Quantum Supremacy Using a Programmable Superconducting Processor

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December 1st, 2023 Physics 596

Arute, F., et al.(2019). Nature, 574(7779), 505–510. https://doi.org/10.1038/s41586-019-1666-5

How do we show quantum supremacy?

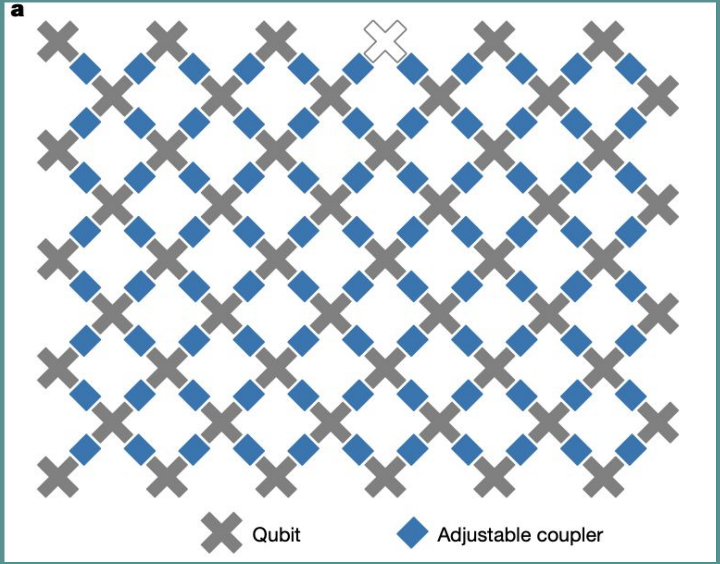
Can a quantum system be engineered to perform a computation in a large enough computational Hilbert space and with a low enough error to provide a speed up?

Can we build a quantum computer?

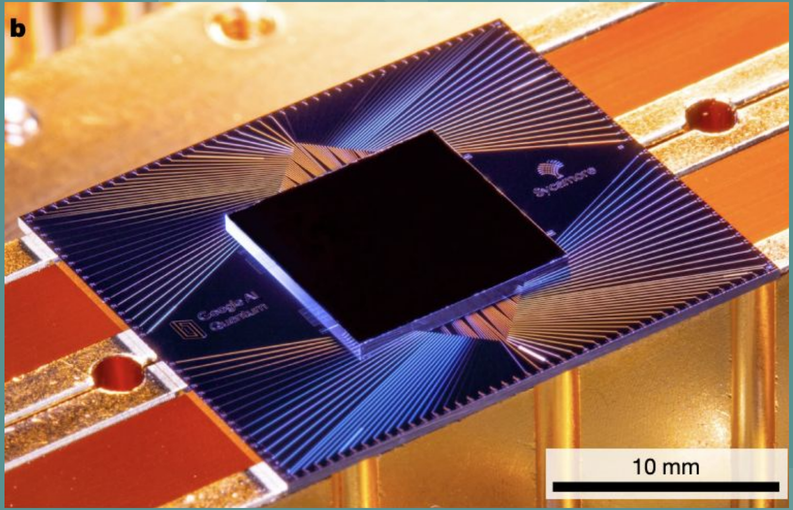
Can we formulate a problem that is hard for a classical computer but easy for a quantum system?

Building the Quantum System

The Sycamore Chip



2d array of 54 qubits with couplers



The physical chip made of aluminum and indium

Formulating the Test Problem

Task: Sampling the output of a pseudo-random quantum circuit

The output is in the form of bitstrings. For example:

0001100, 0010101

Results:

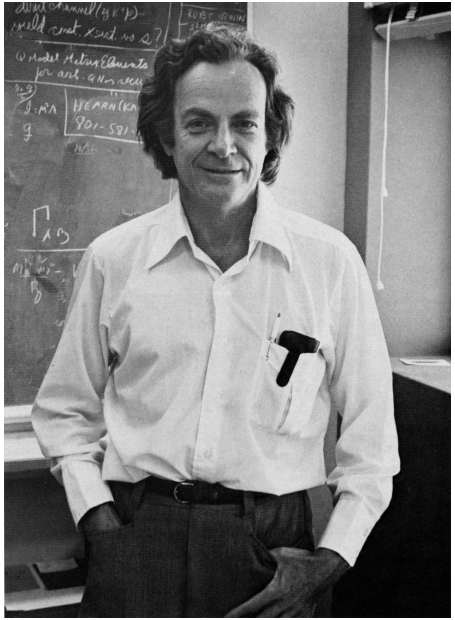
Quantum: 200s

Classical: 10,000yrs

The Idea of Quantum Computing

“[N]ature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical.”

– Feynman, *International Journal of Theoretical Physics*, ‘82



The Hype

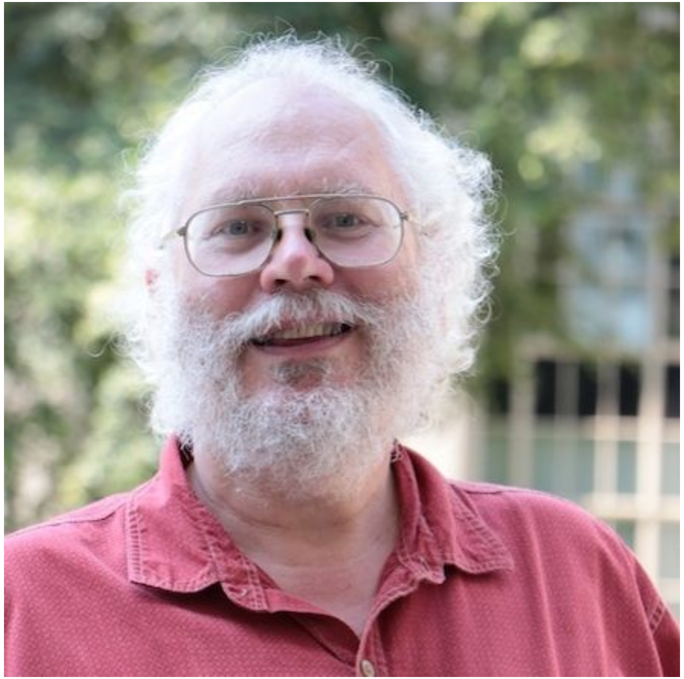
I can hack* into your bank account**
with a quantum computer***!

– Peter Shor, ‘94

*: Polynomial-time prime factorization

**: Which is likely encrypted with some variation of RSA

***: We don’t have it yet



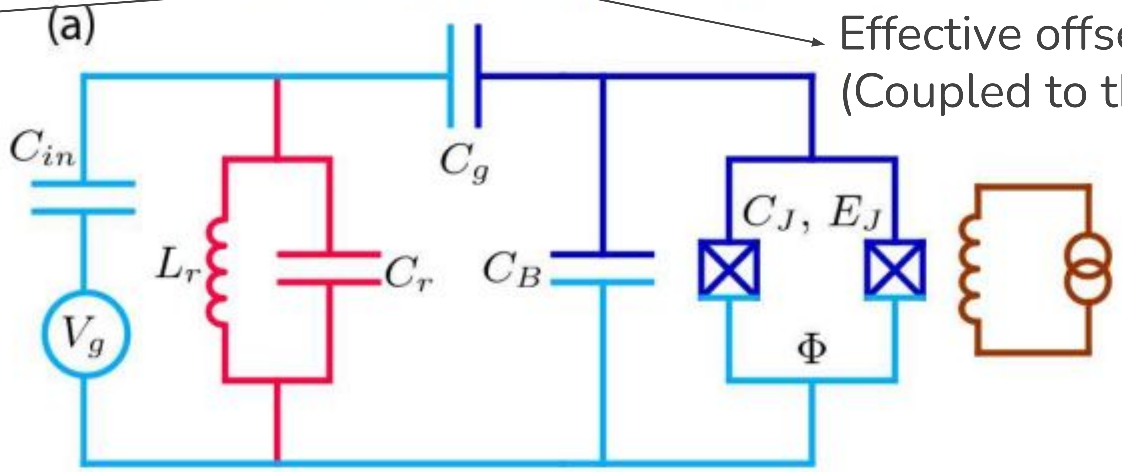
Transmon: The Quantum bit Google Used

Josephson Energy

$$\hat{H} = 4E_C\left(\hat{n} - n_g\right)^2 - E_J \cos\hat{\varphi}.$$

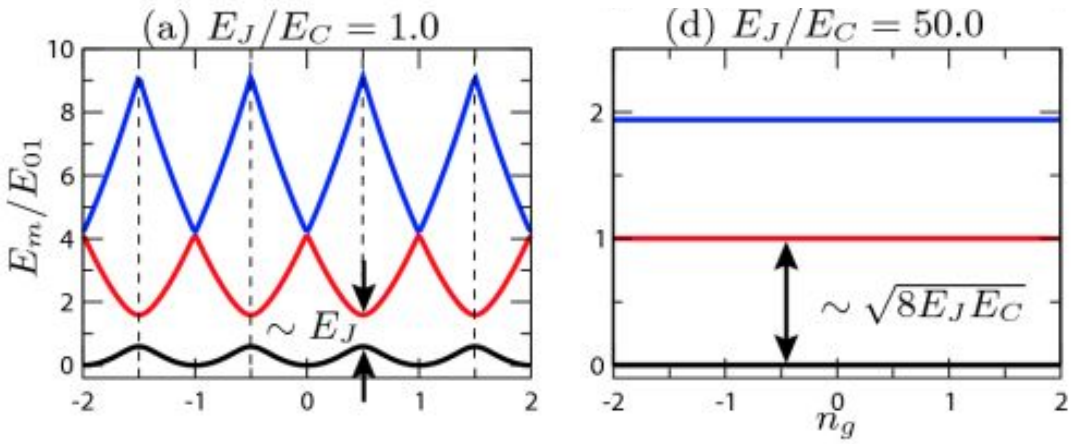
Charging Energy

Effective offset charge
(Coupled to the environment)



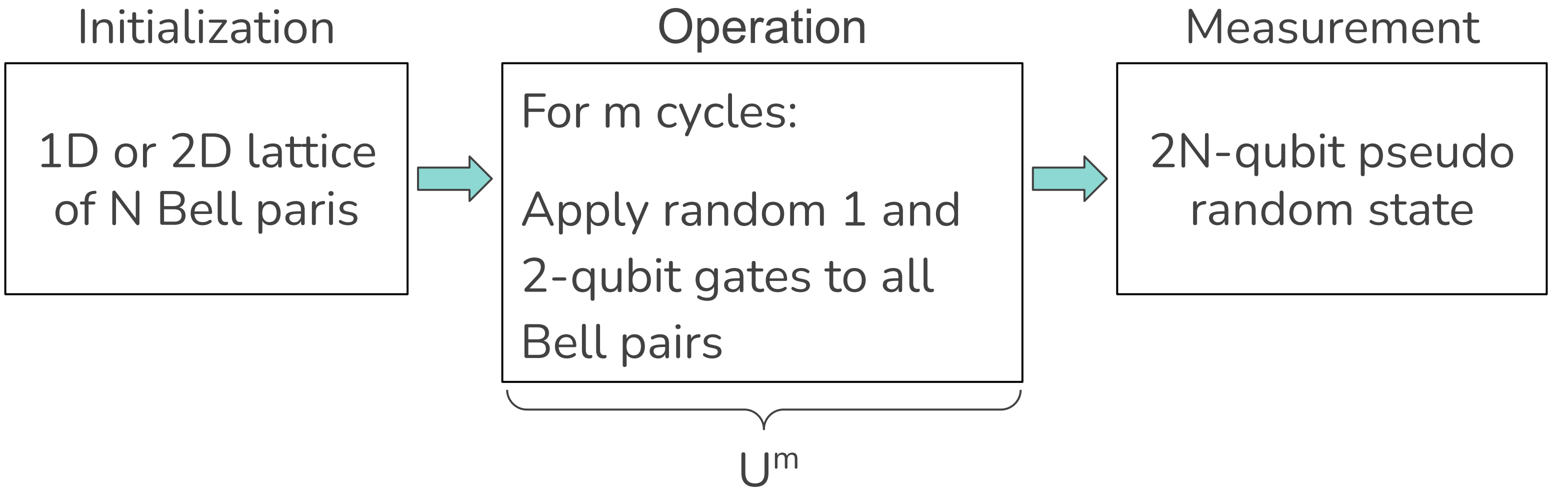
Transmon: transmission line shunted plasma oscillation qubit (Koch et al., PRA, ‘07)

The Energy Eigenstates of Transmon



Charge-invariant energies in the Transmon regime (E_j >> E_c)

The Random Circuit Sampling– Classically Hard, Quantumly Easy



Time complexity: #P-hard >= NP-complete (Bouland et al., *Nat. Physics*, ‘19)

Proposal: Boixo et al., *Nat. Physics*, ‘18

Conclusions : Quantum states on the Sycamore processor and Quantum Supremacy

Important questions to think about:

- Can a quantum system work in a large computational space and with low error rates to provide a quantum speedup?
- Can a problem be “hard” for a classical computer but “easy” for a quantum computer?

The experiment presented in the paper addresses these questions and claims that **Quantum Supremacy** has been achieved!

First experiment on a quantum processor! (computation in such a large Hilbert space using superconducting qubits)

Overall the **dramatic computational speed** with **considerable error rates and limits** from this experiment on Sycamore gives us rays of hope to **run well-known quantum algorithms**.

(Arute et al., 2019)

List of Conclusions : from this paper -

- QUANTUM PROCESSOR IS FASTER :

1. **Quantum speedup is achievable** in a real-world system and is not precluded by any hidden physical laws.
2. **Classically computing becomes exponentially difficult** with number of qubits and number of gate cycles.

Sycamore is a million times faster than classical computers!

- CLASSICAL COMPUTERS ARE NOT VERY GOOD WITH ERRORS:

3. In order to claim quantum supremacy we need quantum processors which execute **programs with low error rates**.
4. Demonstrating an **un-correlated error model** tells us that we can build a system where **quantum resources are considerable**.

Quantum circuit can be sampled in polynomial time low error rates!

No efficient method is known to exist for classical computing machinery!

(Arute et al., 2019)

- HANDLING ERRORS IN SYCAMORE:

5. The model also assumes from the experiment that **the scaling up of the system does not introduce** additional **errors**.

6. **More attention is needed in quantum error corrections** to run well-known algorithms (like Shor and Grover's algorithms).

- HOPES AND FUTURE PROSPECTS:

7. **Computational power** is expected to **grow** at a double exponential rate.

Classical **cost of simulation** will **increase** exponentially with computational volume.

Hardware improvements will **double the computational vol.** in every few years.

(Arute et al., 2019)

Recap

Google™

- As you can see, the authors are fairly optimistic about their results
- "First computation that can only be performed on a quantum processor"
- Growth requires "the engineering of quantum error correction"
- "Only one creative algorithm away from valuable near-term applications"

(Arute et al., 2019)

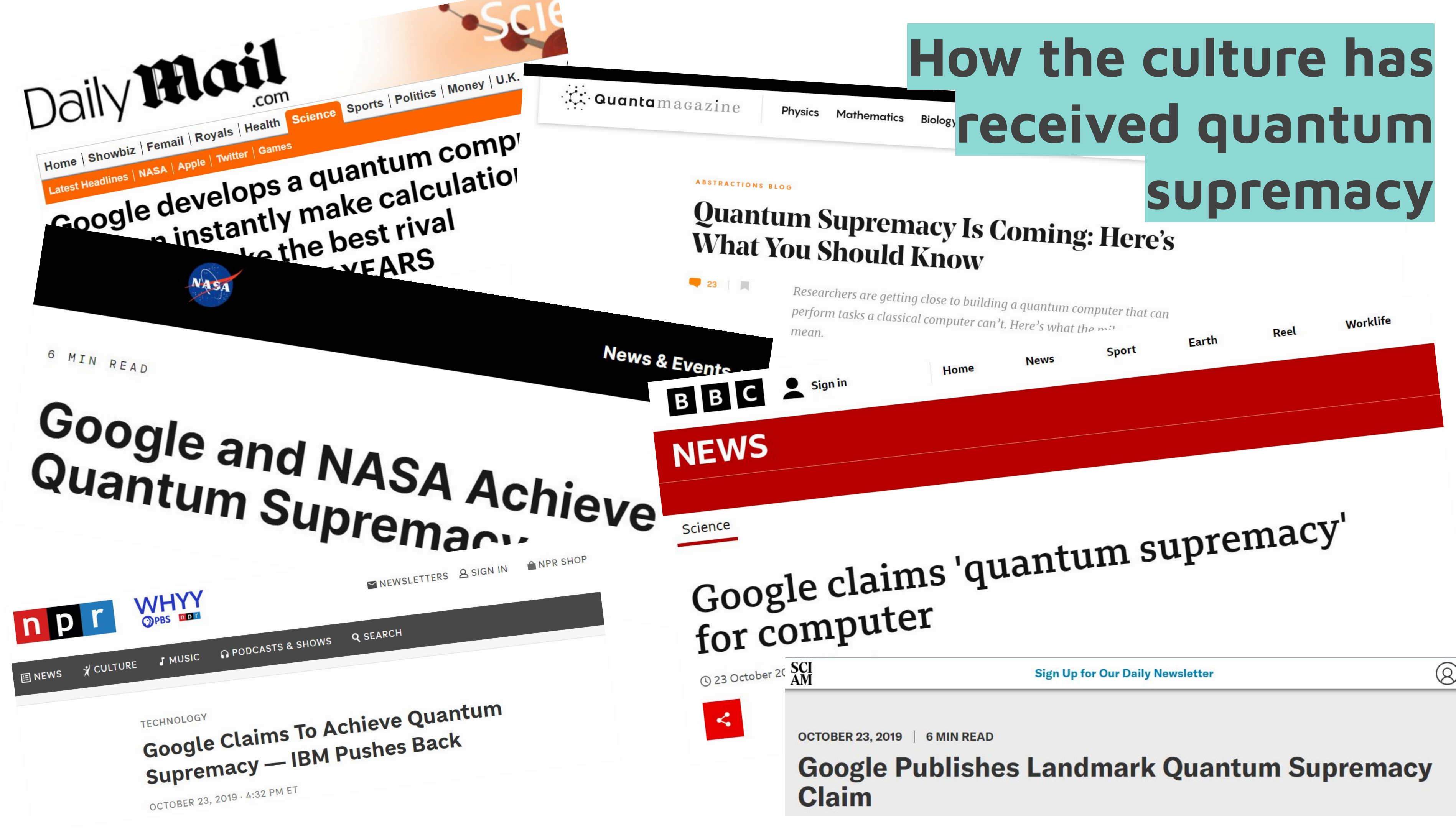
Our conclusions

- Google may have won this bout but...
- Citation analysis reveals different story about the classical difficulty of the task
- Relevancy of the “suitable computation task”
- Need for Quantum Error Correction

“Valuable near-term applications”

- What does this even mean?
- No bank account hacking yet
- Algorithms like the Variational Quantum Eigensolver
- Often used in conjunction with classical computers
- Has been used in places like chemistry and material science

How the culture has received quantum supremacy



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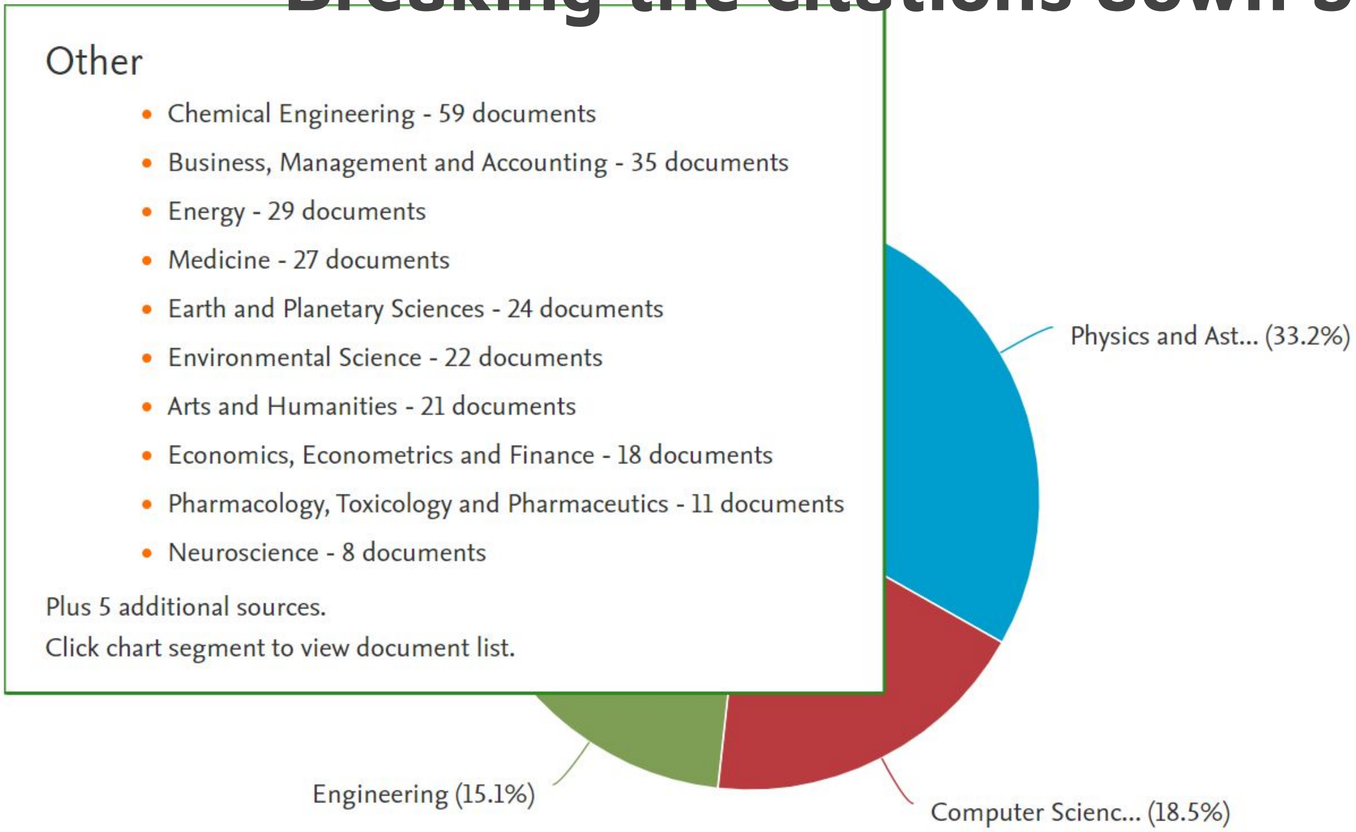


- 2890 articles (78.1%) in fields “clearly” related to quantum computing
- 542 articles (14.6%) in more indirectly related STEM fields
- 269 articles (7.3%) in surprisingly disparate fields

Citations from unexpected fields:

Medicine:

Uthamacumaran, A. (2021). A review of dynamical systems approaches for the detection of chaotic attractors in cancer networks. Patterns, 2(4), 100226. https://doi.org/10.1016/j.patter.2021.100226

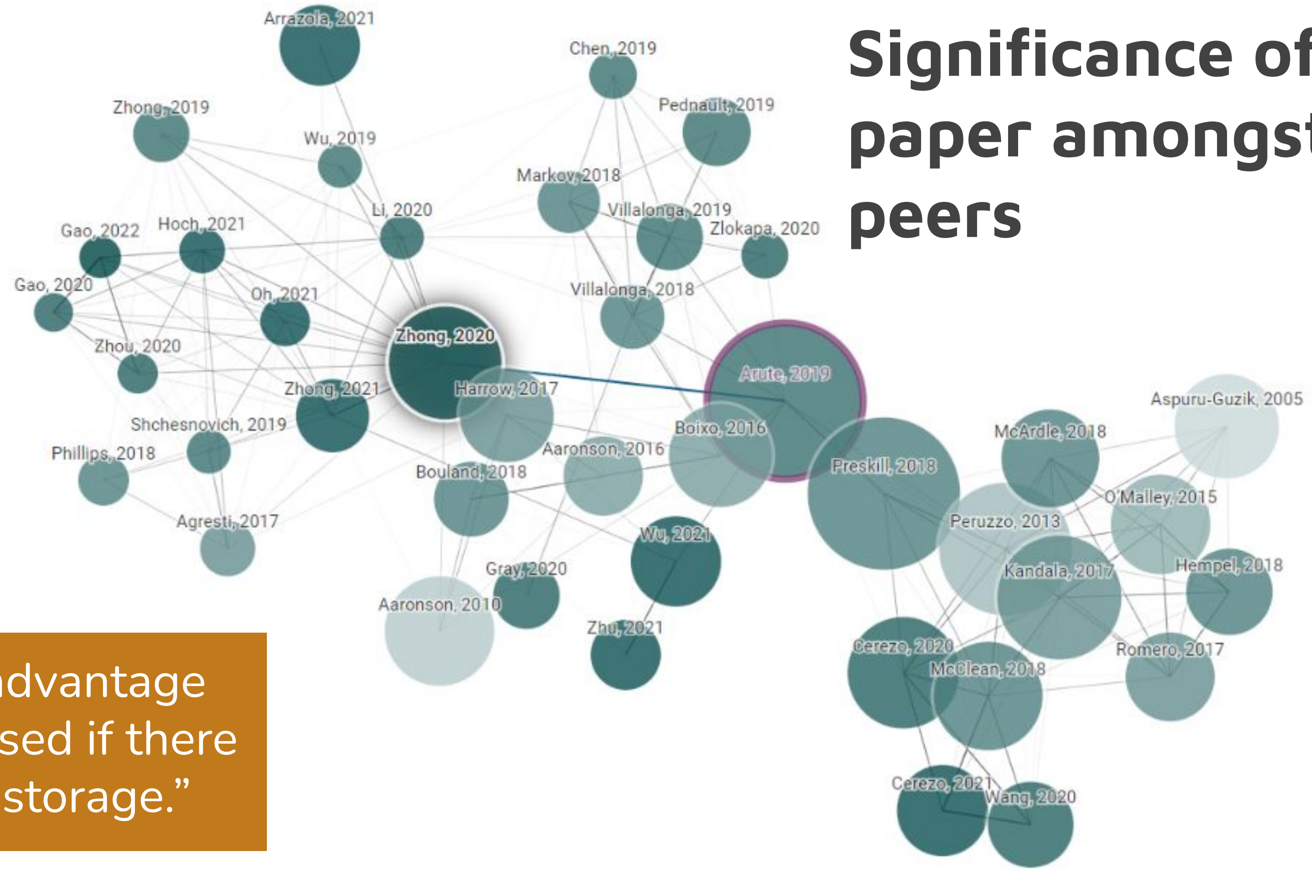
International Security:

Derian, J. D., & Wendt, A. (2020). ‘Quantizing international relations’: The case for quantum approaches to international theory and security practice. Security Dialogue, 51(5), 399–413. https://doi.org/10.1177/0967010620901905

Physics Education:

Fox, M. F. J., et. al. (2020). Preparing for the quantum revolution: What is the role of higher education? Physical Review, 16(2). https://doi.org/10.1103/physrevphyseducres.16.020131

Significance of this paper amongst its peers

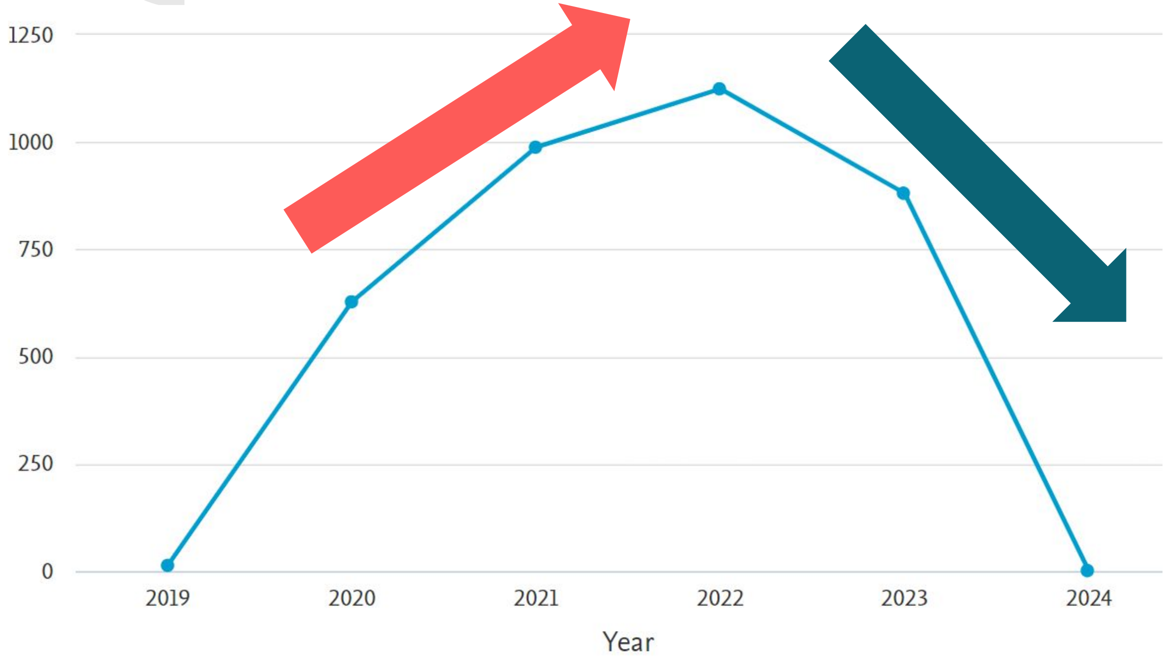


“the quantum advantage would be reversed if there were sufficient storage.”

Zhong, H., et al. (2020). Quantum computational advantage using photons. Science, 370(6523), 1460-1463. https://doi.org/10.1126/science.abe8770

Wu, Y., et al. (2021). Strong quantum computational advantage using a superconducting quantum processor. Physical Review Letters, 127(18). https://doi.org/10.1103/physrevlett.127.180501

Citations by the number



14	628	988	1124	881	2

Citation No.

Quantum computing is super recent, but things look hot, hot, hot!!

Google's quantum computer was just a 2020's fad. Hype but no substance

Being first established Google. However its flaws expose how hype can yield subpar science

Questions?