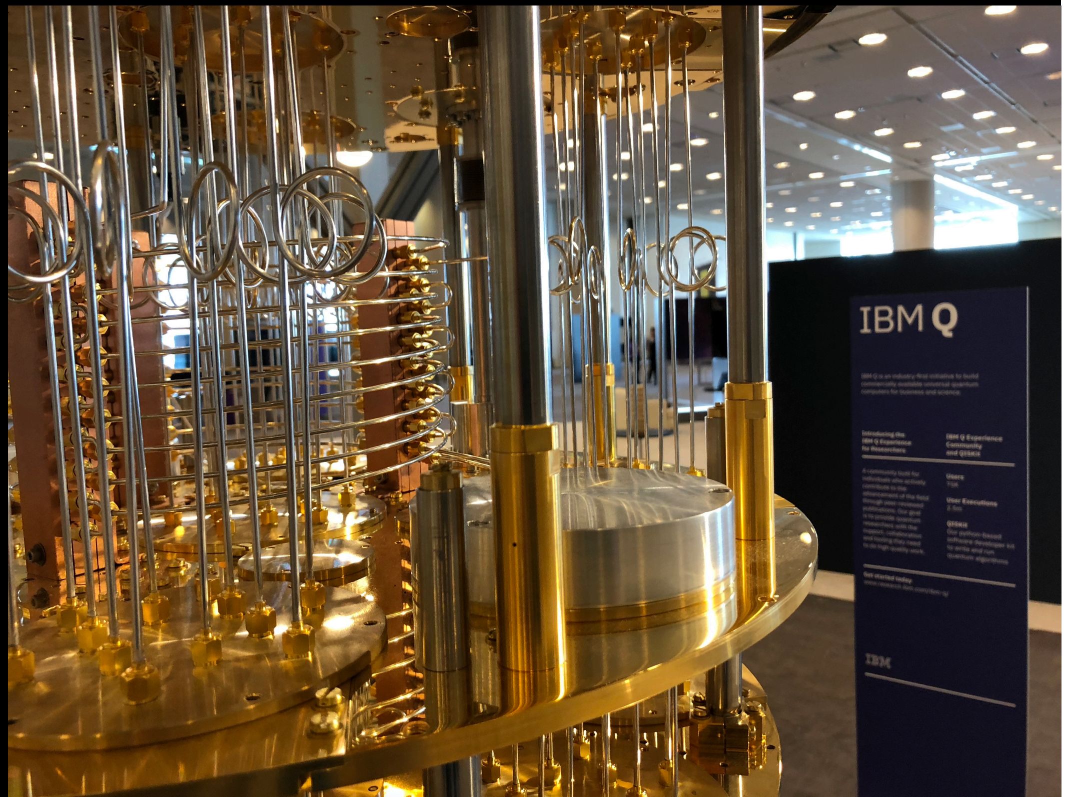
Membership in the network will enable these startups to run experiments and algorithms on IBM quantum computers via cloud-based access.

It will provide startups in the quantum computing race deeper access to APIs and advanced quantum software tools, libraries and applications

These startup members will have access to training and technical SMEs on potential applications, as well as other IBM **Q** Network organizations.

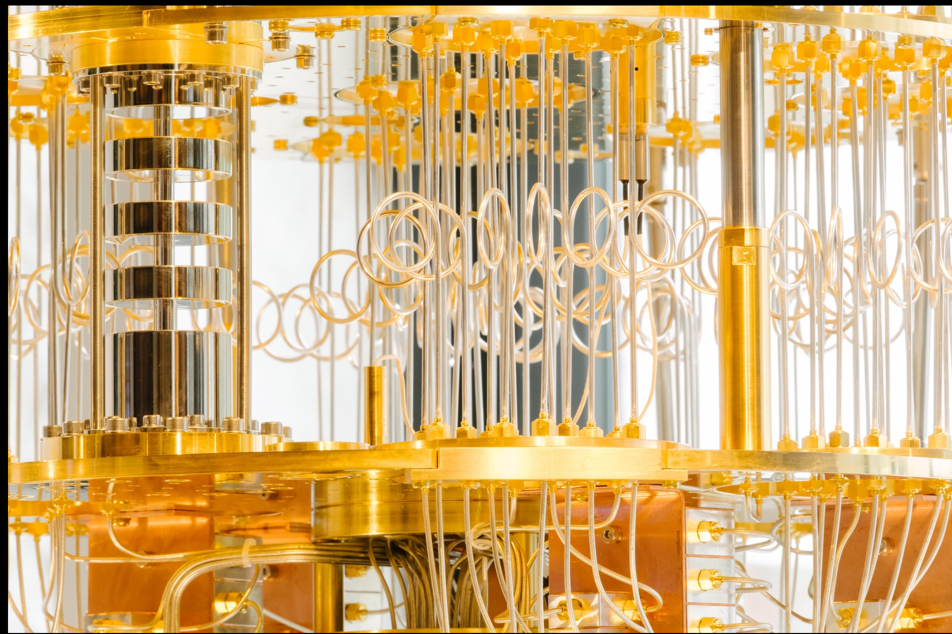
IBM **Q** Network-wide resources and collaboration

- Technical support for system use
- Educational content and resources
- Advisory council of representatives from each organization
- Industry and academic workshops
- Opportunities to share individual ideas and innovations across Network
- Opportunities for researcher exchange and collaboration across network



The Future

The quantum computation centers of today ...



IBM **Q**

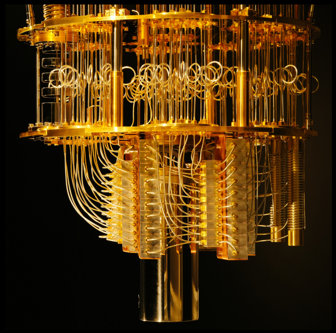
… the quantum computation centers of the future

IBM **Q**

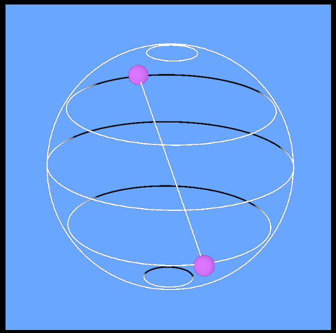
It is time to build a quantum strategy to prepare for one of the most profound shifts in
the history of computing

It is time to learn to program quantum computers to prepare to build commercial applications

Your next steps to getting Quantum Ready



Explore the **IBM Q Experience** and start using real machines today



Learn about and start using the **QISKit** software development kit

Collaborate, research, and start applying quantum computing through the **IBM Q Network**

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