The Vast World of Quantum Advantage

John Preskill

CIQC Annual Meeting

14 July 2025

The vast world of quantum advantage

Hsin-Yuan Huang,[1,2] Soonwon Choi,[3] Jarrod R. McClean,[2] and John Preskill[1,4]

[1] *California Institute of Technology, Pasadena, California 91125, USA*
[2] *Google Quantum AI, Venice, California 90291, USA*
[3] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[4] *AWS Center for Quantum Computing, Pasadena, California 91125, USA*

Rigor is our touchstone, but quantum advantage will sometimes take us by surprise.

Mind the gap

J. Eisert,[1,2,3] S. T. Flammia,[4,5] and J. Preskill[6,7]

[1]*Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany*
[2]*Helmholtz-Zentrum Berlin für Materialien und Energie, 14109 Berlin, Germany*
[3]*Fraunhofer Heinrich Hertz Institute, 10587 Berlin, Germany*
[4]*Department of Computer Science, Virginia Tech, Alexandria, VA 22314, USA*
[5]*Phasecraft Inc., Washington, DC 20001, USA*
[6]*Institute for Quantum Information and Matter, California Institute of Technology, CA 91125, USA*
[7]*AWS Center for Quantum Computing, Pasadena, CA 91125, USA*

Do science for now.

Economic impact will inevitably follow.

arXiv:2501.05694

Myths around quantum computation before full fault tolerance: What no-go theorems rule out and what they don't

Zoltán Zimborás,[1,2,*] Bálint Koczor,[3,4,†] Zoë Holmes,[5,‡] Elsi-Mari Borrelli,[1] András Gilyén,[6] Hsin-Yuan Huang,[7,8] Zhenyu Cai,[4,9] Antonio Acín,[10,11] Leandro Aolita,[12] Leonardo Banchi,[13,14] Fernando G. S. L. Brandão,[15,8] Daniel Cavalcanti,[1] Toby Cubitt,[16,17] Sergey N. Filippov,[1] Guillermo García-Pérez,[1] John Goold,[1,18,19] Orsolya Kálmán,[2] Elica Kyoseva,[20] Matteo A.C. Rossi,[1,21] Boris Sokolov,[1] Ivano Tavernelli,[22] and Sabrina Maniscalco[1,21]

"It is highly plausible that useful applications may be within reach before full fault tolerance is achieved."

quantumfrontiers.com/2025/04/20/ …

Posted on **April 20, 2025** by **robbieking1000**

← Previous Next →

Edit

Quantum Algorithms: A Call To Action

"We should … adopt a more exploratory, scrappier approach … Don't be too afraid."

arXiv:2506.19232

Future of Quantum Computing

Scott Aaronson,[1] Andrew M. Childs,[2] Edward Farhi,[3] Aram W. Harrow,[4] and Barry C. Sanders[5,*]

[1] *Department of Computer Science, The University of Texas at Austin, TX 78712, USA*
[2] *Department of Computer Science, Institute for Advanced Computer Studies, and Joint Center for Quantum Information and Computer Science, University of Maryland, College Park, MD 20742, USA*
[3] *Google Quantum AI, Venice, CA 90291, USA*
[4] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[5] *Institute for Quantum Science and Technology, University of Calgary, Alberta T3A 0E1, Canada*

(Dated: June 25, 2025)

Andrew: “There need to be guiding principles.”

Eddie: “Look at physics and see whether there are phenomena you can translate into some algorithmic advantage.”

arXiv:2502.17368

Beyond NISQ: The Megaquop Machine

JOHN PRESKILL, Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, United States

1M quantum ops or more: Requires QEC, and allows tasks beyond classical, NISQ, or analog quantum.

Realms

Computation
Learning/Sensing
Communication/Crypto
Space

Keystones

Predictability (rigorous evidence)
Typicality (average case)
Robustness (against imperfections)
Verifiability (can check the output)
Usefulness (someone wants the answer)

Ideal quantum advantage: Has all 5 at once.

Predictability / Typicality / Usefulness

Cooling quantum systems to a local energy minimum:
Worst-case hard if BQP ≠ BPP. Solved by quantum thermal gradient descent.

Random circuit sampling:
Average-case hard if PH does not collapse (and other plausible conjectures).

Quantum phase estimation:
Can lower the energy estimate if input has large energy variance.

Discrete logarithm problem:
Average case is as hard as the worst case.

Decoded Quantum Interferometry applied to Optimal Polynomial Intersection:
Approximation ratio achieved by DQI is rigorously established.

Maybe NISQ is useful after all!

Extended reach of error mitigation as gate error rates improve.

Variational methods: Thread the needle between barren plateaus and classical simulability?

Qualitative insights from quantum dynamics (in 2D).

Will AI eat quantum's lunch?

Training data from quantum computers, simulators, experiments.

The world of quantum advantage extends far beyond what we can rigorously establish.

Reasonable … but to what extent can this be formalized as a meta-theorem?

Theorem [Huang 2025, Classical hardness of predicting quantum advantage (informal)]

Decision problem: Does executing a given quantum circuit achieve advantage over classical simulation of that same circuit using low-weight Pauli propagation?

A quantum computer can solve this efficiently; a classical computer cannot unless BPP $=$ BQP.

Questions

What quantum heuristics are particularly promising for exhibiting quantum advantage?

What problems exhibit quantum advantage for typical instances drawn from a natural distribution?

What quantum advantages are simultaneously predictable, typical, robust, verifiable, and useful?

What well-motivated complexity conjectures point toward new varieties of quantum advantage?

How should we broaden our toolkit for predicting quantum advantage?

What can we achieve in the next 5 years?