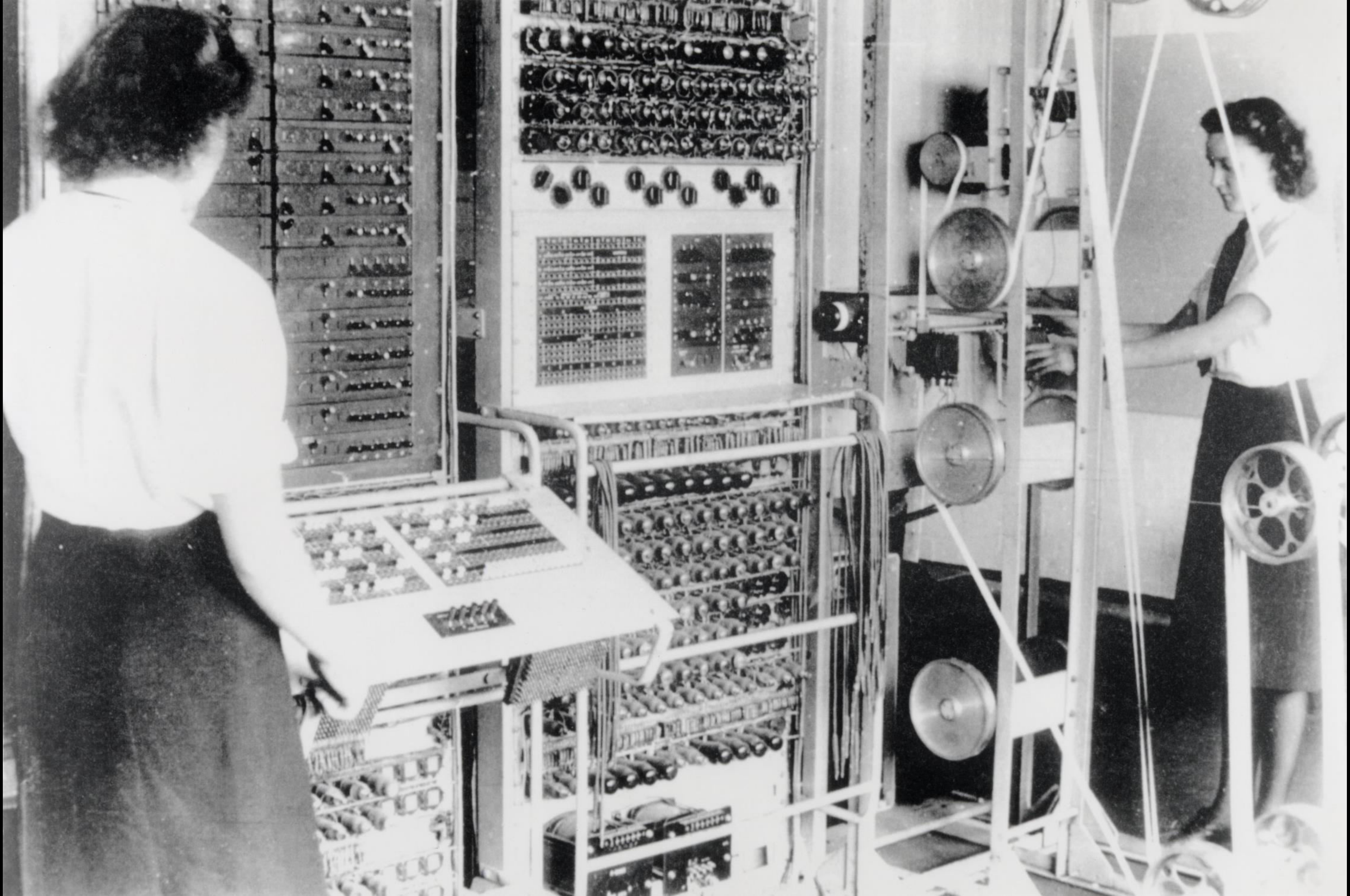
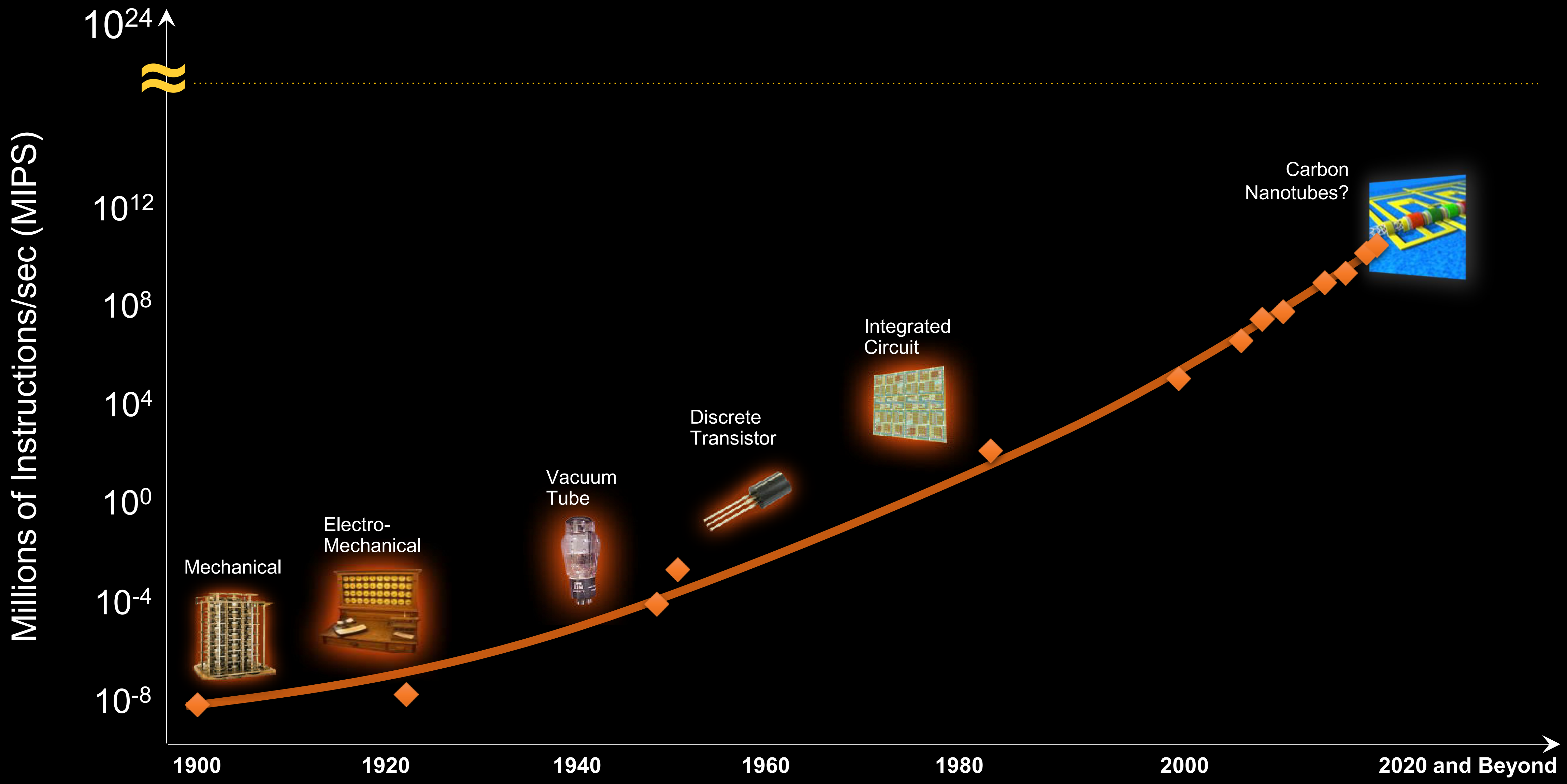
Enabling Quantum Computing over the Cloud

Dr. Jerry M. Chow

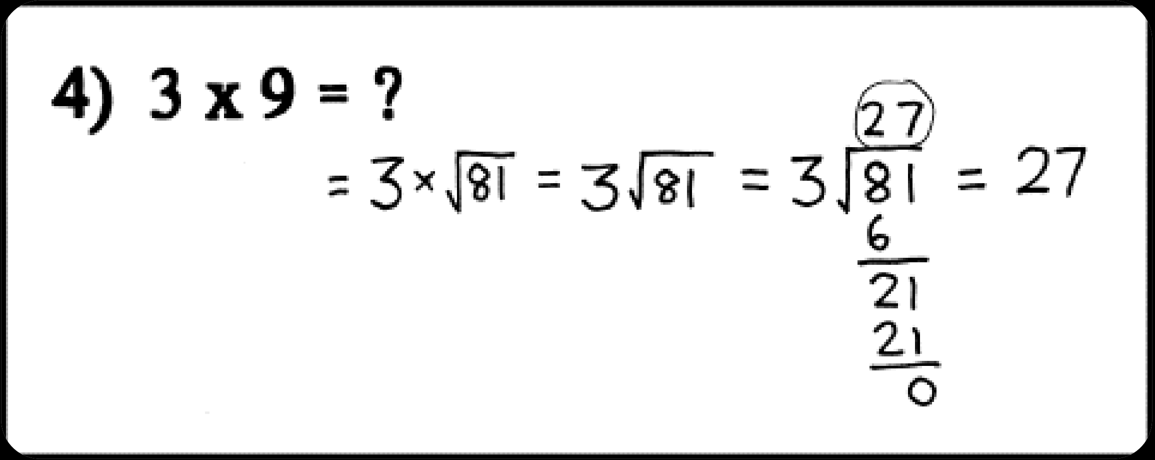
Manager of Experimental Quantum Computing at
IBM Thomas J. Watson Research Center



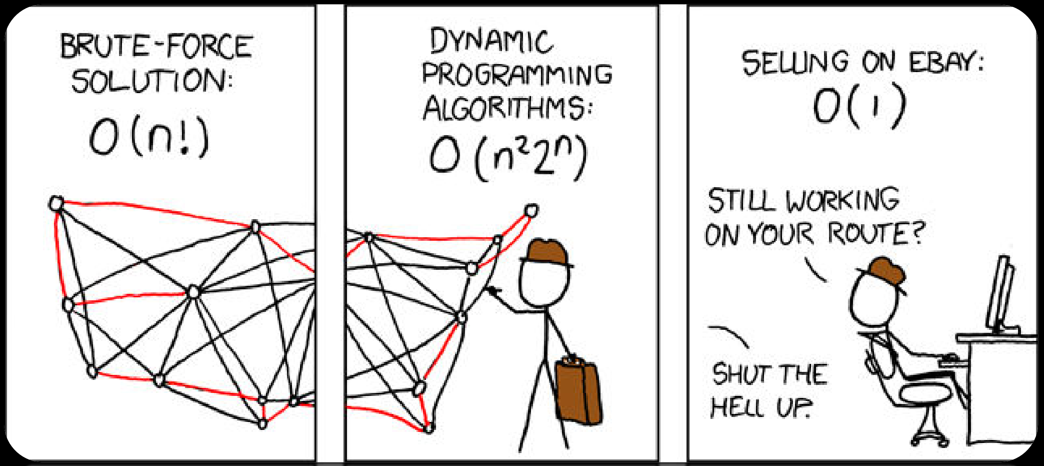


Millions of Instructions/sec (MIPS)
10^{24}
10^{12}
10^{8}
10^{4}
10^{0}
10^{-4}
10^{-8}
Mechanical
Electro-
Mechanical
Vacuum
Tube
Discrete
Transistor
Integrated
Circuit
Carbon
Nanotubes?
1900
1920
1940
1960
1980
2000
2020 and Beyond

Have we reached the limit of computation power?



http://xkcd.com/759/



http://xkcd.com/399/

“easy”

(polynomial $\Rightarrow$ efficient)

- Multiplying numbers
- Word processing

“hard”

(exponential $\Rightarrow$ intractable)

- Algebraic and Number Theoretic Algorithms (factoring)
- Combinatorial optimization (traveling salesman)
- Machine learning
- Simulating quantum mechanics for chemistry

Our intuition about
what we can compute
is wrong

“ **Nature isn’t classical, dammit, and if you want to make a simulation of nature, you’d better make it quantum mechanical, and by golly, it’s a wonderful problem, because it doesn’t look so easy.”**

-Richard P. Feynman

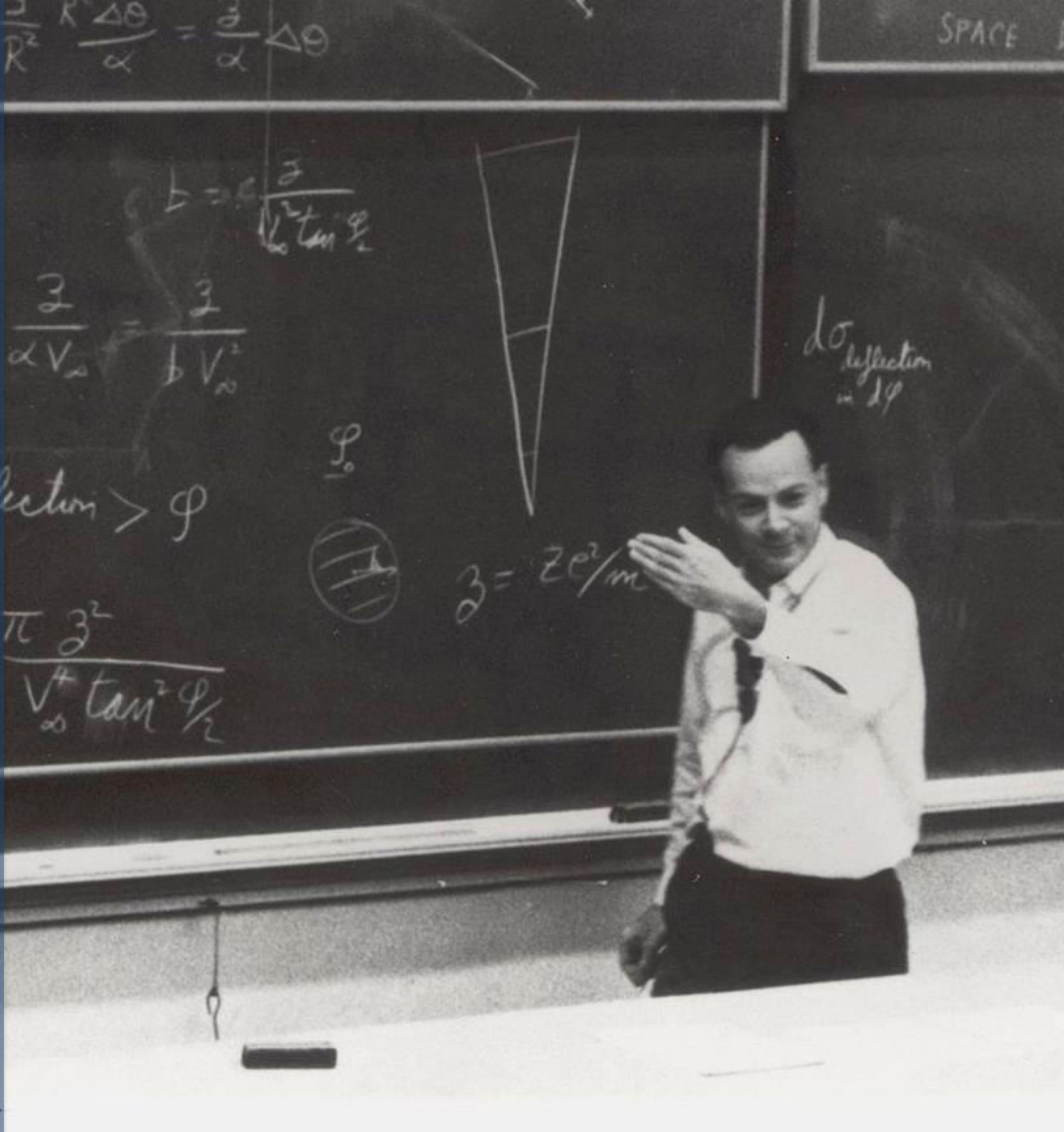
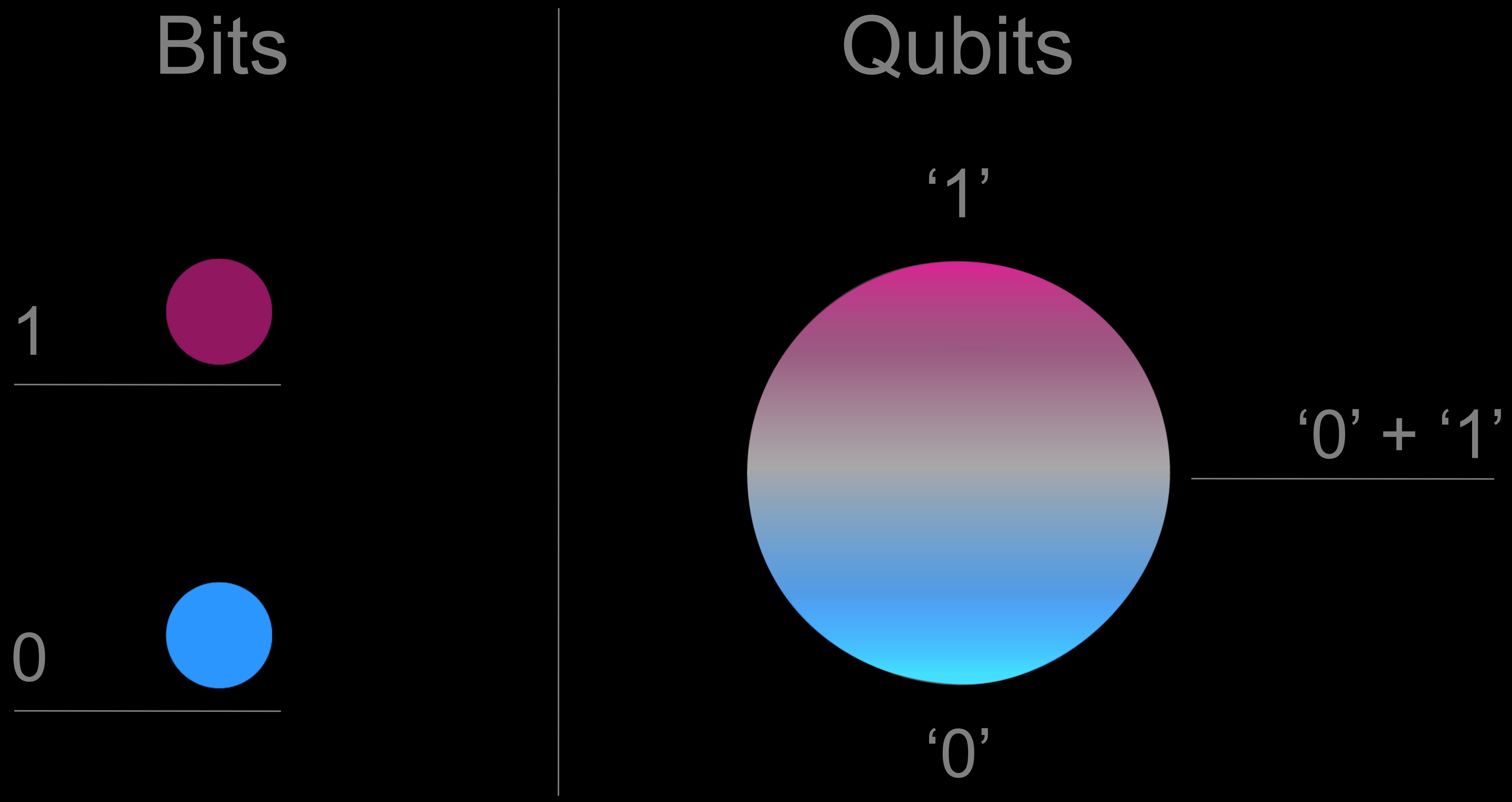
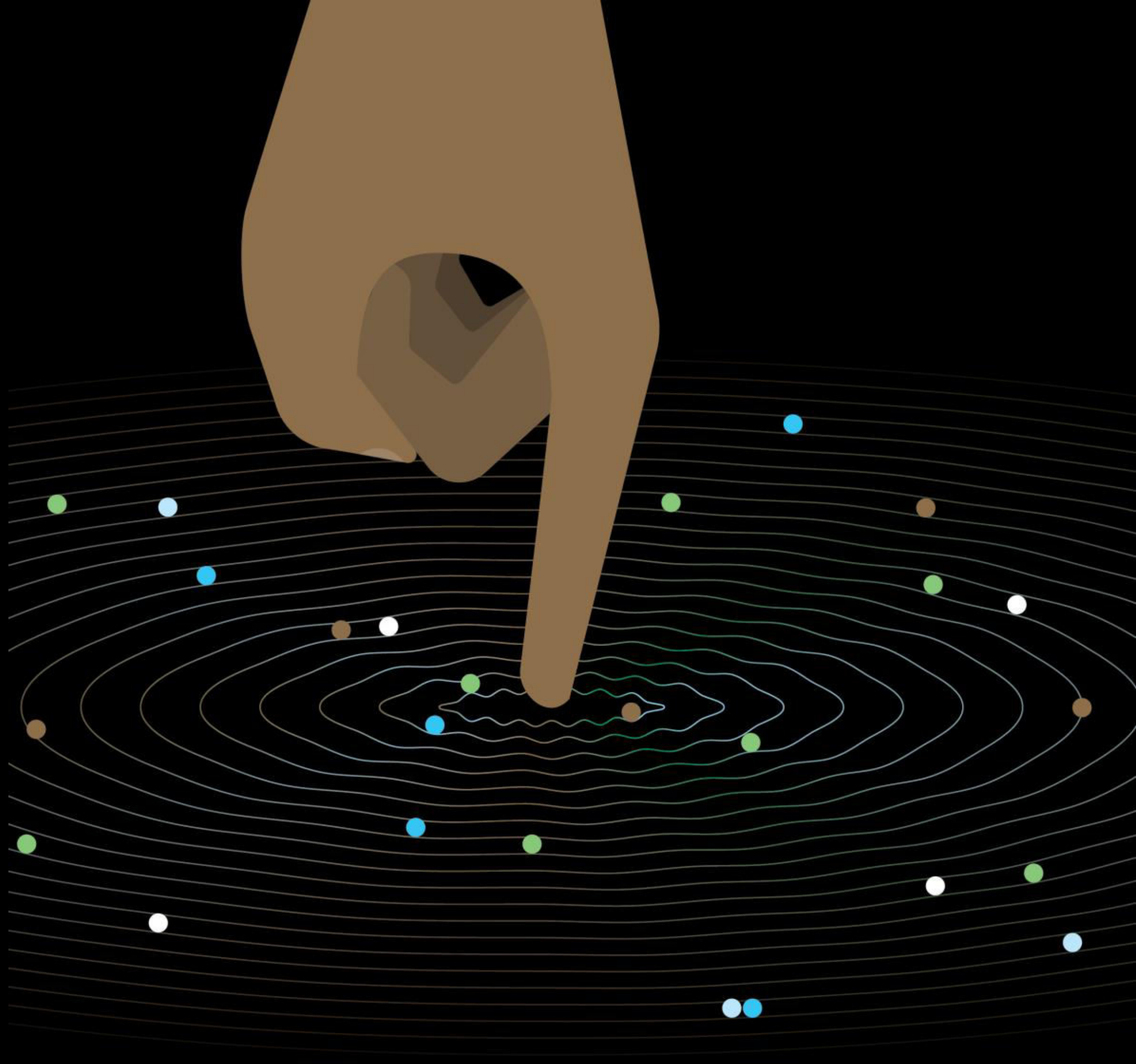


Photo: Bomazi


Bits
1
0
Qubits
‘1’
‘0’ + ‘1’
‘0’

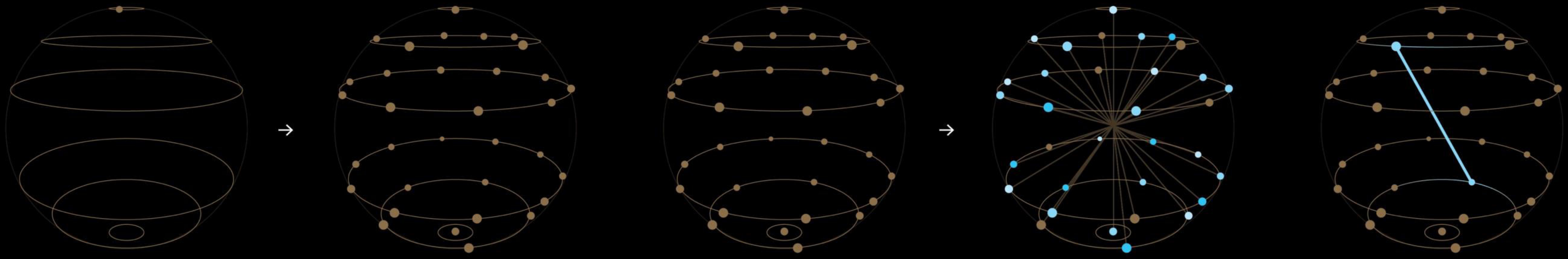
Entanglement

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



Using a Quantum Algorithm to Tackle Big Problems

A step-by-step
guide for how qubits
harness nature
to find solutions



The Spread

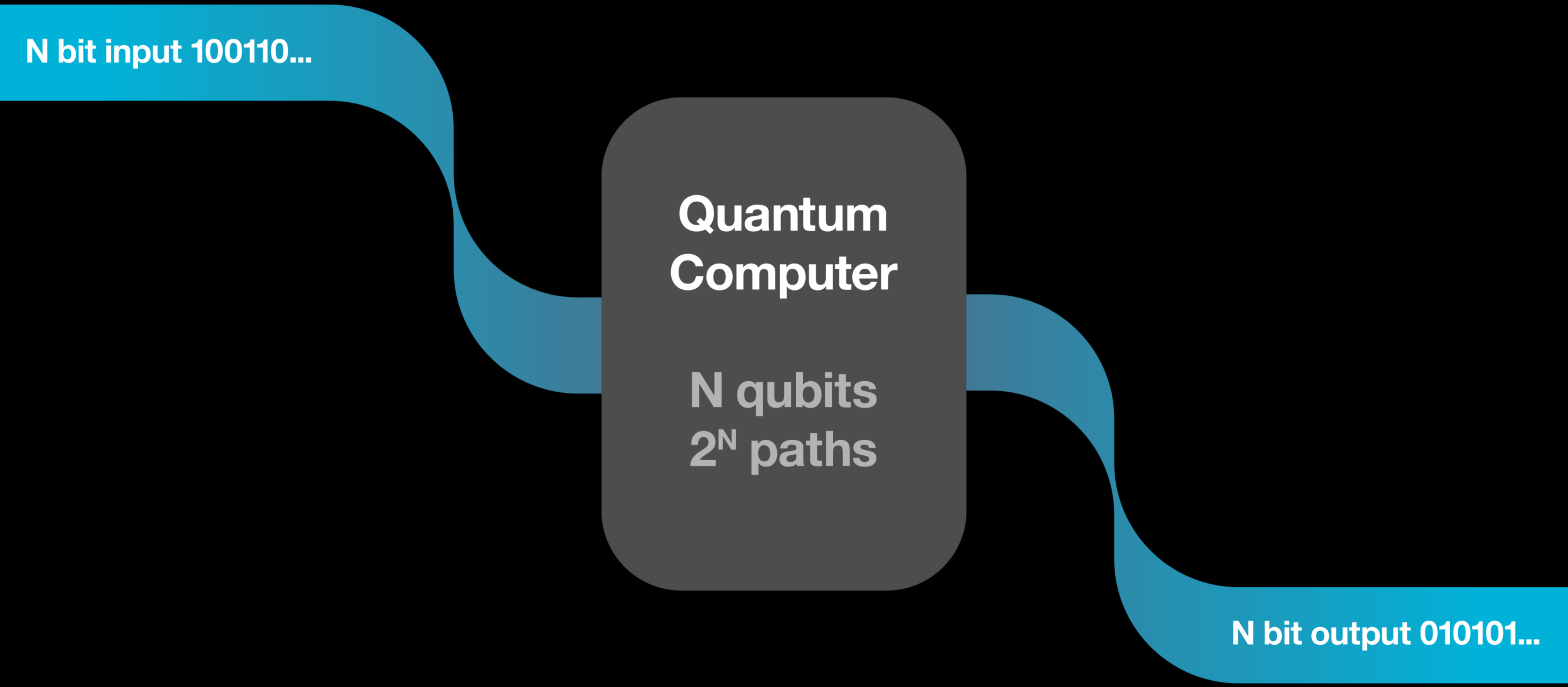
Create an equal superposition of all 2^n states

The Problem

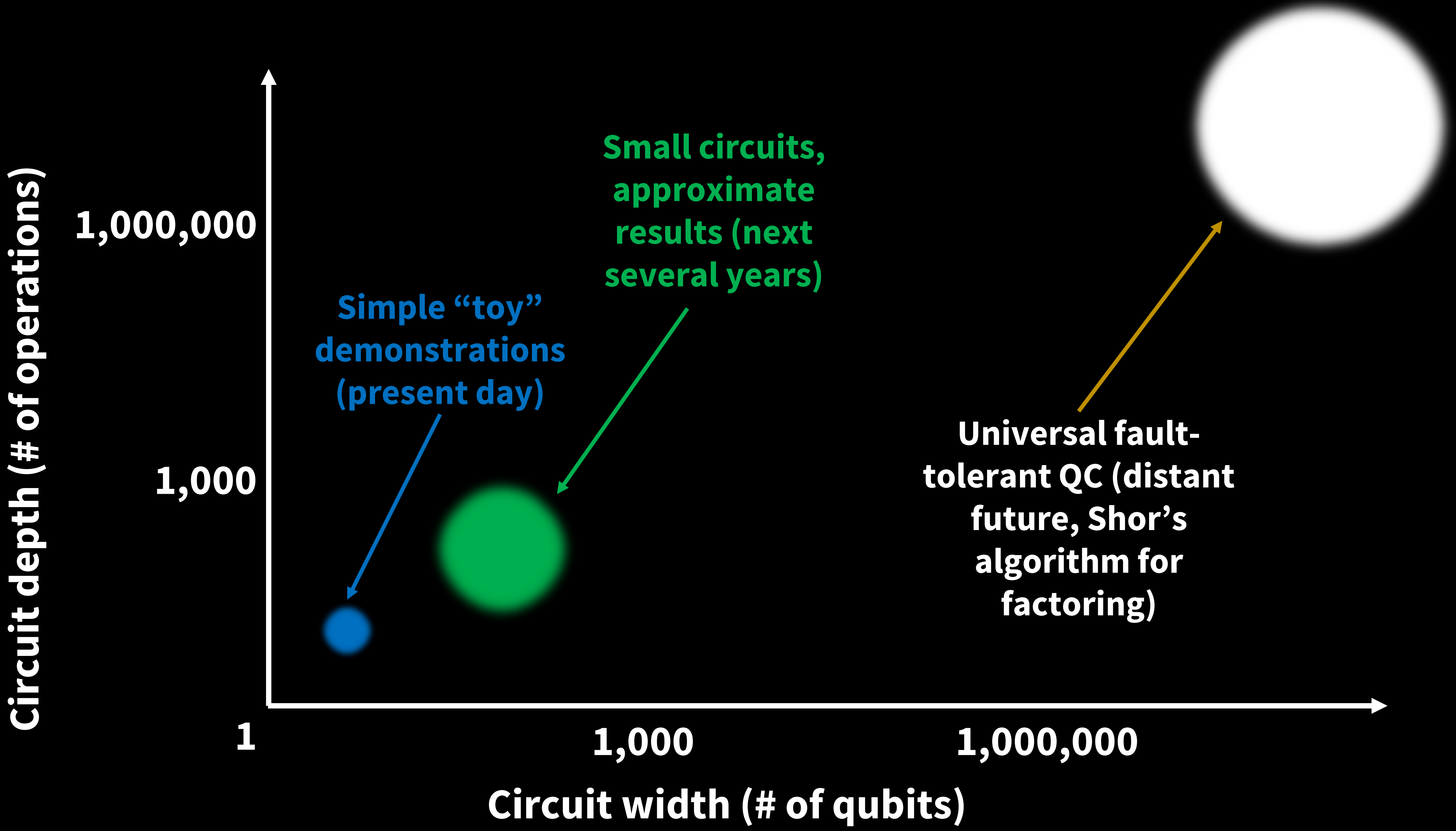
Encode the problem onto the system by applying a phase on all 2^n of the states

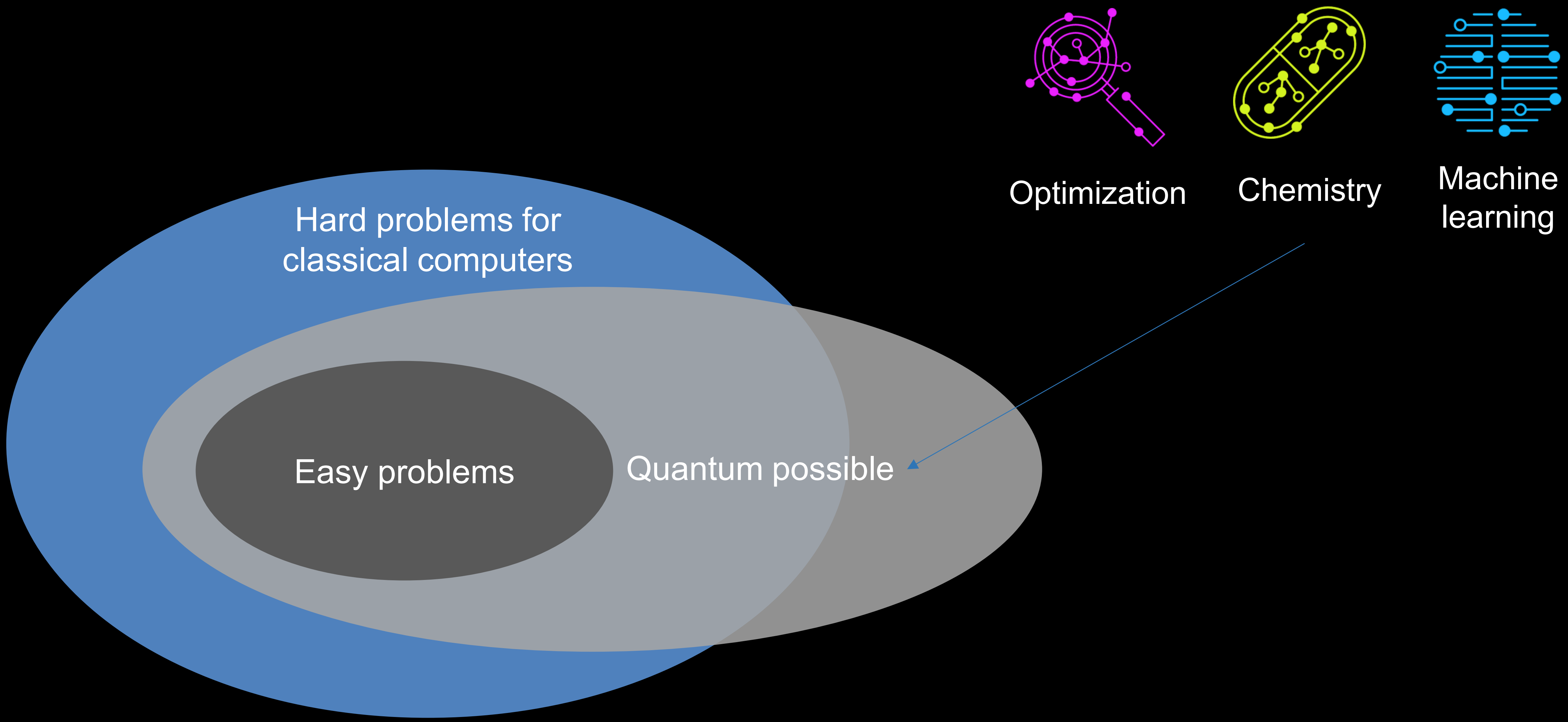
The Magic

Interfere all of these states back to a few outcomes containing the solution


N bit input 100110...
Quantum Computer
N qubits
2^N paths
N bit output 010101...

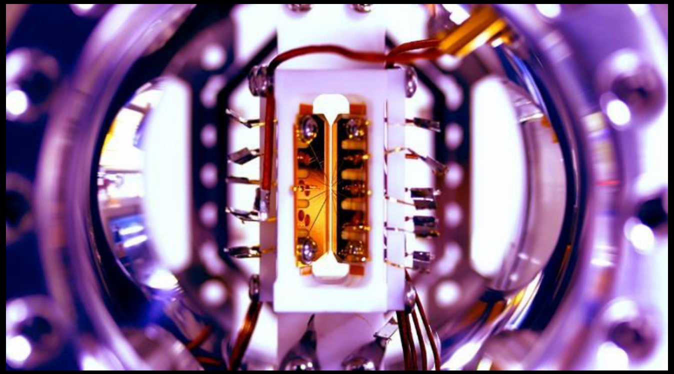
Towards a quantum advantage




Optimization
Chemistry
Machine learning
Hard problems for classical computers
Easy problems
Quantum possible

Quantum Computing Technologies

Ions



Credit: S. Debnath and E. Edwards/JQI
Monroe Group, University of Maryland/JQI

Photons

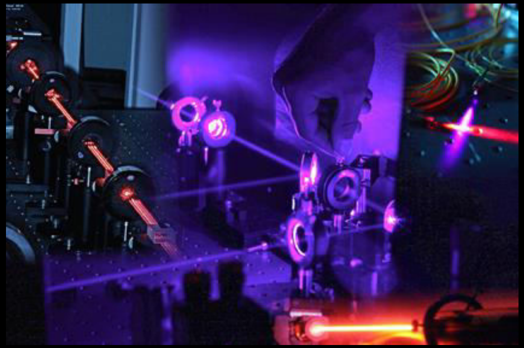


Image from the Centre for Quantum Computation & Communication Technology, credit Matthew Broome

Nanowires

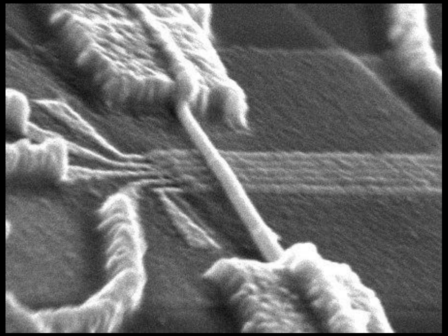


Image from Kouwenhoven Group, Delft

Neutral Atoms

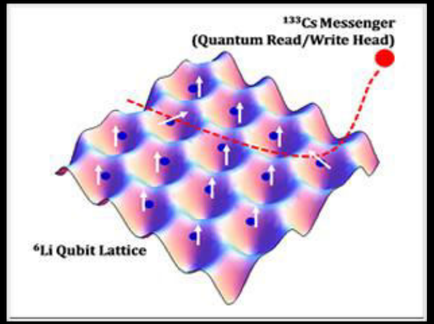
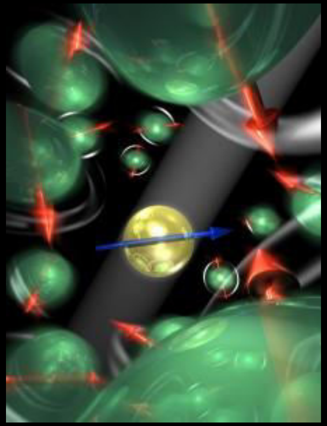


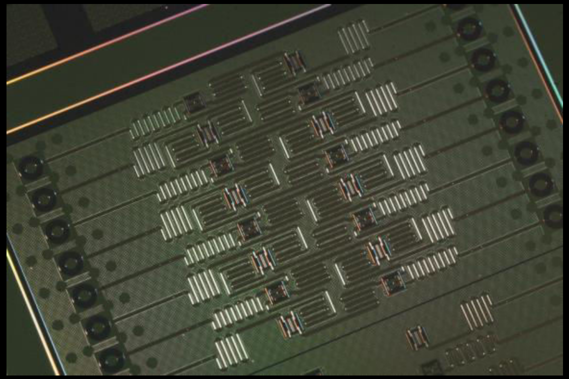
Image from Cheng Group, University of Chicago

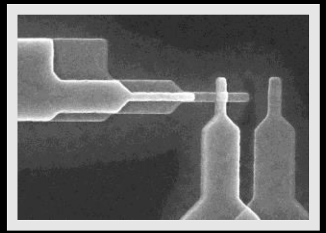
Solid-state defects

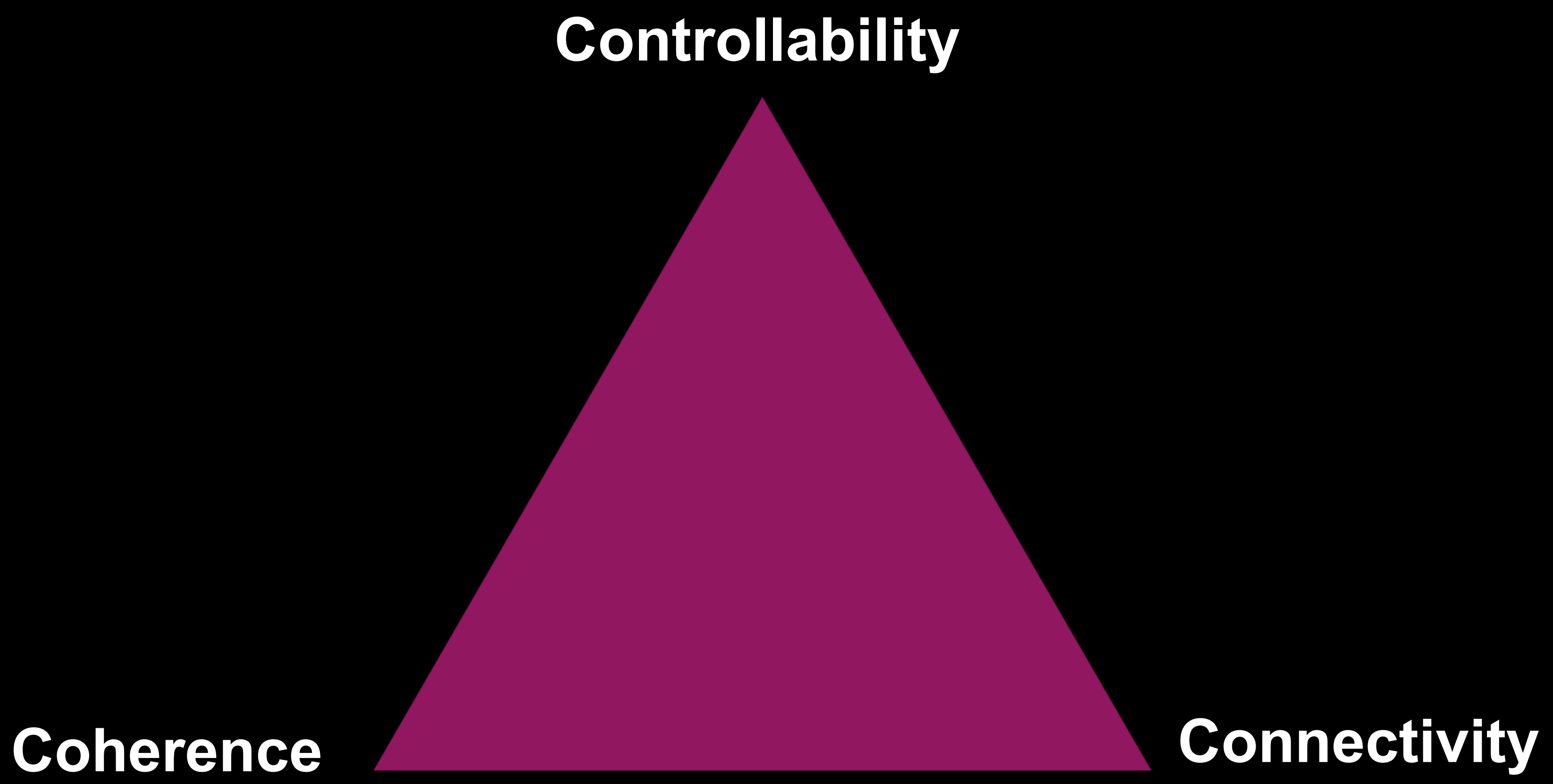
NV Centers, Phosphorous in Si, SiC defects, etc.

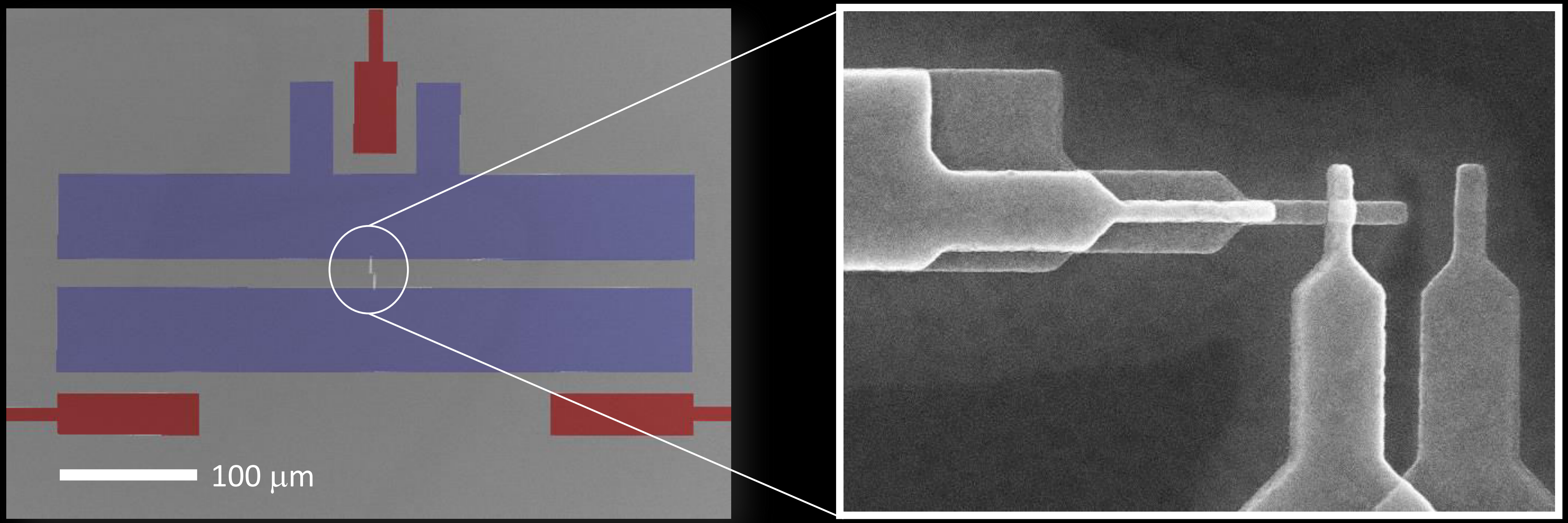


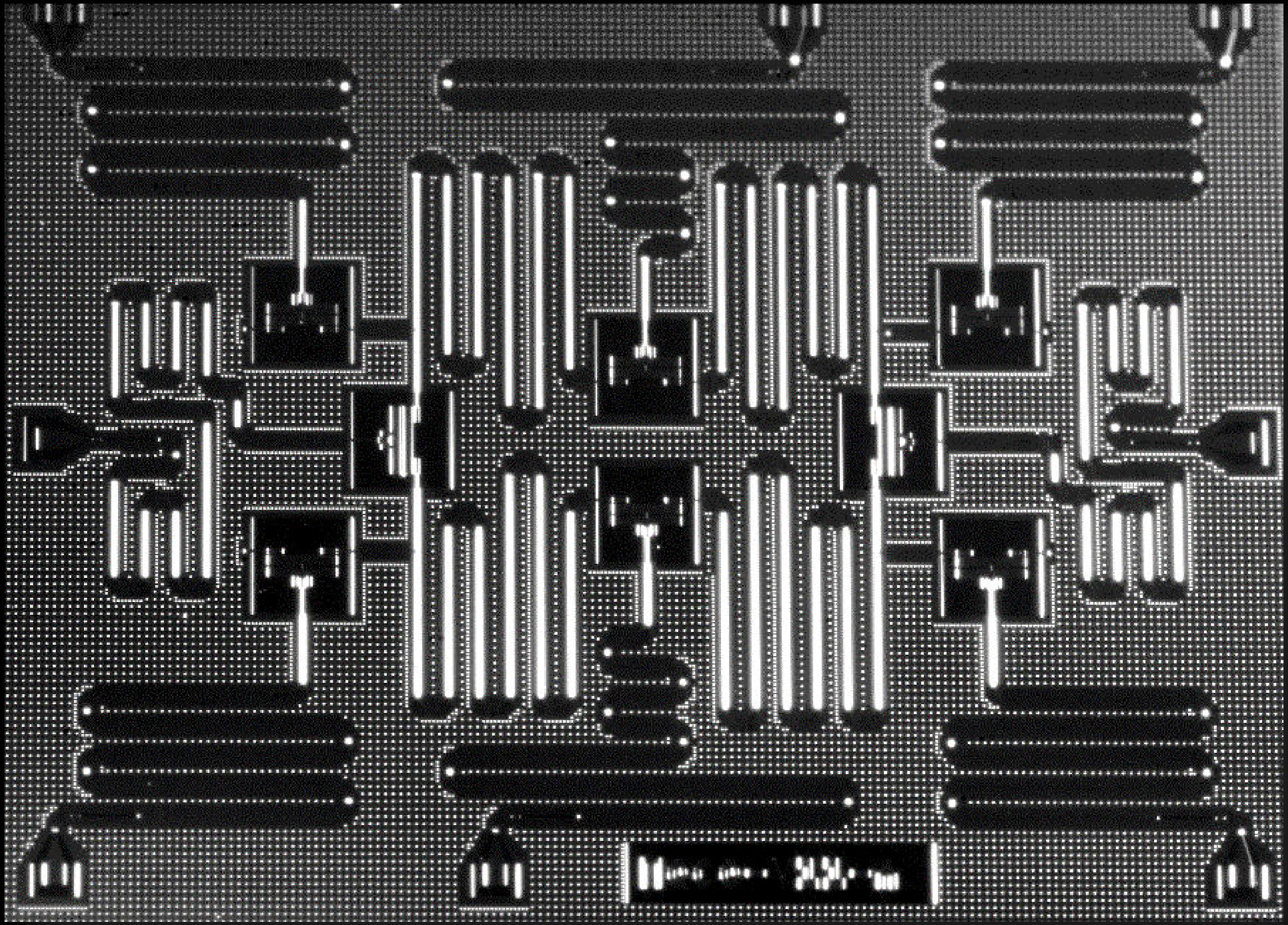
Superconducting Circuits



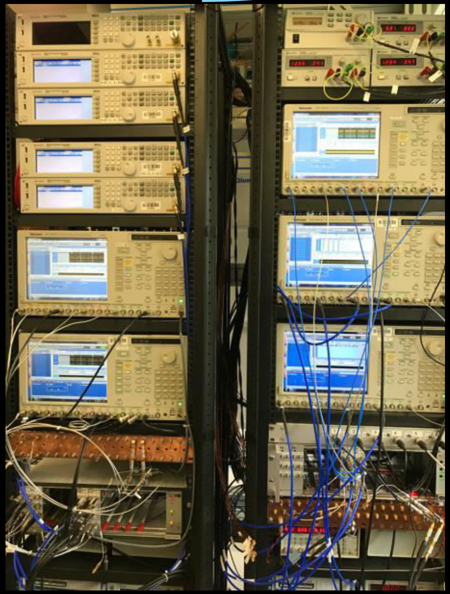



Controllability
Coherence
Connectivity


100 μm



Room Temperature



Microwave electronics

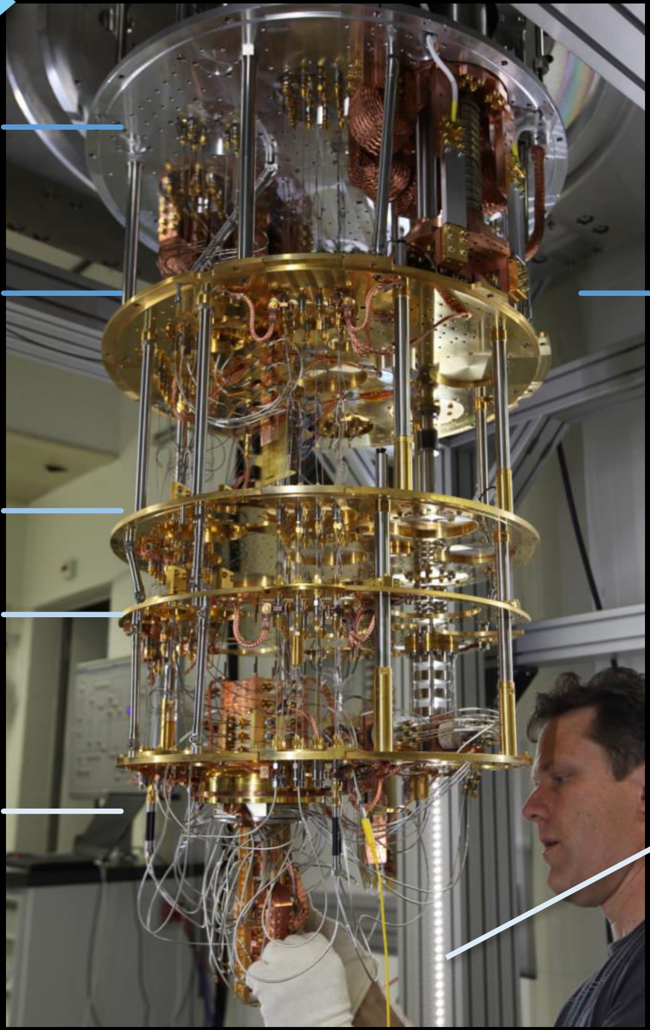
40K

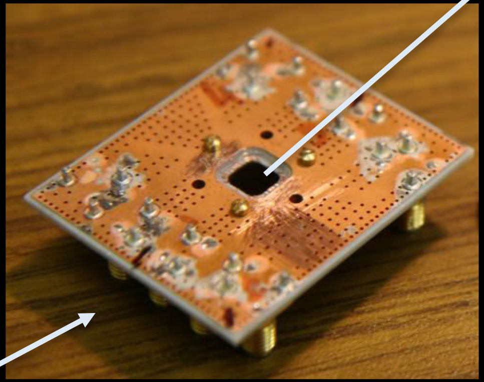
3K

0.9K

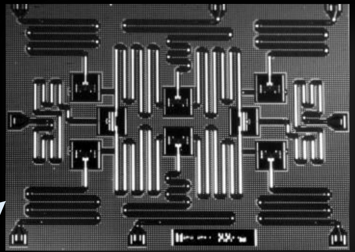
0.1K

0.015K

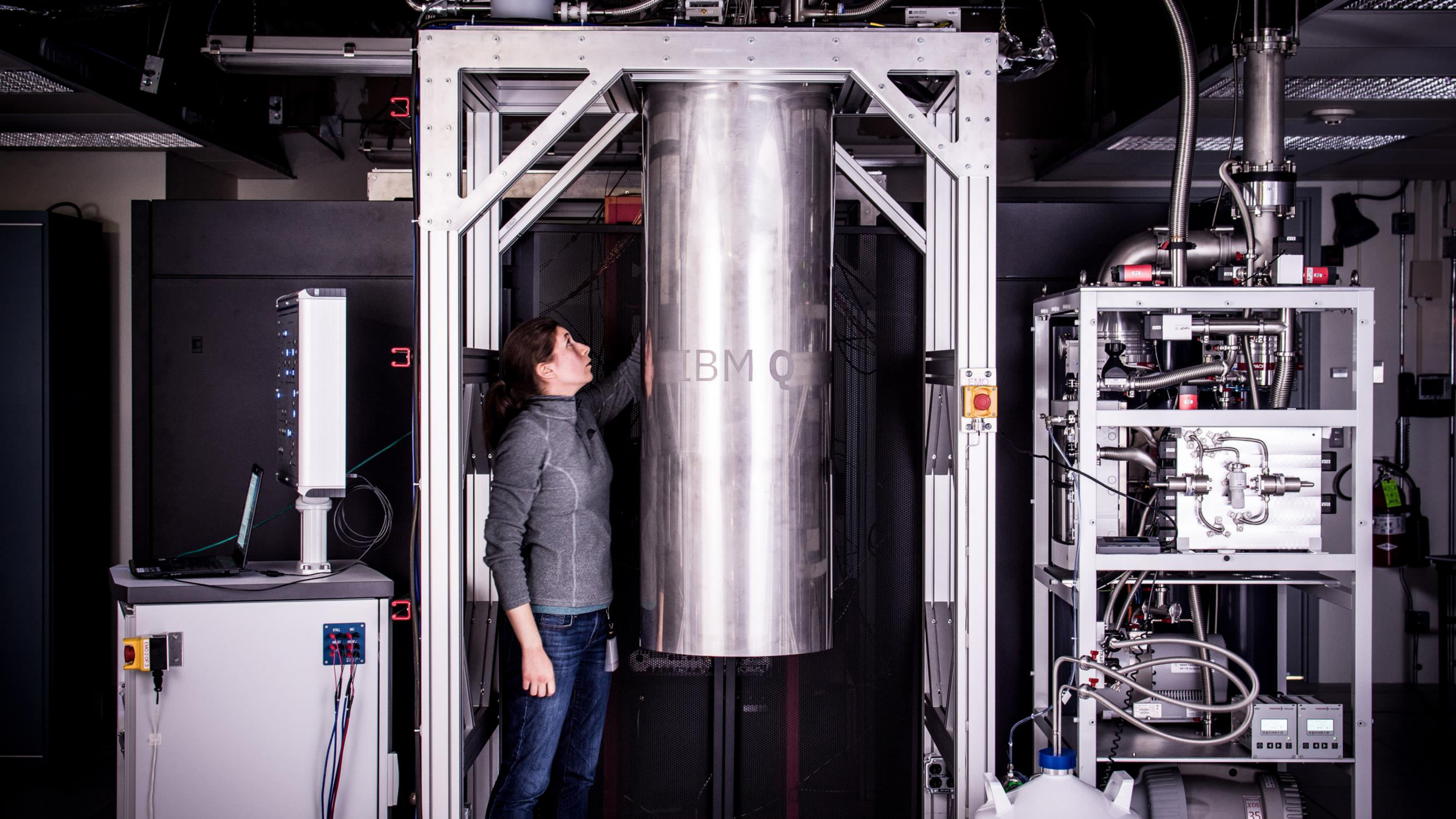


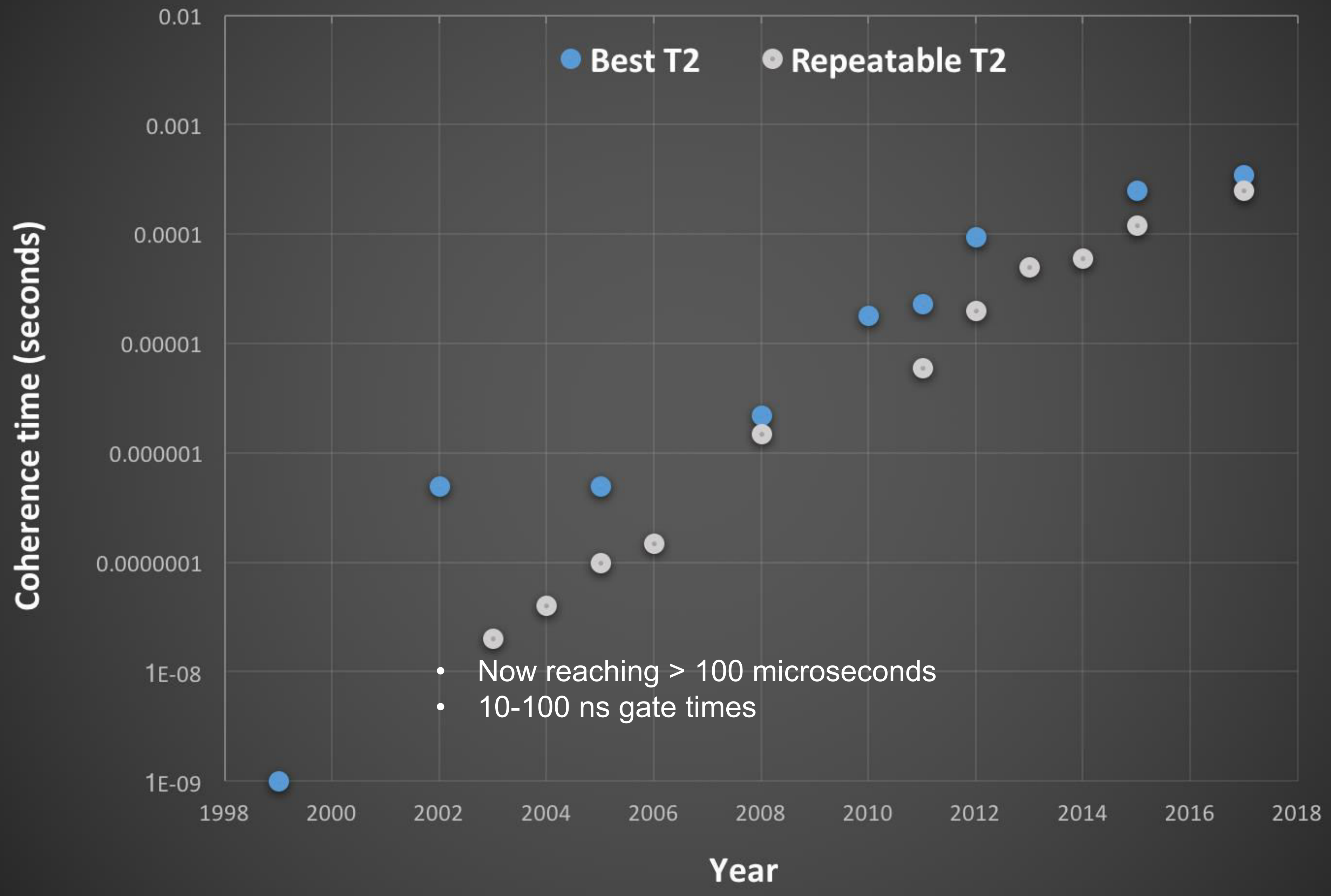


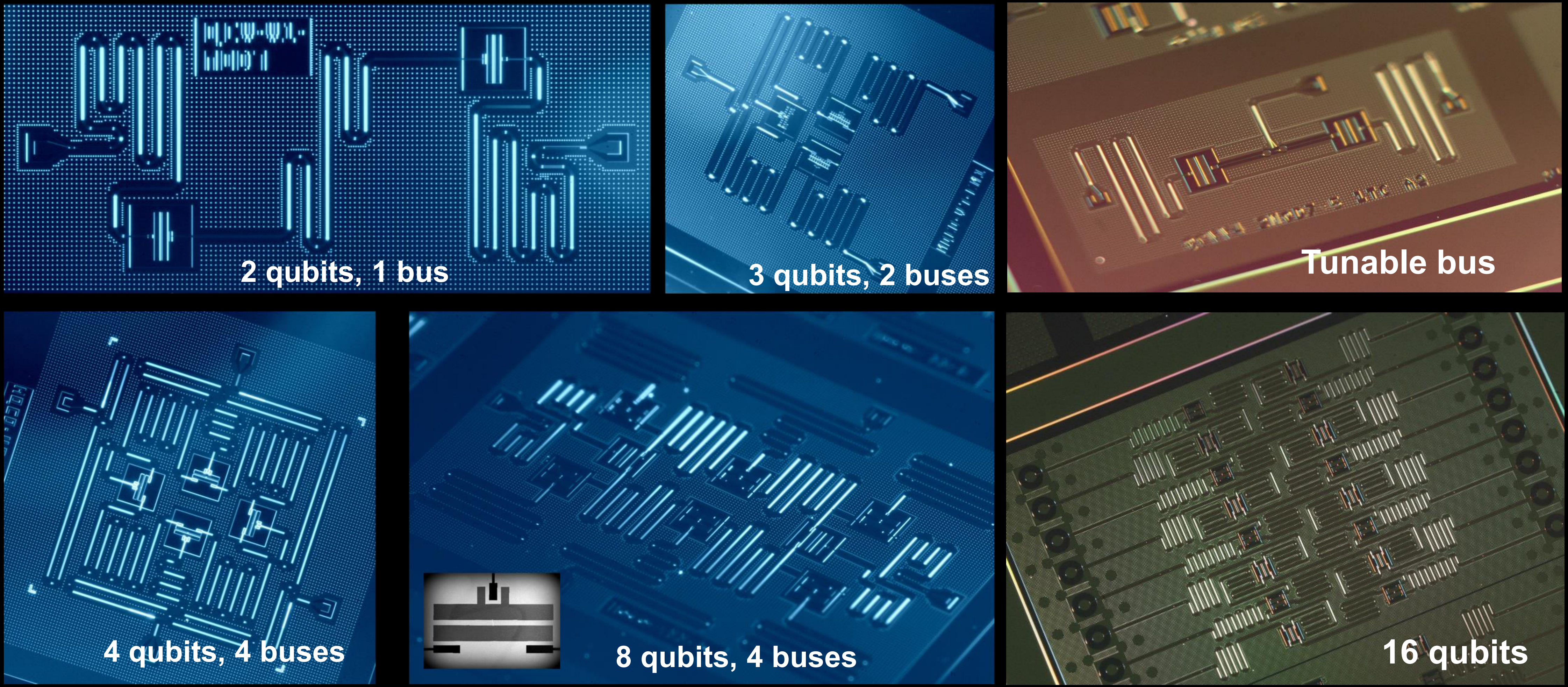
Circuit board

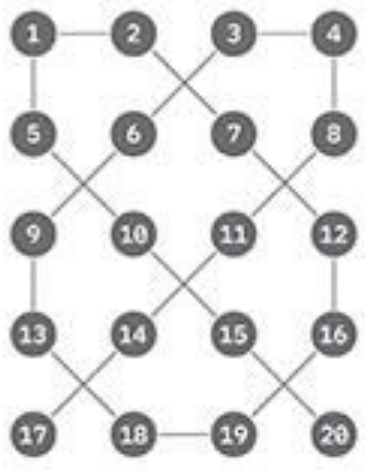


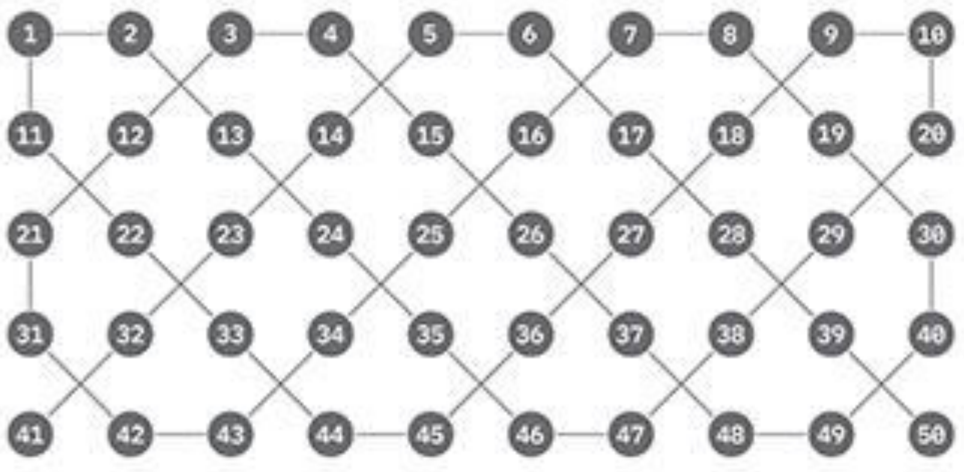
Qubit Processor

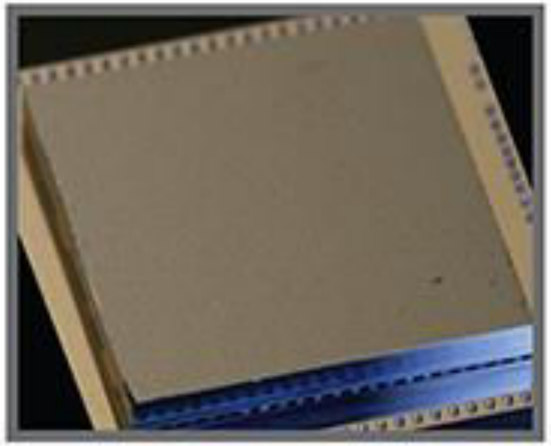

IBM Q


Best T2
Repeatable T2
Coherence time (seconds)
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
1E-08
1E-09
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
Year
• Now reaching > 100 microseconds
• 10-100 ns gate times


2 qubits, 1 bus
3 qubits, 2 buses
Tunable bus
4 qubits, 4 buses
8 qubits, 4 buses
16 qubits


1 2 3 4
5 6 7 8
9 10 11 12
13 14 15 16
17 18 19 20


1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50



IBM Q Experience (IBM QX)

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Open to public for research and education

Access via online with the web interface

MORE THAN 70,000 IBM QX USERS WORLDWIDE

>1500 colleges/universities,

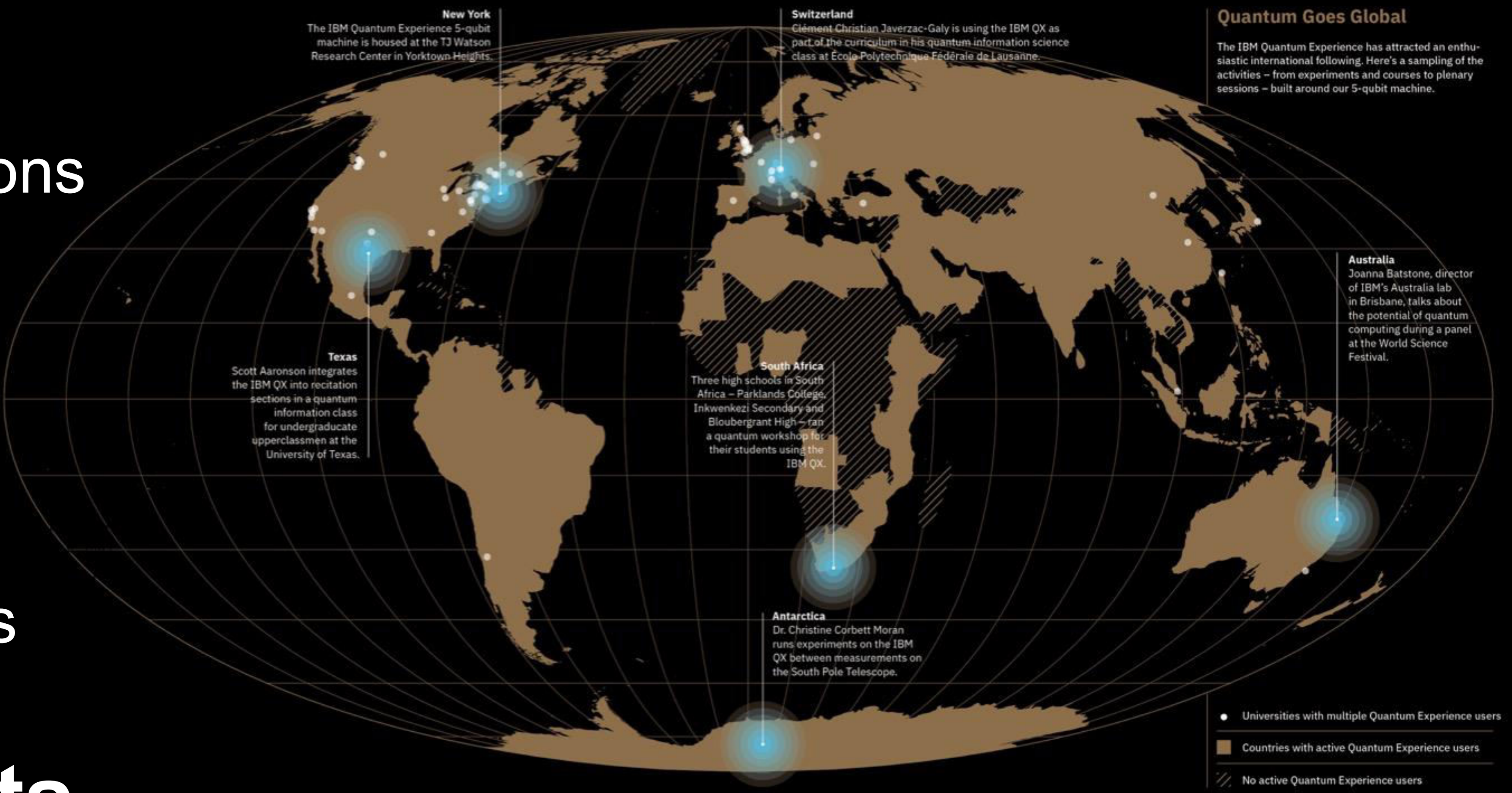
300 high schools

300 private institutions

> 2.0 million
experiments

60+ external papers

All 7 continents



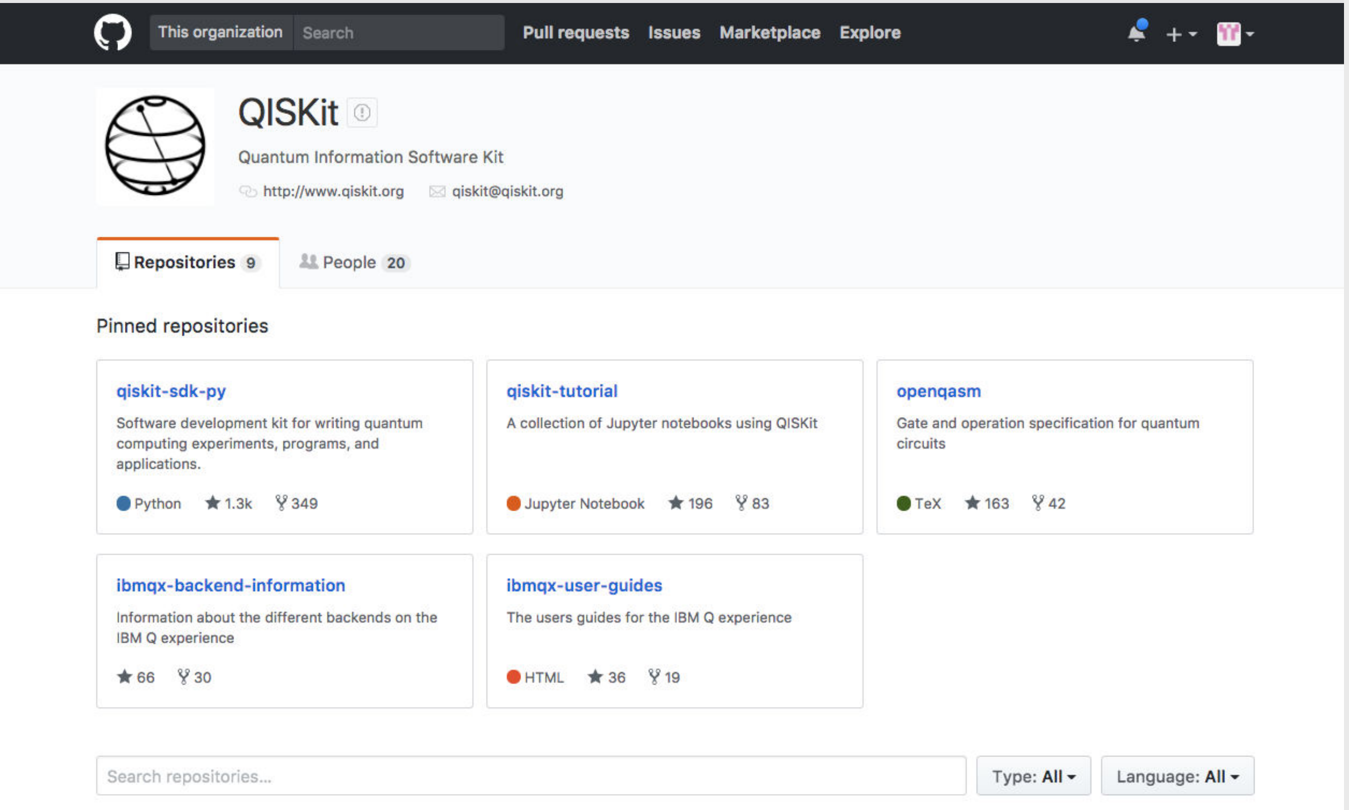
FOSTERING A QUANTUM COMMUNITY

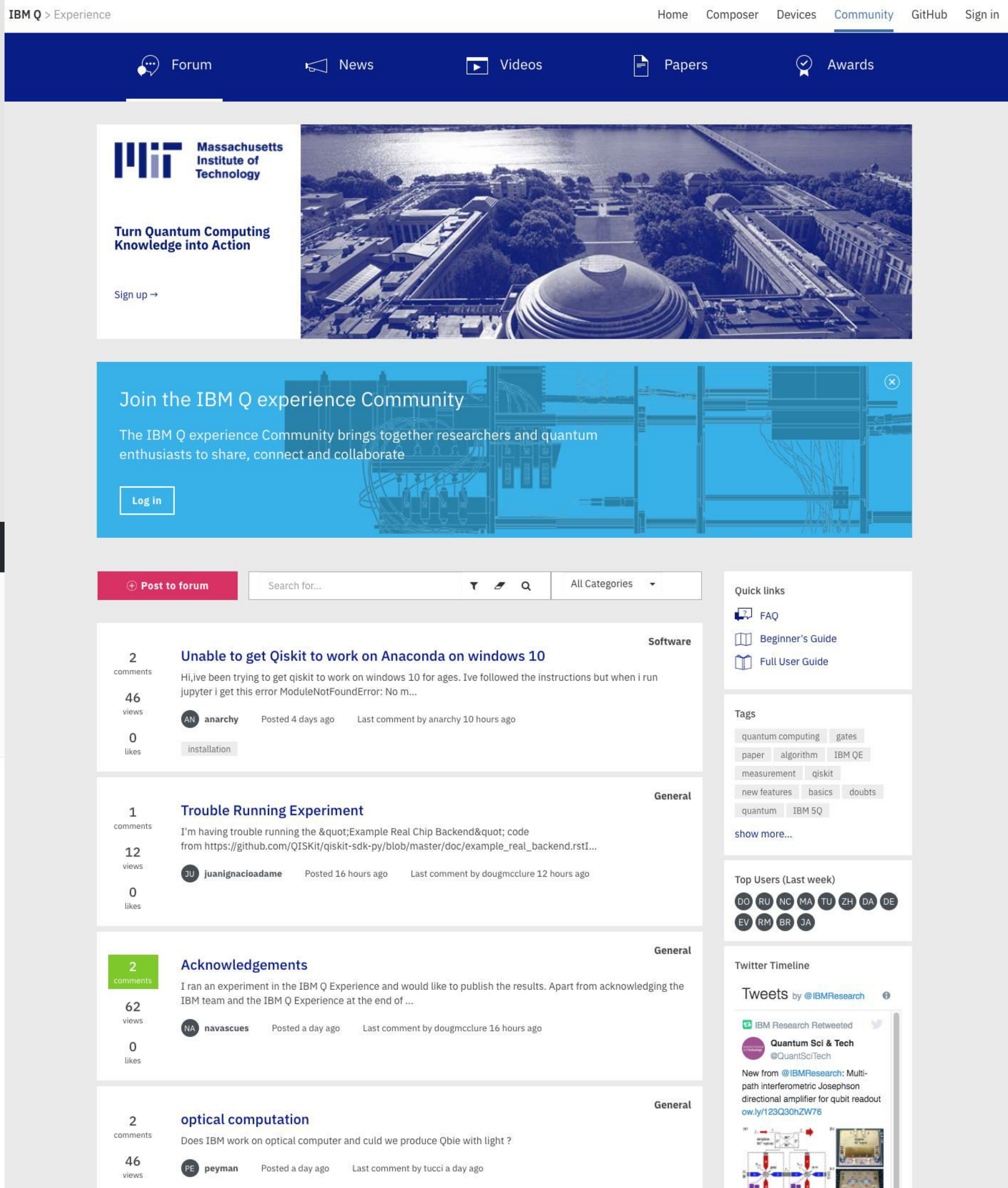
QISKit Open Source Quantum Software Development Kit

Fostering developer community.

QX User Forums

Exchange information and research results among QX users worldwide and IBM Q team members.





FOSTERING A QUANTUM COMMUNITY

Quantum Computing Outreach

IBM Q team members giving quantum tutorials and talks at colleges and universities.

QX for Education

MIT Quantum Information Science course material by Prof. Ike Chuang

IQC @QuantumIQC — Following

#USEQIP students testing algorithms with the #IBM #QuantumExperience. Thank you Chris Wood and @IBMResearch! #dayinthelifeofuseqip

IBM NA Careers @IBMNAjobs — Follow

#MITatIBM tech demo: MIT students are learning about #IBMQ and quantum computing! ibm.biz/Bdjaxb #MITatIBM

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Quantum Information Science I, Part 1

Want to learn about quantum bits, quantum logic gates, quantum algorithms, and quantum communications, and know some linear algebra but haven't yet learned much about quantum mechanics? This is the course for you!

MIT Massachusetts Institute of Technology

In Session
Started on January 15, 2018

Enroll Now

I would like to receive email from Massachusetts Institute of Technology and learn about other offerings related to Quantum Information Science I, Part 1.

About this course

This course is part of a three-course series that provides an introduction to the theory and practice of quantum computation. We cover:

- the physics of information processing
- quantum logic
- quantum algorithms including Shor's factoring algorithm and Grover's search algorithm
- quantum error correction
- quantum communication and key distribution

This course will help you establish a foundation of knowledge for understanding what quantum computers can do, how they work, and how you can contribute to discovering new things and solving problems in quantum information science and engineering.

The three-course series comprises:

- 8.370.1x: Foundations of quantum and classical computing – quantum mechanics, reversible computation, and quantum measurement
- 8.370.2x: Simple quantum protocols and algorithms – teleportation and superdense coding, the Deutsch-Jozsa and Simon's algorithm, Grover's quantum search algorithm, and Shor's quantum factoring algorithm
- 8.370.3x: Foundations of quantum communication – noise and quantum channels, and quantum key distribution

Prior knowledge of quantum mechanics is helpful but not required. It is best if you know some linear algebra.

This course has been authored by one or more members of the Faculty of the Massachusetts Institute of Technology. Its educational objectives, methods, assessments, and the selection and presentation of its content are solely the responsibility of MIT. MIT gratefully acknowledges major support for this course, provided by IBM Research. This course on quantum information science is a collective effort to further advance knowledge and understanding in quantum information and quantum computing.

IBM Q

For more information about MIT's Quantum Curriculum, visit quantumcurriculum.mit.edu.

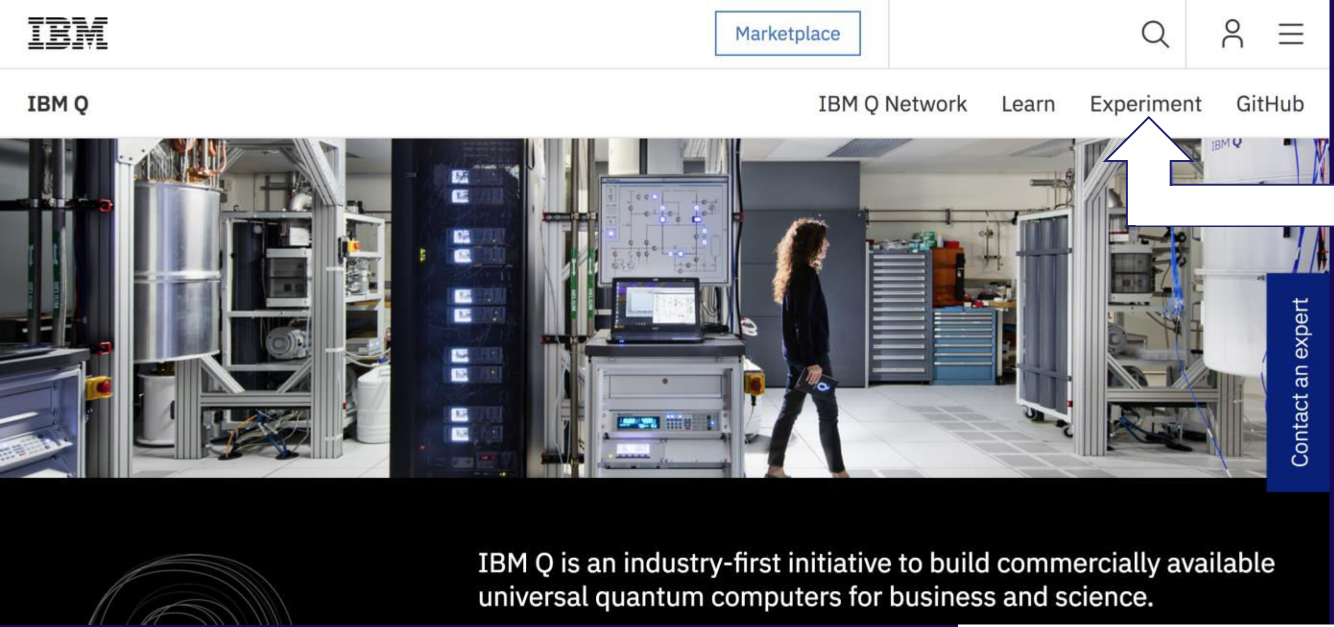
What you'll learn

- quantum mechanics

Length:	5 weeks
Effort:	11 to 13 hours per week
Price:	FREE Add a Verified Certificate for $49 USD
Institution:	MITx
Subject:	Computer Science
Level:	Intermediate
Language:	English
Video Transcripts:	English

Share this course with a friend

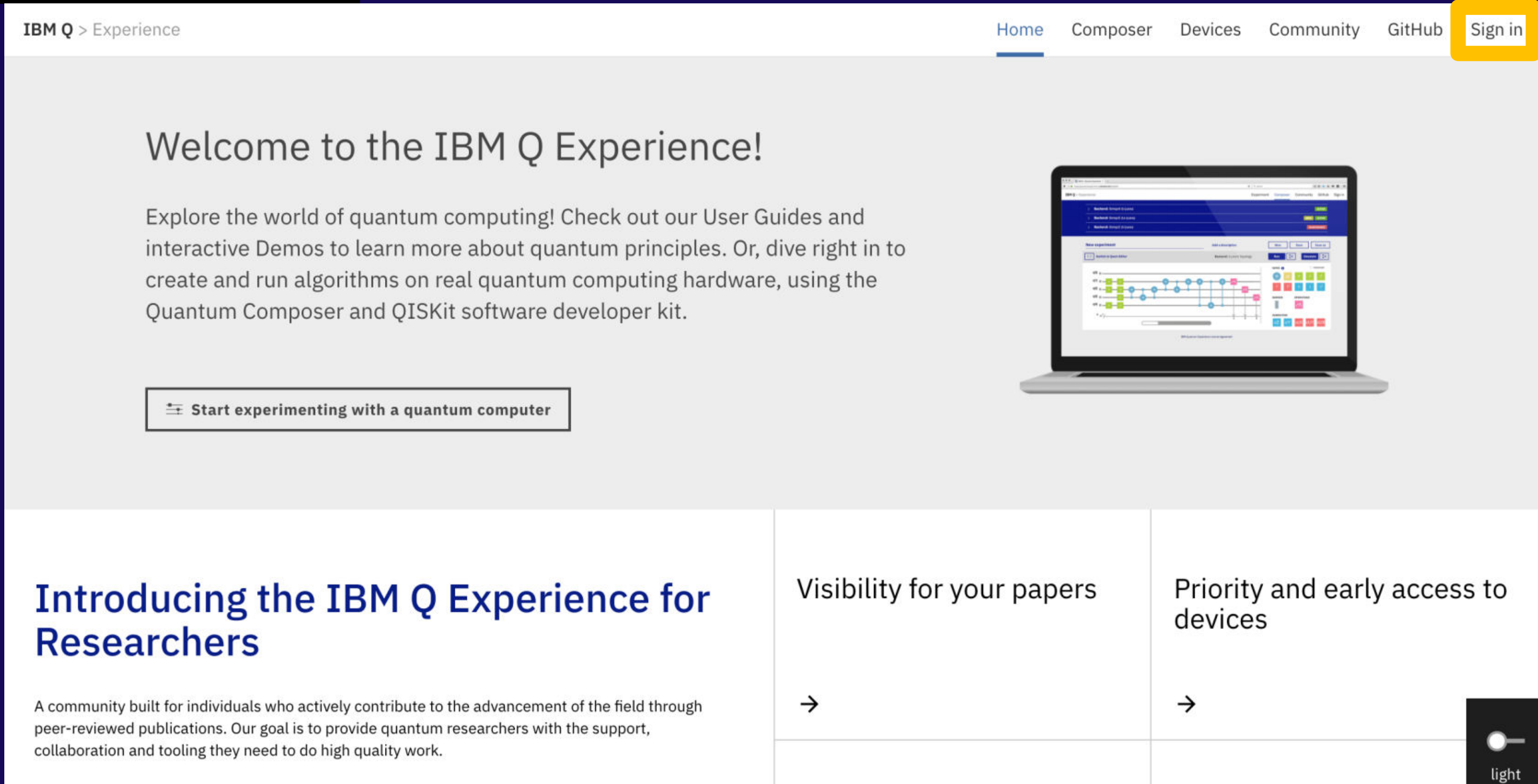
Prerequisites
Calculus and linear algebra



ibm.com/ibmq

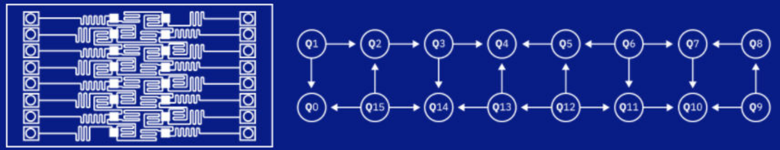
Go to Experiment

Sign in to access
IBM Q Experience



5-Qubit 16-Qubit and 20-qubit simulator are Available for public

Backend: ibmqx5 (16 Qubits) — ACTIVE — AVAILABLE ON QISKIT

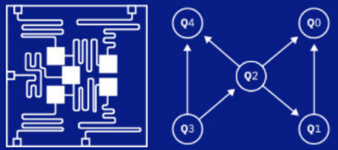


Date Calibration: 2018-01-31 06:25:30
Fridge Temperature: 0.0135672 K

More details

	Q0	Q1	Q2	Q3	Q4	Q5	Q6
Frequency (GHz)	5.26	5.40	5.28	5.08	4.98	5.15	5.31
T1 (µs)	35.10	37.20	42.50	39.50	52.20	33.00	47.50
T2 (µs)	29.30	50.30	65.60	67.10	86.40	52.50	85.40
Gate error (10^{-3})	2.41	4.26	4.83	2.11	1.13	2.61	1.37
Readout error (10^{-2})	7.13	6.93	4.29	10.50	8.70	5.71	4.03
MultiQubit gate error (10^{-2})		**CX1_0** 6.39	**CX2_3** 4.99	**CX3_4** 3.55		**CX5_4** 4.88	**CX6_5** 3.62
		CX1_2 8.56		**CX3_14** 3.92			**CX6_7** 4.79
							CX6_11 3.94

Backend: ibmqx4 (5 Qubits) — ACTIVE — AVAILABLE ON QISKIT



Date Calibration: 2018-01-31 08:18:35
Fridge Temperature: 0.021 K

More details

	Q0	Q1	Q2	Q3	Q4
Frequency (GHz)	5.24	5.30	5.35	5.43	5.18
T1 (µs)	40.60	49.60	42.50	43.20	52.60
T2 (µs)	22.90	45.20	40.10	12.10	29.00
Gate error (10^{-3})	7.13	0.94	1.55	1.55	1.80
Readout error (10^{-2})	6.20	4.70	10.10	8.80	6.20
MultiQubit gate error (10^{-2})		**CX1_0** 16.13	**CX2_0** 9.94	**CX3_2** 2.36	
			CX2_1 5.13	**CX3_4** 2.70	
			CX2_4 4.96		

Backend: ibmqx_qasm_simulator — ACTIVE — SIMULATOR — AVAILABLE ON QISKIT

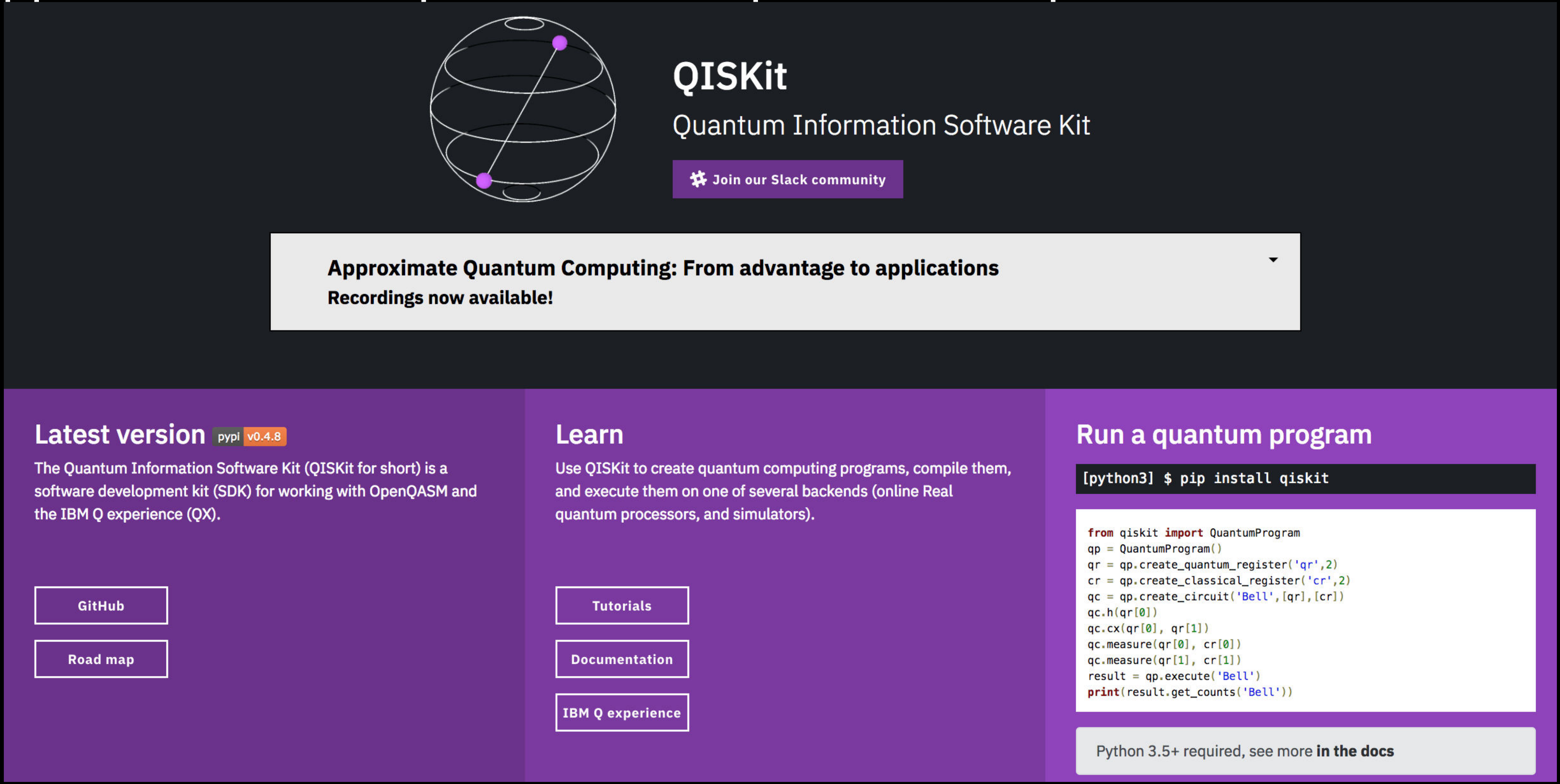
Number of qubits	20
Conditionals (if)	Yes

Backend: ibmqx_hpc_qasm_simulator — ACTIVE — SIMULATOR — AVAILABLE ON QISKIT

Number of qubits	32
Conditionals (if)	No

www.qiskit.org, twitter: @qiskit

Software kit for short depth quantum circuits and building near term applications and experiments on quantum computers.



Quantum Information Software Kit

QISKit Documentation

Quantum Information Software Kit (QISKit), SDK Python version for working with OpenQASM and the IBM Q experience (QX).

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Installation and setup

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Documentation from getting started to developing

QISKit / qiskit-sdk-py

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Python software development kit for writing quantum computing experiments, programs, and applications.

http://www.qiskit.org

quantum-computing | qiskit | sdk | python | quantum-programming-language

Open development process with lots of example code

1,080 commits | 5 branches | 10 releases | 35 contributors | Apache-2.0

Branch: master | New pull request | Find file | Clone or download

westurner committed with **diego-plan9** Update README.md Jupyter Notebook(s) (#176) ... Latest commit d2e9c2d 3 hours ago

.github | Add templates for issues and pull requests | 5 months ago

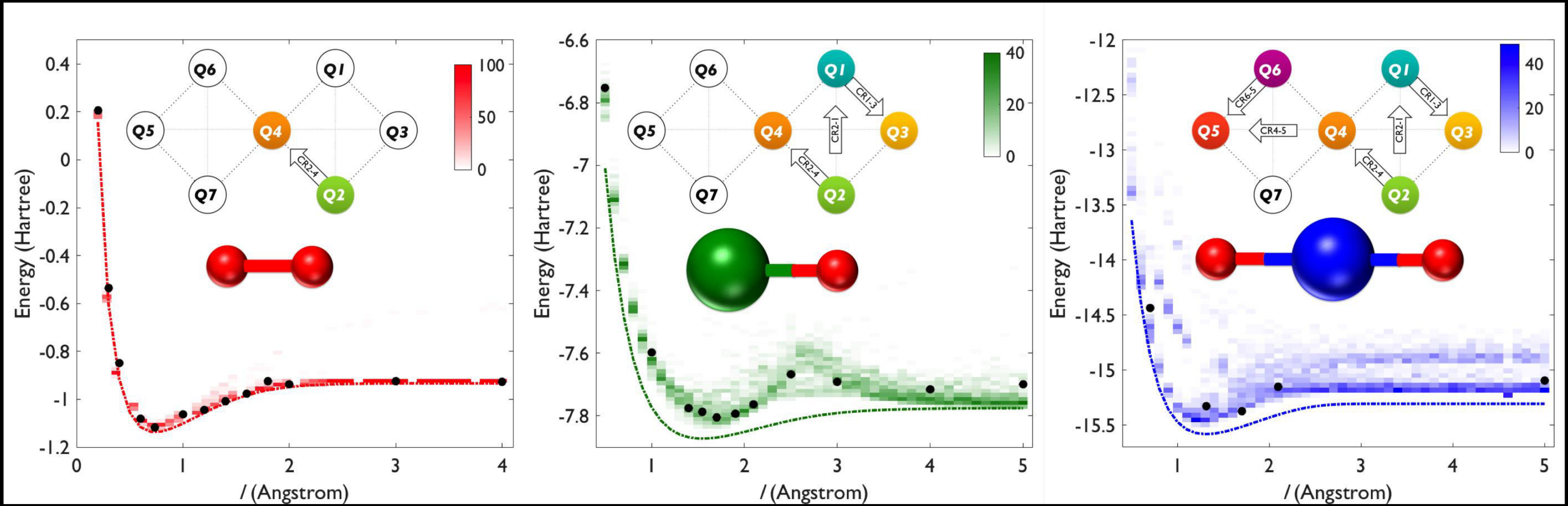
Construct a quantum program in QISKit

In QISKit, a quantum program is a collection of quantum circuits, together with methods to execute them on different backends (simulators, devices)

```
from qiskit import QuantumProgram
import Qconfig

qp = QuantumProgram()
q = qp.create_quantum_registers("q", 5)
c = qp.create_classical_registers("c", 5)
qc = qp.create_circuit("ghz", [q], [c])
```

```
# Create a GHZ state
qc.h(q[0])
for i in range(4):
    qc.cx(q[i], q[i+1])

# Insert a barrier before measurement
qc.barrier()

# Measure all of the qubits in the standard basis
for i in range(5):
    qc.measure(q[i], c[i])
```

Chemistry with a quantum computer!



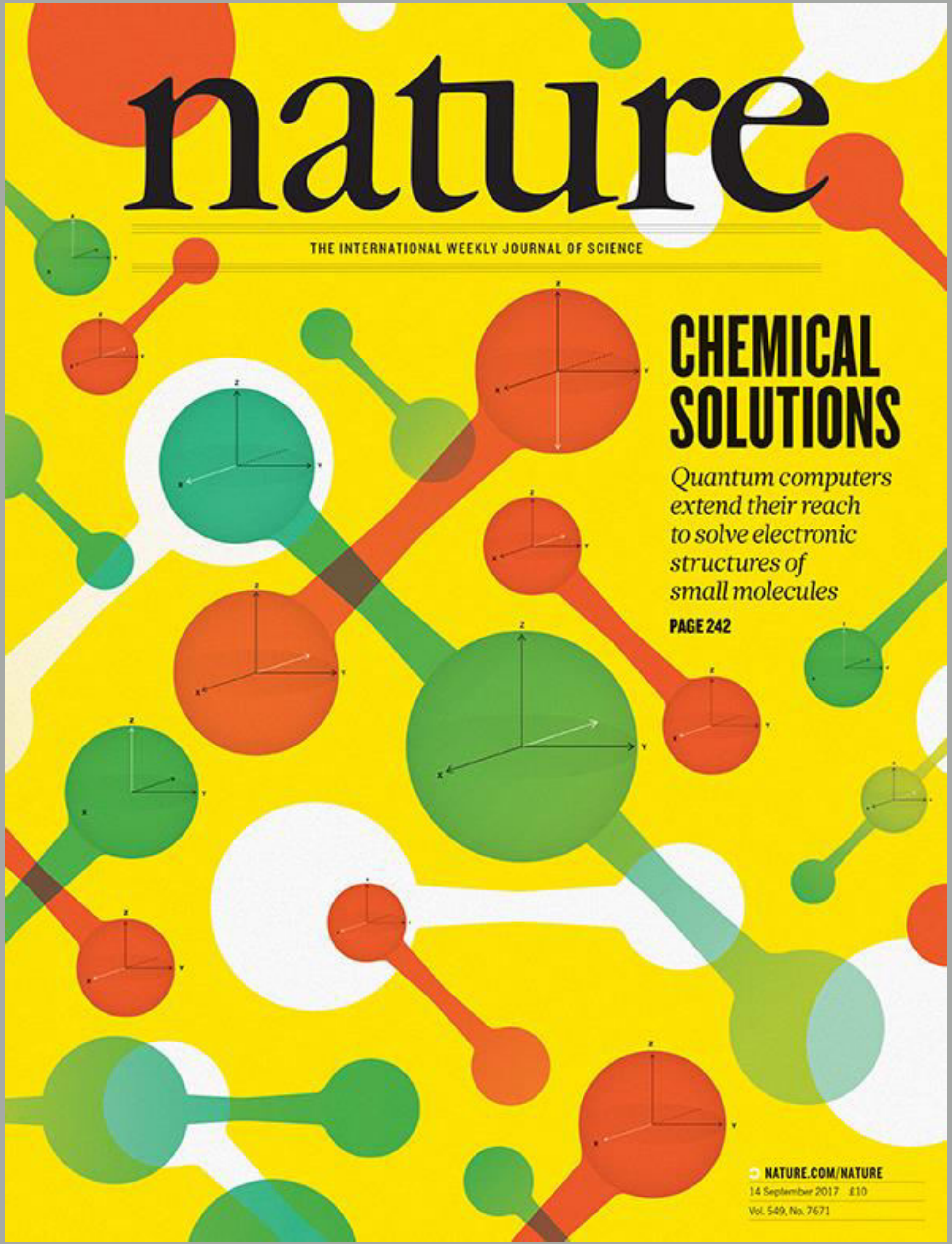
H_2: 2 qubits

LiH: 4 qubits

BeH_2: 6 qubits

Provided as a QISKit notebook using IBM Q Experience devices

Hardware-efficient variational quantum eigensolver for small molecules and quantum magnets
Abhinav Kandala, Antonio Mezzacapo, Kristan Temme, Maika Takita, Markus Brink, Jerry M. Chow & Jay M. Gambetta, doi:10.1038/nature23879



LETTER

doi:10.1038/nature23879

Hardware-efficient variational quantum eigensolver for small molecules and quantum magnets

Abhinav Kandala[1*], Antonio Mezzacapo[1*], Kristan Temme[1], Maika Takita[1], Markus Brink[1], Jerry M. Chow[1] & Jay M. Gambetta[1]

Quantum computers can be used to address electronic-structure problems and problems in materials science and condensed matter physics that can be formulated as interacting fermionic problems, problems which stretch the limits of existing high-performance computers[1]. Finding exact solutions to such problems numerically has a computational cost that scales exponentially with the size of the system, and Monte Carlo methods are unsuitable owing to the fermionic sign problem. These limitations of classical computational

problem using the quantum phase estimation algorithm[15]. Although this algorithm can produce extremely accurate energy estimates for quantum chemistry[2,3,5,8], it applies stringent requirements on the coherence of the quantum hardware.

An alternative approach is to use quantum optimizers, which have previously demonstrated utility, for example, for combinatorial optimization problems[16,17] and in quantum chemistry as variational quantum eigensolvers (VQEs) where they were introduced to reduce

Published in the journal **Nature** in September, 2017

Thank You!

1. Join our community to explore the world of quantum
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   - qiskit.org
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   - 1-on-1 meetings
   - Personalized solution demos