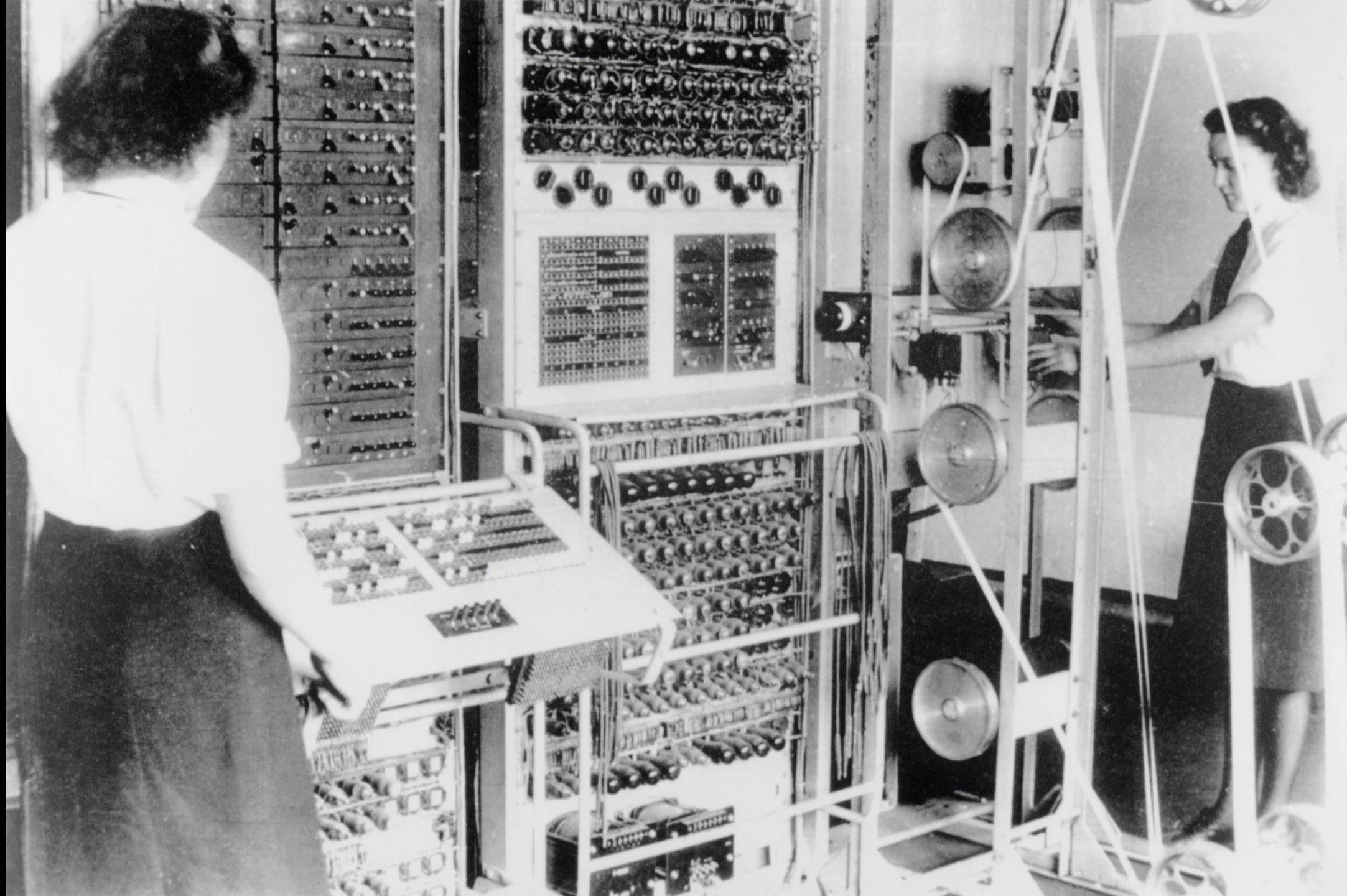
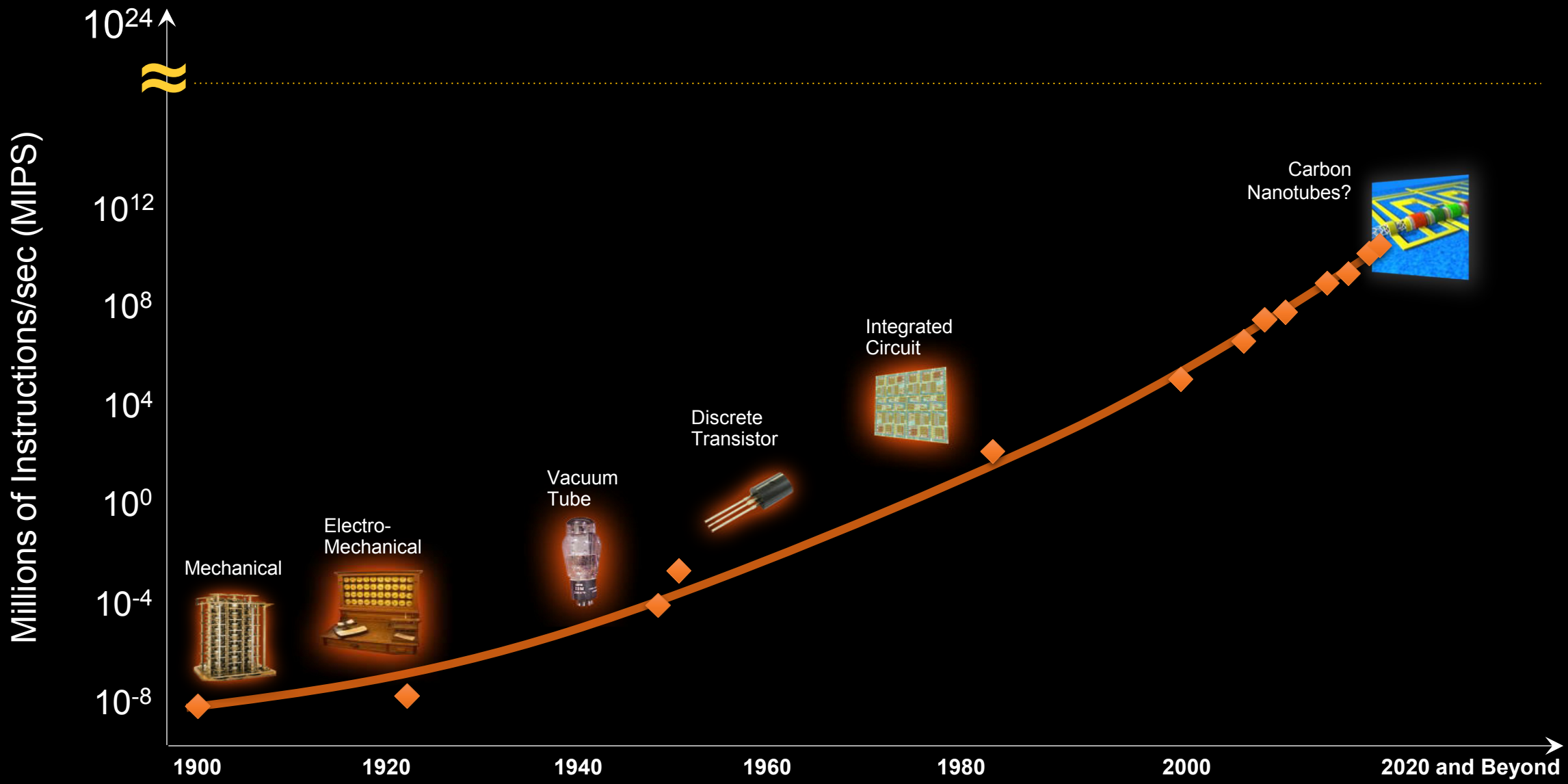


Enabling Quantum Computing over the Cloud

Dr. Jerry M. Chow

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





Have we reached the limit of **computation power**?

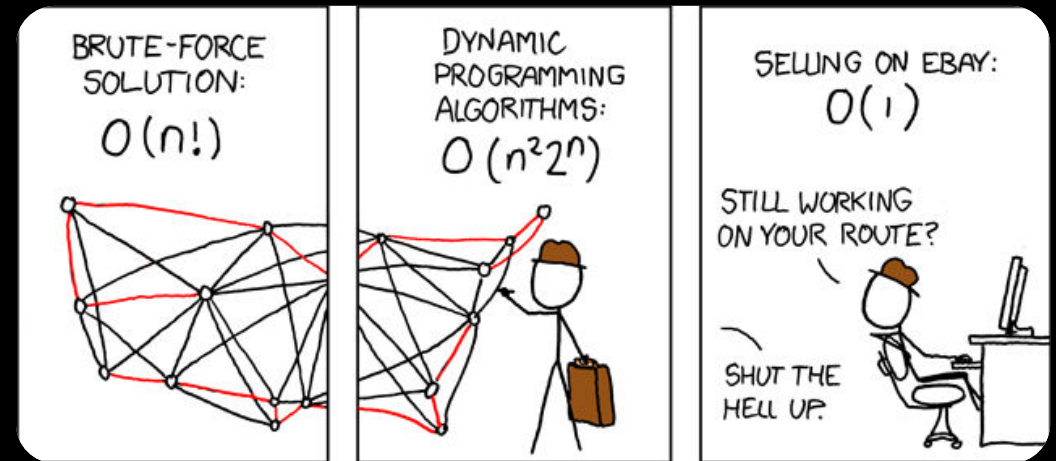
$$4) 3 \times 9 = ?$$
$$= 3 \times \sqrt{81} = 3 \sqrt{81} = 3 \sqrt[6]{81} = 27$$
$$\begin{array}{r} 27 \\ 6 \\ \hline 21 \\ 21 \\ \hline 0 \end{array}$$

<http://xkcd.com/759/>

“easy”

(polynomial \Rightarrow efficient)

- Multiplying numbers
- Word processing



<http://xkcd.com/399/>

“hard”

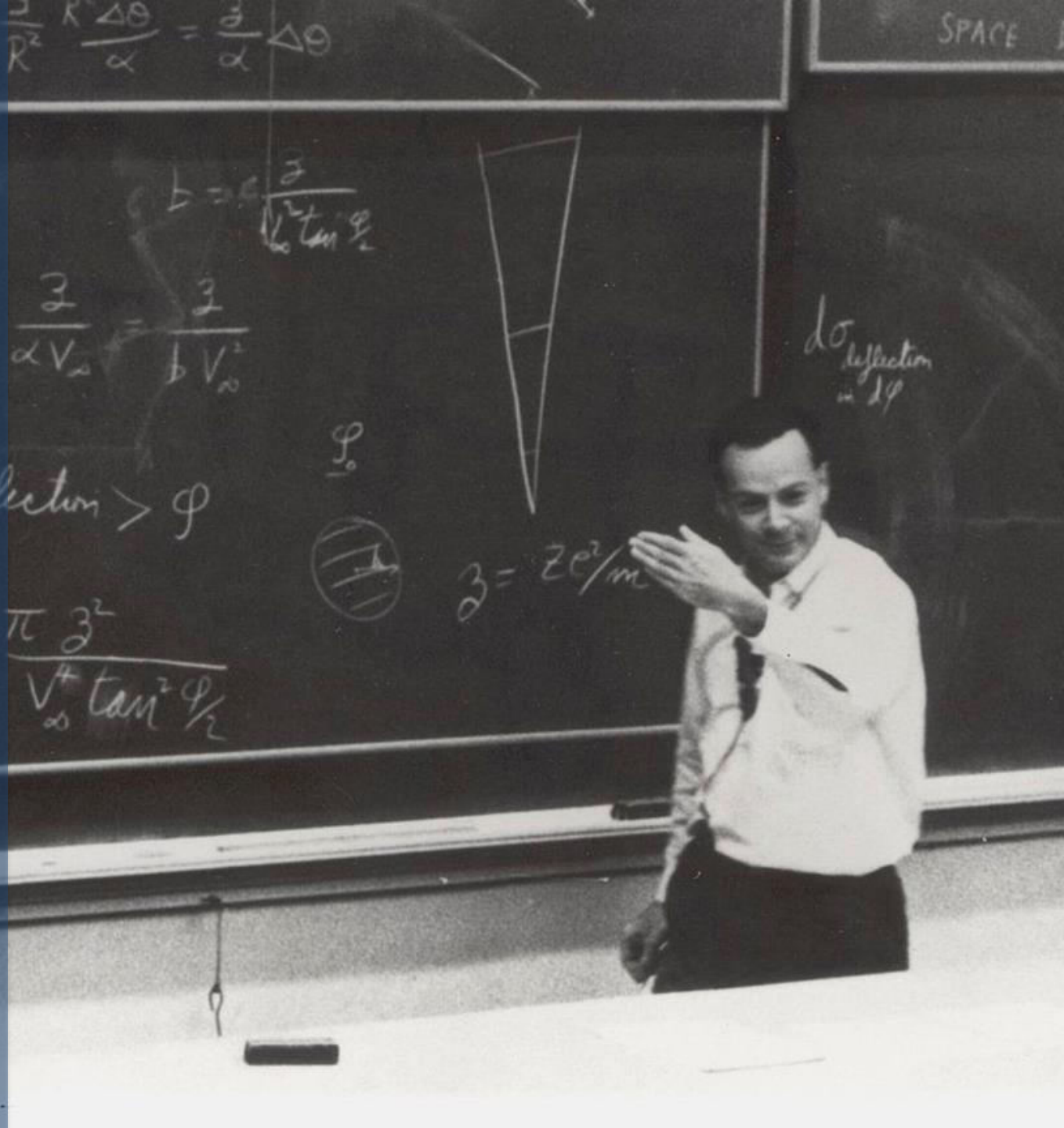
(exponential \Rightarrow intractable)

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

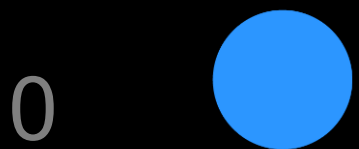
Our intuition about
what we can compute
is wrong

“ 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.”

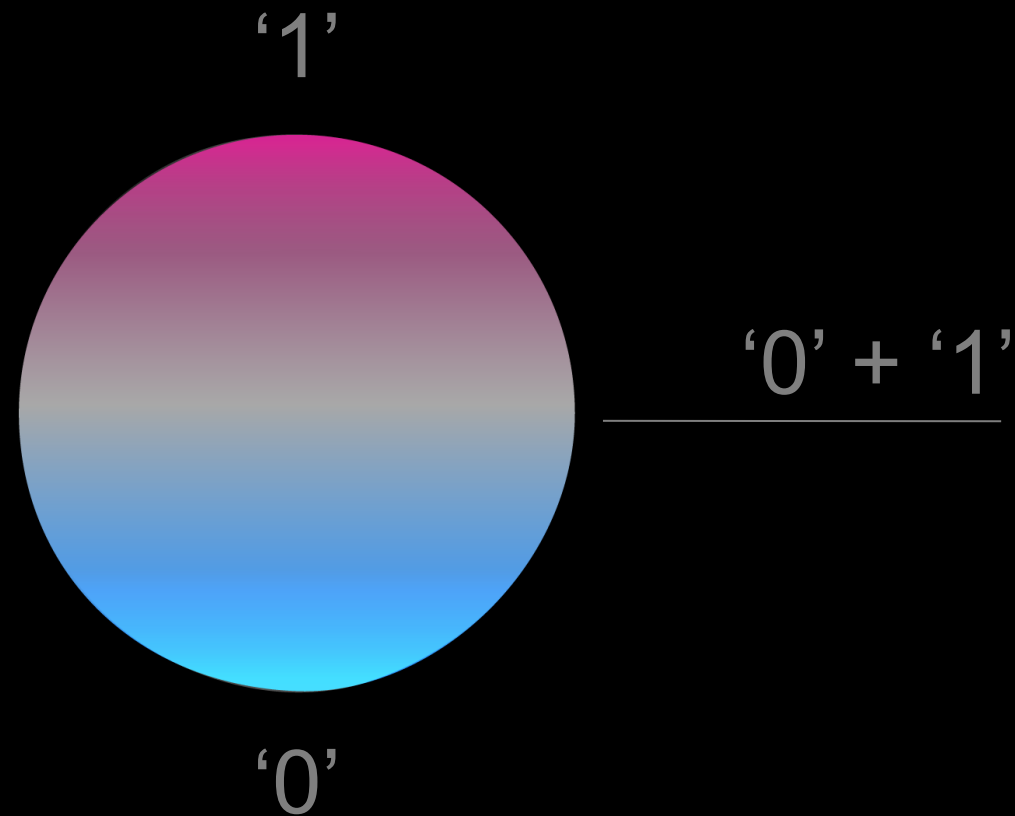
-Richard P. Feynman



Bits

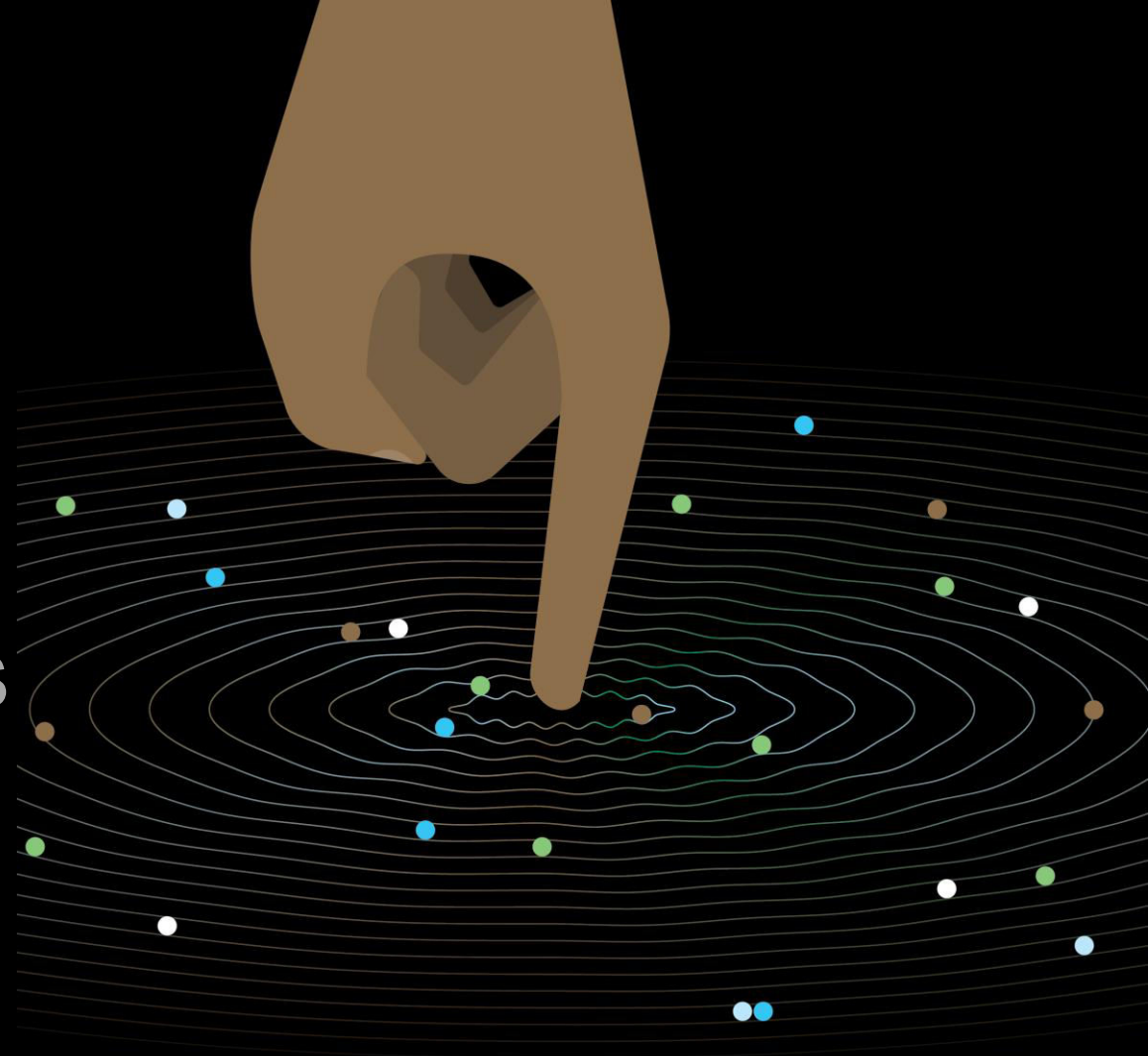


Qubits



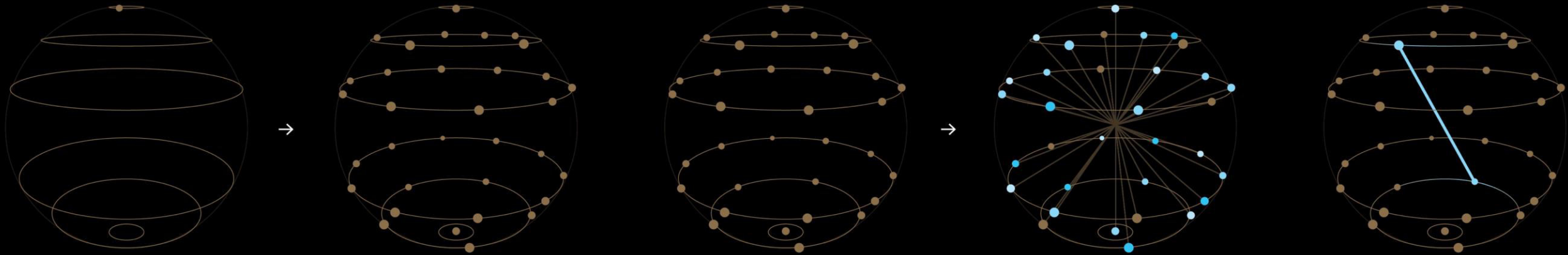
Entanglement

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

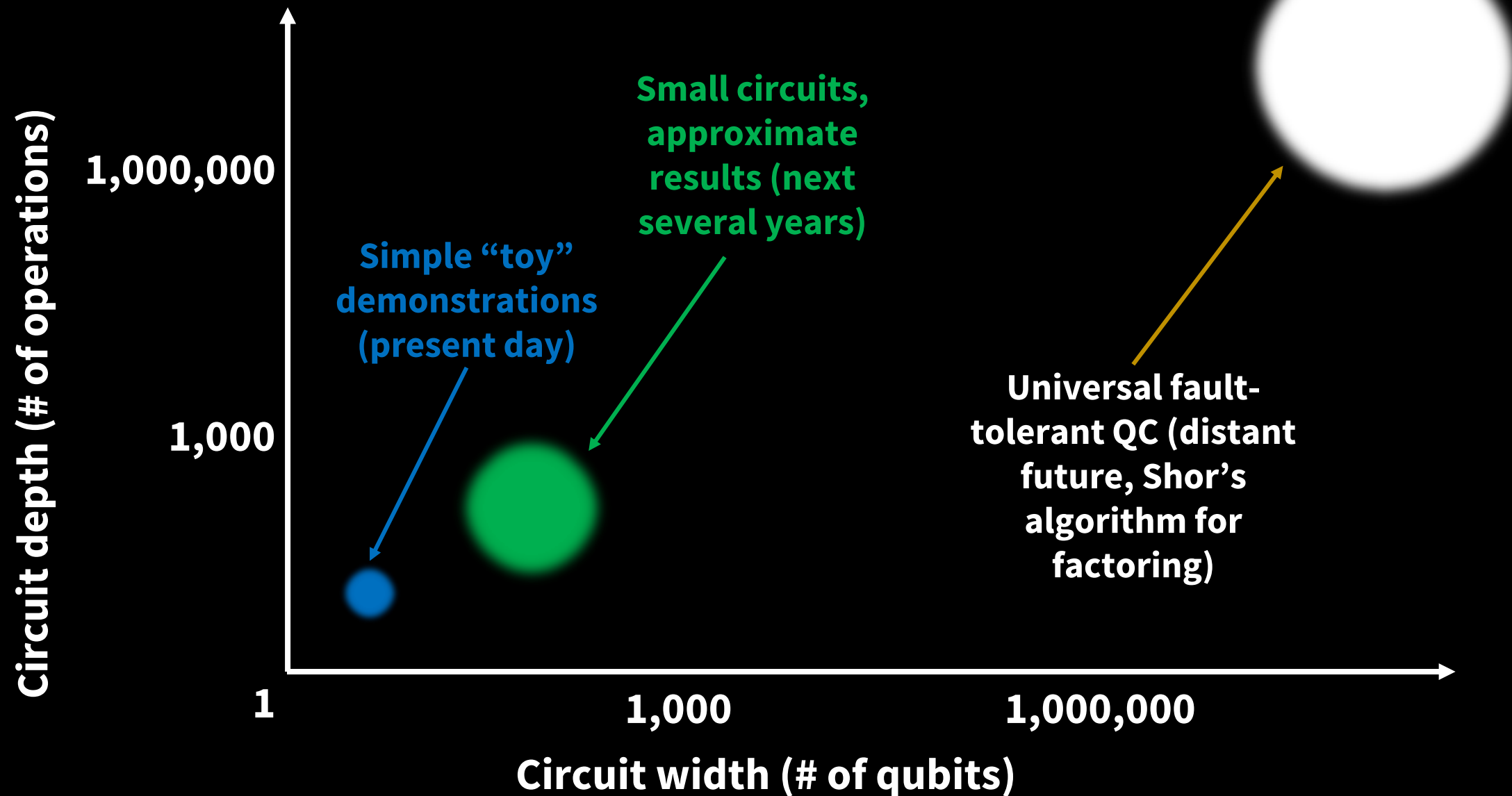
N bit input 100110...

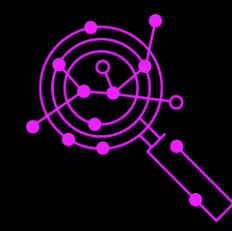
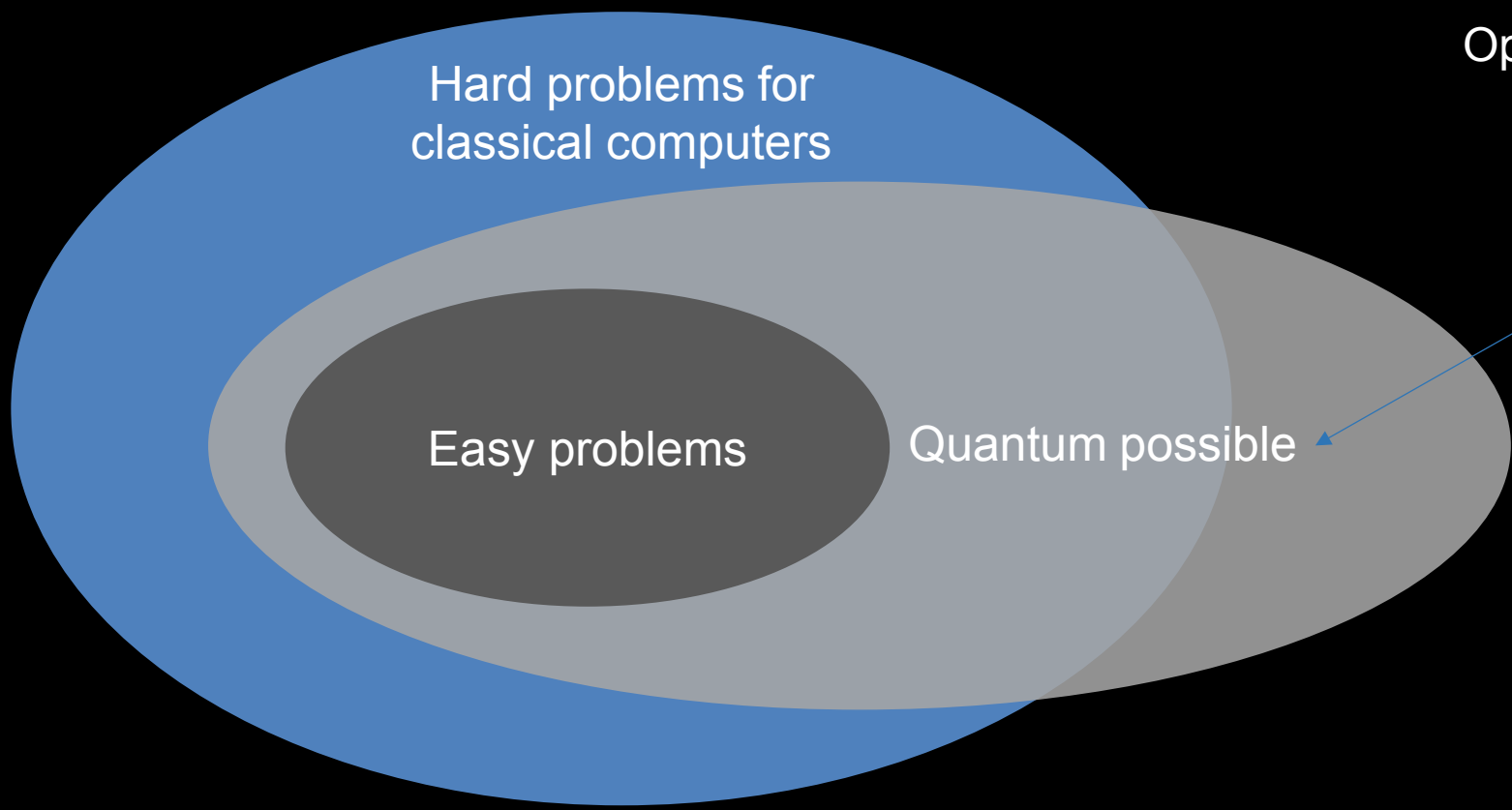
**Quantum
Computer**

**N qubits
 2^N paths**

N bit output 010101...

Towards a quantum advantage





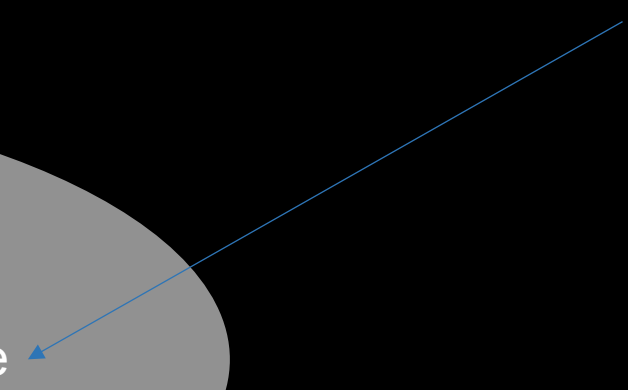
Optimization



Chemistry

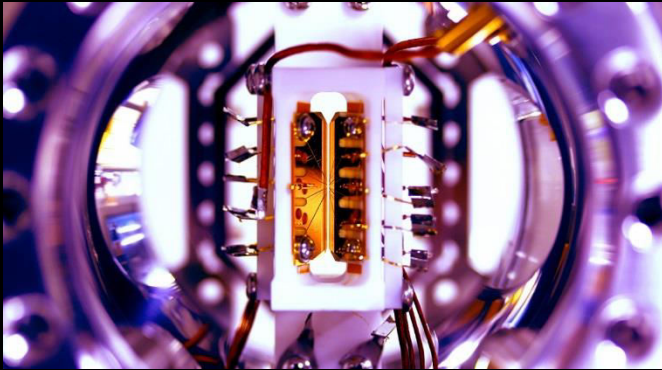


Machine learning



Quantum Computing Technologies

Ions



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

Photons

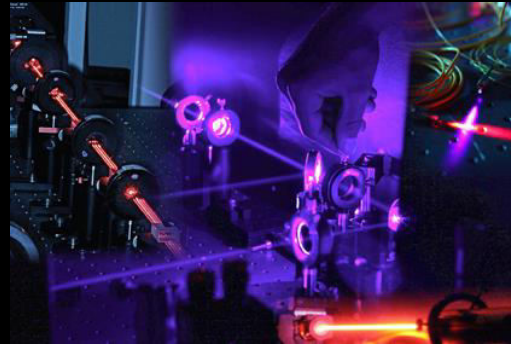


Image from the Centre for Quantum Computation & Communication Technology, credit Matthew Broome

Nanowires

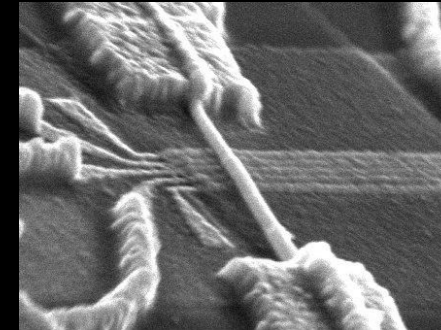
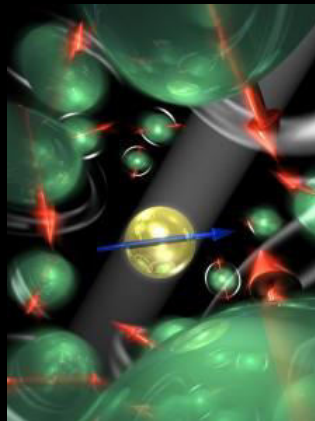


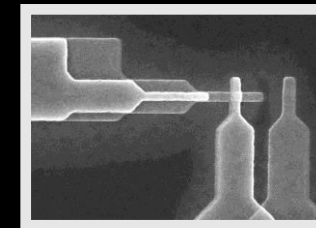
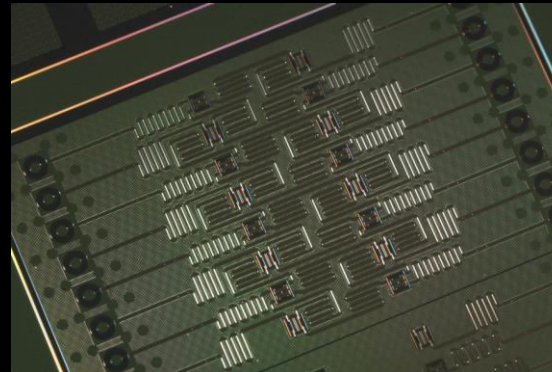
Image from Kouwenhoven Group, Delft

Solid-state defects

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



Superconducting Circuits



Neutral Atoms

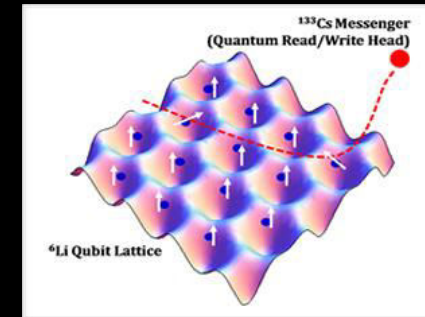
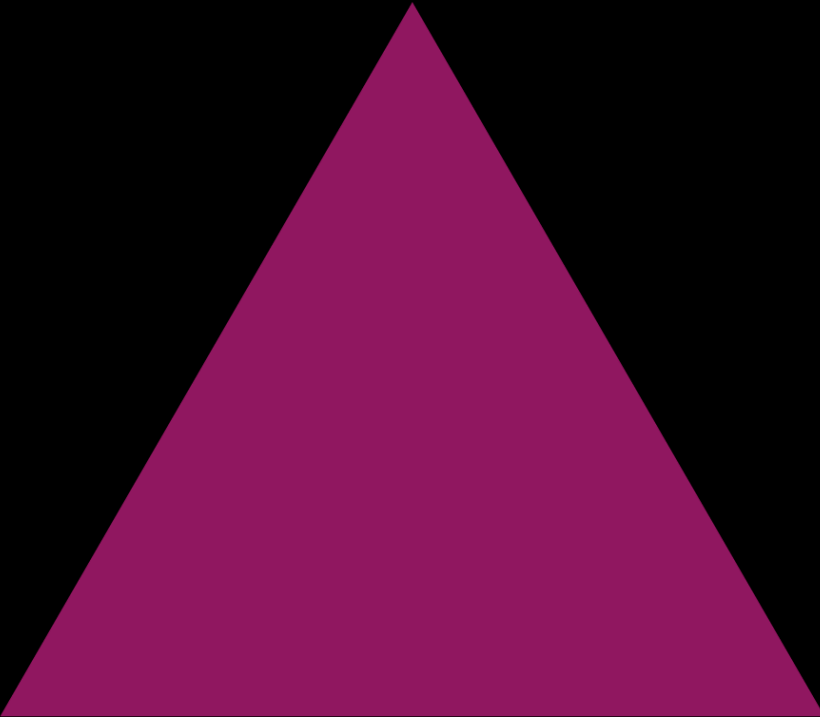


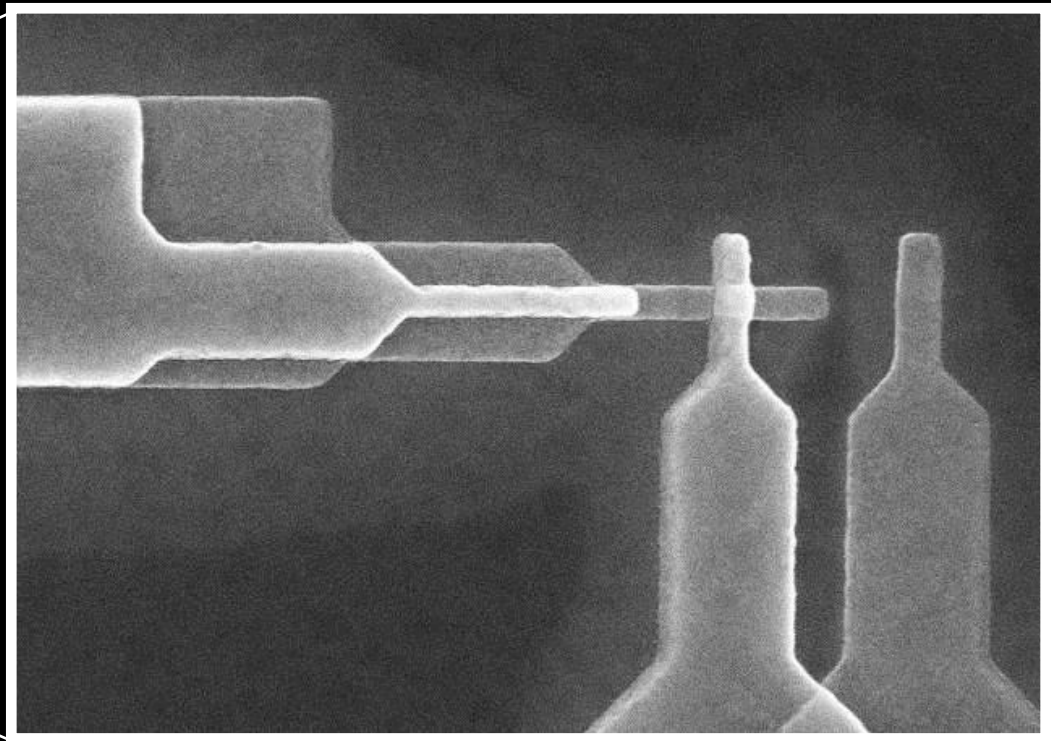
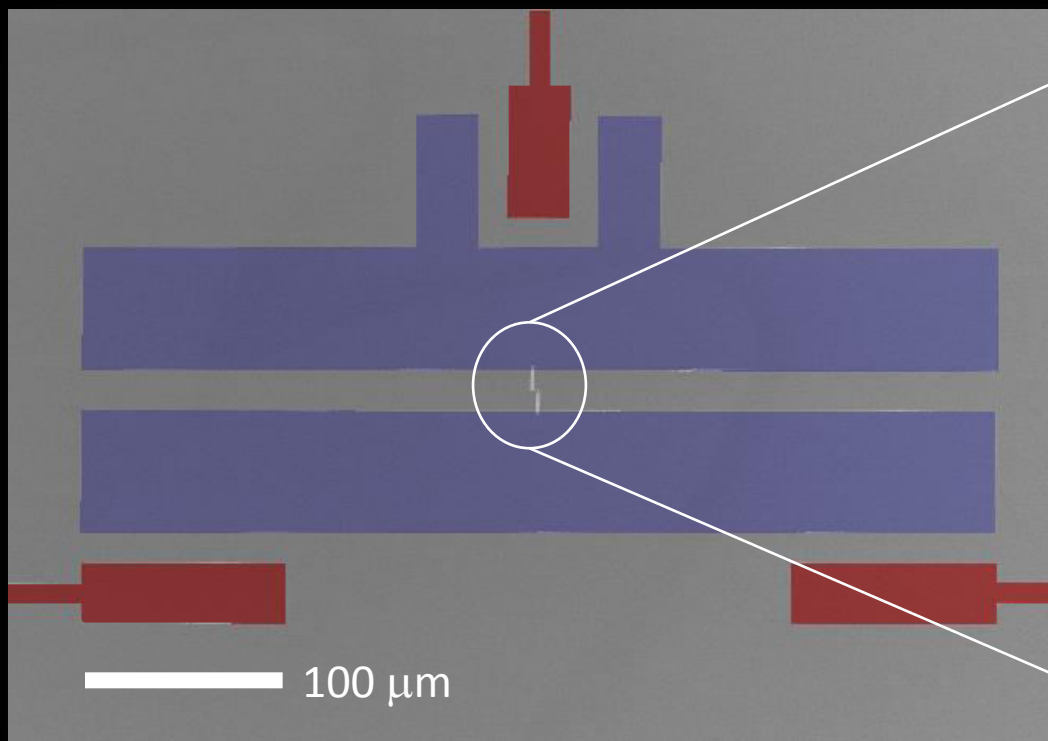
Image from Cheng Group, University of Chicago

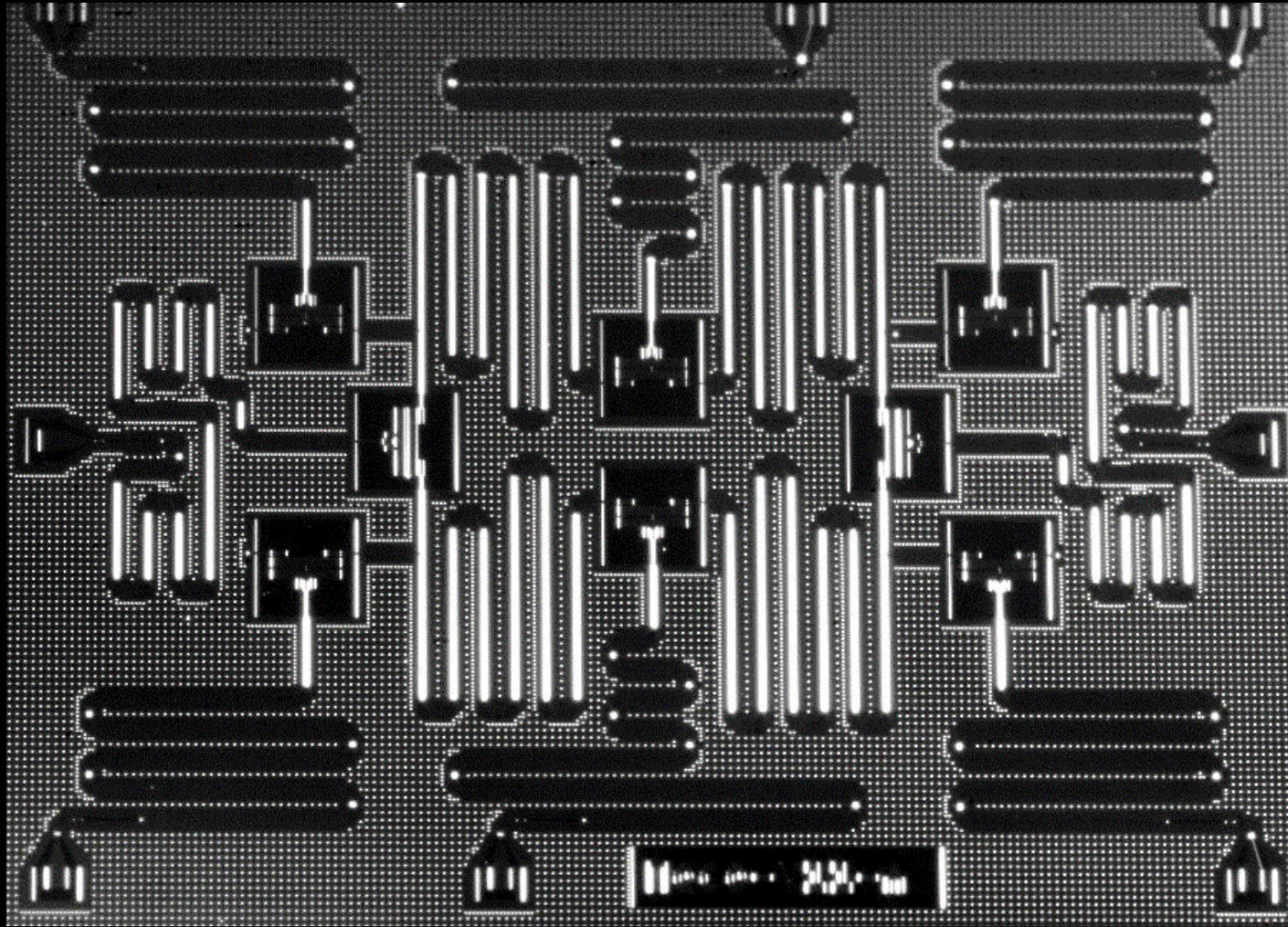
Controllability



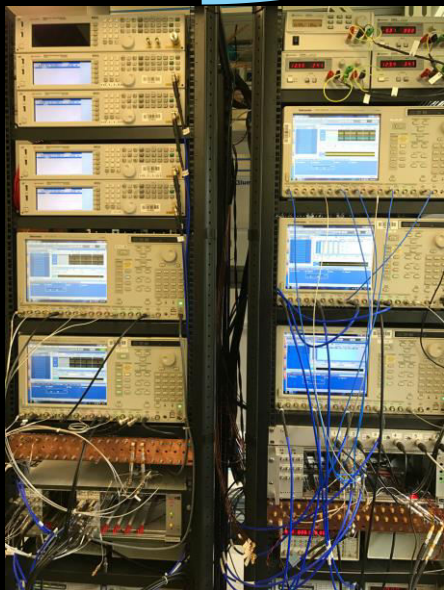
Coherence

Connectivity





Room
Temperature



Microwave electronics

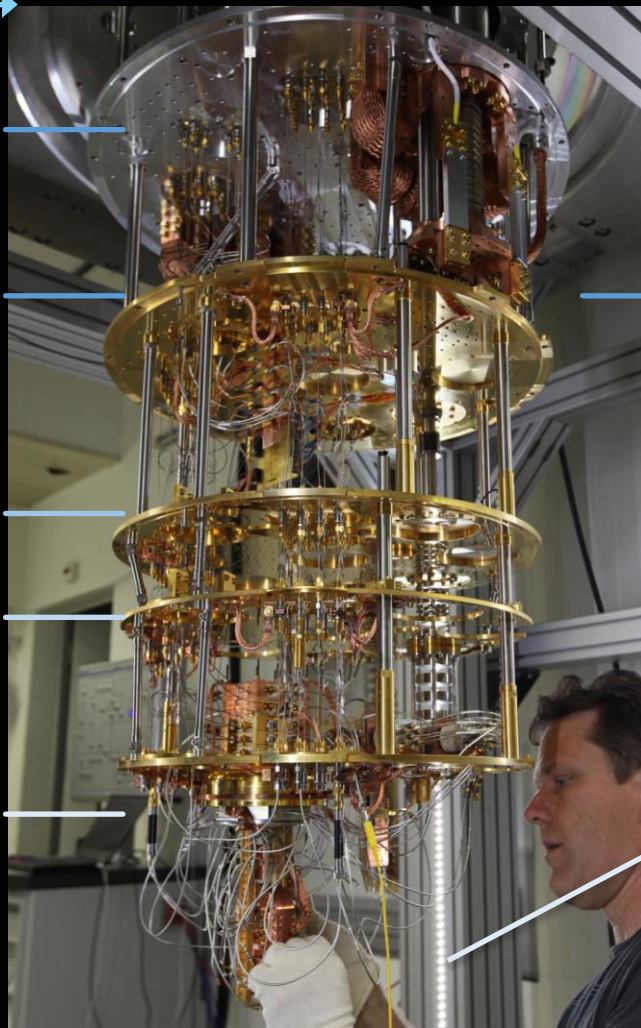
0.015K

0.1K

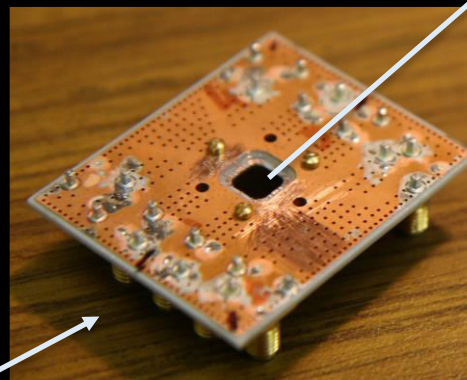
0.9K

3K

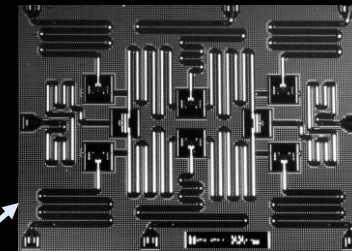
40K

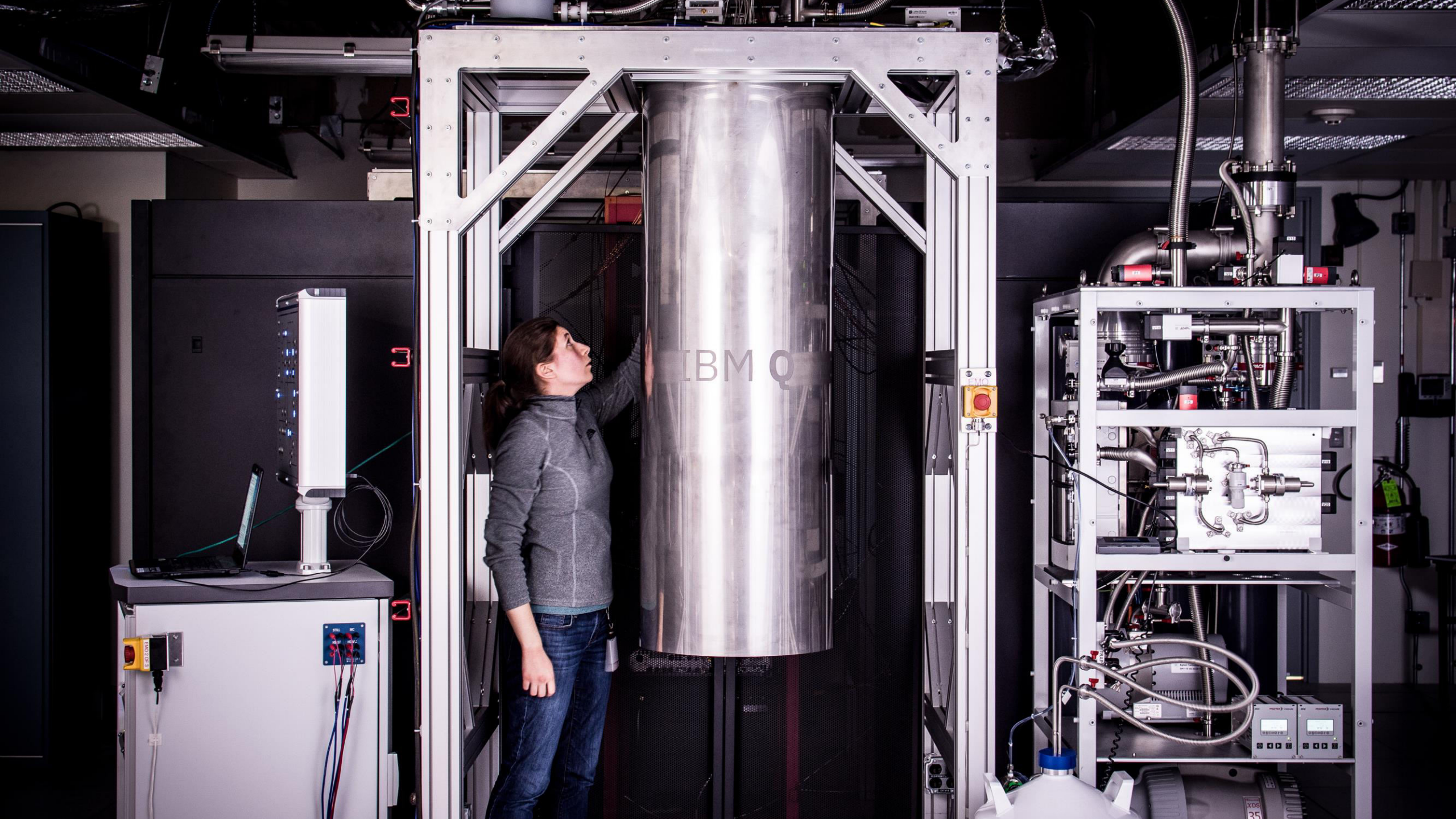


Circuit board

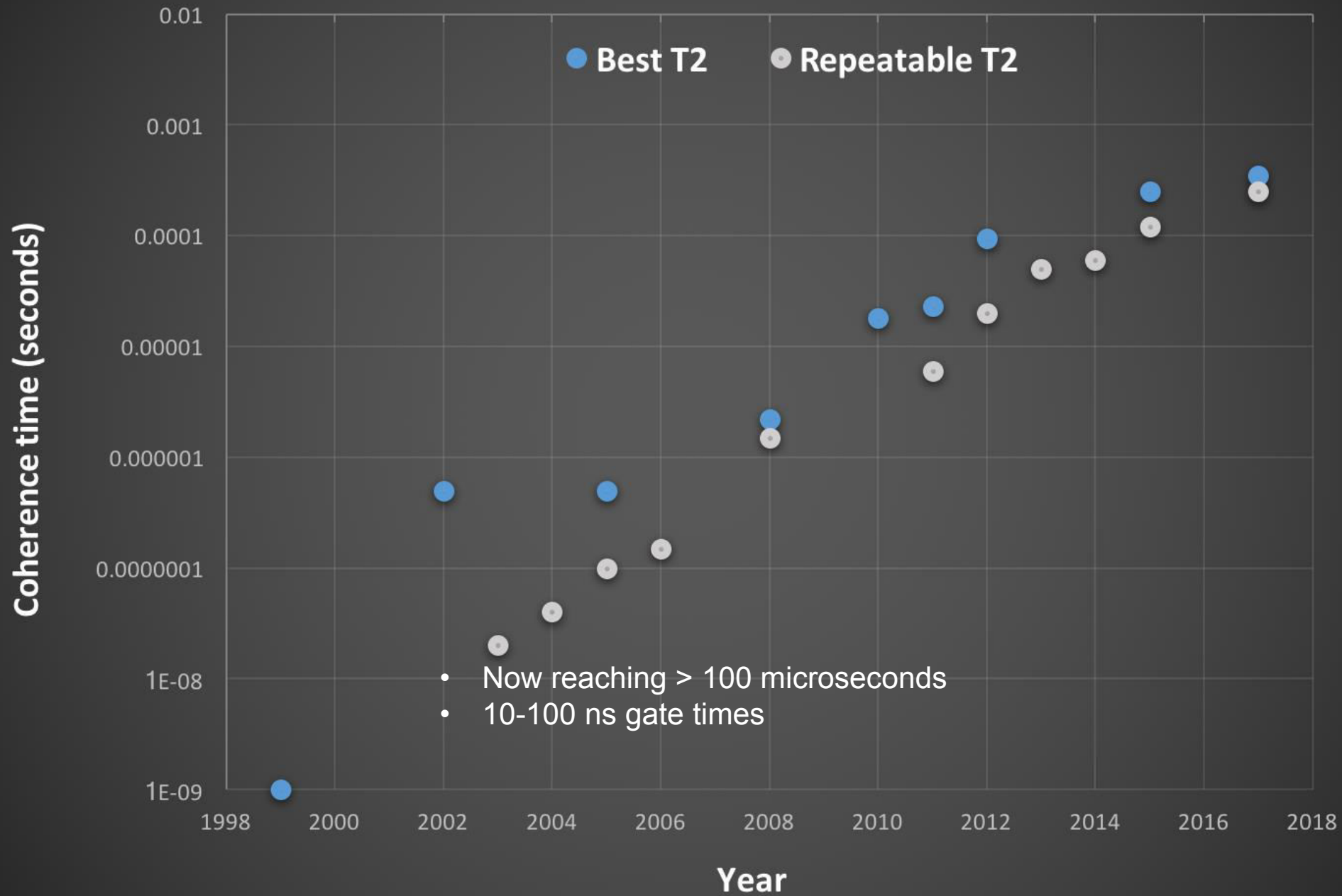


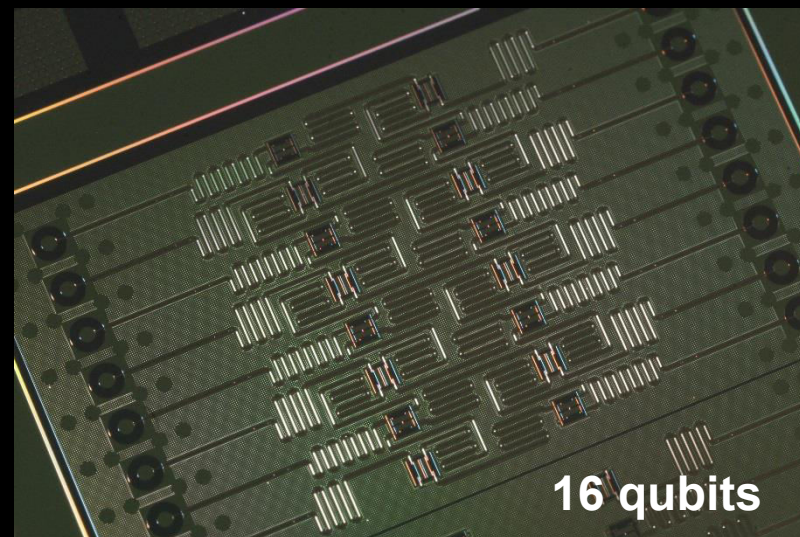
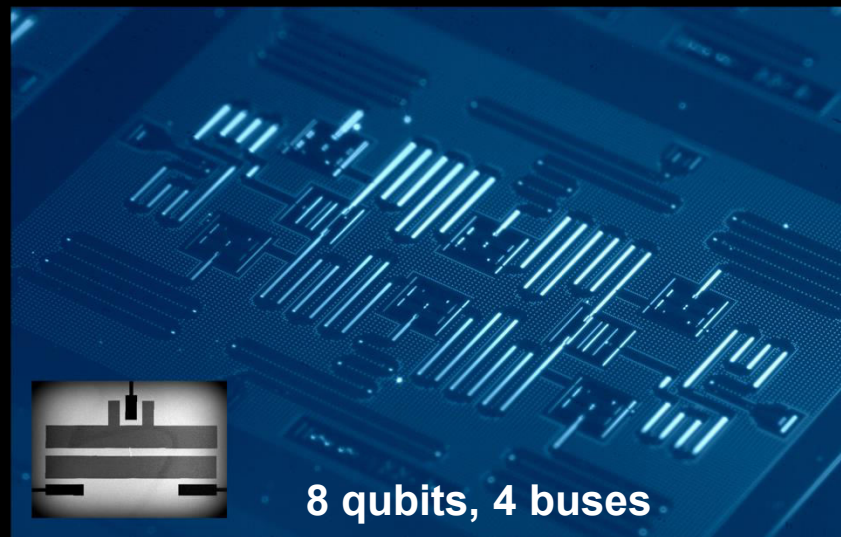
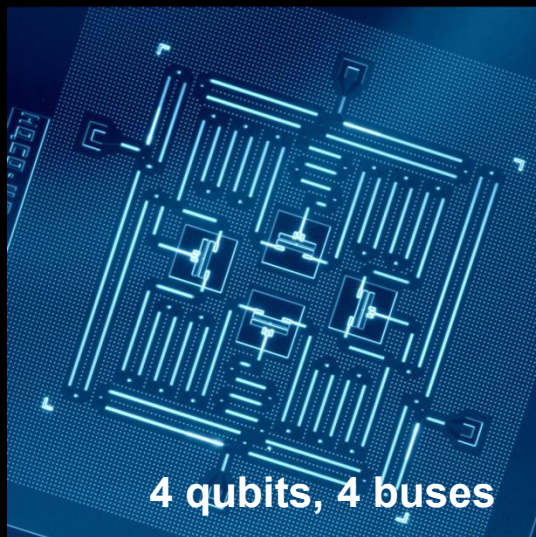
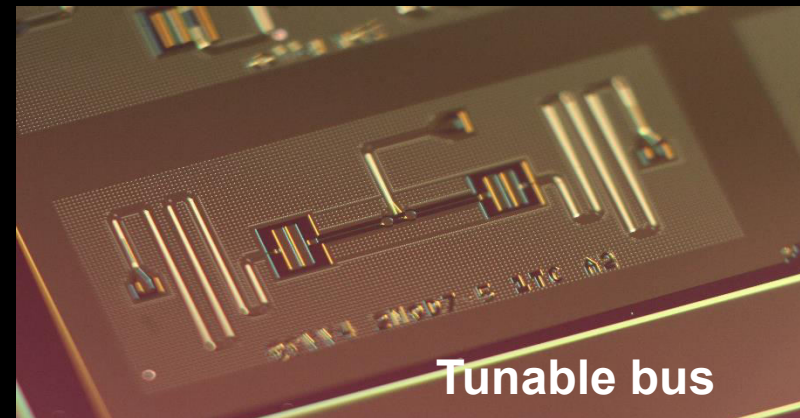
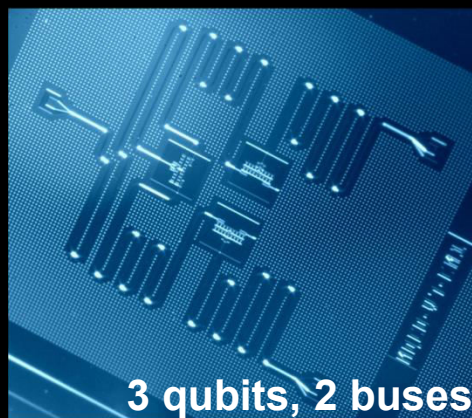
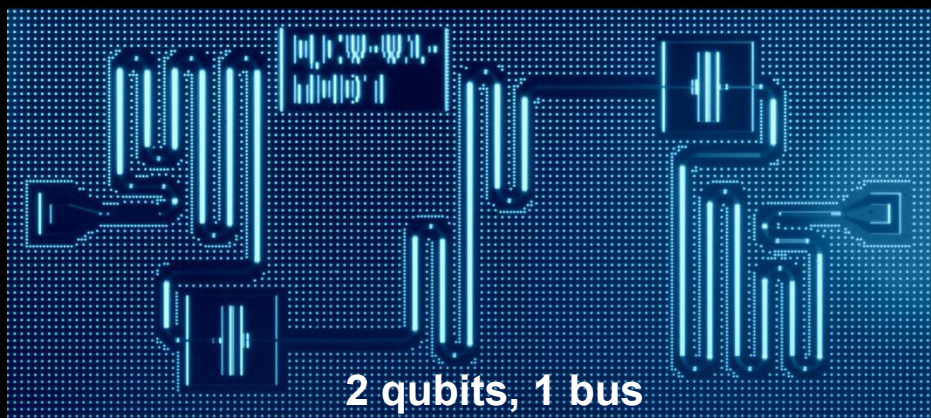
Qubit Processor

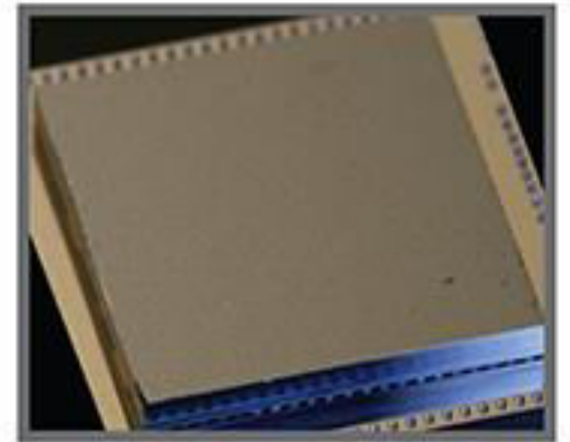
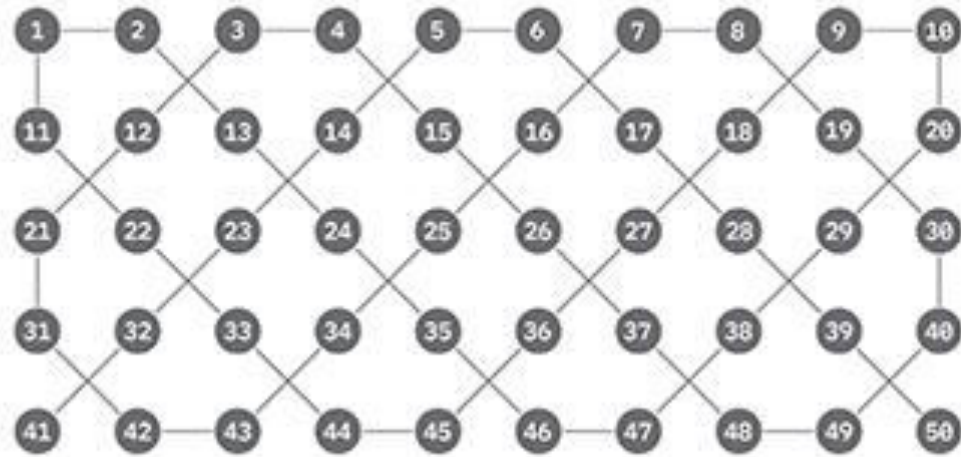
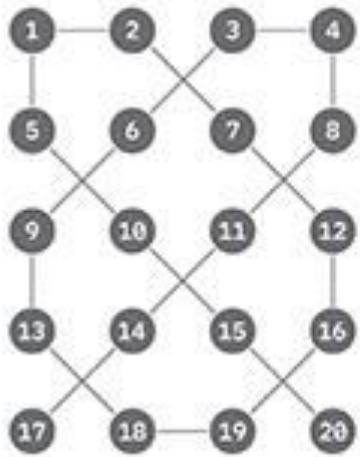




IBM Q







IBM Q Experience (IBM QX)

The World's first *Cloud quantum computing platform* with quantum researchers, educators and developers ecosystem.

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,

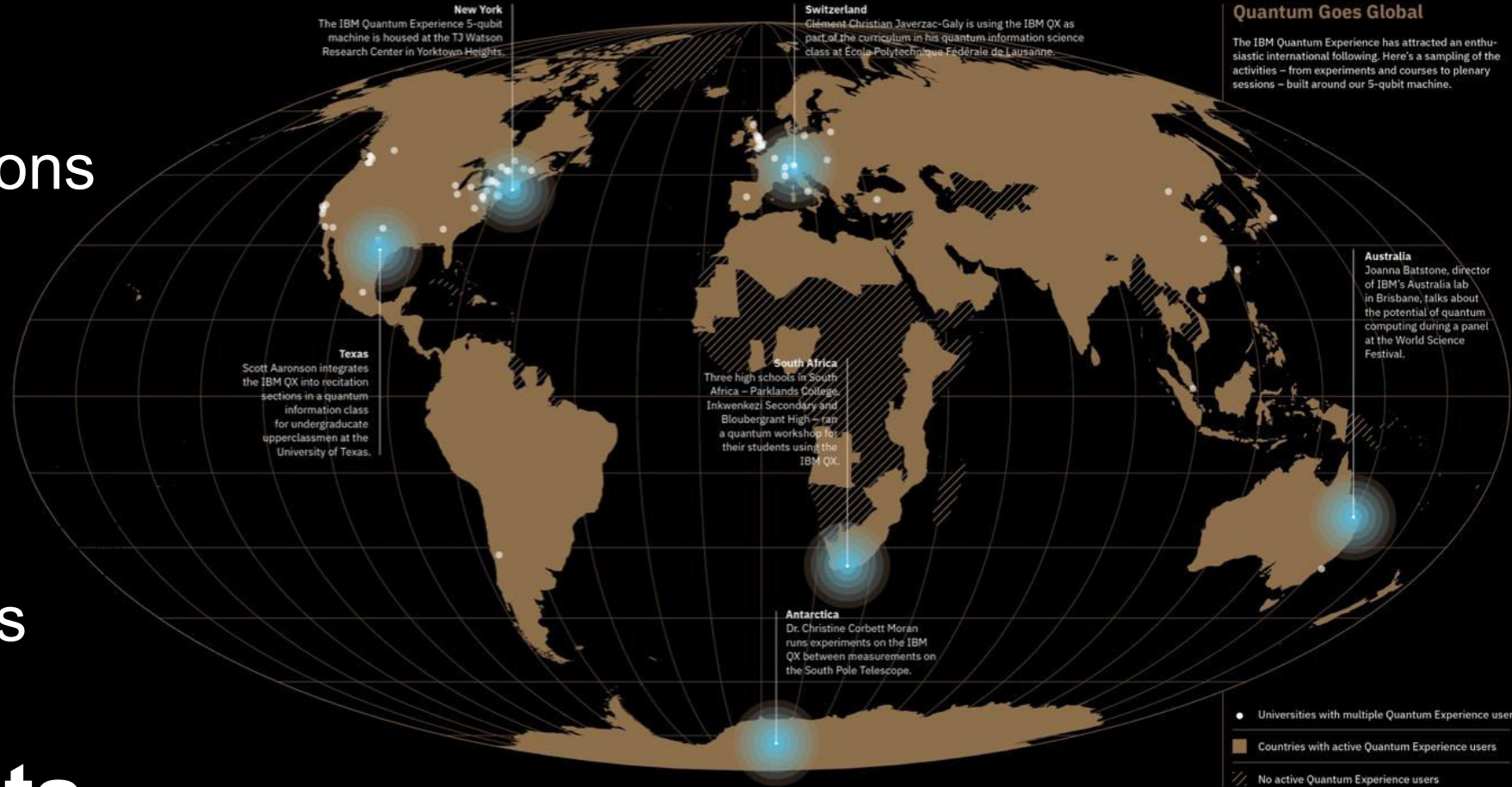
300 high schools

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.

 **QISKit**
Quantum Information Software Kit
<http://www.qiskit.org> qiskit@qiskit.org

Repositories 9 People 20

Pinned repositories

- qiskit-sdk-py**
Software development kit for writing quantum computing experiments, programs, and applications.
Python 1.3k 349
- qiskit-tutorial**
A collection of Jupyter notebooks using QISKit.
Jupyter Notebook 196 83
- openqasm**
Gate and operation specification for quantum circuits.
TeX 163 42
- ibmqx-backend-information**
Information about the different backends on the IBM Q experience.
66 30
- ibmqx-user-guides**
The users guides for the IBM Q experience.
HTML 36 19

Search repositories...

Type: All

Language: All

 **Massachusetts Institute of Technology**

Turn Quantum Computing Knowledge into Action

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The IBM Q experience Community brings together researchers and quantum enthusiasts to share, connect and collaborate

Log in

- 2** comments
46 views
0 likes
Unable to get Qiskit to work on Anaconda on windows 10 **Software**
Hi, I've been trying to get qiskit to work on windows 10 for ages. I've followed the instructions but when I run jupyter I get this error: ModuleNotFoundError: No m...
anarchy Posted 4 days ago Last comment by anarchy 10 hours ago
installation
- 1** comment
12 views
0 likes
Trouble Running Experiment **General**
I'm having trouble running the "Example Real Chip Backend" code from https://github.com/QISKit/qiskit-sdk-py/blob/master/doc/example_real_backend.rst...
juanignacioladame Posted 16 hours ago Last comment by dougmclure 12 hours ago
- 2** comments
62 views
0 likes
Acknowledgements **General**
I ran an experiment in the IBM Q Experience and would like to publish the results. Apart from acknowledging the IBM team and the IBM Q Experience at the end of ...
navascues Posted a day ago Last comment by dougmclure 16 hours ago
- 2** comments
46 views
optical computation **General**
Does IBM work on optical computer and could we produce Qbics with light?
peyman Posted a day ago Last comment by tucci a day ago

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Tweets by @IBMRResearch

- IBM Research Retweeted **Quantum Sci & Tech** @QuantSciTech
- New from @IBMRResearch: Multi-path interferometric Josephson directional amplifier for qubit readout [ow.ly/123Q30hZw76](https://doi.org/10.1038/nature24776)



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



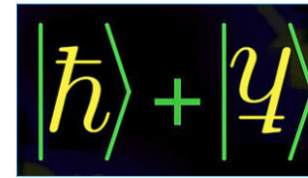
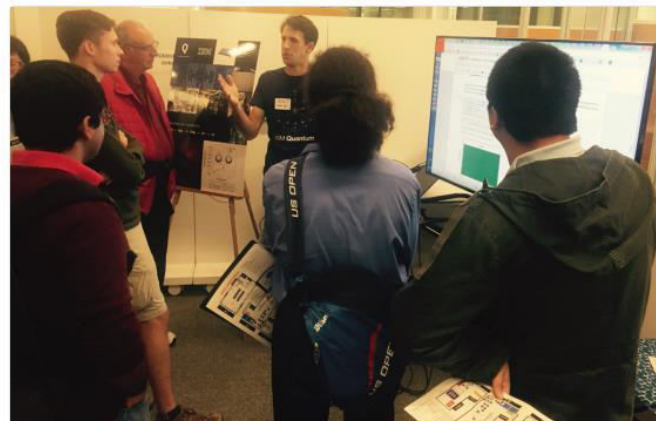
Following

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



Follow

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



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!



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

[Contact an expert](#)

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

ibm.com/ibmq
Go to Experiment

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IBM Q Experience

Welcome to the IBM Q Experience!

Explore the world of quantum computing! Check out our User Guides and interactive Demos to learn more about quantum principles. Or, dive right in to create and run algorithms on real quantum computing hardware, using the Quantum Composer and QISKit software developer kit.

[Start experimenting with a quantum computer](#)

Introducing the IBM Q Experience for Researchers

A community built for individuals who actively contribute to the advancement of the field through peer-reviewed publications. Our goal is to provide quantum researchers with the support, collaboration and tooling they need to do high quality work.

Visibility for your papers

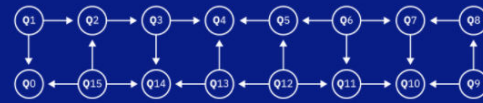
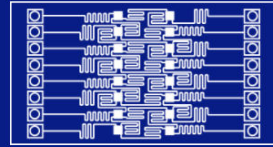


Priority and early access to devices



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

Backend: ibmqx5 (16 Qubits)



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

[More details](#)

Frequency (GHz)
T1 (μ s)
T2 (μ s)

Gate error (10^{-3})
Readout error (10^{-2})

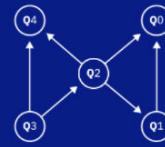
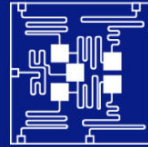
MultiQubit gate error (10^{-2})

	Q0	Q1	Q2	Q3	Q4	Q5	Q6
Frequency (GHz)	5.26	5.40	5.28	5.08	4.98	5.15	5.31
T1 (μ s)	35.10	37.20	42.50	39.50	52.20	33.00	47.50
T2 (μ s)	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	CX2_3	CX3_4		CX5_4	CX6_5	
	6.39	4.99	3.55		4.88	3.62	
	CX1_2		CX3_14			CX6_7	
	8.56		3.92			4.79	
						CX6_11	
						3.94	

ACTIVE

AVAILABLE ON QISKIT

Backend: ibmqx4 (5 Qubits)



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

[More details](#)

Frequency (GHz)
T1 (μ s)
T2 (μ s)

Gate error (10^{-3})
Readout error (10^{-2})

MultiQubit gate error (10^{-2})

	Q0	Q1	Q2	Q3	Q4
Frequency (GHz)	5.24	5.30	5.35	5.43	5.18
T1 (μ s)	40.60	49.60	42.50	43.20	52.60
T2 (μ s)	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	CX2_0	CX3_2		
	16.13	9.94	2.36		
		CX2_1	CX3_4		
		5.13	2.70		
		CX2_4			
		4.96			

ACTIVE

AVAILABLE ON QISKIT

Backend: ibmqx_qasm_simulator

Number of qubits 20
Conditionals (if) Yes

ACTIVE

SIMULATOR

AVAILABLE ON QISKIT

Backend: ibmqx_hpc_qasm_simulator

Number of qubits 32
Conditionals (if) No

ACTIVE

SIMULATOR

AVAILABLE ON QISKIT

www.qiskit.org, twitter: @qiskit

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



QISKit

Quantum Information Software Kit

[Join our Slack community](#)

Approximate Quantum Computing: From advantage to applications
Recordings now available!

Latest version pypi **v0.4.8**

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 Documentation

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

Table Of Contents

Installation and setup
Getting started
QISKit overview
Developer documentation
SDK reference

Next topic

Installation and setup

This Page

Show Source

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 - [Installation](#)
 - [Install Jupyter-based tutorials](#)
 - [FAQ](#)
- [Getting started](#)
 - [Quantum Chips](#)
 - [Project Organization](#)
- [QISKit overview](#)
 - [Philosophy](#)
 - [Project Overview](#)
- [Developer documentation](#)
 - [Programming interface](#)

Documentation from getting started to developing

QISKit / [qiskit-sdk-py](#)

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909

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Code

Issues 15

Pull requests 8

Boards

Reports

Projects 0

Wiki

Insights

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

<http://www.qiskit.org>

quantum-computing

qiskit

sdk

python

quantum-programming-language

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

Open development process with lots of example code

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])
```

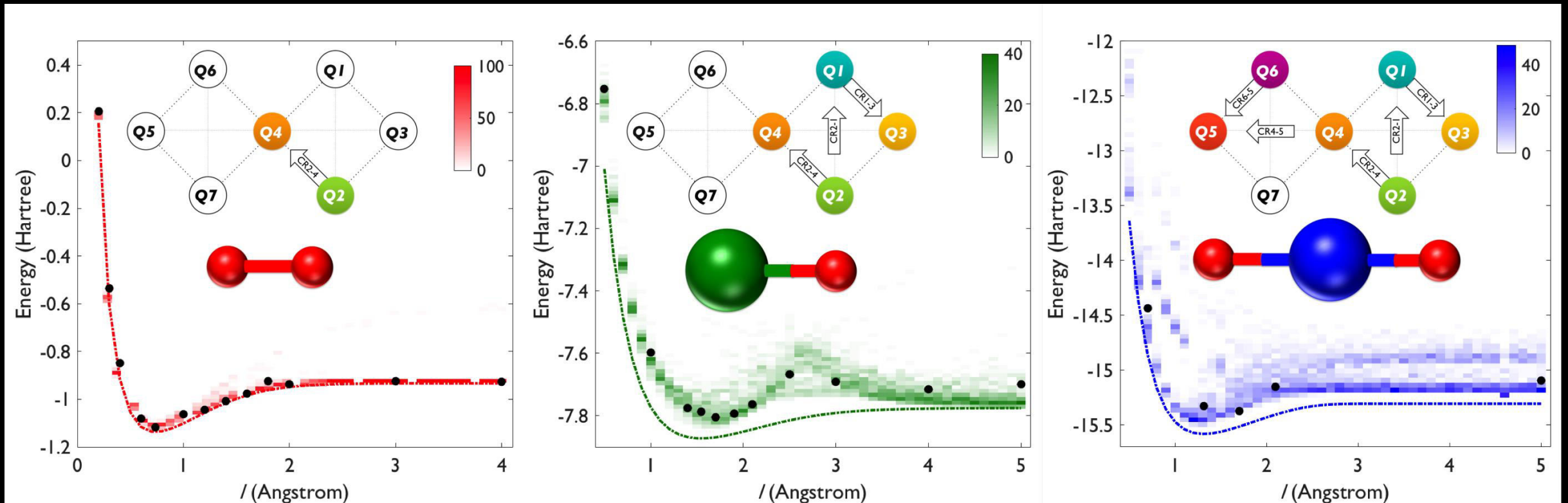
```
# Insert a barrier before measurement
```

```
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!



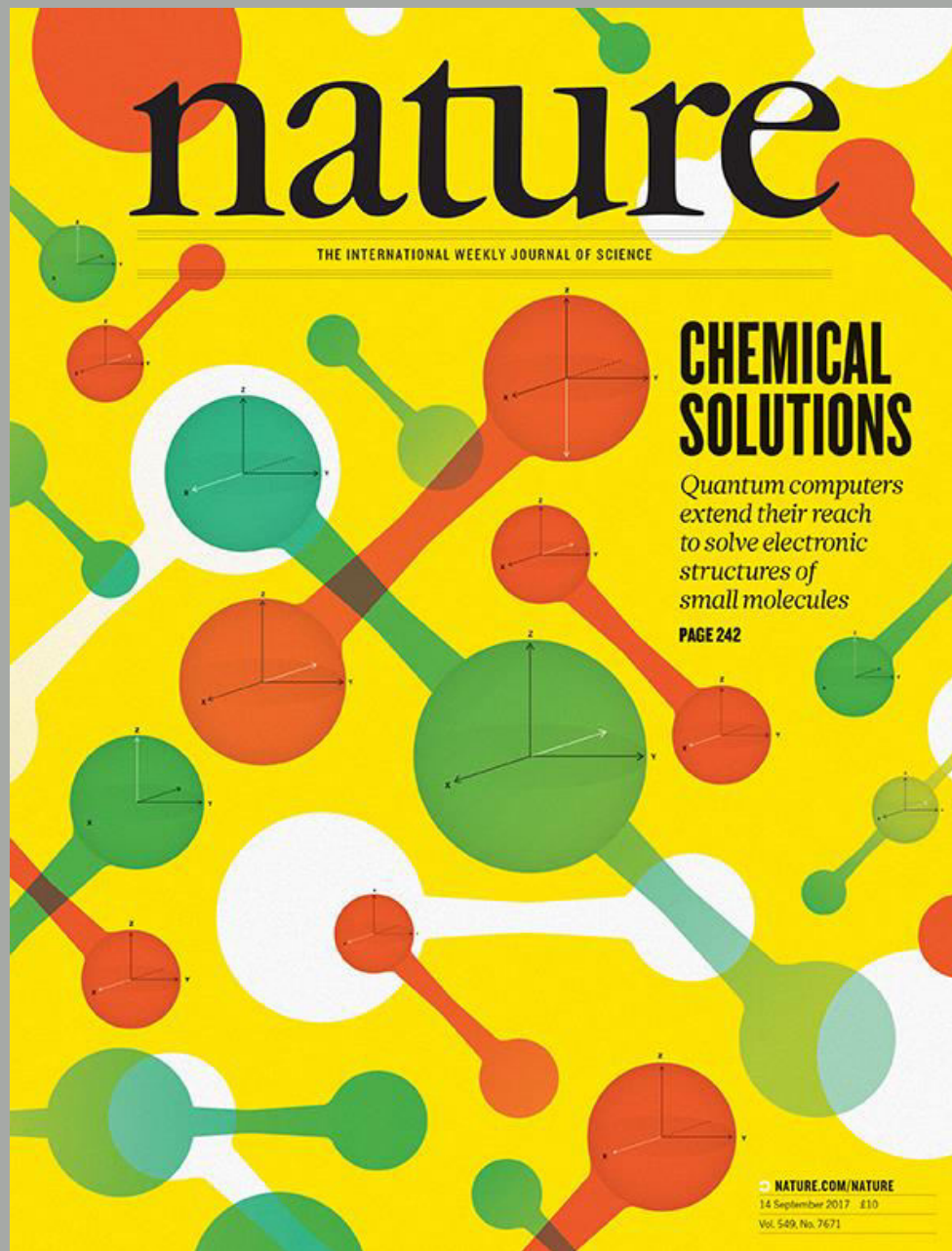
H₂: 2 qubits

LiH: 4 qubits

BeH₂: 6 qubits

Provided as a QISKit notebook using IBM Q Experience devices





LETTER

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

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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 computers¹. 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 algorithm¹⁵. 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

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