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Google has built a quantum computer. Now what?

A Q&A session*

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* Neither of us were involved in the work from Google that we are about to describe and answer questions on. We're holding this session as researchers who are interested in what Google has achieved and would like to share our view of it and what it means for the state of the field of quantum computing. We do not represent Google, or even Cornell, but only ourselves.

MIT Technology Review

Quantum computing October 23, 2019

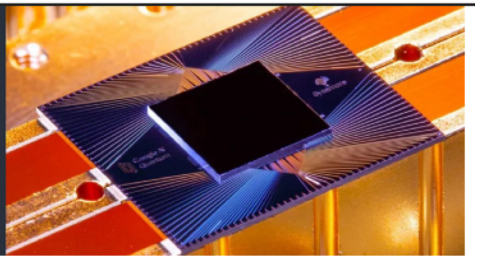
Exclusive: Google CEO Sundar Pichai on achieving quantum supremacy

In an interview, Pichai explains why quantum computing could be as important for Google as AI.

nature

Hello quantum world! Google publishes landmark quantum supremacy claim

Google says that its quantum computer is the first to perform a calculation that would be practically impossible for a classical machine.



OUT THERE?

Quantum Computing Is Coming, Bit by Qubit

With transmons and entanglement, scientists strive to put subatomic weirdness to work on the human scale.

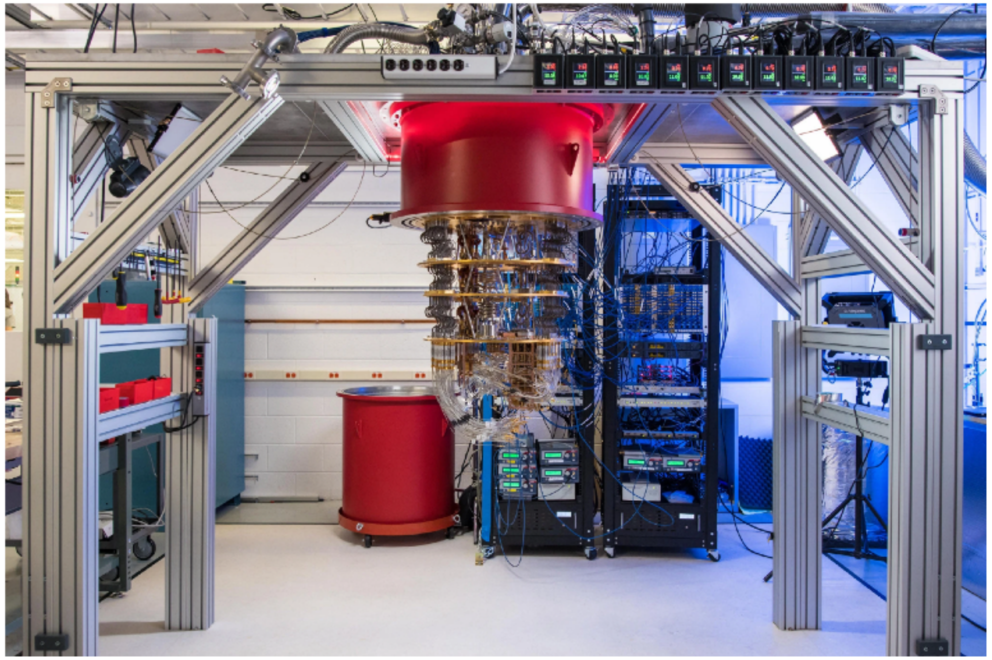
By Dennis Overbye

Oct. 21, 2019 Updated 8:08 a.m. ET

YORKTOWN HEIGHTS, N.Y. — A bolt from the maybe-future struck the technology community in late September. A paper by Google computer scientists appeared on a NASA website, claiming that an innovative new machine called a quantum computer had demonstrated "quantum supremacy."

TECHNOLOGY The New York Times

Google Claims a Quantum Breakthrough That Could Change Computing



Google's quantum computer. The company said in a paper published on Wednesday that the machine needed only a few minutes to perform a task that would take a supercomputer at least 10,000 years.
Google

FORTUNE

TECH • QUANTUM COMPUTING

It's Official: Google Claims 'Quantum Supremacy'

By Robert Hackett October 23, 2019

The Washington Post
Democracy Dies in Darkness

Health & Science

Google touts quantum computing milestone

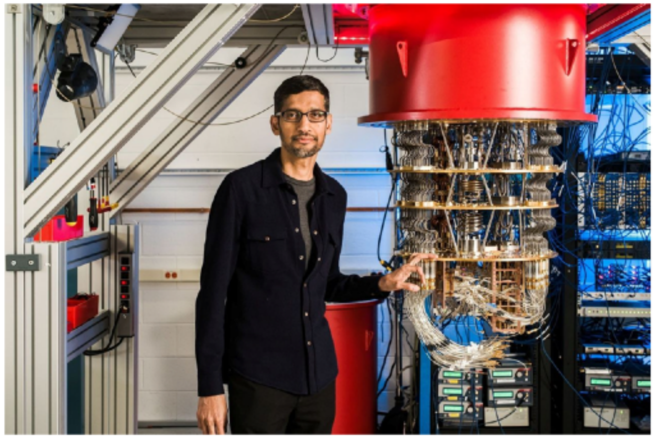
THE WALL STREET JOURNAL.

English Edition ▾ | October 23, 2019 | Print Edition | Video

CIO JOURNAL

Google Claims Breakthrough in Quantum Computing

Others, including IBM, dispute the science behind Google's 'quantum supremacy'



What is the paper we're talking about?

F. Arute, et al. "Quantum supremacy using a programmable superconducting processor." *Nature* **574**, 505 (2019)

(If you want to read more after this session and get information straight from the source, this paper is a good place to start.)

Article

Quantum supremacy using a programmable superconducting processor

https://doi.org/10.1038/s41586-019-1666-5

Received: 22 July 2019

Accepted: 20 September 2019

Published online: 23 October 2019

Frank Arute[1], Kunal Arya[1], Ryan Babbush[1], Dave Bacon[1], Joseph C. Bardin[1,2], Rami Barends[1], Rupak Biswas[3], Sergio Boixo[1], Fernando G. S. L. Brandao[1,4], David A. Buell[1], Brian Burkett[1], Yu Chen[1], Zijun Chen[1], Ben Chiaro[5], Roberto Collins[1], William Courtney[1], Andrew Dunsworth[1], Edward Farhi[1], Brooks Foxen[1,5], Austin Fowler[1], Craig Gidney[1], Marissa Giustina[1], Rob Graff[1], Keith Guerin[1], Steve Habegger[1], Matthew P. Harrigan[1], Michael J. Hartmann[1,6], Alan Ho[1], Markus Hoffmann[1], Trent Huang[1], Travis S. Humble[7], Sergei V. Isakov[1], Evan Jeffrey[1], Zhang Jiang[1], Dvir Kafri[1], Kostyantyn Kechedzhi[1], Julian Kelly[1], Paul V. Klimov[1], Sergey Knysh[1], Alexander Korotkov[1,8], Fedor Kostritsa[1], David Landhuis[1], Mike Lindmark[1], Erik Lucero[1], Dmitry Lyakh[9], Salvatore Mandrà[3,10], Jarrod R. McClean[1], Matthew McEwen[5], Anthony Megrant[1], Xiao Mi[1], Kristel Michielsen[11,12], Masoud Mohseni[1], Josh Mutus[1], Ofer Naaman[1], Matthew Neeley[1], Charles Neill[1], Murphy Yuezhen Niu[1], Eric Ostby[1], Andre Petukhov[1], John C. Platt[1], Chris Quintana[1], Eleanor G. Rieffel[3], Pedram Roushan[1], Nicholas C. Rubin[1], Daniel Sank[1], Kevin J. Satzinger[1], Vadim Smelyanskiy[1], Kevin J. Sung[1,13], Matthew D. Trevithick[1], Amit Vainsencher[1], Benjamin Villalonga[1,14], Theodore White[1], Z. Jamie Yao[1], Ping Yeh[1], Adam Zalcman[1], Hartmut Neven[1] & John M. Martinis[1,5*]

The promise of quantum computers is that certain computational tasks might be executed exponentially faster on a quantum processor than on a classical processor[1]. A fundamental challenge is to build a high-fidelity processor capable of running quantum algorithms in an exponentially large computational space. Here we report the use of a processor with programmable superconducting qubits[2–7] to create quantum states on 53 qubits, corresponding to a computational state-space of dimension 2^{53} (about 10^{16}). Measurements from repeated experiments sample the resulting probability distribution, which we verify using classical simulations. Our Sycamore processor takes about 200 seconds to sample one instance of a quantum circuit a million times—our benchmarks currently indicate that the equivalent task for a state-of-the-art classical supercomputer would take approximately 10,000 years. This dramatic increase in speed compared to all known classical algorithms is an experimental realization of quantum supremacy[8–14] for this specific computational task, heralding a much-anticipated computing paradigm.

In the early 1980s, Richard Feynman proposed that a quantum computer would be an effective tool with which to solve problems in physics and chemistry, given that it is exponentially costly to simulate large quantum systems with classical computers[1]. Realizing Feynman's vision poses substantial experimental and theoretical challenges. First, can a quantum system be engineered to perform a computation in a large enough computational (Hilbert) space and with a low enough error rate to provide a quantum speedup? Second, can we formulate a problem that is hard for a classical computer but easy for a quantum computer? By computing such a benchmark task on our superconducting qubit processor, we tackle both questions. Our experiment achieves quantum supremacy, a milestone on the path to full-scale quantum computing[8–14].

In reaching this milestone, we show that quantum speedup is achievable in a real-world system and is not precluded by any hidden physical laws. Quantum supremacy also heralds the era of noisy intermediate-scale quantum (NISQ) technologies[15]. The benchmark task we demonstrate has an immediate application in generating certifiable random numbers (S. Aaronson, manuscript in preparation); other initial uses for this new computational capability may include optimization[16,17], machine learning[18–21], materials science and chemistry[22–24]. However, realizing the full promise of quantum computing (using Shor's algorithm for factoring, for example) still requires technical leaps to engineer fault-tolerant logical qubits[25–29].

To achieve quantum supremacy, we made a number of technical advances which also pave the way towards error correction. We

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What is quantum computational supremacy?

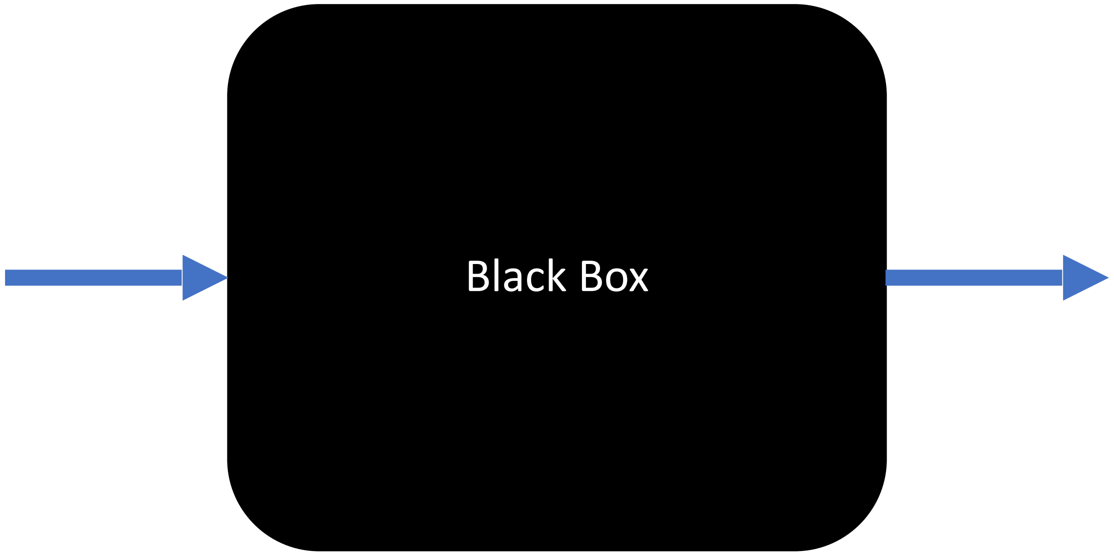
- Google's quantum computer has been used to **perform a computation that takes even a supercomputer much longer to do**. (200 seconds vs >2.5 days)

- **Quantum computational supremacy** is usually defined as the regime where a QC performs a computation that cannot be plausibly performed classically. (It seems like Google is not actually quite at this point yet, but because the difficulty of simulating a QC grows exponentially in the number of qubits, they just need to add another 10-20 more qubits to be solidly in the supremacy regime.)

- **Important caveat**: supremacy experiments solve a very **contrived** computational problem (more on this later). Nevertheless, this is a massive milestone. Think of it like the **moon landing**: it's not directly useful (e.g., by giving us practical access to resources on the moon), but is a milestone human achievement that paves the way for future human exploration and technology that is useful. *Other analogies*: **Sputnik**; **Wright Flyer**.

What task did Google's QC perform?

Circuit C

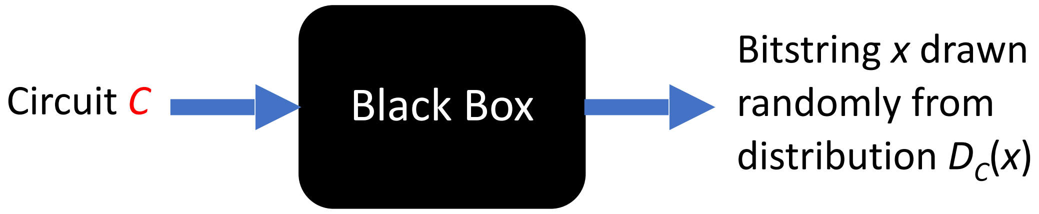


Bitstring x drawn randomly from distribution $D_C(x)$

It is understood that classically **sampling from $D_C(x)$ is hard**.

See: A. Bouland, et al. *Nature Physics* **15**, 159 (2019)
S. Aaronson and S. Gunn. *arXiv*:1910.12085 (2019)

Random-Circuit Sampling



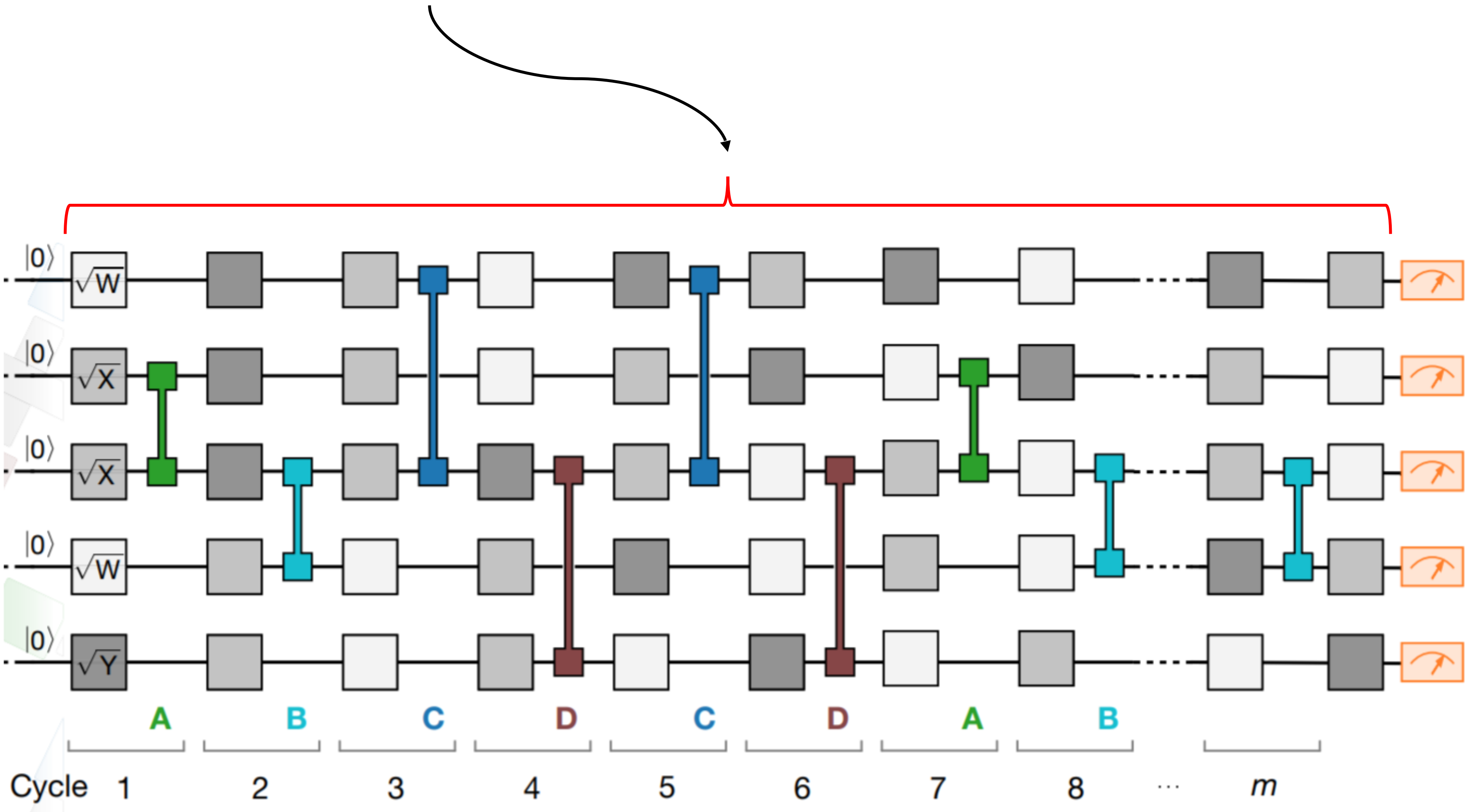
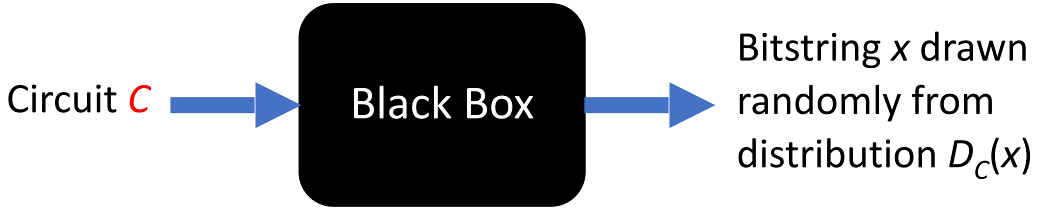


Figure modified from: F. Arute, et al. *Nature* **574**, 505 (2019)

Random-Circuit Sampling



For those already familiar with QC, the distribution is: $D_C(x) = \left|\langle x| \, C \, |0^{\otimes n}\rangle\right|^2$

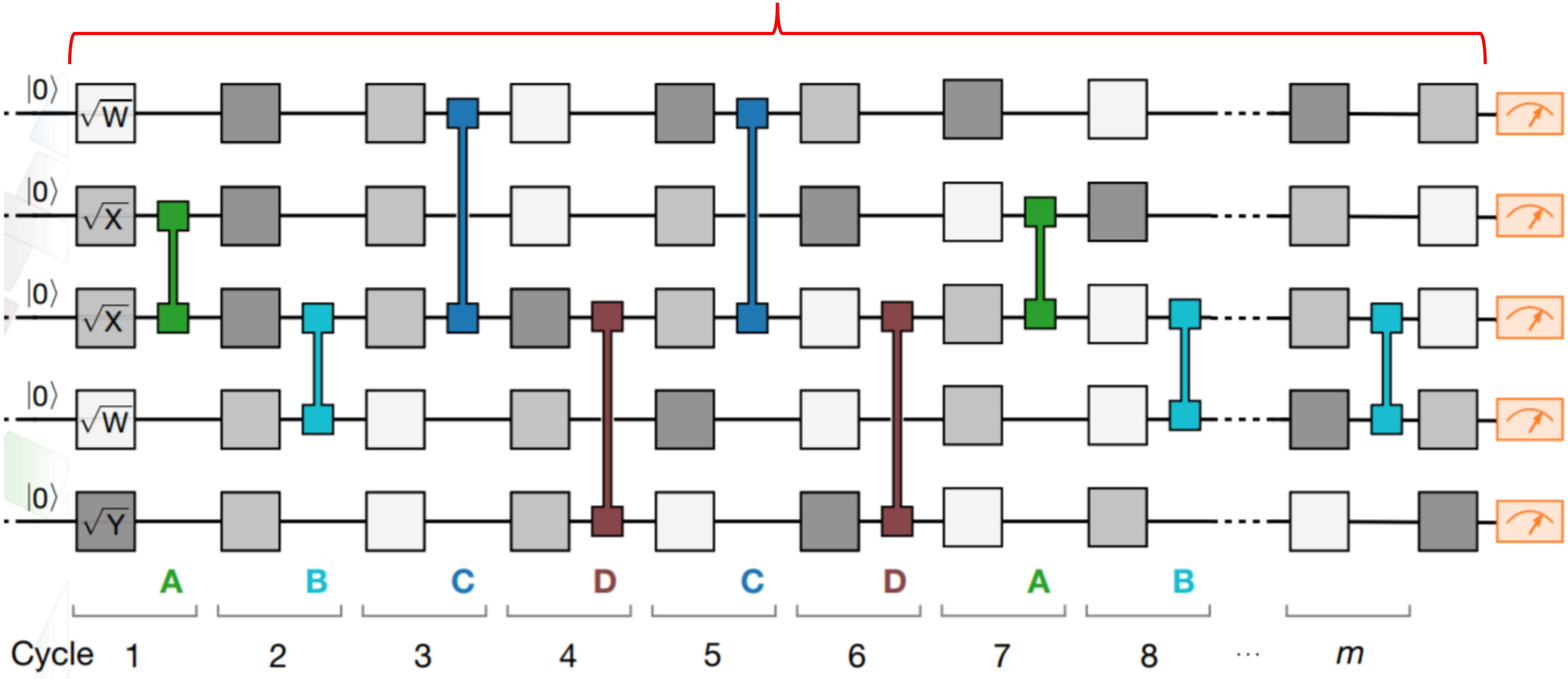


Figure modified from: F. Arute, et al. *Nature* **574**, 505 (2019)

The exact hardware used is not particularly important. (At least not conceptually / from a user's perspective.)

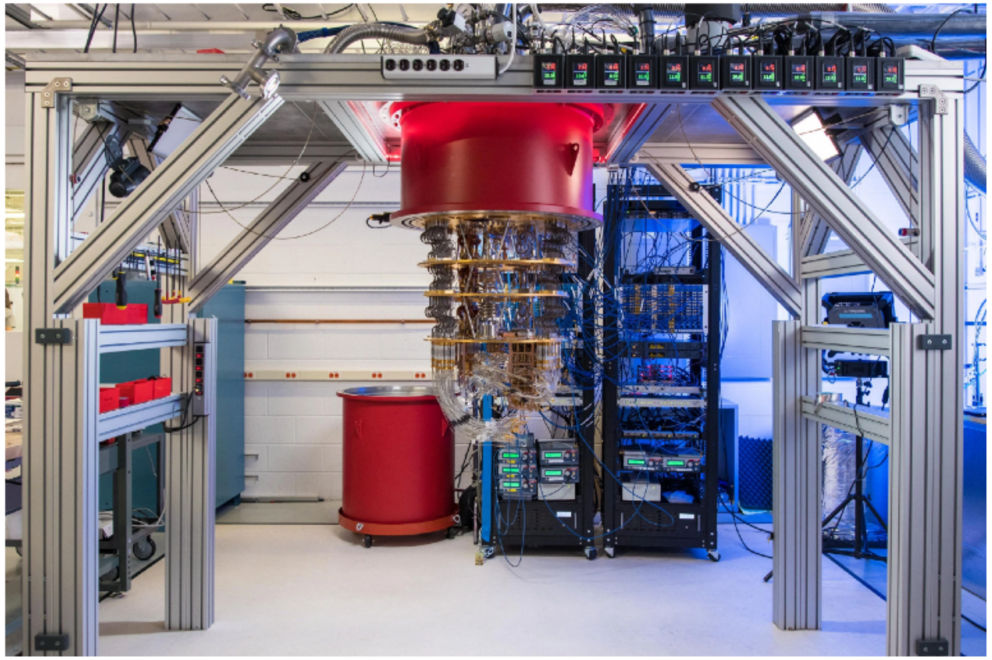


Figure credit: New York Times

- **Google's QC** uses **superconducting-circuit qubits**. However, their experiment, and quantum computers in general, can be understood without any knowledge of the underlying hardware. The **abstraction layer** that is relevant in this session is the one of **quantum circuits**.
- It is an **accident of history** that this supremacy-related milestone has been achieved using superconducting-circuit qubits. There are multiple other candidate physical platforms with which one can build quantum computers, and in which we will likely soon see similarly powerful machines. **Trapped-ion** and **neutral-atom** platforms are very advanced. There is also much interesting progress in **photonic** quantum computers. S**emiconductor-quantum-dot** qubits are still being actively pursued. All of these technologies are undergoing active development in academia and in industry.
- ***Take-home message***: you don't need to worry about the hardware details of how Google built their computer if you don't want to, although of course the hardware-inclined among you will likely find this very interesting too!

Is this the first ever quantum computer?

- **No!** But it is the first to *have enough qubits* and be *low-noise enough* to be faster than a supercomputer at some task.*
- *Very brief history*:
  - 1998: NMR 2-qubit QC (Deutsch's Algorithm)
  - 2001: NMR 7-qubit QC (Shor's Algorithm)
  - 2009: Superconducting-Circuit 2-qubit QC (Grover's Algorithm)
  - 2009: Photonic 4-qubit QC (Shor's Algorithm)
  - 2016: Trapped-Ion 11-qubit QC (Shor's Algorithm)
  - 2018: Superconducting-Circuit 9-qubit QC (Random Circuits)
  - 2019: Superconducting-Circuit 53-qubit QC (Random Circuits)

* A criterion generally agreed upon in the community as being necessary for a QC to be called a QC is that it should be programmable. There have been some quantum simulators demonstrated over the past few years that may or may not be hard to simulate on the supercomputer, but they are not generally considered contenders for quantum computational supremacy because of their lack of programmability.

Error Correction and Fault Tolerance

- **Physical qubits are intrinsically noisy.** Despite this, at the scale of 10's-100's of qubits, and with circuit depths of 10's-100's of gates, we can perform *some* meaningful computations that deliver a speedup over classical computing. (Google has now demonstrated this for one particular computation.)
- **Most quantum algorithms** need numbers of qubits and circuit depths that are far beyond what can feasibly be run **without correcting errors** that occur due to noise.
- The solution to this has been worked out in principle – one needs to build a **fault-tolerant QC** that incorporates **error correction** – but a lot of work remains to be done to build a fault-tolerant QC in practice.
- This is arguably the **central challenge** for QC for the next 10-50 years.

We are not yet at the point where QCs can run most known quantum algorithms and deliver speedups.

- Explicitly:
  - **Shor's Algorithm cannot run at meaningful scale on pre-fault-tolerant QCs**, so we do not expect Shor's Algorithm to become practically useful for factoring large numbers for at least 10 more years.
  - **Grover's algorithm also cannot run at meaningful scale on pre-fault-tolerant QCs**, so we similarly do not expect Grover's Algorithm (or derivatives thereof) to become practically useful for at least 10 more years.
  - Combining these two predictions: it is not likely that public-key cryptography or cryptocurrencies will become vulnerable to attacks from QCs for at least 10 more years.

If you want to read more about this, see: D. Aggarwal, et al. "Quantum attacks on Bitcoin, and how to protect against them." arXiv:1710.10377 (2017)

What *might** near-term quantum computers be useful for?

- **Quantum Simulation**
  - Variational Quantum Eigensolver (for Chemistry, Physics, Materials Science)
  - Tensor Networks (for High-Energy Physics)
- **Optimization**
  - Quantum Approximate Optimization Algorithm
- **Machine Learning**
  - Quantum Neural Networks

If you want to read more about the above, there are several paper suggestions in the NISQ reading list at: http://mcmahon.aep.cornell.edu/research.html

* Nobody knows for sure that near-term quantum computers will actually be useful for any practical application. But it's certainly interesting to try find out what, if anything, we can benefit from running on near-term quantum computers now that we have machines we can play with!

How to study quantum computing at Cornell

- *Coursework*
  - **PHYS 4481** / **CS 4812**: Quantum Information Processing
  - **AEP 2550**: Quantum Information Hardware Engineering (*new in Spring 2020*)

- *Research*
  - **AEP 4900**: Independent Study in Engineering Physics
  - **PHYS 4490**: Independent Study in Physics

(And Independent Study in other departments, depending on which faculty member you work with.)

Look out for a new **Quantum Science and Engineering at Cornell** website that will be launched, which will contain a comprehensive list of people at Cornell working on topics related to quantum computing, as well as other useful resources for students wanting to get involved in quantum research. (*Contact person*: Mark Hurwitz)