Breaking News…

- Google claims quantum supremacy
- IBM announces Quantum Computation Center and 53-qubit system

FINANCIAL TIMES

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Google claims to have reached quantum supremacy

Researchers say their quantum computer has calculated an impossible problem for ordinary machines

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Rivals rubbish Google's claim of quantum supremacy

Researchers take aim at tech company for declaring computing milestone

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NASA/TP-2019-220319

Quantum Supremacy Using a Programmable Superconducting Processor

Eleanor G. Rieffel
NASA Ames Research Center

Quantum supremacy using a programmable superconducting processor

Google AI Quantum and collaborators[†]

The tantalizing promise of quantum computers is that certain computational tasks might be executed exponentially faster on a quantum processor than on a classical processor. A fundamental challenge is to build a high-fidelity processor capable of running quantum algorithms in an exponentially large computational space. Here, we report using a processor with programmable superconducting qubits to create quantum states on 53 qubits, occupying a state space $2^{53} \sim 10^{16}$. Measurements from repeated experiments sample the corresponding probability distribution, which we verify using classical simulations. While our processor takes about 200 seconds to sample one instance of the quantum circuit 1 million times, a state-of-the-art supercomputer would require approximately 10,000 years to perform the equivalent task. This dramatic speedup relative to all known classical algorithms provides an experimental realization of quantum supremacy on a computational task and heralds the advent of a much-anticipated computing paradigm.

Rod Van Meter @rdviii · 16h

By my count, on the new Google supremacy paper, there are 1.43 authors per qubit.

39

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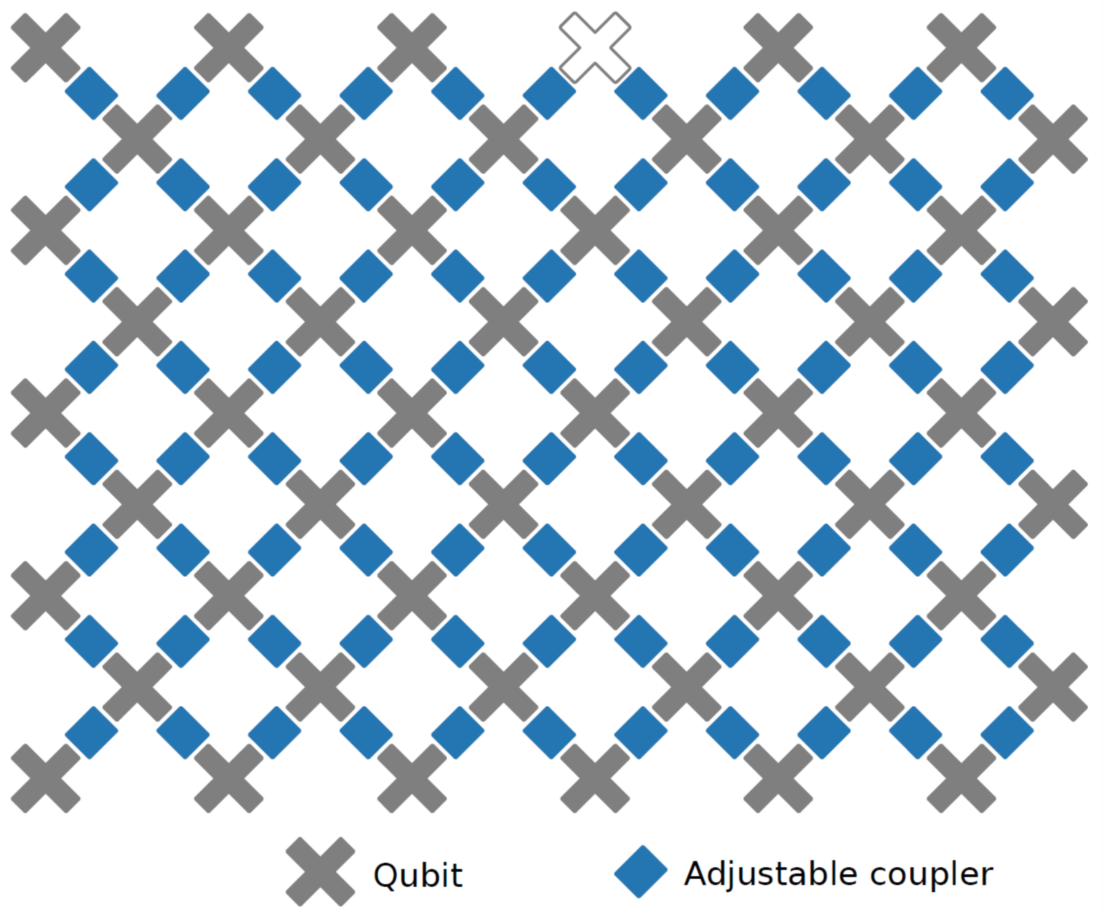
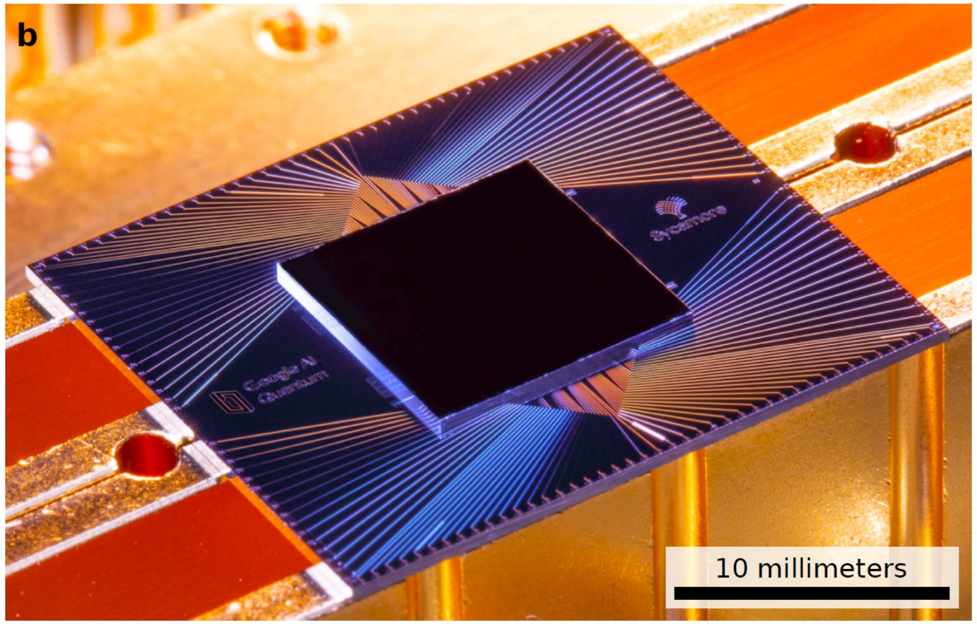
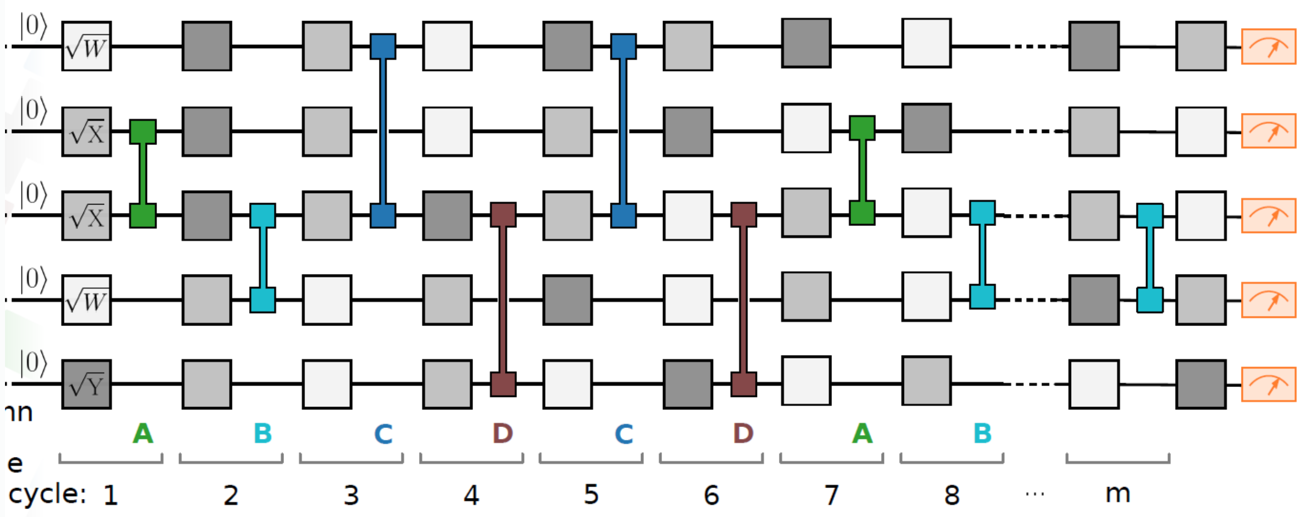
The Chip (Sycamore)





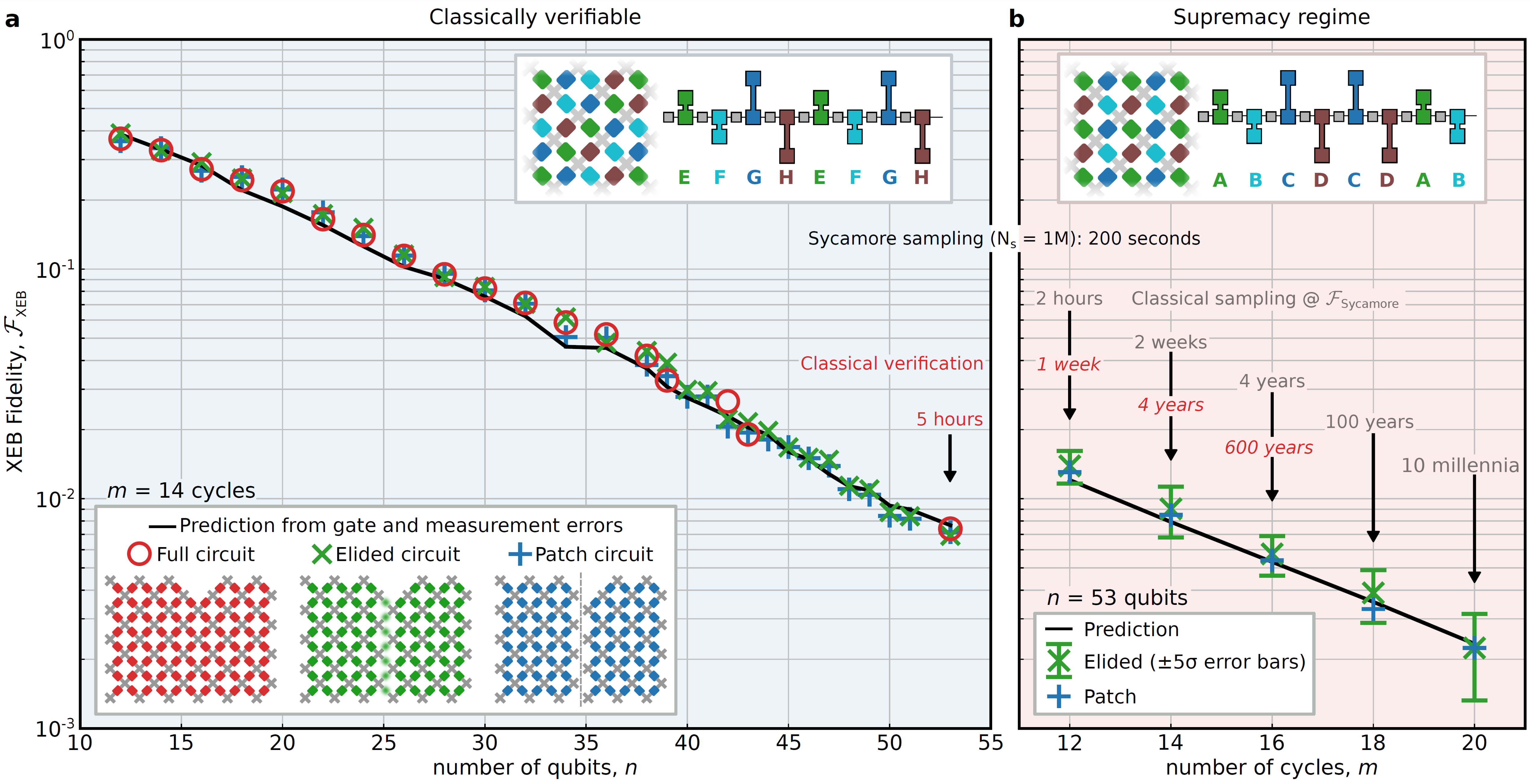
Quantum Supremacy

- What is the task?
  - sampling the output of a pseudo-random quantum circuit
  - probability distribution of the [measured] bitstrings resembles a speckled intensity pattern produced by light interference in laser scatter
  - classically computing […] becomes exponentially more difficult as the number of qubits (width) and number of gate cycles (depth) grows



$$\mathcal{F}_{\mathrm{XEB}} = 2^n \langle P(x_i) \rangle_i - 1$$

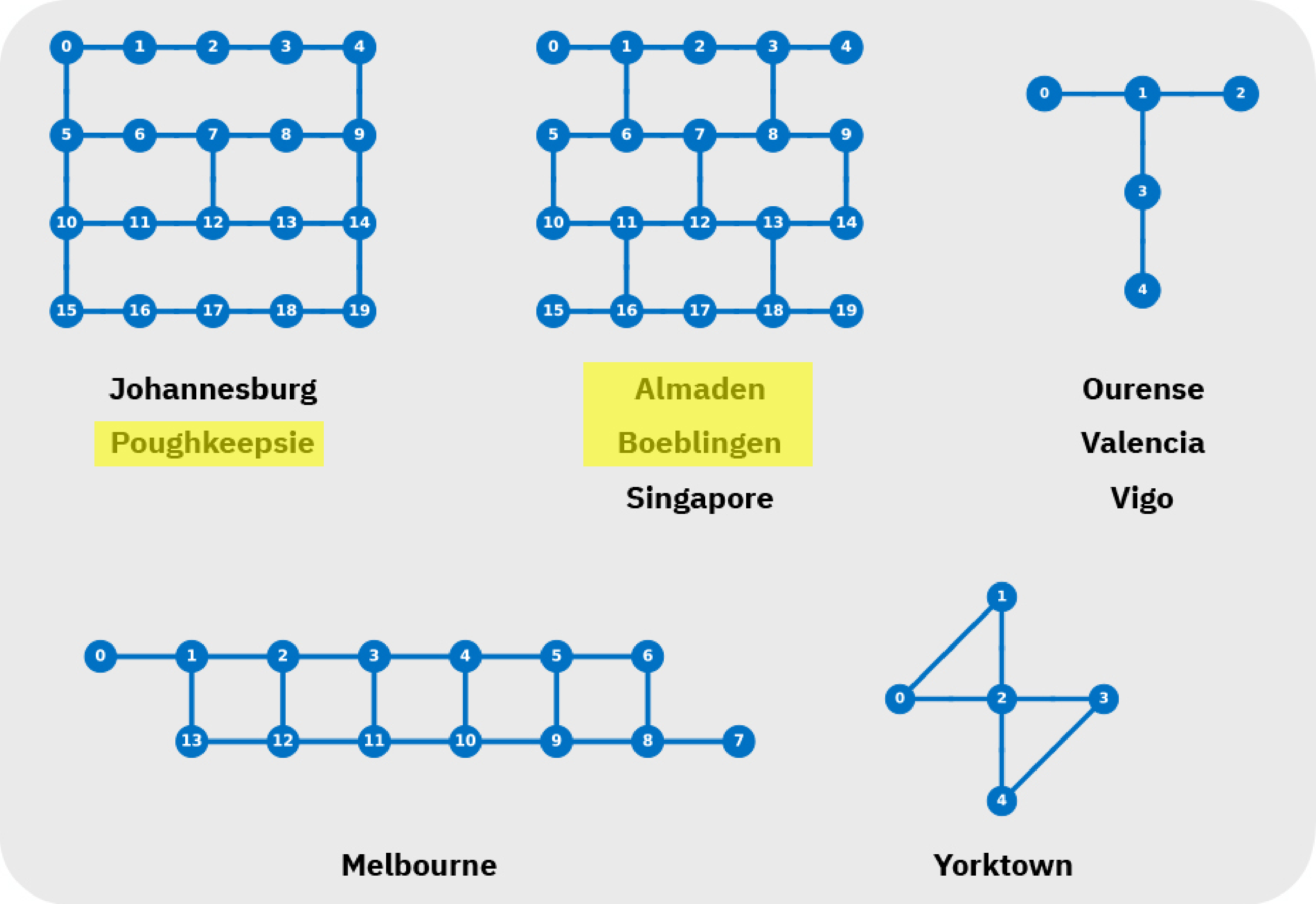
53 qubits, 1113 single-qubit gates, 430 two-qubit gates = 0.002



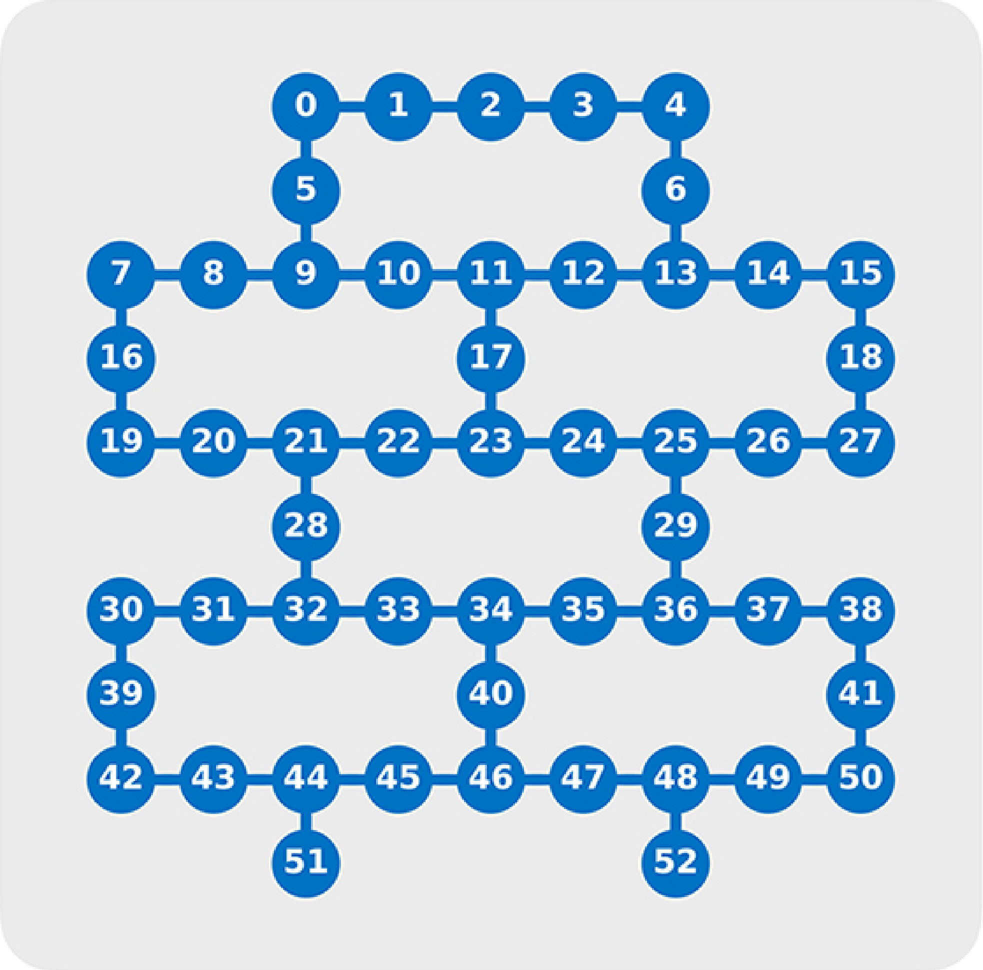
a
Classically verifiable
b
Supremacy regime
E F G H E F G H
A B C D C D A B
Sycamore sampling (N$_s$ = 1M): 200 seconds
Classical verification
5 hours
m = 14 cycles
Prediction from gate and measurement errors
Full circuit
Elided circuit
Patch circuit
XEB Fidelity, $\mathcal{F}_{XEB}$
number of qubits, n
2 hours
Classical sampling @ $\mathcal{F}_{Sycamore}$
1 week
2 weeks
4 years
4 years
600 years
100 years
10 millennia
n = 53 qubits
Prediction
Elided (±5σ error bars)
Patch
number of cycles, m

IBM Quantum Computing Center

IBM's 10 Quantum Device Lineup



53 Qubit Rochester Device



Deutsch-Josza Algorithm

Problem: Given an *n*-bit Boolean function (mapping *n* bits to 1) that is known to be either constant or balanced, determine whether it is balanced or constant. A function is "balanced" if an equal number of input values return 0 and 1.

Apply phase shift of π to negate elements where $f(x) = 1$.
Apply Walsh-Hadamard to the result.

For constant f, the final output is $|0\rangle$ with probability 1.
For balanced f, the final output is non-zero with probability 1.

(Details on next slides.)

Requires only a single call to black box U_f, while classical algorithm requires at least $2^{n-1} + 1$ calls.

Background: Hamming Distance

The Hamming distance $\boldsymbol{d_H(x,y)}$ between two bit strings x and y is the number of bits in which the two strings differ.

The Hamming weight $\boldsymbol{d_H(x)}$ of a bit string x is the number of 1 bits.

For two bit strings x and y, the operator $\boldsymbol{x \cdot y}$ gives the number of common 1 bits.

Some interesting notes:

$$x \cdot y = d_H(x \wedge y)$$

$$\sum_{x=0}^{2^n-1} (-1)^{x \cdot x} = 0$$

$$\sum_{x=0}^{2^n-1} (-1)^{x \cdot y} = \begin{cases} 2^n & \text{if } y = 0 \\ 0 & \text{otherwise} \end{cases}$$

More on Walsh-Hadamard

$$W|0\rangle = \frac{1}{\sqrt{N}}\sum_{x=0}^{N-1}|x\rangle$$

$$\begin{aligned}
W|r\rangle &= (H\otimes\cdots\otimes H)(|r_{n-1}\rangle\otimes\cdots\otimes|r_0\rangle) \\
&= \frac{1}{\sqrt{2^n}}(|0\rangle + (-1)^{r_{n-1}}|1\rangle)\otimes\cdots\otimes(|0\rangle + (-1)^{r_0}|1\rangle) \\
&= \frac{1}{\sqrt{2^n}}\sum_{s=0}^{2^n-1}(-1)^{s_{n-1}r_{n-1}}|s_{n-1}\rangle\otimes\cdots\otimes(-1)^{s_0 r_0}|s_0\rangle \\
&= \frac{1}{\sqrt{2^n}}\sum_{s=0}^{2^n-1}(-1)^{s\cdot r}|s\rangle
\end{aligned}$$

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For balanced f, the final output is non-zero with probability 1.

(Details on next slides.)

Quirk Circuit

Requires only a single call to black box U_f, while classical algorithm requires at least $2^{n-1} + 1$ calls.

First, prepare a complete superposition, and then apply the phase shift algorithm to negate the terms corresponding to vectors $|x\rangle$ where $f(x) = 1$.

$$|\psi\rangle = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} (-1)^{f(i)} |i\rangle$$

Next, apply the Walsh-Hadamard transform to obtain:

$$|\phi\rangle = \frac{1}{N} \sum_{i=0}^{N-1} \left((-1)^{f(i)} \sum_{j=0}^{N-1} (-1)^{i \cdot j} |j\rangle \right)$$

$$|\phi\rangle = \frac{1}{N}\sum_{i=0}^{N-1}\left((-1)^{f(i)}\sum_{j=0}^{N-1}(-1)^{i\cdot j}|j\rangle\right)$$

For constant f, the $(-1)^{f(i)} = (-1)^{f(0)}$ is simply a global phase, and the state $|\phi\rangle$ is $|0\rangle$:

$$\begin{aligned}
|\phi\rangle &= (-1)^{f(0)}\frac{1}{N}\sum_{j}\left(\sum_{i}(-1)^{i\cdot j}\right)|j\rangle \\
&= (-1)^{f(0)}\frac{1}{N}\sum_{i}(-1)^{i\cdot 0}|0\rangle \\
&= (-1)^{f(0)}|0\rangle
\end{aligned}$$

because $\sum_i(-1)^{i\cdot j} = 0$ for $j \neq 0$.

$$|\phi\rangle = \frac{1}{N}\sum_{i=0}^{N-1}\left((-1)^{f(i)}\sum_{j=0}^{N-1}(-1)^{i\cdot j}|j\rangle\right)$$

For balanced f,

$$|\phi\rangle = \frac{1}{N}\sum_{j}\left(\sum_{i\in X_0}(-1)^{i\cdot j} - \sum_{i\notin X_0}(-1)^{i\cdot j}\right)|j\rangle, \text{where} \quad X_0 = \{x|f(x) = 0\}$$

In this case, when $j = 0$, the amplitude is zero.
Therefore, measuring $|\phi\rangle$ in the standard basis will return a non-zero j with probability 1.

Links to Quirk Circuits

- Deutsch
- Selective Phase Change
- Deutsch-Josza

Simon's Algorithm

Problem: Given a 2-to-1 function f, such that $f(x) = f(x \oplus a)$, find the hidden string a.

Create superposition $|x\rangle|f(x)\rangle$

Measure the right part, which projects the left state into $\frac{1}{\sqrt{2}}(|x_0\rangle + |x_0 \oplus a\rangle)$.

Apply Walsh-Hadamard. (Details next slide.)

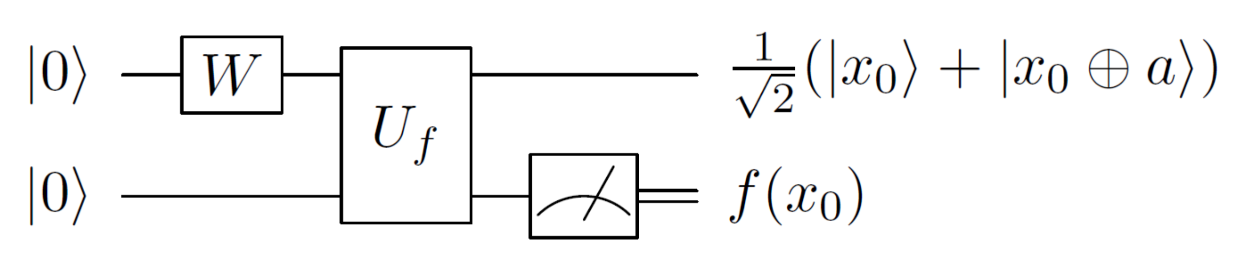
Measurement yields a random y such that $y \cdot a = 0$ (mod 2).

Computation is repeated until n independent equations – about $2n$ times.

Solve for a in $O(n^2)$ steps.

Requires $O(n)$ calls to U_f, followed by $O(n^2)$ steps to solve for a.

Classical approach requires $O(2^{n/2})$ calls to f.



$$
\begin{aligned}
W\left(\frac{1}{\sqrt{2}}(|x_0\rangle + |x_0 \oplus a\rangle)\right) &= \frac{1}{\sqrt{2}}\left(\frac{1}{\sqrt{2^n}}\sum_y ((-1)^{x_0 \cdot y} + (-1)^{(x_0 \oplus a)\cdot y)}\, |y\rangle\right) \\
&= \frac{1}{\sqrt{2^{n+1}}}\sum_y (-1)^{x_0 \cdot y}(1 + (-1)^{a \cdot y})\, |y\rangle \\
&= \frac{2}{\sqrt{2^{n+1}}}\sum_{y \cdot a \ \text{even}} (-1)^{x_0 \cdot y}\, |y\rangle
\end{aligned}
$$

Measurement yields random y such that $y \cdot a = 0 \mod 2$, so the unknown bits of a_i of a must satisfy this equation:

$$y_0 \cdot a_0 \oplus \cdots \oplus y_{n-1} \cdot a_{n-1} = 0$$

Computation is repeated until n linearly independent equations have been found. Each time, the resulting equation has at least a 50% probability of being linearly independent of the previous equations. After repeating $2n$ times, there is a 50% chance that n linearly independent equations have been found. These equations can be solved to find a in $O(n^2)$ steps.

Summary

- Any efficient reversible classical circuit can be efficiently implemented as a quantum circuit.
  - Use inverse function to reduce space and unentangle temporary bits.
- For quantum advantage, add some non-classical operations.
  - E.g, phase change.
- Are these algorithms really useful?
  - Perhaps not directly, but they illustrate ways in which quantum computing may have an advantage over classical computing.