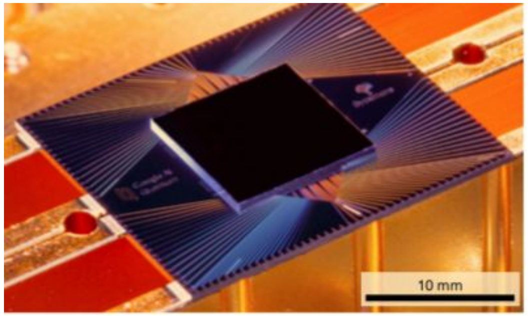
Google's - Quantum Supremacy Claim and the IBM Rebuttal of it!

Are we there yet?



Sycamore

Summit at Oak Ridge

Vesselin G. Gueorguiev

Institute for Advanced Physical Studies
& Ronin Institute

Outline of the Talk

- **Is Quantum Supremacy a suitable term?**
- **What did the Google team do?**
- **What is the IBM rebuttal?**
- **Q&A – Discussion.**

Is Quantum Supremacy a suitable term?

- “In quantum computing, quantum supremacy is the potential ability of devices to solve problems that classical computers practically cannot.[1]”

- “…[QC] dates back to Yuri Manin's (1980)[3] and Richard Feynman's (1981) proposals of quantum computing.[4]”

https://en.wikipedia.org/wiki/Quantum_supremacy

1. ^ a b Preskill, John (2012-03-26). "Quantum computing and the entanglement frontier". arXiv:1203.5813 [quant-ph].

4. ^ Feynman, Richard P. (1982-06-01). "Simulating Physics with Computers". *International Journal of Theoretical Physics*. **21** (6–7): 467–488. Bibcode:1982IJTP...21..467F. CiteSeerX 10.1.1.45.9310. doi:10.1007/BF02650179. ISSN 0020-7748.

^ Manin, Yu. I. (1980). *Vychislimoe i nevychislimoe* [*Computable and Noncomputable*] (in Russian). Sov.Radio. pp. 13–15. Archived from the original on 2013-05-10. Retrieved 2013-03-04.

What did the Google team do?

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*]

Google Chief Sundar Pichai

Chief Scientists:

John Martinis - Quantum Hardware

Sergio Boixo - Quantum Computing Theory

What did the Google team do?

- ✧ Completed a problem within 200s as compared to 10,000y on a supercomputer;
- ✧ Programmable Superconducting Processor 54¯ qubits processor – Sycamore;
- ✧ Quality control over the qubits;
  - ✧ "… improved two-qubit gates with enhanced parallelism that reliably…"
  - ✧ "… new type of control knob that is able to turn off interactions between neighboring qubits…"
- ✧ Sensitive computational benchmark!

Google AI Blog

The latest news from Google AI

Sycamore Qubits Geometry!

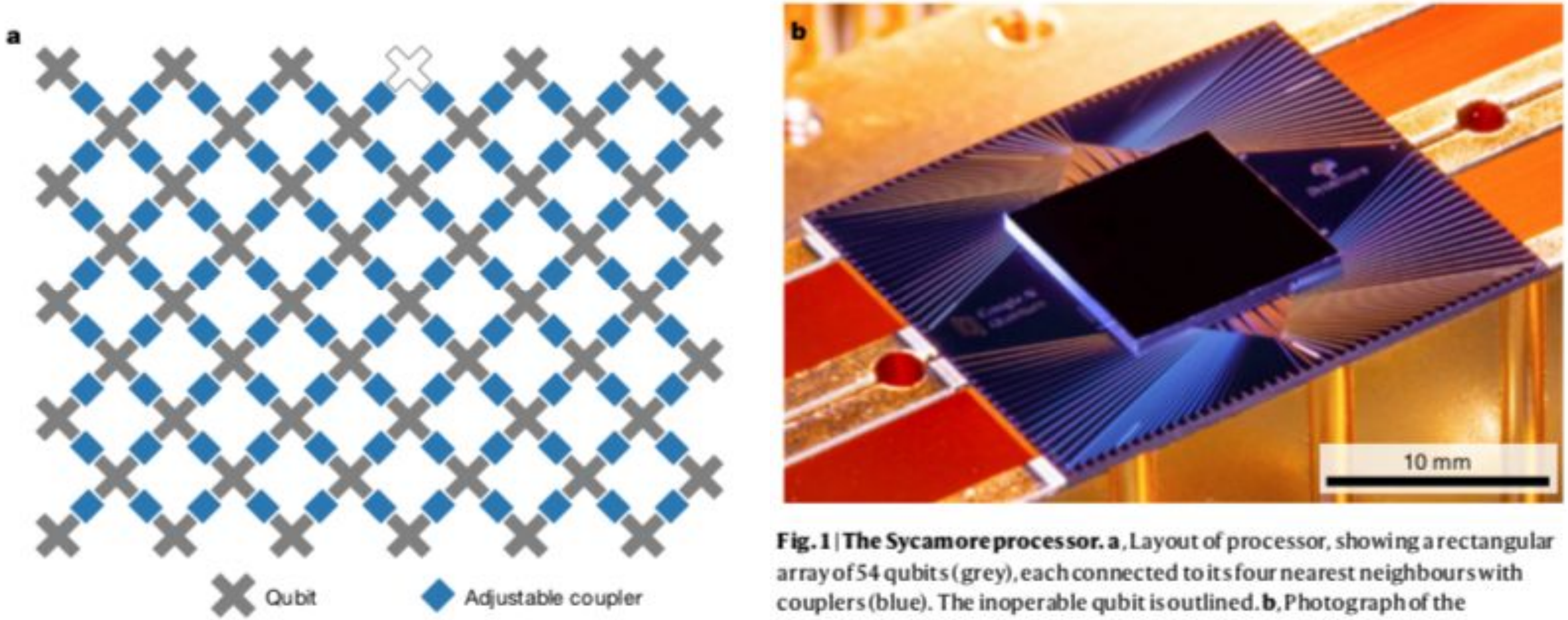
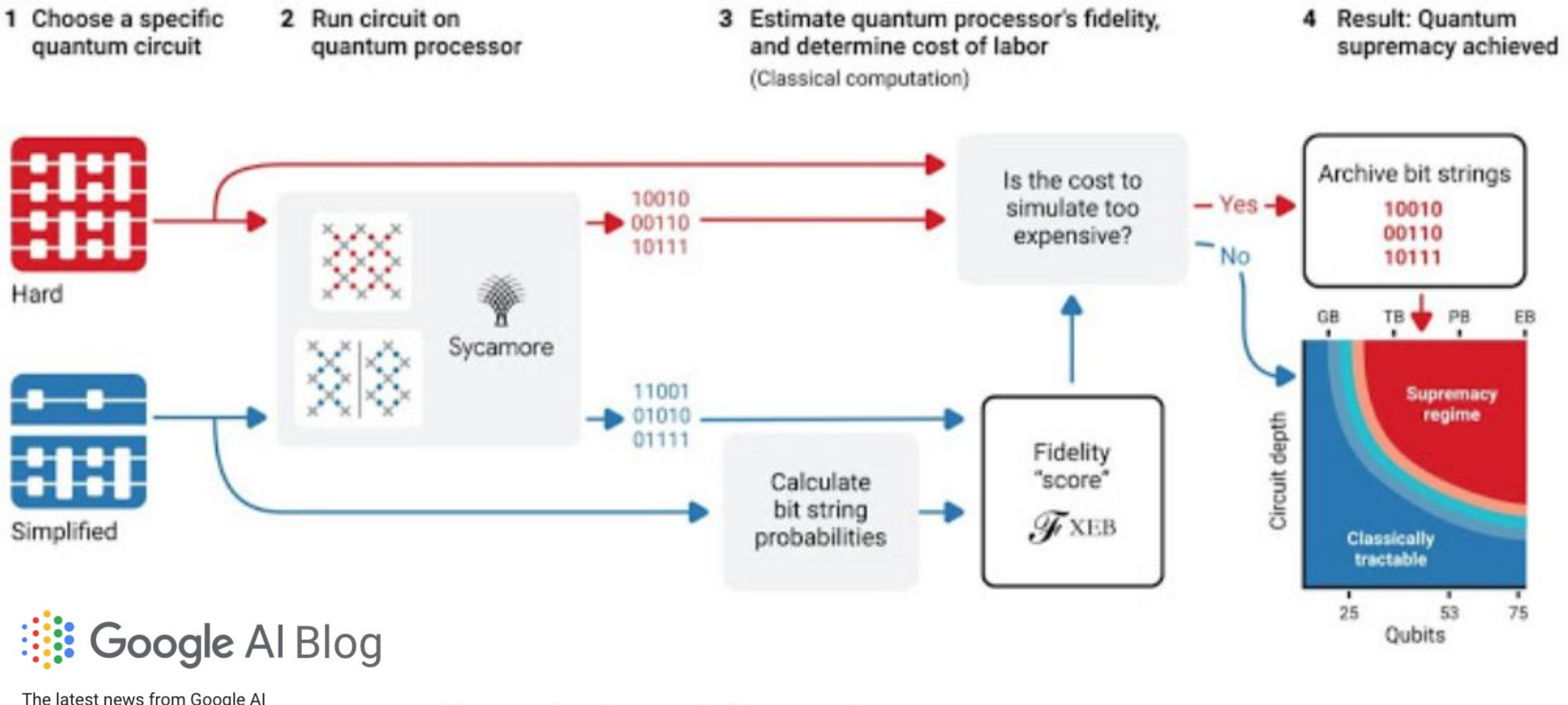


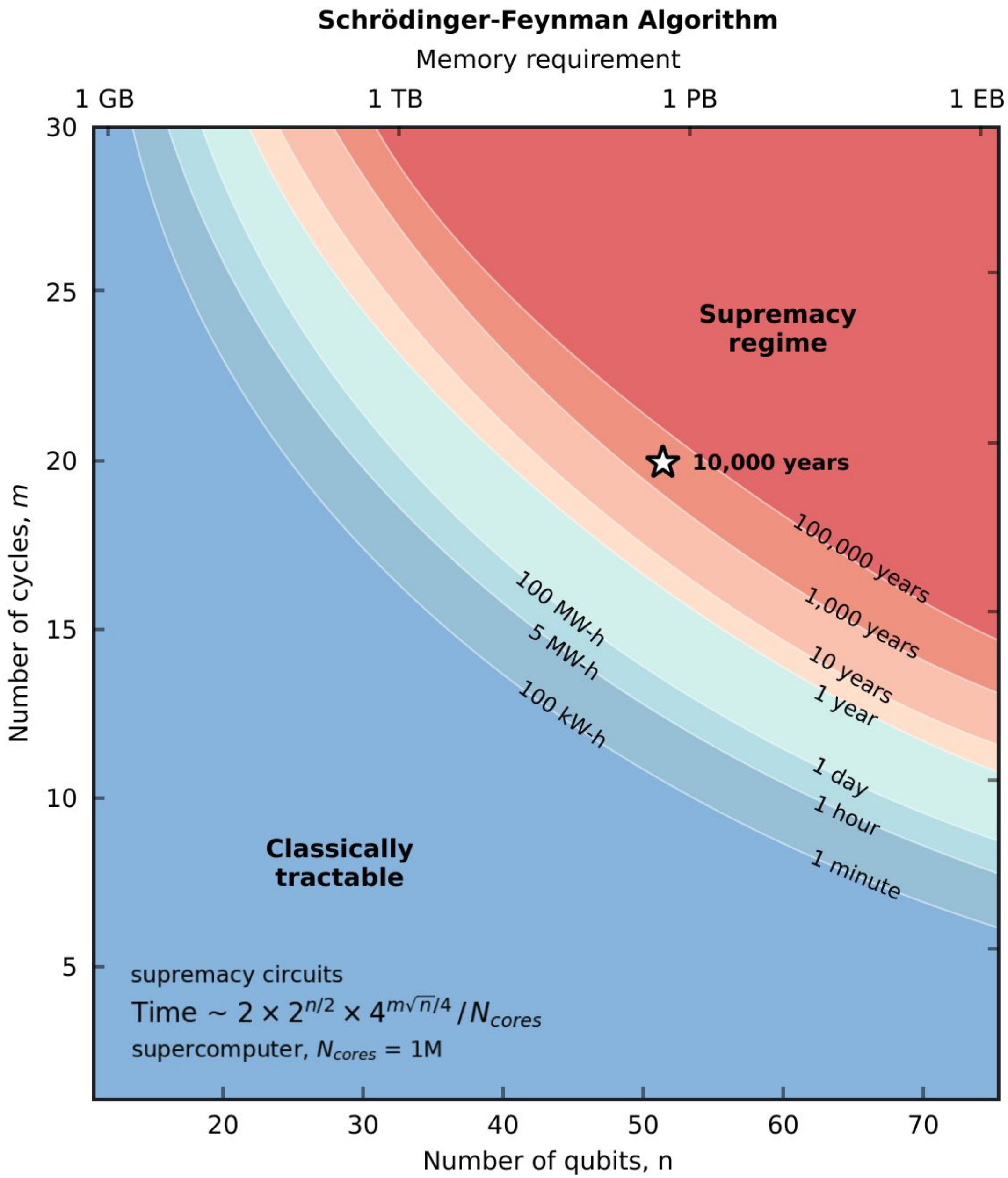
Fig. 1 | The Sycamore processor. a, Layout of processor, showing a rectangular array of 54 qubits (grey), each connected to its four nearest neighbours with couplers (blue). The inoperable qubit is outlined. **b**, Photograph of the Sycamore chip.

Nature | Vol574 | 24OCTOBER2019

Google's process for demonstrating quantum supremacy



Process for demonstrating quantum supremacy.



the Phase-Space Diagram

Estimate of the equivalent classical computation time assuming 1M CPU cores for quantum supremacy circuits as a function of the number of qubits and number of cycles for the Schrödinger-Feynman algorithm. The star shows the estimated computation time for the largest experimental circuits.

Google AI Blog

The latest news from Google AI

Linear cross-entropy benchmarking fidelity function

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

where n is the number of qubits, $P(x_i)$ is the probability of bitstring x_i computed for the ideal quantum circuit, and the average is over the observed bitstrings. Intuitively, $\mathcal{F}_{\mathrm{XEB}}$ is correlated with how often we sample high-probability bitstrings. When there are no errors in the quantum circuit, the distribution of probabilities is exponential (see Supplementary Information), and sampling from this distribution will produce $\mathcal{F}_{\mathrm{XEB}} = 1$. On the other hand, sampling from the uniform distribution will give $\langle P(x_i) \rangle_i = 1/2^n$ and produce $\mathcal{F}_{\mathrm{XEB}} = 0$. Values of $\mathcal{F}_{\mathrm{XEB}}$ between 0 and 1 correspond to the probability that no error has occurred

Nature | Vol574 | 24OCTOBER2019

Control operations for the quantum supremacy circuits

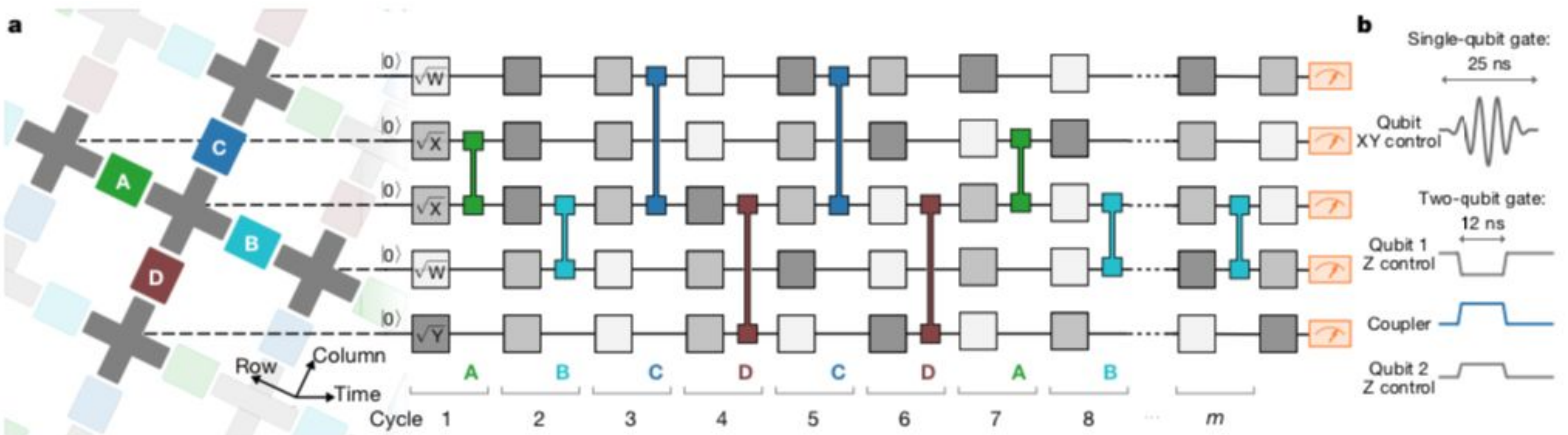


Fig. 3 | Control operations for the quantum supremacy circuits. a, Example quantum circuit instance used in our experiment. Every cycle includes a layer each of single- and two-qubit gates. The single-qubit gates are chosen randomly from $\{\sqrt{X}, \sqrt{Y}, \sqrt{W}\}$, where $W = (X+Y)/\sqrt{2}$ and gates do not repeat sequentially. The sequence of two-qubit gates is chosen according to a tiling pattern, coupling each qubit sequentially to its four nearest-neighbour qubits. The couplers are divided into four subsets (ABCD), each of which is executed simultaneously across the entire array corresponding to shaded colours. Here we show an intractable sequence (repeat ABCDCDAB); we also use different coupler subsets along with a simplifiable sequence (repeat EFGHEFGH, not shown) that can be simulated on a classical computer. **b**, Waveform of control signals for single- and two-qubit gates.

Nature | Vol574 | 24OCTOBER2019

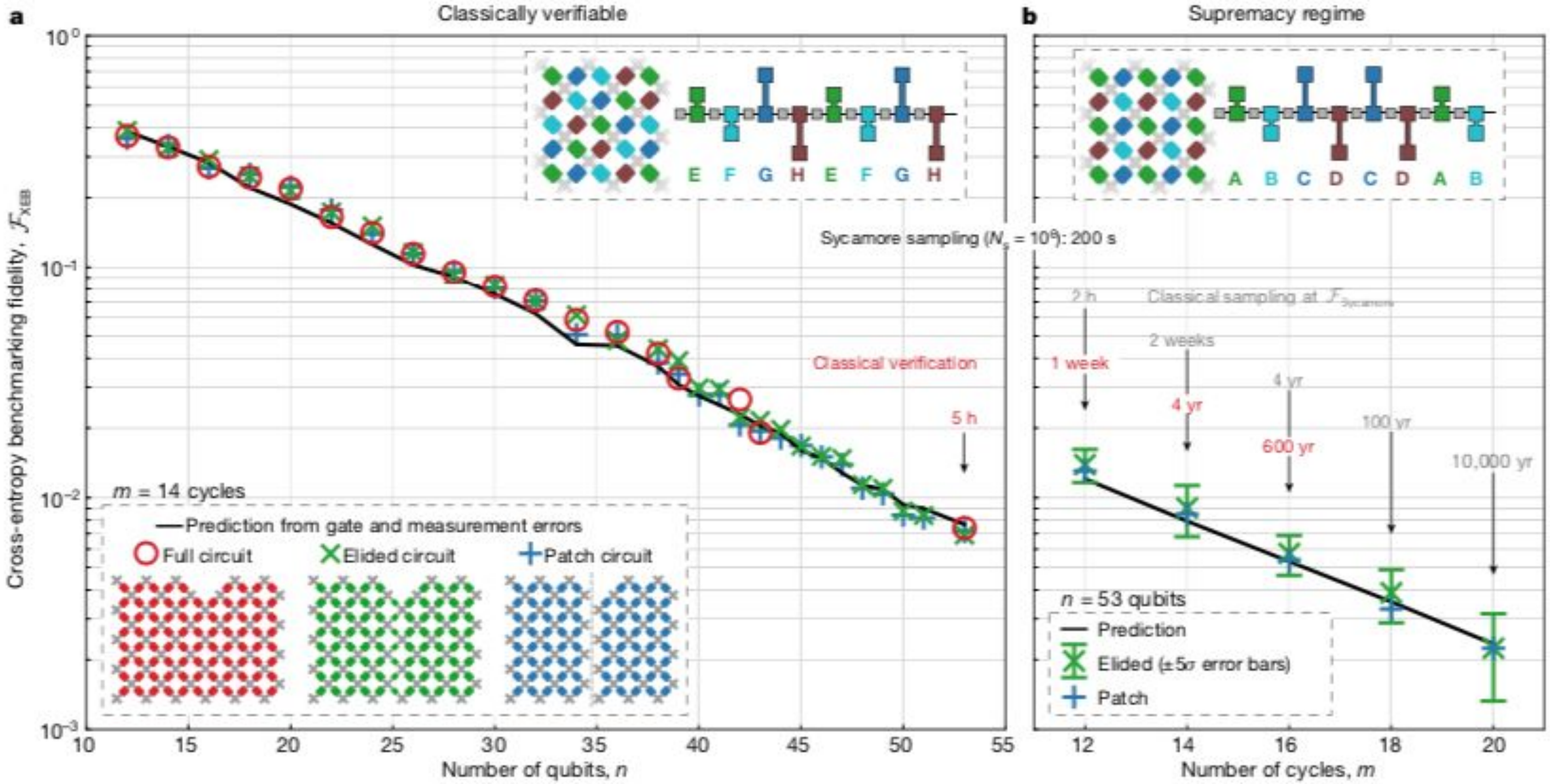


Fig. 4 | Demonstrating quantum supremacy. a, Verification of benchmarking methods. $\mathcal{F}_{XEB}$ values for patch, elided and full verification circuits are calculated from measured bitstrings and the corresponding probabilities predicted by classical simulation. Here, the two-qubit gates are applied in a simplifiable tiling and sequence such that the full circuits can be simulated out to $n = 53$, $m = 14$ in a reasonable amount of time. Each data point is an average over ten distinct quantum circuit instances that differ in their single-qubit gates (for n = 39, 42 and 43 only two instances were simulated). For each n, each instance is sampled with N_s of 0.5–2.5 million. The black line shows the predicted $\mathcal{F}_{XEB}$ based on single- and two-qubit gate and measurement errors. The close correspondence between all four curves, despite their vast differences in complexity, justifies the use of elided circuits to estimate fidelity in the supremacy regime. **b**, Estimating $\mathcal{F}_{XEB}$ in the quantum supremacy regime. Here, the two-qubit gates are applied in a non-simplifiable tiling and sequence for which it is much harder to simulate. For the largest elided data ($n = 53$, $m = 20$, total N_s = 30 million), we find an average $\mathcal{F}_{XEB} > 0.1\%$ with 5σ confidence, where σ includes both systematic and statistical uncertainties. The corresponding full circuit data, not simulated but archived, is expected to show similarly statistically significant fidelity. For $m = 20$, obtaining a million samples on the quantum processor takes 200 seconds, whereas an equal-fidelity classical sampling would take 10,000 years on a million cores, and verifying the fidelity would take millions of years.

Nature | Vol574 | 24OCTOBER2019

Summary - what did Google do.

- Completed a problem within 200s as compared to expected 10,000y on a supercomputer;
- The Sycamore quantum computer is fully programmable and can run general-purpose quantum algorithms;
- Sensitive computational benchmark!
- Quality control over the qubits.
- Certifiable Quantum Random Numbers Generator!
- Forward compatible for the implementation of quantum error-correction!

What is the IBM rebuttal?

Leveraging Secondary Storage to Simulate Deep 54-qubit Sycamore Circuits

Edwin Pednault*[1], John A. Gunnels[1], Giacomo Nannicini[1], Lior Horesh[1], and Robert Wisnieff[1]

[1]IBM T.J. Watson Research Center, Yorktown Heights, NY

Abstract

In a recent paper, we showed that secondary storage can extend the range of quantum circuits that can be practically simulated with classical algorithms. Here we refine those techniques and apply them to the simulation of Sycamore circuits with 53 and 54 qubits, with the entanglement pattern ABCDCDAB that has proven difficult to classically simulate with other approaches. Our analysis shows that on the Summit supercomputer at Oak Ridge National Laboratories, such circuits can be simulated with high fidelity to arbitrary depth in a matter of days, outputting all the amplitudes.

https://arxiv.org/abs/1910.09534

What is the IBM rebuttal?

https://arxiv.org/abs/1910.09534

[9] T. Häner and D. S. Steiger. 0.5 petabyte simulation of a 45-qubit quantum circuit. In *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis*, SC '17, pages 33:1–33:10, New York, NY, USA, 2017. ACM.

[13] E. Pednault. Quantum computing—breaking through the 49 qubit simulation barrier. *IBM Research Blog posting also posted on phys.org* (`https://www.ibm.com/blogs/research/2017/10/quantum-computing-barrier/` and `https://phys.org/news/2017-10-quantum-computingbreaking-qubit-simulation-barrier.html`), 2017.

[14] E. Pednault, J. A. Gunnels, G. Nannicini, L. Horesh, T. Magerlein, E. Solomonik, and R. Wisnieff. Breaking the 49-qubit barrier in the simulation of quantum circuits. *arXiv preprint arXiv:1710.05867*, 2017.

[15] E. G. Rieffel and al. Quantum supremacy using a programmable superconducting processor. *NASA AMES Research Center Technical Report NASA/TP-2019-220319*, 2019. August?

What is the IBM rebuttal?

- Secondary storage can extend the range of quantum circuits that can be practically simulated with classical algorithms;
- It is possible to simulate the Sycamore circuits with 53 and 54 qubits, with the entanglement pattern ABCDCDAB quality control over the qubits.
- Summit supercomputer at Oak Ridge could simulate it with high fidelity to arbitrary depth in a matter of days!
- Q-circuits can be simulated with high fidelity to arbitrary depth in a matter of days;

Partitioning Numbers

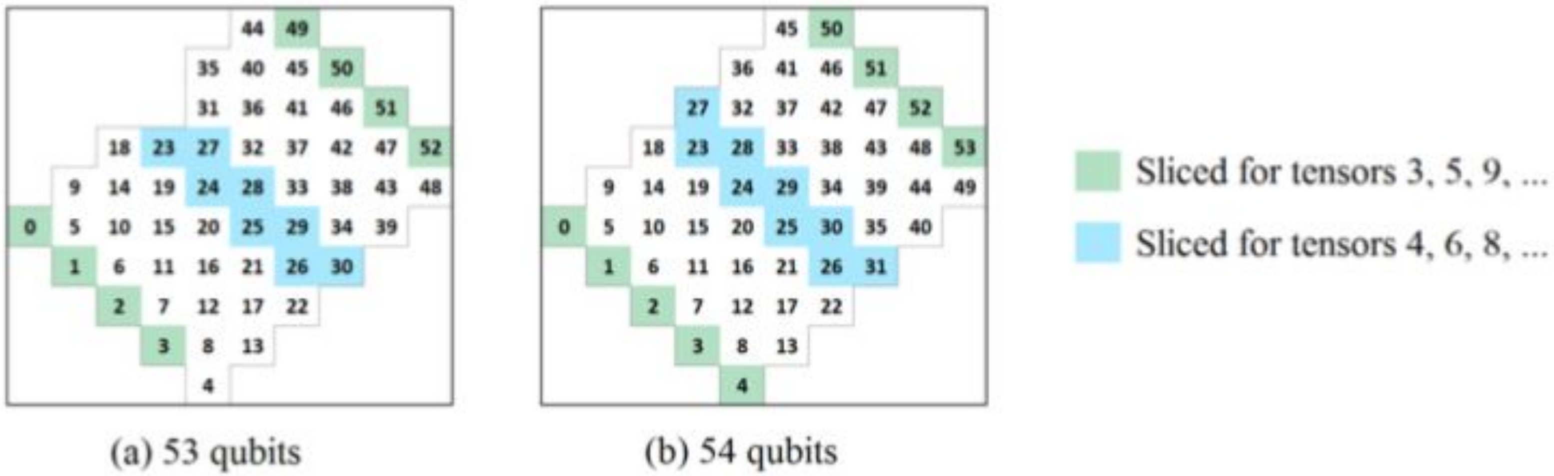


Figure 5: Qubit numbering scheme and first-level tensor slicing strategy for 53- and 54-qubit Sycamore circuits.

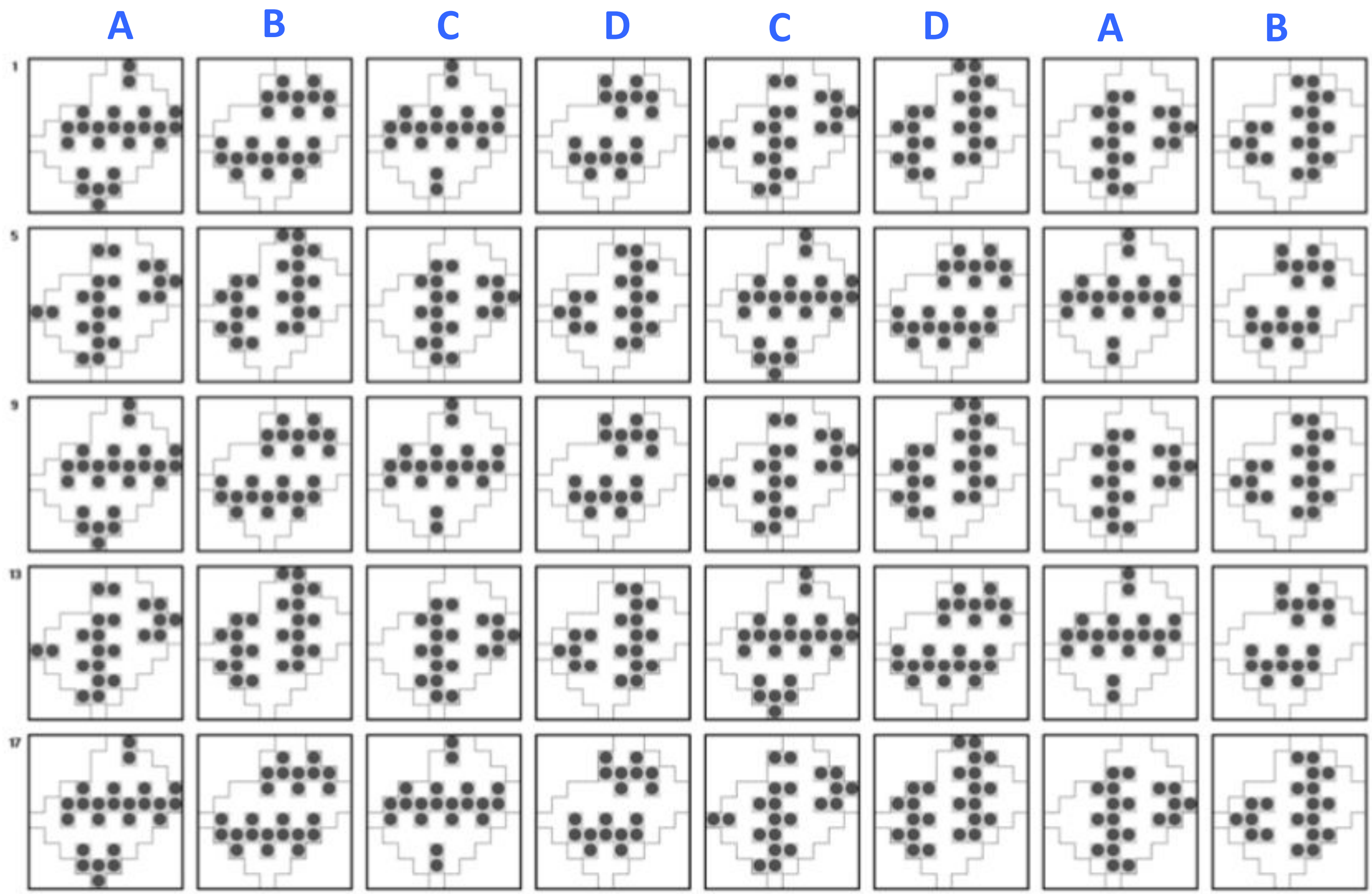


Figure 1: Gate pattern for a 20-cycle, 53-qubit, Sycamore ABCDCDAB circuit. Single-qubit gates are merged into their neighboring two-qubit gates, and the two-qubit gates in each cycle are partitioned into two layers for illustration purposes to make the individual gates easy to identify. These transformations result in the 40-layer circuit depicted. Dots and shading are used to identify which pairs of qubits are being operated upon.

Estimated running times

Number of Cycles	Disk Xfers per Disk Slice	All-to-Alls per Disk Slice	5-Qubit Kernels per Disk Slice	Run Time (days)
10	1	3.002	65	0.67
14	3	6.002	89	1.61
20	5	9.002	120	2.55
24	7	13.002	141	3.54
28	9	16.002	162	4.47
32	11	20.002	182	5.46
36	13	24.002	206	6.45

Table 3: Estimates of total run times for simulating 53-qubit, Sycamore ABCDCDAB circuits of various depths.

Estimated running times

Number of Cycles	Disk Xfers per Disk Slice	All-to-Alls per Disk Slice	5-Qubit Kernels per Disk Slice	Run Time (days)
10	1	3.004	66	2.05
14	3	6.004	90	3.92
20	5	9.004	122	5.80
24	7	13.004	144	7.78
28	9	16.004	166	9.65
32	11	20.004	187	11.63
36	13	24.004	211	13.62

Table 4: Estimates of total run times for simulating 54-qubit, Sycamore ABCDCDAB circuits of various depths.

Estimated running times

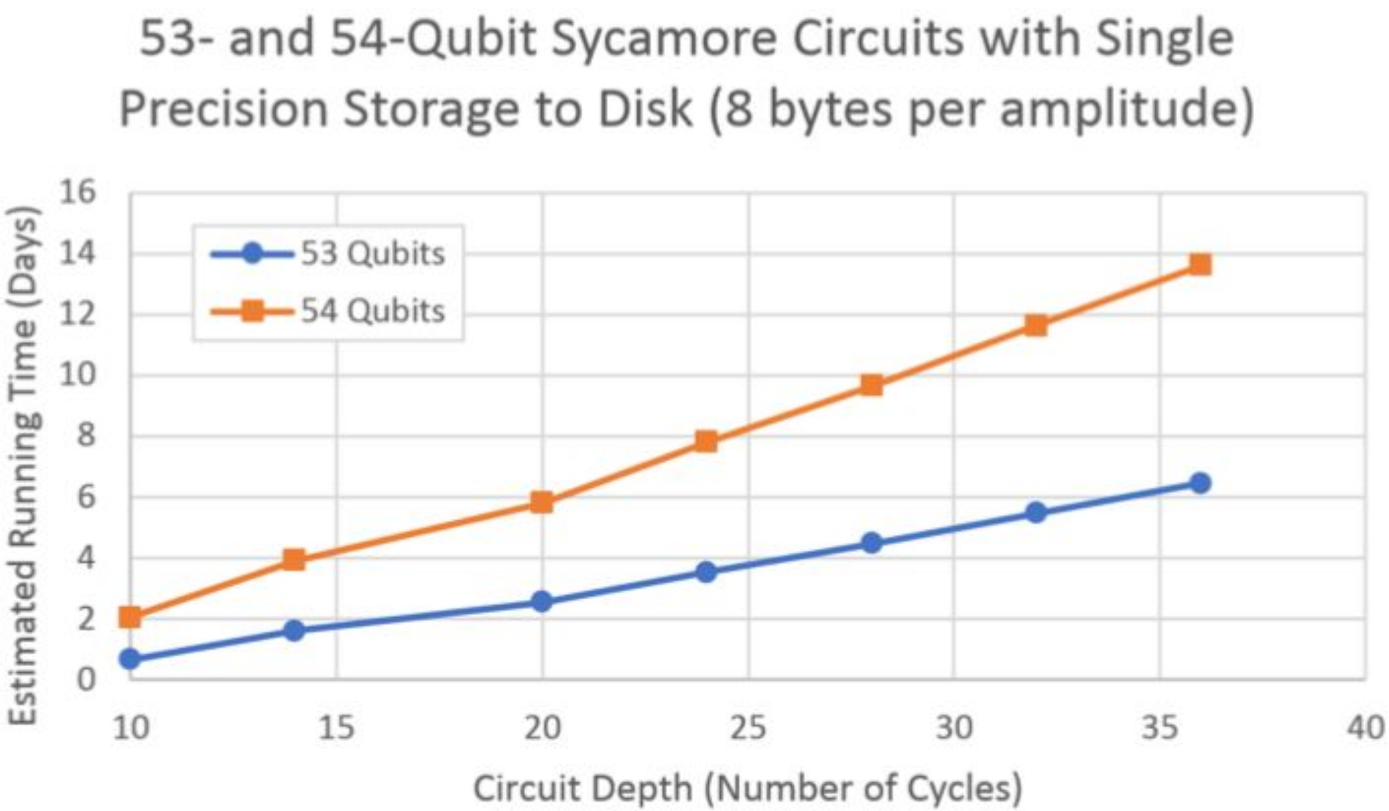


Figure 12: Graph of total runtime estimates for fully simulating both 53- and 54-qubit, Sycamore ABCD-CDAB circuits of various depths, with all amplitudes calculated and stored on disk.

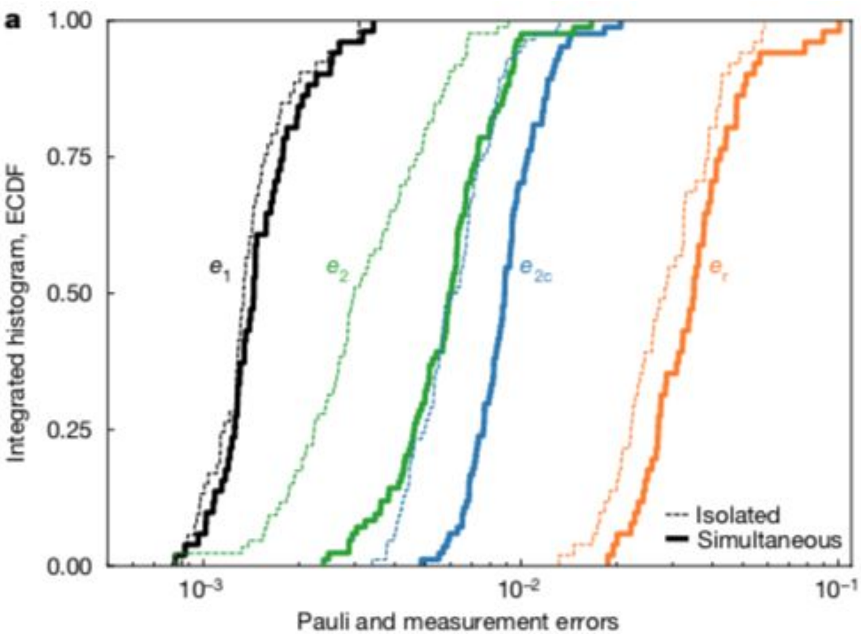
Thank You!

Q&A

Open Discussion

Pauli and Measurement Errors

“Having found the error rates of the individual gates and readout, **we can model the fidelity of a quantum circuit as the product of the probabilities of error-free operation of all gates and measurements**. Our largest random quantum circuits have 53 qubits, 1,113 single-qubit gates, 430 two-qubit gates, and a measurement on each qubit, for which we predict a total fidelity of 0.2%.”



Average error	Isolated	Simultaneous
Single-qubit (e_1)	0.15%	0.16%
Two-qubit (e_2)	0.36%	0.62%
Two-qubit, cycle (e_{2c})	0.65%	0.93%
Readout (e_r)	3.1%	3.8%

Fig. 2 | System-wide Pauli and measurement errors. a, Integrated histogram (empirical cumulative distribution function, ECDF) of Pauli errors (black, green, blue) and readout errors (orange), measured on qubits in isolation (dotted lines) and when operating all qubits simultaneously (solid). The median of each distribution occurs at 0.50 on the vertical axis. Average (mean) values are shown below. **b**, Heat map showing single- and two-qubit Pauli errors e_1 (crosses) and e_2 (bars) positioned in the layout of the processor. Values are shown for all qubits operating simultaneously.

Nature | Vol574 | 24OCTOBER2019

Tensor	Disk trasfers per disk slice	All-to-alls per disk slice	5Q kernels per disk slice	Tensor ranks per socket	Num gates	Contraction cost tot. FLOPs	Compute time (days)	% of total time	Achieved PFLOPS
1		0.000977	28	28	84		0.002082	0.08%	0.0308
2		0.000977	25	27	84		0.001859	0.07%	0.0173
Contraction				31		$1.181 \cdot 10^{21}$	0.117058	4.59%	116.7304
3.3			16	32	63		0.010658	0.42%	18.4865
3.4		1	6	32	23		0.003997	0.16%	17.9975
3.5		1	8	32	26		0.005329	0.21%	15.2587
Disk write	1	1							
Disk read	1	1							
4.4			11	32	49		0.007327	0.29%	20.9141
4.5		1	10	32	45		0.006661	0.26%	21.1275
Disk write	1	1							
Disk read	1	1							
5.5			9	32	35		0.005995	0.24%	18.2583
5.6		1	7	32	21		0.004663	0.18%	14.0850
Disk write	1	1							
Subtotals									
Compute			120			$1.181 \cdot 10^{21}$	0.165631	6.50%	87.4462
All-to-alls		9.001953					0.487725	19.13%	
Disk I/O	5						1.896296	74.37%	
Total	5	9.001953	120	32.67243	430		2.549652	100.00%	87.4462

Table 1: Running time estimates to simulate the 20-cycle, 53-qubit Sycamore circuit shown in Fig. 1. Tensors 3.3, 3.4, and 3.5 correspond to the partitionings of subcircuit 3 shown in Fig. 6, tensors 4.4 and 4.5 to the partitionings of subcircuit 4 shown in Fig. 7, and tensors 5.5 and 5.6 to the partitionings of subcircuit 5 shown in Fig. 8. The number of 5-qubit kernels is the number of aggregated gates spanning