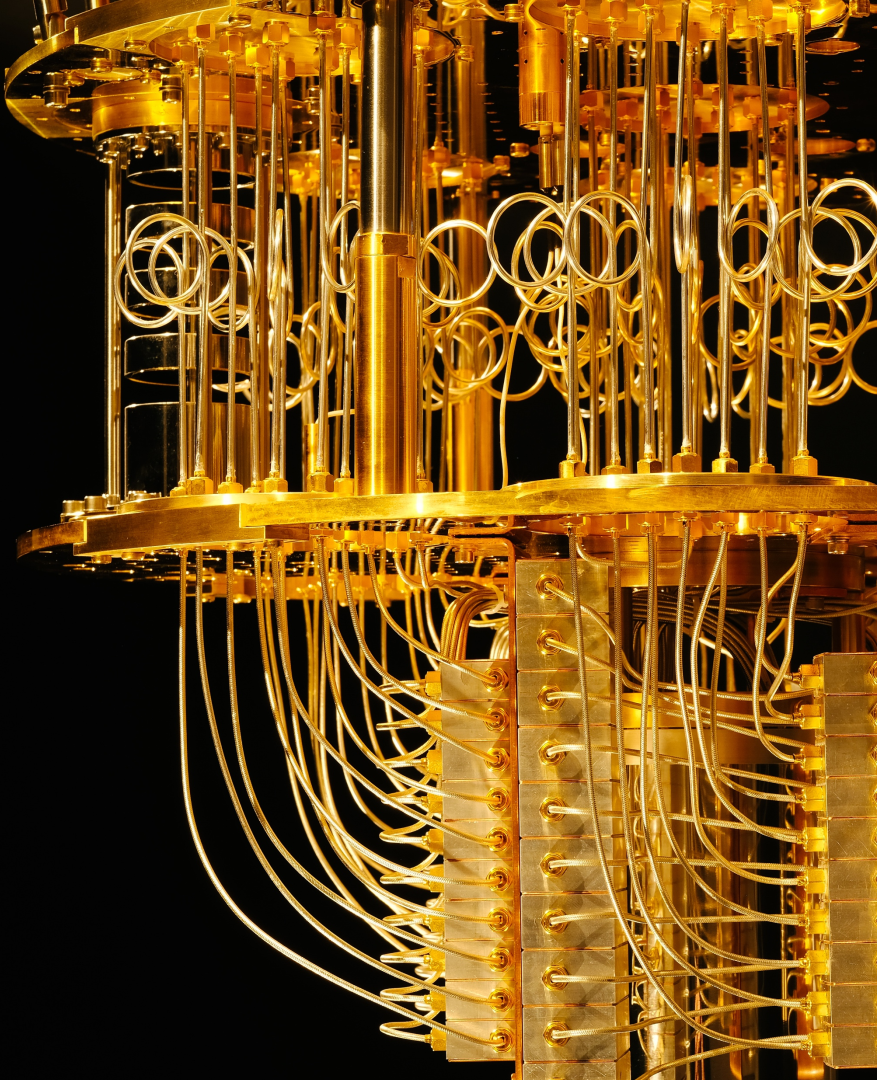
Quantum Computing and IBM **Q**

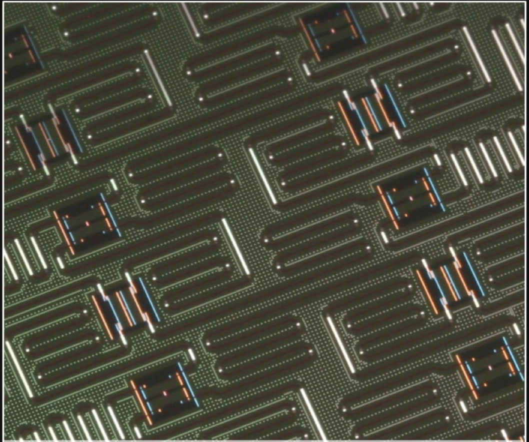
Federico Accetta
IBM **Q** Ambassador
IBM Italy



IBM

IBM released the IBM Q Experience in 2016

Quantum computer at IBM Research


IBM quantum bit device


IBM Quantum Experience

In May 2016, IBM made **a quantum computing platform available via the IBM Cloud**, giving students, scientists and enthusiasts hands-on access to run algorithms and experiments

The IBM Q Experience has seen extraordinary adoption

- First quantum computer on the cloud
- > 82,000 users
- All 7 continents
- > 4 **Million** experiments run
- > 65 papers
- > 1500 colleges and universities, 300 high schools, 300 private institutions

What will be the applications 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

IBM Research

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

The Abdus Salam International Centre for Theoretical Physics

Research | Scientific Calendar | Programmes

Home > About ICTP > Prizes & Awards > The Dirac Medal > The Medallists

The Medallists

The Medallists

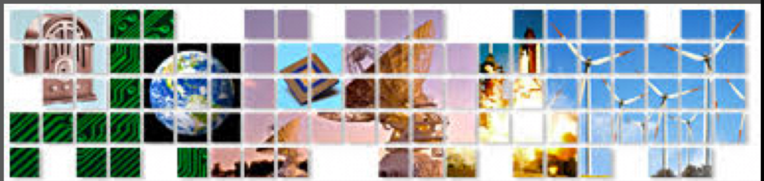
A list of past Dirac Medallists

2017	Charles H. Bennett , David Deutsch , Peter W. Shor
2016	Nathan Seiberg , Mikhail Shifman , Arkady Vainshtein
2015	Alexei Kitaev , Gregory W. Moore , Nicholas Read
2014	Ashoke Sen , Andrew Strominger , Gabriele Veneziano

ICTP's Dirac Medal to Charles H. Bennett (IBM Research)

IEEE SPECTRUM

Follow on:



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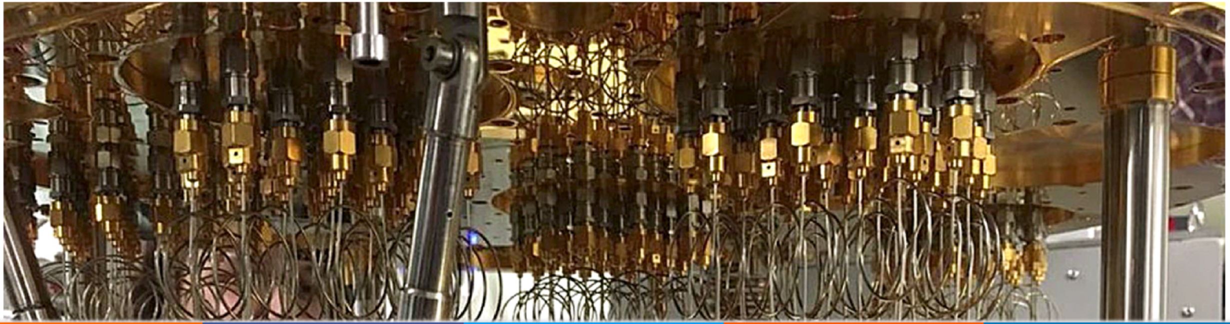
Tech Talk | Computing | Hardware

IBM Simulates a 56-Qubit Machine

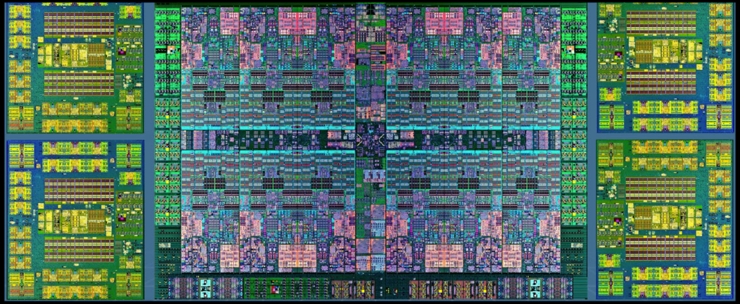
By Charles Q. Choi

Posted 30 Oct 2017 | 18:00 GMT

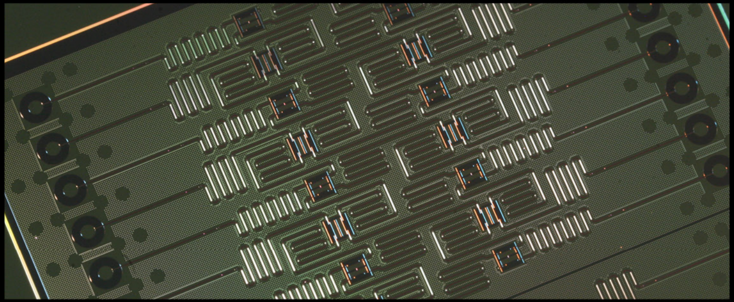


Whereas a 56-qubit quantum computer can theoretically perform 2^56 operations simultaneously, IBM's accomplishment involved dividing this task into 2^19 slices that each essentially consisted of 2^36 operations. This strategy meant the researchers only needed about **3 terabytes of memory** for their simulated quantum computer.

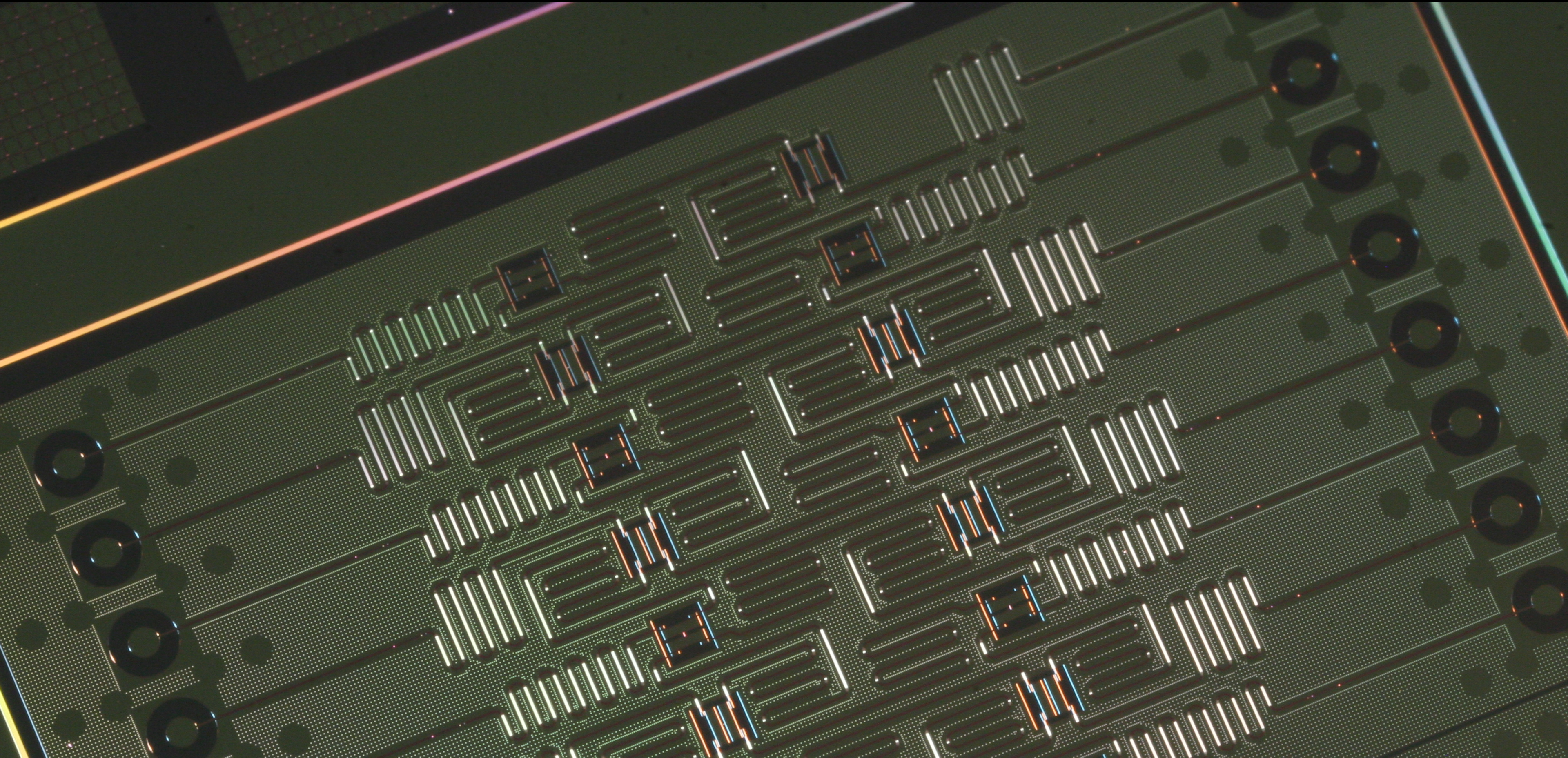
In contrast, earlier in 2017, a 45-qubit simulation at the Swiss Federal Institute of Technology in Zurich required **500 terabytes** of memory.



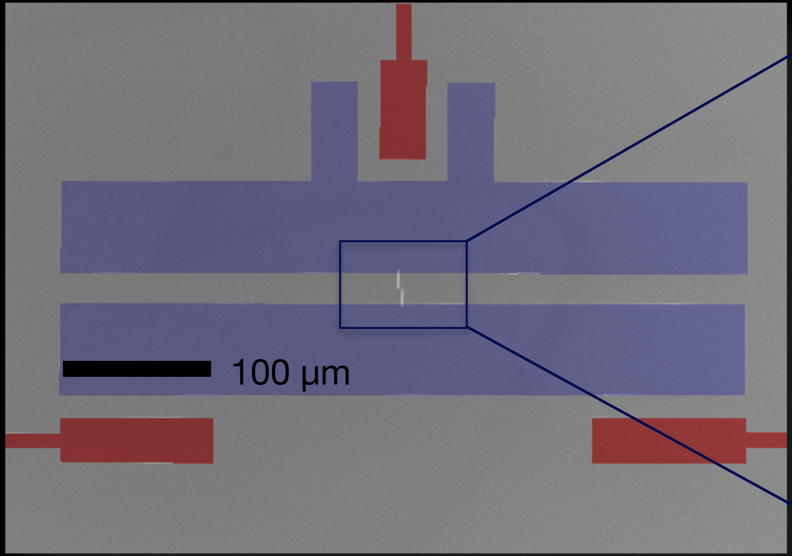
HARDWARE

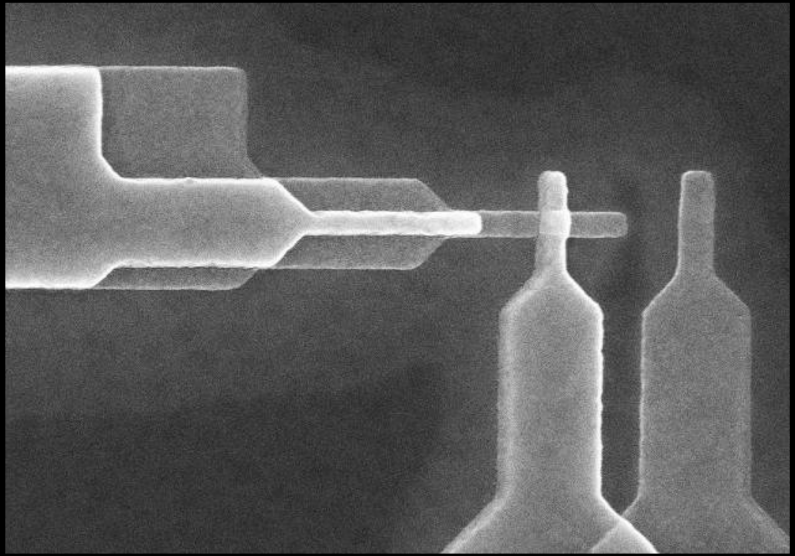


An IBM Quantum Processor



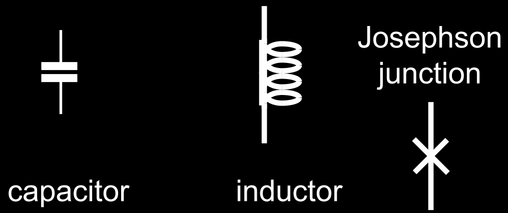
An IBM Quantum Processor



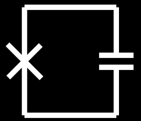


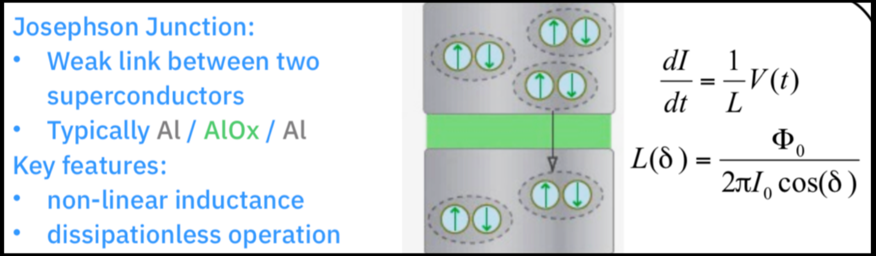
Single-junction transmon qubits

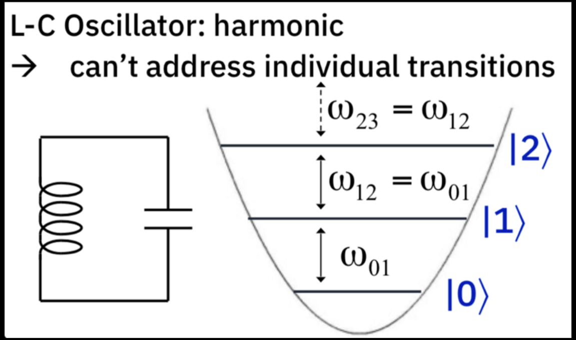
Circuit elements

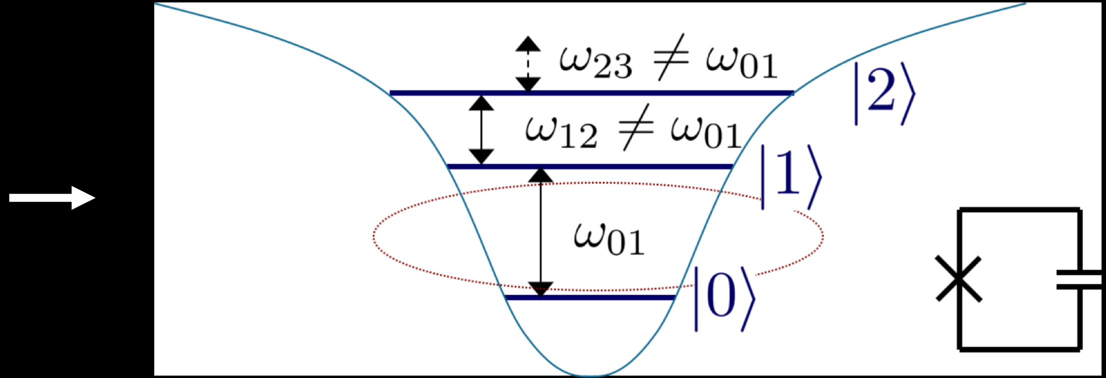


'anharmonic' oscillator



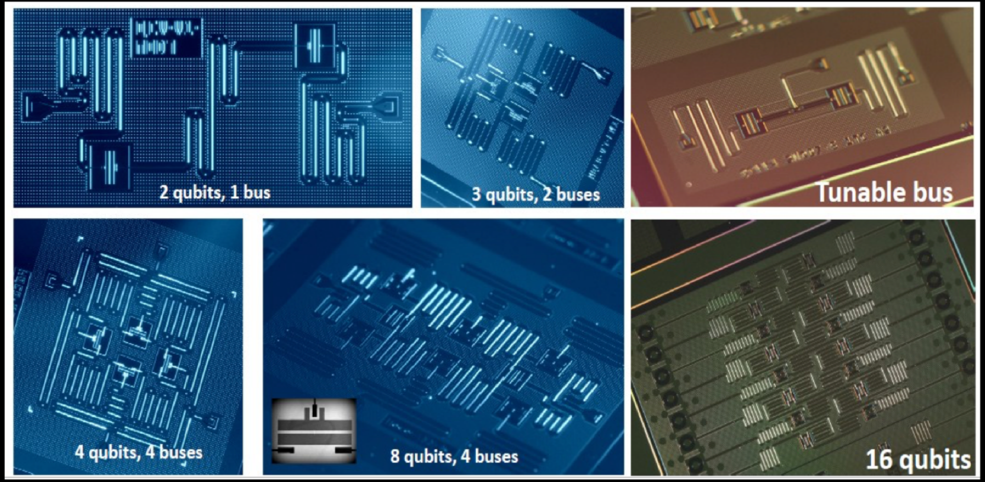


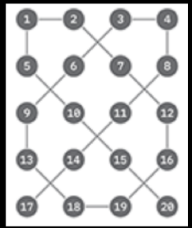




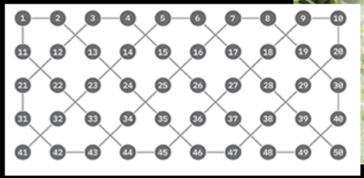
Transmon pioneered by Schoelkopf group, from Yale University
Koch et. al. PRA **76**, 04319 (2007)

Scalability





20 qubits



50 qubits

https://www.ibm.com/blogs/research/2017/11/the-future-is-quantum/
https://www-03.ibm.com/press/us/en/pressrelease/53374.wss

News room > News releases >

IBM Announces Advances to IBM Quantum Systems & Ecosystem

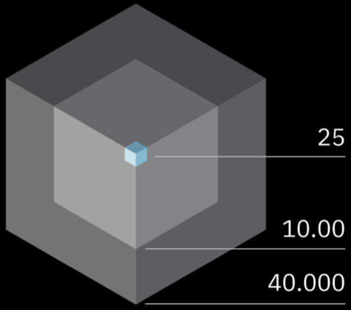
-- Client systems with 20 qubits ready for use; next-generation IBM Q system in development with first working 50 qubit processor
-- IBM expands its open-source quantum software package QISKit; offers the world's most advanced ecosystem for quantum computing

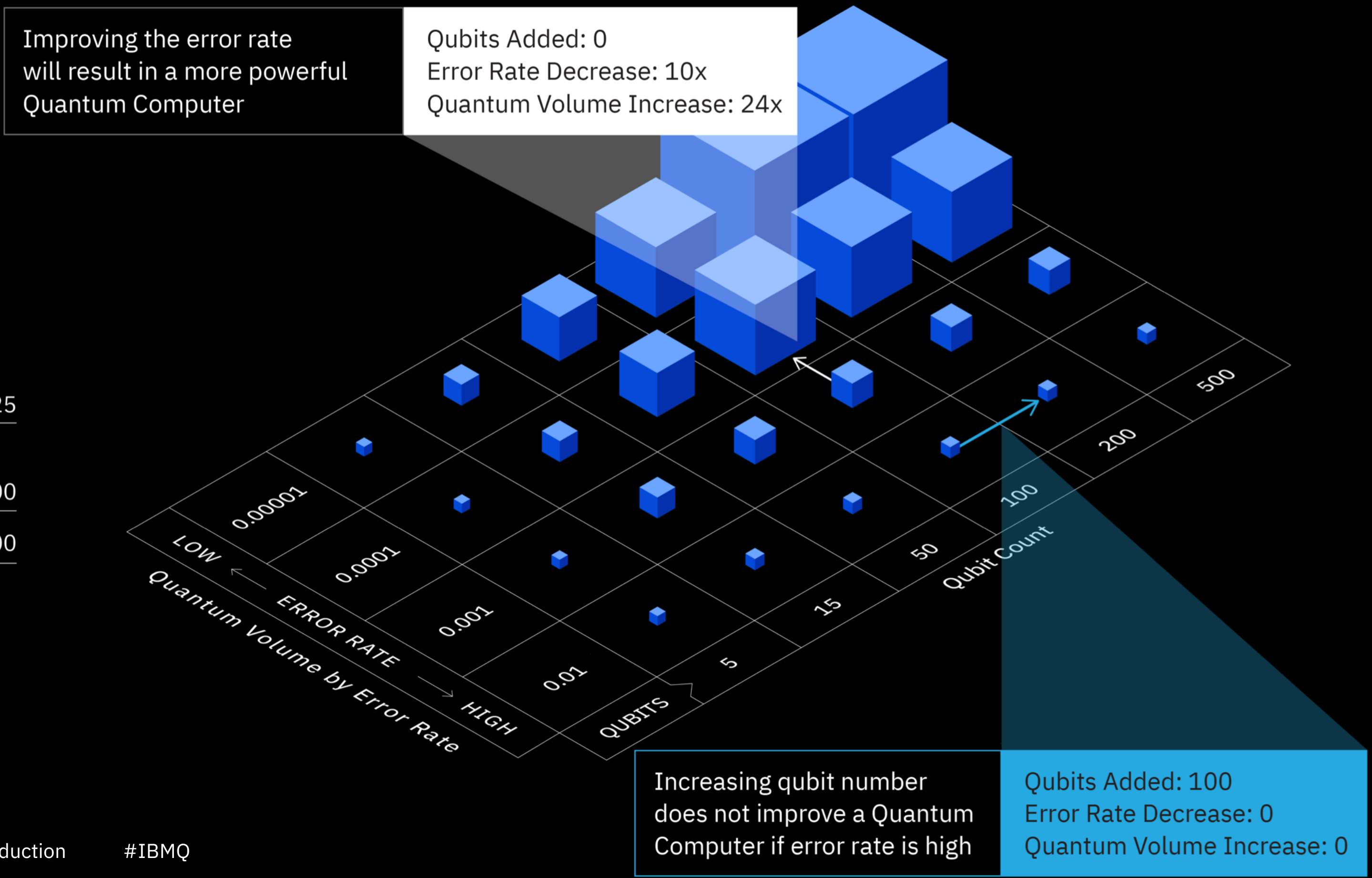
Yorktown Heights, N.Y. - 10 Nov 2017: IBM (NYSE: IBM) announced today two significant quantum processor upgrades for its IBM Q early-access commercial systems. These upgrades represent rapid advances in quantum hardware as IBM continues to drive progress across the entire quantum computing technology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



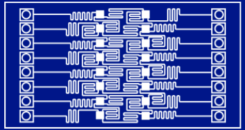


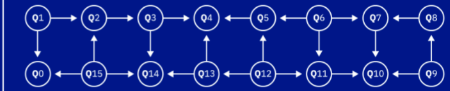
Source: IBM Research

Operating metrics for the IBM **Q** Experience quantum computers are publicly available

IBM Q 20 [QS1_1] — AVAILABLE TO HUBS, PARTNERS, AND MEMBERS OF THE IBM Q NETWORK

IBM Q 16 [ibmqx5] — ACTIVE: USERS | AVAILABLE ON QISKIT





Last Calibration: 2018-04-19 07:30:32
Fridge Temperature: 0.0142945 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)	37.60	28.30	45.80	45.30	24.30	44.40	48.30
T2 (μs)	34.40	39.30	67.40	81.60	25.10	48.20	76.30
Gate error (10^{-3})	1.98	3.84	2.90	2.21	1.99	1.75	2.56
Readout error (10^{-2})	4.26	6.39	5.09	5.29	7.22	4.05	4.77
MultiQubit gate error (10^{-2})		**CX1_0** 4.61	**CX2_3** 3.11	**CX3_4** 5.04		**CX5_4** 4.68	**CX6_5** 4.23
		CX1_2 4.69		**CX3_14** 4.42			**CX6_7** 2.35
							CX6_11 4.75

IBM Q 5.1 [ibmqx4] — ACTIVE: USERS | AVAILABLE ON QISKIT

IBM Q 5 [ibmqx2] — ACTIVE: USERS | AVAILABLE ON QISKIT

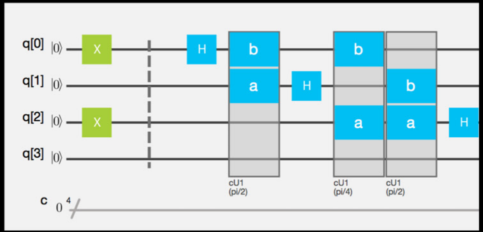
IBM Q QASM Simulator [ibmqx_qasm_simulator] — ACTIVE | SIMULATOR | AVAILABLE ON QISKIT

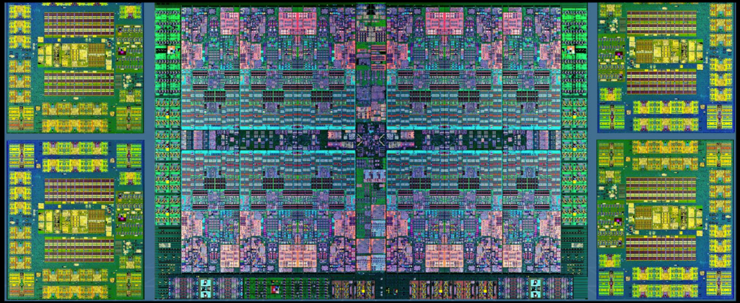
IBM Q QASM HPC Simulator [ibmqx_hpc_qasm_simulator] — ACTIVE | SIMULATOR | AVAILABLE ON QISKIT

```
449a:  ff40 4e00 0400 mov.b    #0x4e, 0x4(r15)
44a0:  ff40 2f00 0500 mov.b    #0x2f, 0x5(r15)
44a6:  ff40 2900 0600 mov.b    #0x29, 0x6(r15)
44ac:  cf43 0700      mov.b    #0x0, 0x7(r15)
44b0:  3041           ret
44b2 <get_password>
44b2:  3e40 6400      mov      #0x64, r14
44b6:  b012 8445      call     #0x4584 <getsn>
44ba:  3041           ret
```

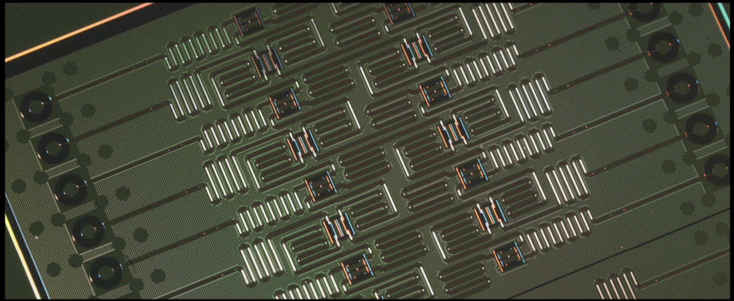
PROGRAMMING LANGUAGE

```
IBMQASM 2.0;
include "qelib1.inc";
qreg q[4];
creg c[4];
x q[0];
x q[2];
barrier q;
h q[0];
cu1(pi/2) q[1],q[0];
h q[1];
cu1(pi/4) q[2],q[0];
```





HARDWARE



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

A Mechanical Qubit

Dr Muir Kumph explains a mechanical analogy of a qubit. It cant explain everything about a qubit but its pretty cool.

JA jaygambetta IBM Staff
Published 5 months ago

quantum computing

The qubit

Our very own Dr Maika Takita @mtakita talking about our qubits and IBM QX devices

JA jaygambetta IBM Staff
Published 5 months ago

quantum computing

Quantum Gates

Dr. Sarah Sheldon @sarahsheldon explains how quantum gates are done in our systems.

JA jaygambetta IBM Staff
Published 5 months ago

quantum gates

Charlie Bennett demonstrating his famous quantum cryptography experiment

IBM Fellow Charlie Bennett explaining his quantum cryptography experiment. This for me is very cool as this is one of the first experiments showing quantum info...

JA jaygambetta IBM Staff
Published 5 months ago

A Beginner's Guide to Quantum Computing

Hey guys! I gave this talk at Maker Faire in San Mateo last weekend. It's intended for total beginners. Enjoy :)

TS tsgersho IBM Staff Published 9 months ago

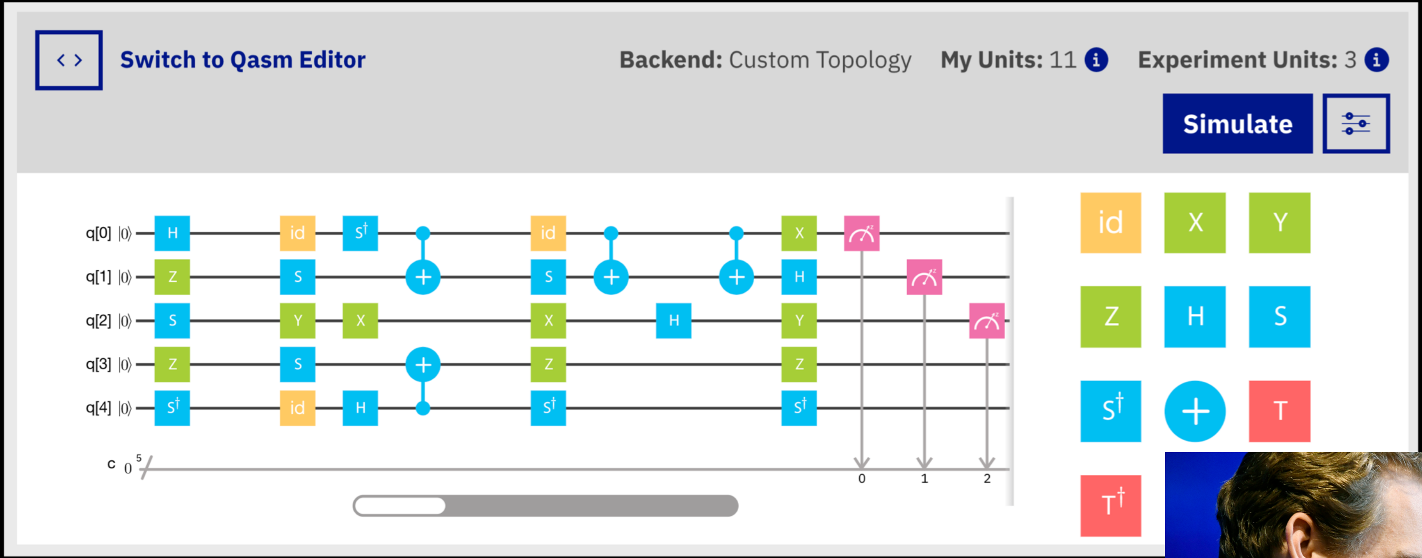
presentation | quantum computing | beginner

IBM Developerworks QISKit tutorial by Lev Bishop

An introduction to quantum computing and the QISKit open source project. QISKit enables developers to conduct explorations on IBM's Quantum Experience using a P...

JM jmchow IBM Staff
Published 10 months ago

quantum computing | qiskit | presentation



Quantum programs for the 5 qubit machine can be constructed visually and then either simulated or run on the hardware.

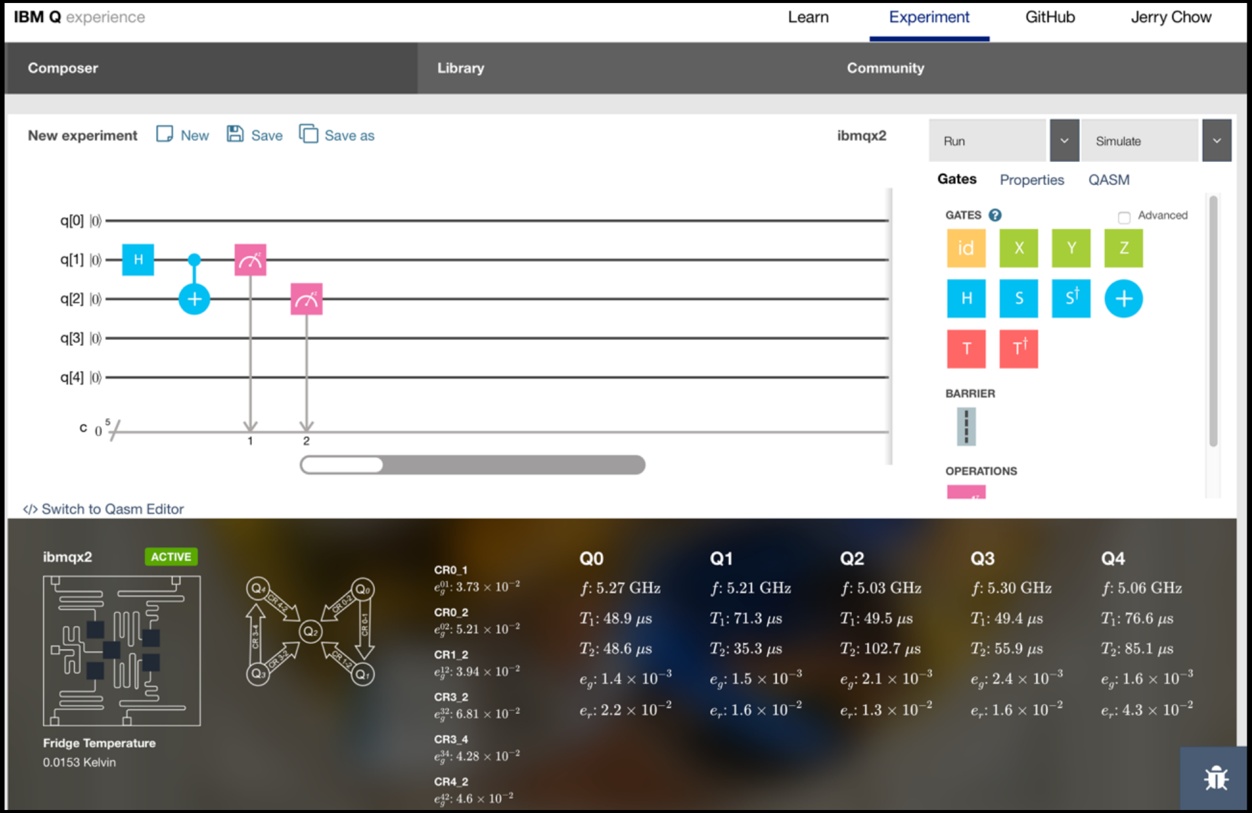
IBM **Q**

IBM Q experience

Launched May 2016
Program 5 qubit quantum processor from any web browser

Upgraded Mar 2017
API access
SDK launched

Upgraded May 2017
16 qubit beta program



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

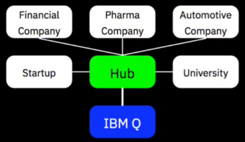
Ismael Faro, Jay Gambetta, Andrew Cross

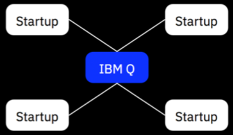
QISKit (Quantum Information Software developer Kit)

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.



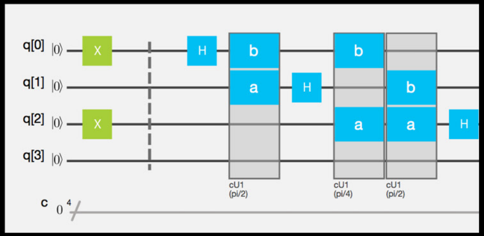


NETWORK

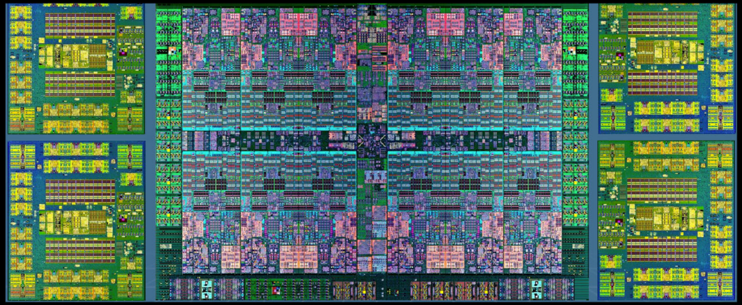
```
449a:  ff40 4e00 0400 mov.b    #0x4e, 0x4(r15)
44a0:  ff40 2f00 0500 mov.b    #0x2f, 0x5(r15)
44a6:  ff40 2900 0600 mov.b    #0x29, 0x6(r15)
44ac:  cf43 0700      mov.b    #0x0, 0x7(r15)
44b0:  3041           ret
44b2 <get_password>
44b2:  3e40 6400      mov      #0x64, r14
44b6:  b012 8445      call     #0x4584 <getsn>
44ba:  3041           ret
```

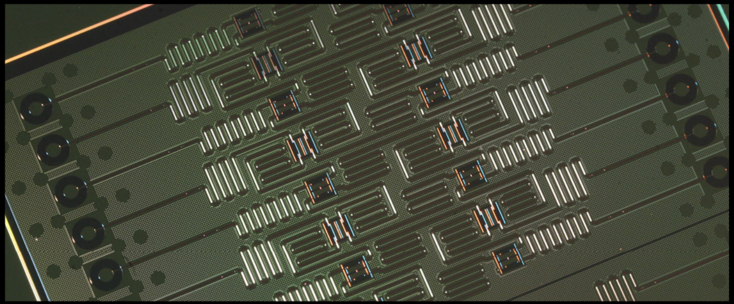
PROGRAMMING LANGUAGE

```
IBMQASM 2.0;
include "qelib1.inc";
qreg q[4];
creg c[4];
x q[0];
x q[2];
barrier q;
h q[0];
cu1(pi/2) q[1],q[0];
h q[1];
cu1(pi/4) q[2],q[0];
```



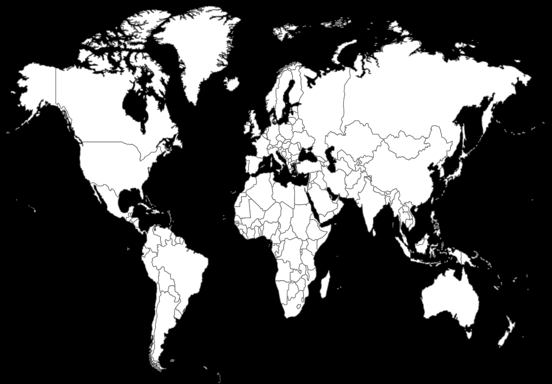
HARDWARE





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.

Recent IBM **Q** Network news

April 5, 2018
Posted in: Quantum Computing

IBM Collaborating With Top Startups to Accelerate Quantum Computing

There's no denying it – we're approaching the dawn of the commercial quantum era – a formative period when quantum computing and its early use cases rapidly develop. Predictably, hype is setting in around the potential for quantum computing to impact our world, as media, VC firms, investors, and the general public continue to learn and understand more about the technology.

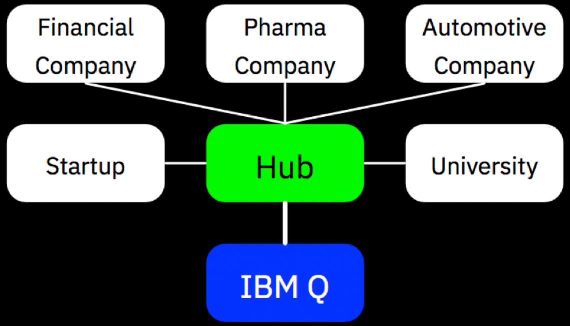
Today, I am joining nearly 100 startup founders, venture capitalists and industry thought leaders at the first IBM Q Summit Silicon Valley event in Palo Alto, CA. The goal of the day: cut through the hype and focus on the present state of quantum computing and how organizations, and developers can prepare for the future.

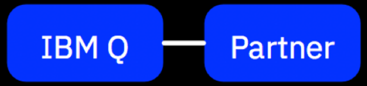
IBM Q Summit attendees are gathering to discuss what to expect over the next five years and what it means to be "quantum ready." The discussion will inevitably also center on the emerging role of the quantum developer and what that means for future application development.

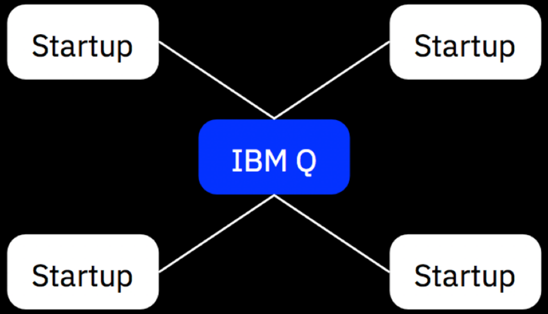
Scientists inside the IBM Q computation center, which houses IBM's most advanced quantum computers, accessed via IBM Cloud by the IBM Q Network.

Today, IBM is taking another substantial step in broadening access to quantum computing. IBM is announcing the first startups to join the IBM Q Network, a worldwide community dedicated to advancing quantum computing and exploring practical applications for business and science. Membership in the network will enable these startups to run experiments and algorithms on IBM quantum computers via cloud-based access. Additionally, these startup members will have the opportunity to collaborate with IBM researchers and technical SMEs on potential applications, as well as other IBM Q Network organizations.

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-wide resources and collaboration

Technical support for system use

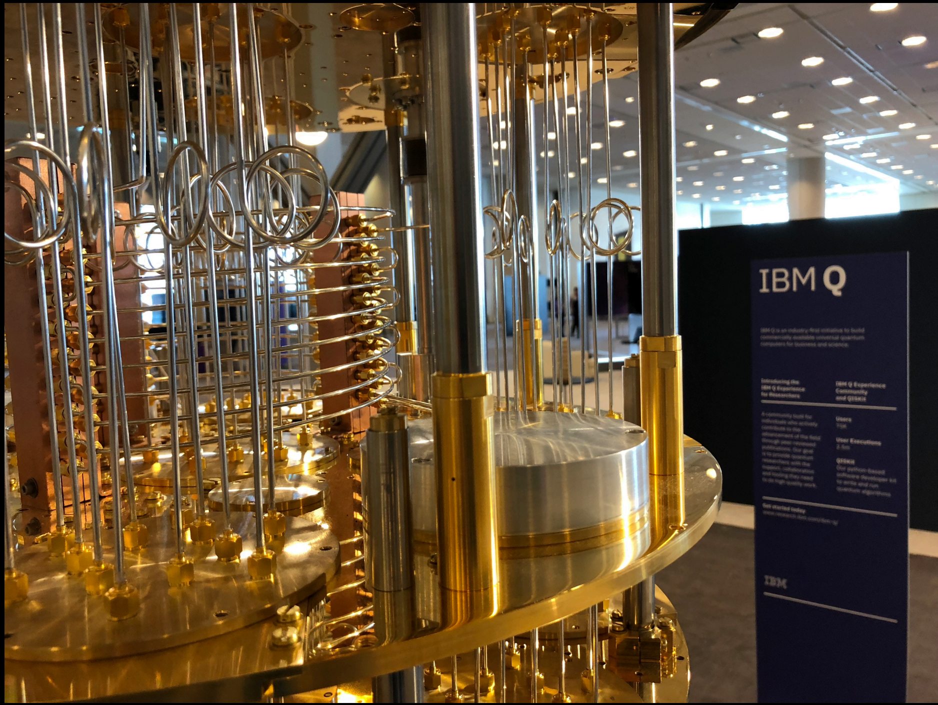
Educational content and resources

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



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

~1900

Quantum Ready

Core algorithm development

Increase quantum volume

Standardize performance benchmarks

System infrastructure and software enablement

2016

2020s

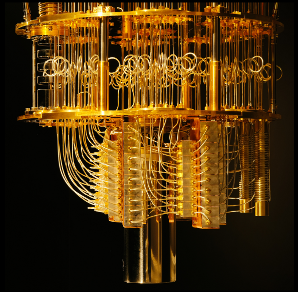
Quantum Advantage

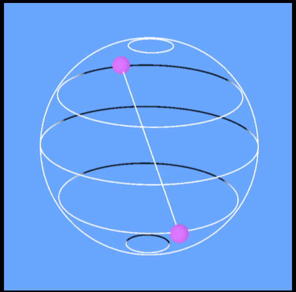
Demonstrate an advantage to using QC for real problems of interest

Extract Commercial Value

Enable scientific discovery

getting Quantum Ready





Discover more about IBM's quantum computing initiative

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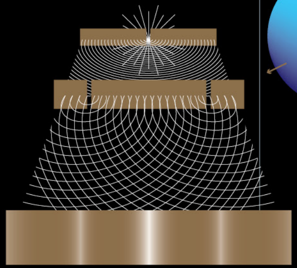
In May of 1981, IBM and MIT hosted the Physics of Computation Conference

The dawn of Quantum Information Science

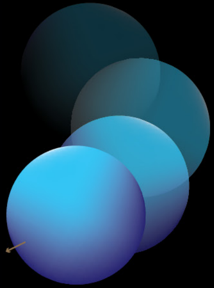
1927

The Uncertainty Principle



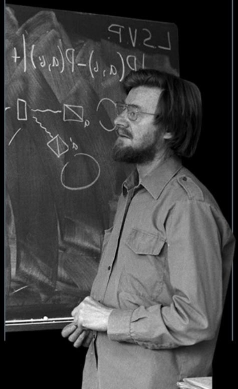
1935

The EPR Paradox



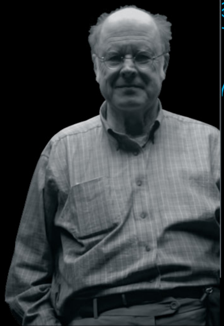
1964

Bell's Inequality



1964

Birth of Quantum Information Theory

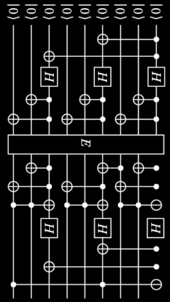


1981

Quantum Call to Arms

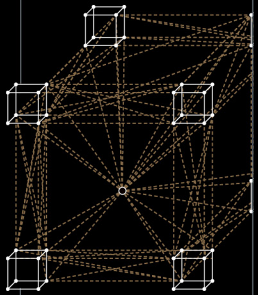
1994

Shor's Factoring Algorithm



1995

Quantum Error Correction



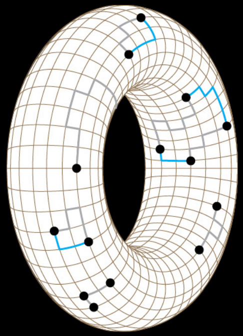
1996

DiVincenzo Criteria

The Building blocks of Quantum Computing

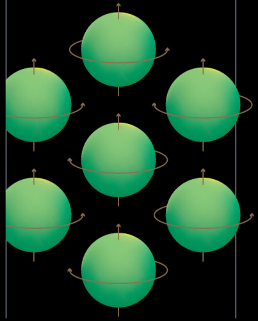
1997

Topological Codes



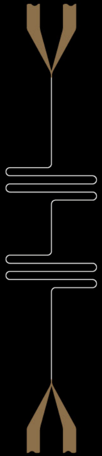
2001

Experimentally Factoring



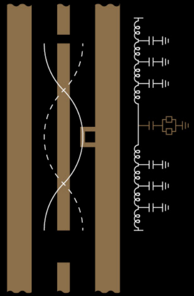
2004

Circuit QED



2007

Transomon Super-conducting Qubit



2012

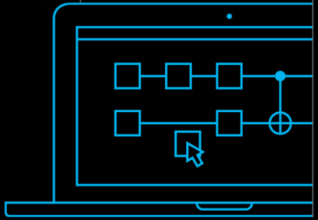
Coherence Time Improvement

2015

[[2,0,2]] Code

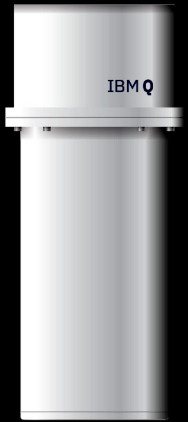
2016

Quantum Computing on IBM Cloud

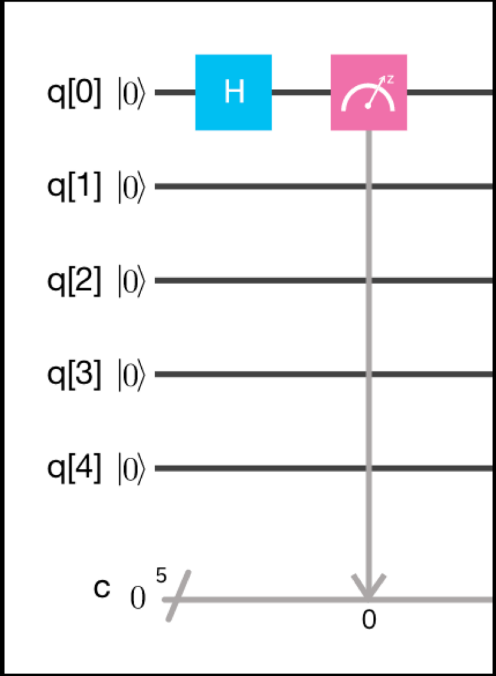


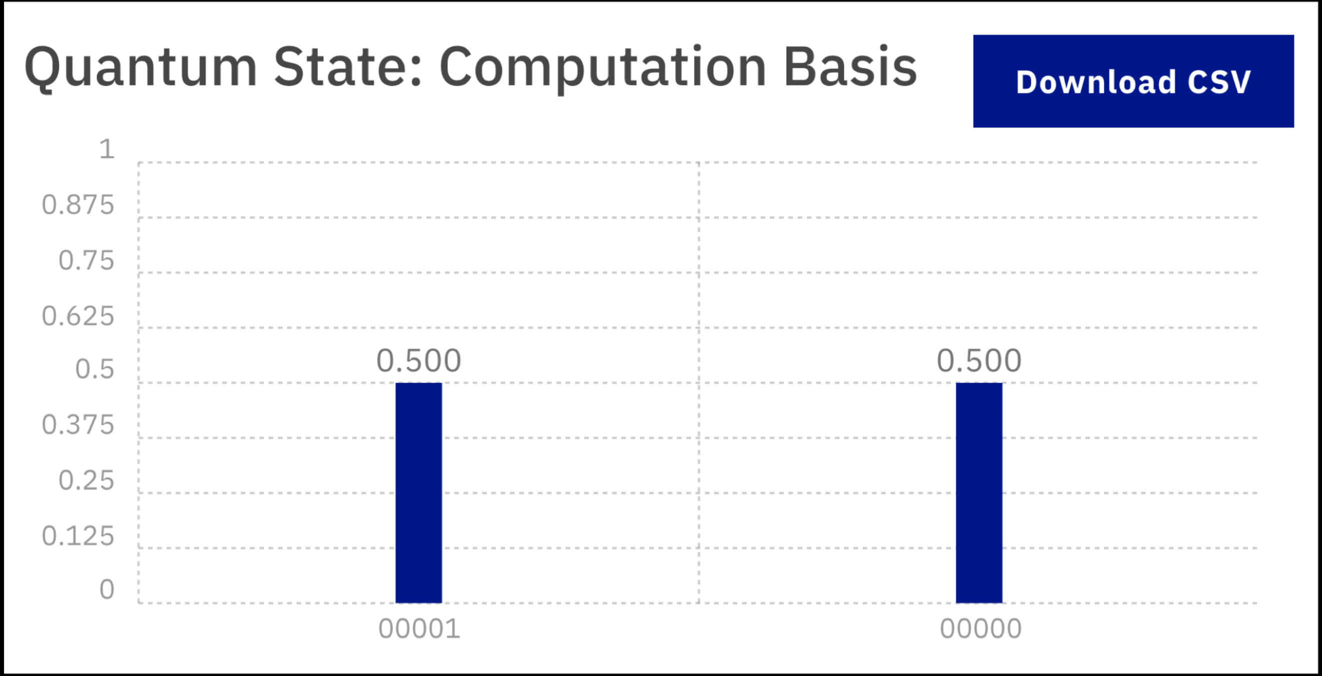
2017

Launch of IBM **Q**



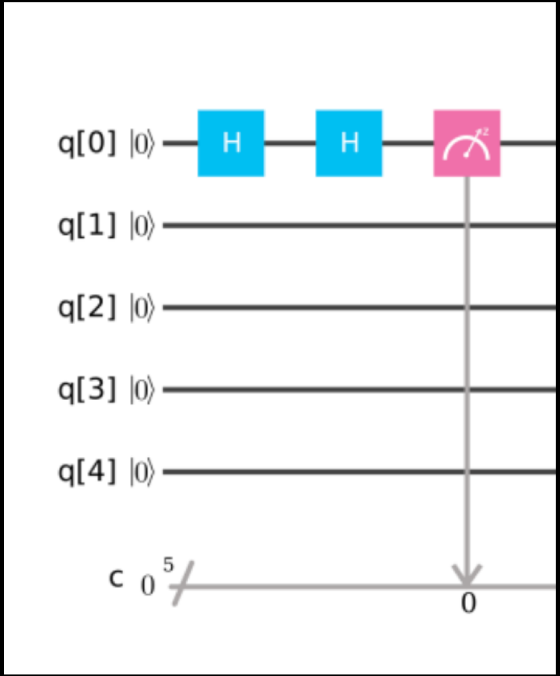
IBM Q Experience Experiment
Apply one Hadamard gate to **0** and measure

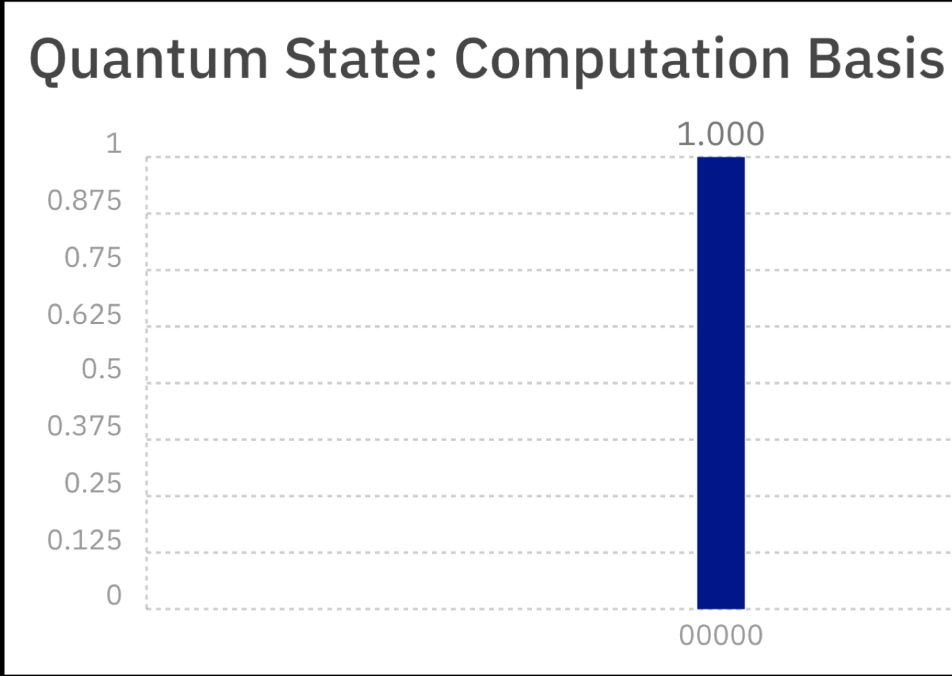




We expect to get **0** half the time and **1** the other half. Random!?

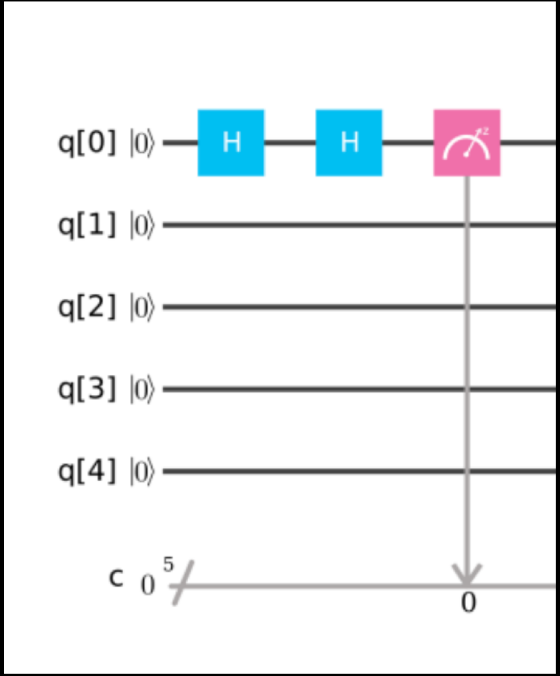
IBM Q Experience Experiment
Apply two Hadamard gates to 0 and measure

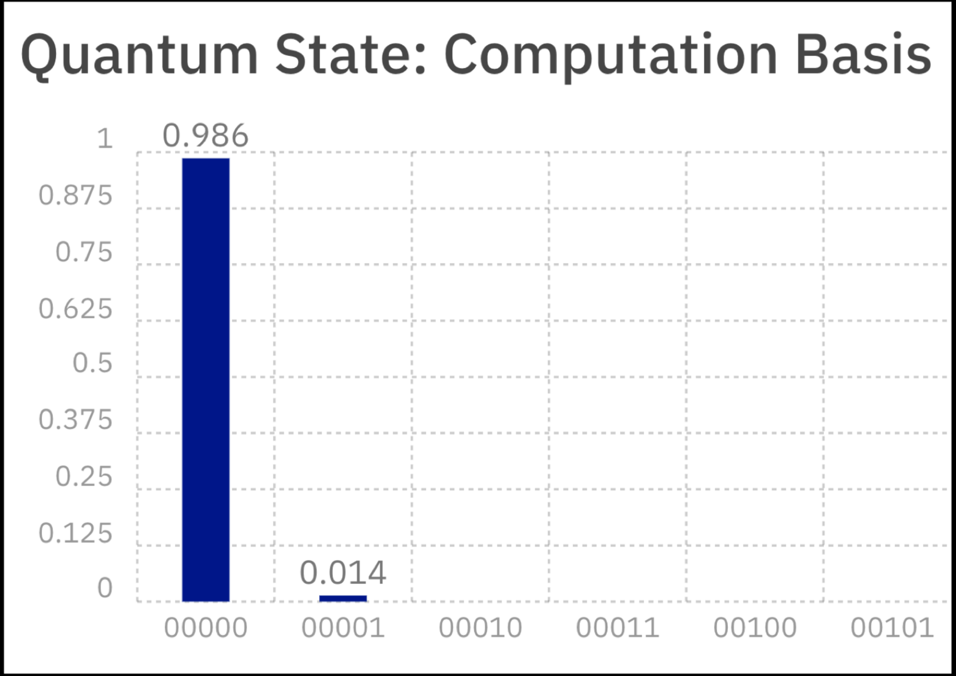




Surely doing it again should give random results. It doesn't!

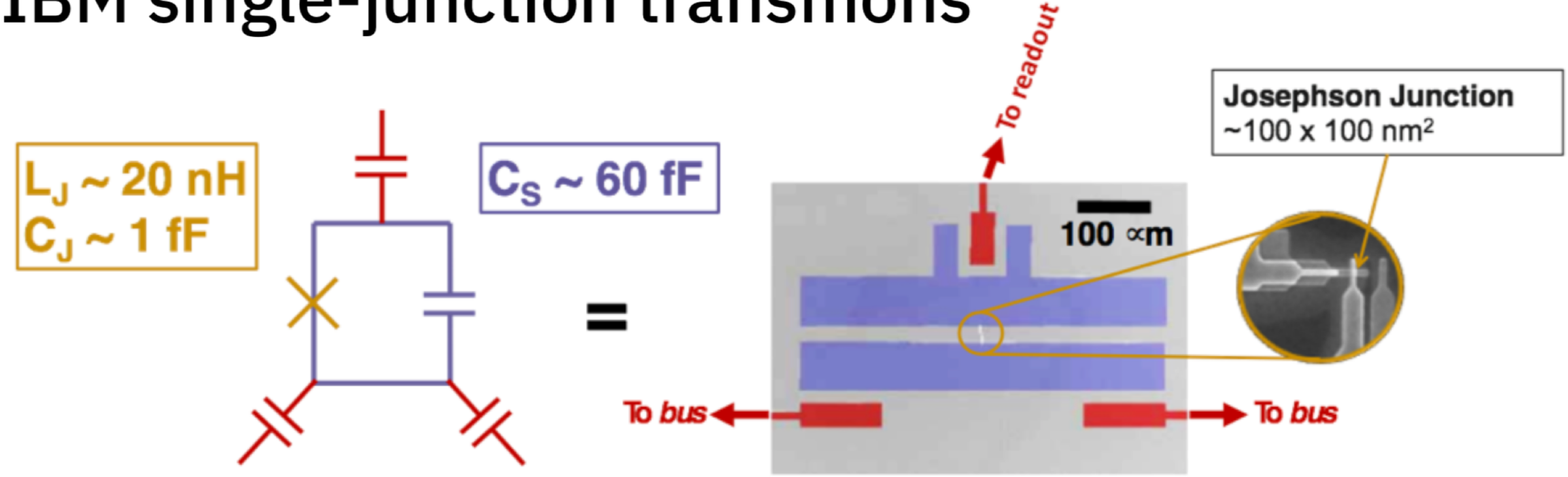
IBM Q Experience Experiment
Apply two Hadamard gates to **0** and measure





With an actual quantum computer, errors enter the picture.

IBM single-junction transmons

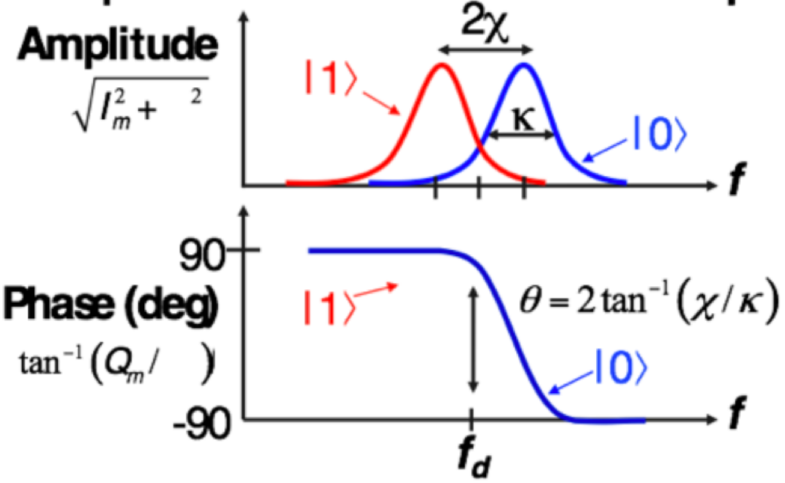


- Patterned superconducting metal (**niobium** + **aluminum**) on silicon
  – Qubit capacitance dominated by **shunting capacitance C_S**
- Resonant frequency ~ **5 GHz** → energy splitting ~ 20 ∝eV, or 240 mK
  → Cool in a dilution refrigerator (~ 10 mK) to reach ground state
- Interactions mediated by **capacitively coupled co-planar waveguide resonators** (circuit QED)

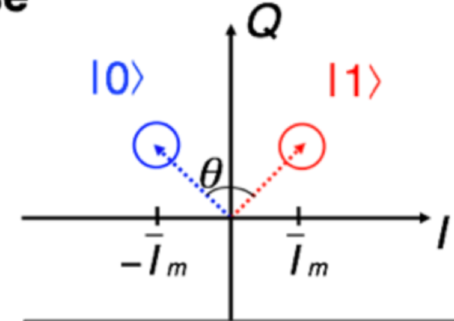
Qubit Readout in cQED

Readout freq. near ω_r; control freq. at ω_0

Resonator frequency depends on qubit state
→ Infer qubit state from resonator response



I = in-phase
Q = out-of-phase



For $2\chi = \kappa$, $\theta = 90°$

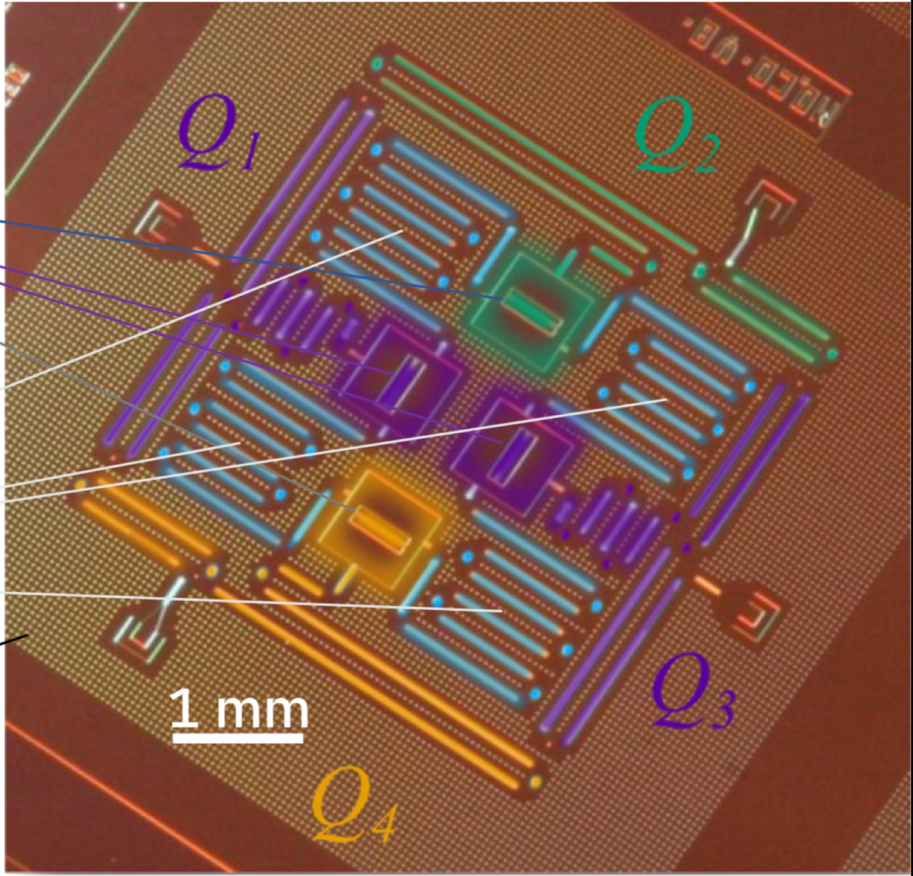
Gambetta et al., PRA 77, 012112 (2008)
Jeffrey et al., PRL 112, 190504 (2014)
Magesan et al., PRL 114, 200501 (2015)

Anatomy of a multi-qubit device

Qubits:
- Single-junction transmon
- Frequency ~ 5 GHz
- Anharmonicity ~ 0.3 GHz

Resonators:
- Co-planar waveguide
- Frequency ~ 6 – 7 GHz
- Roles:
  - Individual qubit readout
  - Qubit coupling ("bus")

Ground plane
Periodic holes prevent stray magnetic field from hurting superconductor performance



Corcoles et al., Nat. Commun. 6, 6979 (2015)