Quantum Computing
40 years later and 4 years later

Richard Feynman, May 1981:
“By golly it’s a wonderful problem because it doesn’t look so easy.”

Matt Johnson, December 2017:
“Identify and discuss the ground truths around quantum computing”

aws

IQIM
INSTITUTE FOR QUANTUM INFORMATION AND MATTER

John Preskill, Caltech
Q2B 2021, Santa Clara CA
8 December 2021

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Quantum computing 40 years later

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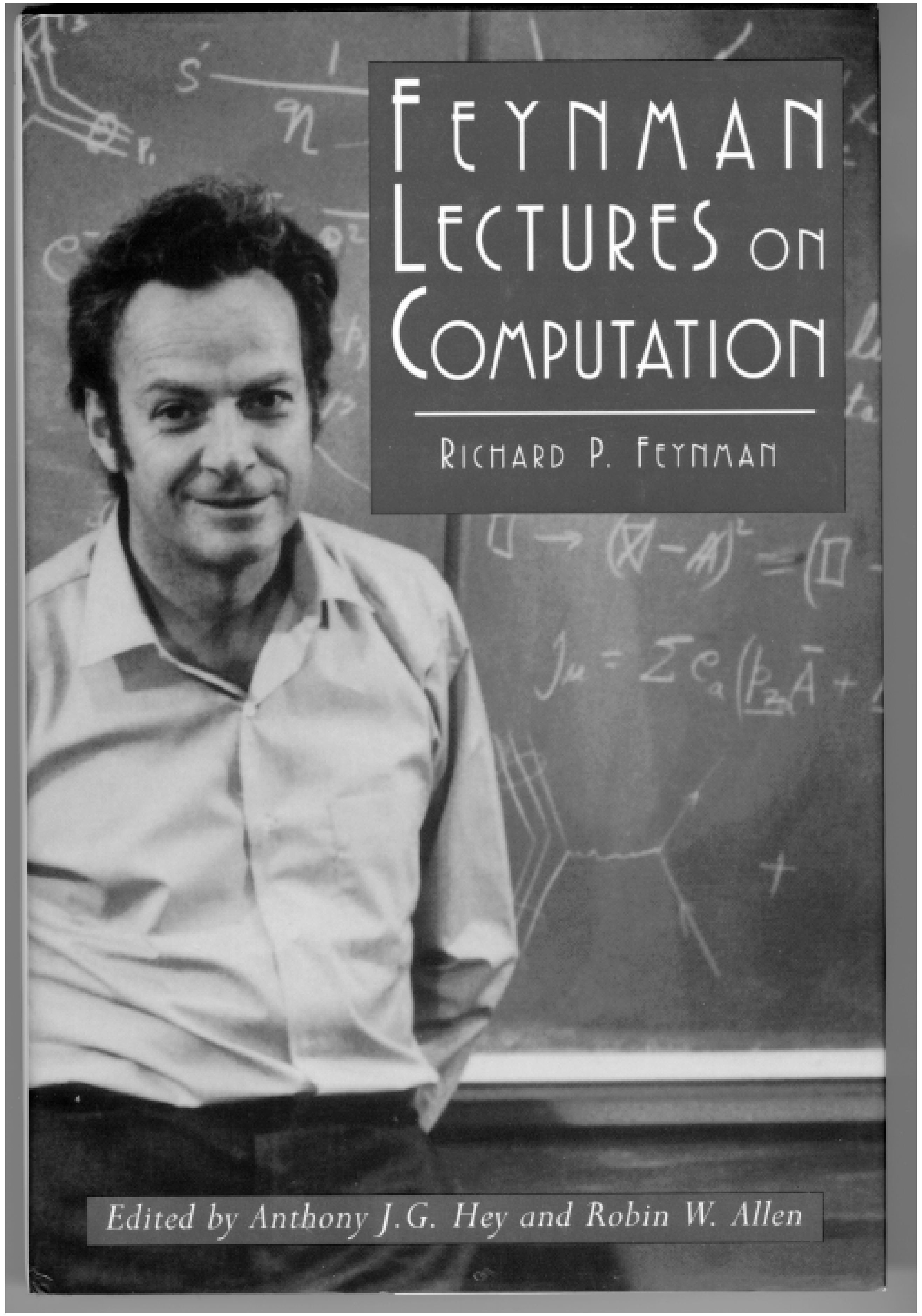
6 June 2021

Abstract

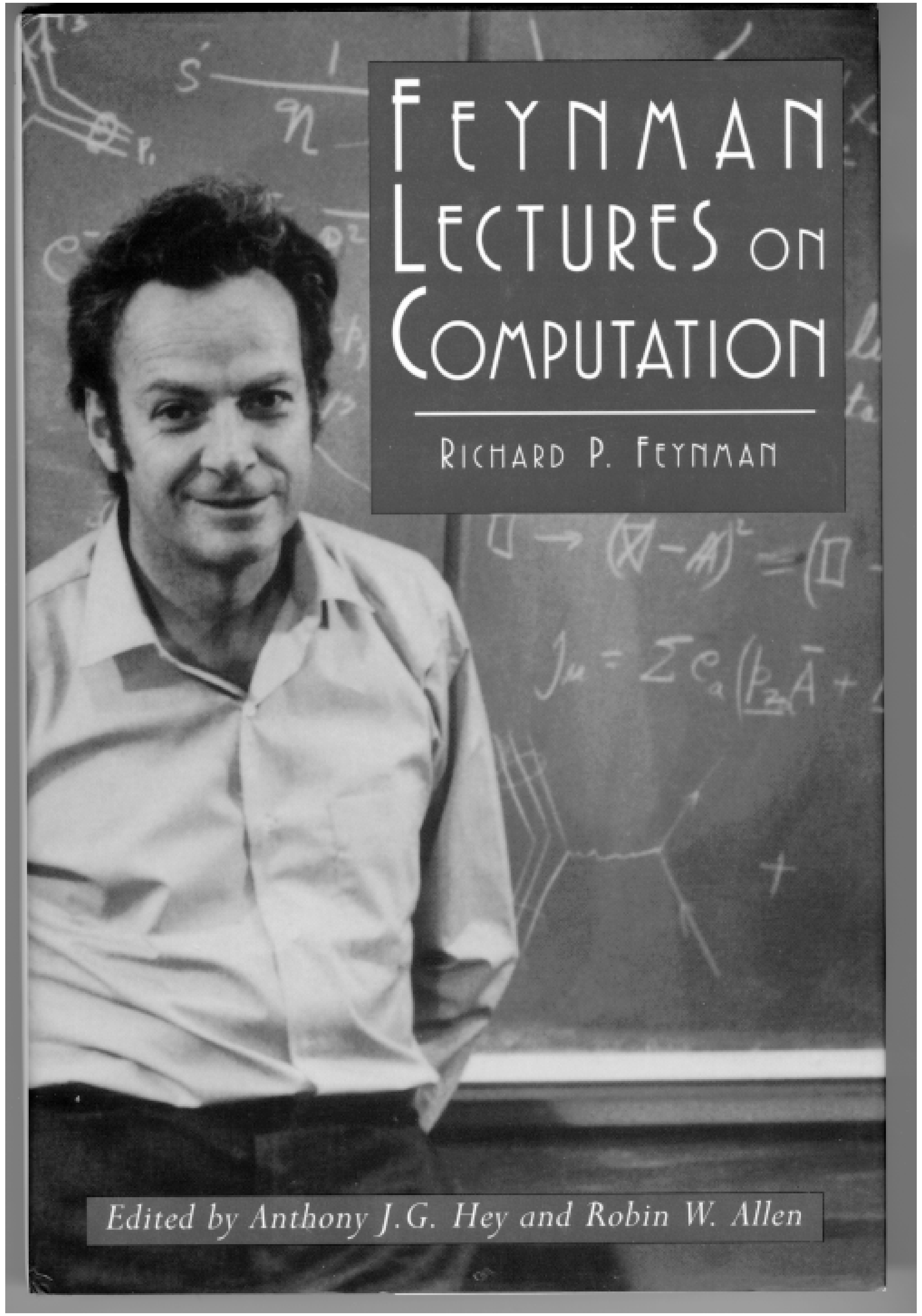
Forty years ago, Richard Feynman proposed harnessing quantum physics to build a more powerful kind of computer. Realizing Feynman's vision is one of the grand challenges facing 21st century science and technology. In this article, we'll recall Feynman's contribution that launched the quest for a quantum computer, and assess where the field stands 40 years later. To appear in *Feynman Lectures on Computation, 2nd edition*, published by Taylor & Francis Group, edited by Anthony J. G. Hey.

arXiv:2106.10522
To appear in Feynman Lectures on Computation
2nd Edition



Richard Feynman
(May 1981)

"You can simulate this with a quantum system, with quantum computer elements. It's not a Turing machine, but a machine of a different kind."



Peter Shor

(1994)

“These algorithms take a number of steps polynomial in the input size, for example, the number of digits of the integer to be factored.”

Quantum Computing in the NISQ era and beyond

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30 July 2018

Noisy Intermediate-Scale Quantum (NISQ) technology will be available in the near future. Quantum computers with 50-100 qubits may be able to perform tasks which surpass the capabilities of today's classical digital computers, but noise in quantum gates will limit the size of quantum circuits that can be executed reliably. NISQ devices will be useful tools for exploring many-body quantum physics, and may have other useful applications, but the 100-qubit quantum computer will not change the world right away — we should regard it as a significant step toward the more powerful quantum technologies of the future. Quantum technologists should continue to strive for more accurate quantum gates and, eventually, fully fault-tolerant quantum computing.

Q2B: Quantum Computing for Business
NASA Ames Research Center
5 December 2017

Quantum 2, 79 (2018)
arXiv:1801.00862

Open Questions

How will we scale up to quantum computing systems that can solve hard problems?

What are the important applications for science and for industry?

What to do with near-term quantum computers?

Learn how to build more powerful quantum computers.

And learn how to use them for advancing science and for practical applications.

Prospects for the next 5 years

Encouraging progress toward scalable fault-tolerant quantum computing.

Scientific discoveries enabled by programmable quantum simulators and circuit-based quantum computers.

"As the quantum community eagerly seizes the impending opportunity to experiment with NISQ devices, we must not lose sight of the essential longer-term goal: hastening the onset of the fault-tolerant era."

Quantum computing in the NISQ era and beyond

Quantum error correction

Repeated rounds of accurate error syndrome measurement.

Quantum memory times that improve sharply as codes increase in size.

Logical two-qubit gates with (much) higher fidelity than physical two-qubit gates.

Logical gate fidelities that improve sharply as codes increase in size.

We’re not there yet. But soon?

Quantum error correction circa 2021

Google 2021 (superconducting): 11-qubit *repetition code* + 10 ancilla qubits (Sycamore processor). 50 rounds of syndrome measurement, each taking about 1 microsecond. Logical error rate improves by 10X when code distance increases by 4. [arXiv:2102.06132]

Honeywell 2021 (ions): 7-qubit color code + 3 ancilla qubits. 6 rounds of syndrome measurement, each taking about 200 milliseconds. [arXiv:2107.07505]

Also notable: UMD/Duke (9-qubit code + 4 ancilla qubits, ions), Innsbruck (two 7-qubit code blocks + 2 ancilla qubits, ions), Delft (5-qubit code + 2 ancilla qubits, NV centers in diamond).

Alexei Kitaev

(1997)

“Such computation is fault-tolerant by its physical nature.”

Fault tolerance with the surface code

Logical error (per round of syndrome measurement):

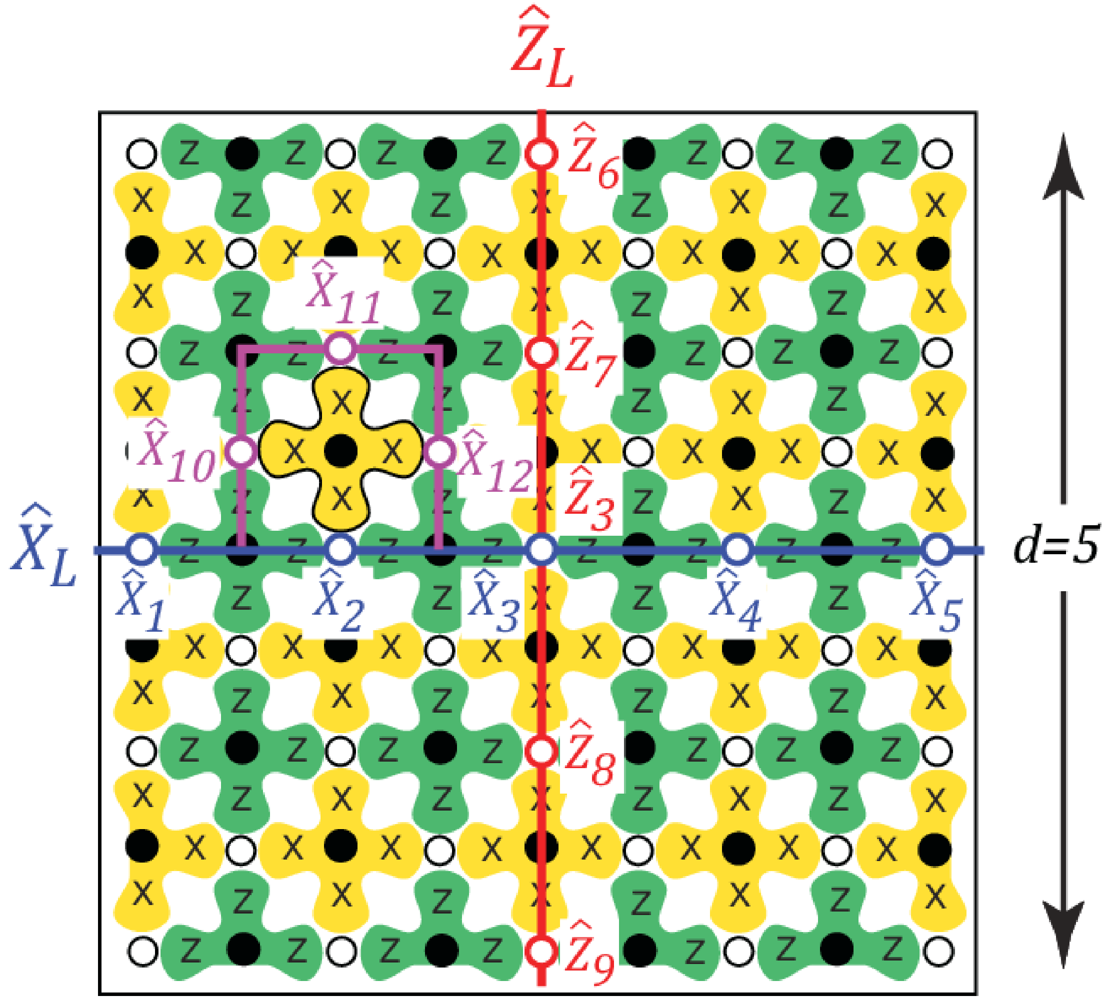
$$p_L(p_{\mathrm{phys}}, d) = 0.1(100 p_{\mathrm{phys}})^{(d+1)/2}$$

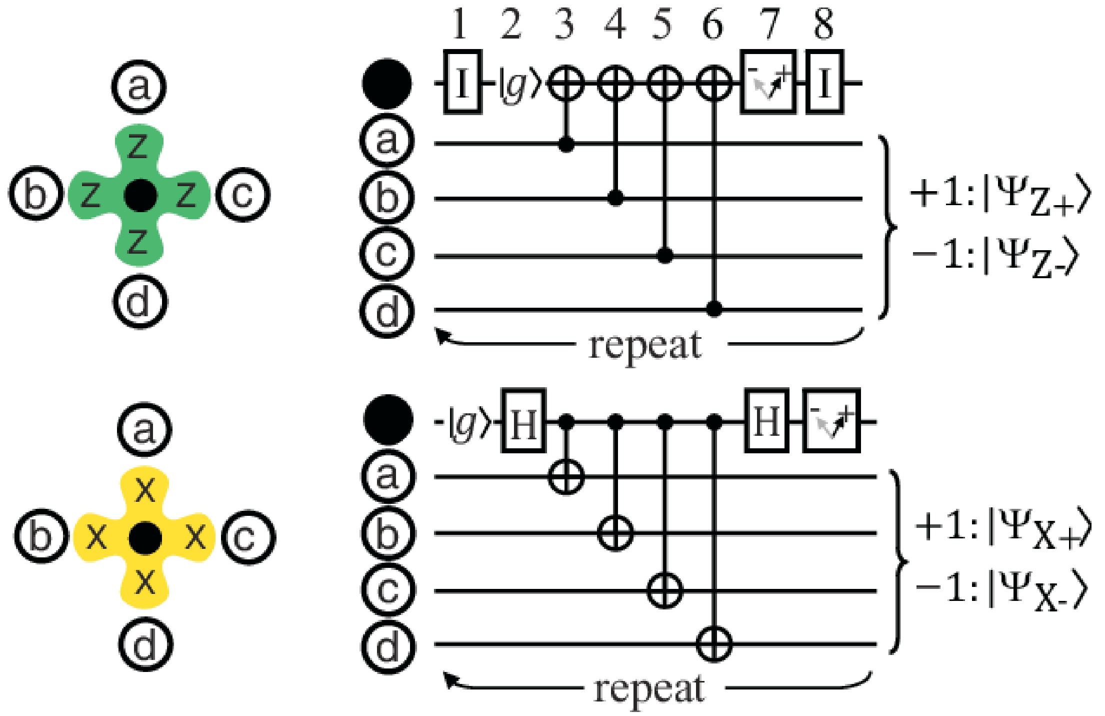
physical qubits per block: $2(d+1)^2$ (Fowler et al. 2013)

	d=5	d=9	d=15
p_{phys}= 0.5%	1.2%	0.3%	4x10^{-4}
p_{phys}= 0.1%	10^{-4}	10^{-6}	10^{-9}
p_{phys}= 10^{-4}	10^{-7}	10^{-11}	10^{-17}
# qubits	72	200	512

currently: $p_{\mathrm{phys}} \cong$ 1%

To break RSA for N = 2048 with $p_{\mathrm{phys}} \cong$ 0.1%:
d=27 → $2(d+1)^2$ = 1568 physical qubits per logical qubit.
(Gidney and Ekerå 2021)





“Physicists are excited about this NISQ technology, which gives us new tools for exploring the physics of many entangled particles.”

Quantum computing in the NISQ era and beyond

Quantum phases of matter circa 2021

Harvard/MIT 2021 (Rydberg atoms): Experimental confirmation of a topologically ordered quantum spin liquid. 219 atomic qubits in a programmable quantum simulator, frustrated by “Rydberg blockade.” Measurement of topological string operators. [arXiv:2104.04119]

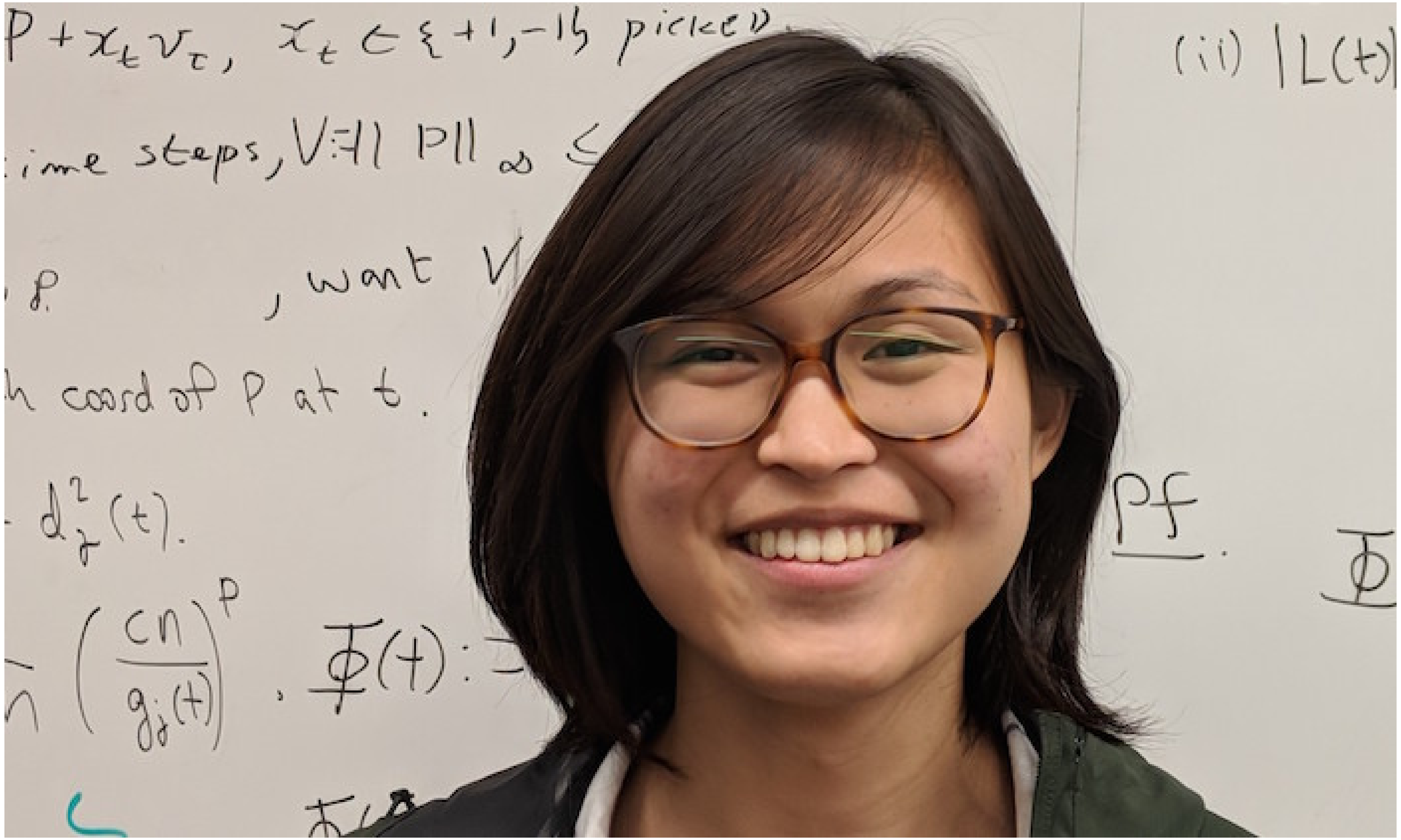
Google/Stanford/MPI/Princeton/etc. 2021 (superconducting): Observation of a discrete time crystal, a periodically driven disordered phase which spontaneously breaks discrete time-translation invariance. 20 transmon qubits in a gate-based quantum computer. Measurement of temporal autocorrelations. [arXiv:2107.13571]

What next? Observations of other novel quantum phases, both in equilibrium and far from equilibrium?

"Quantum deep learning might be very well suited for quantum tasks, but for applications of deep learning that are widely pursued today it is unclear why quantum networks would have an advantage."

Quantum computing in the NISQ era and beyond

Dequantization!



Ewin Tang (U. Washington)

Quantum machine learning circa 2021

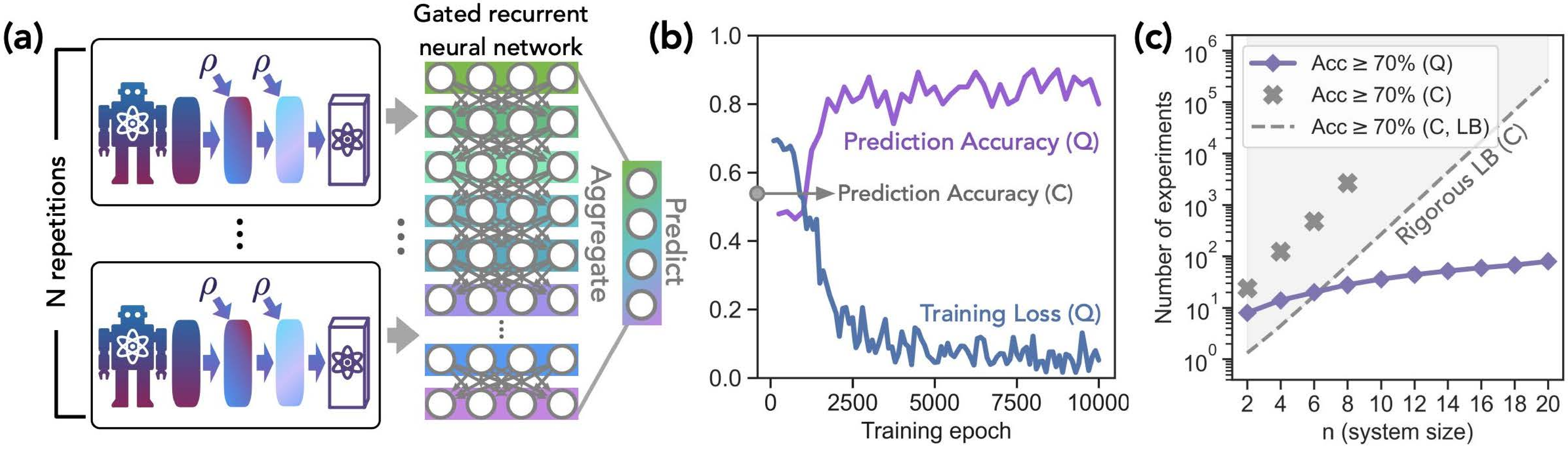
Caltech/Google/Harvard/Microsoft/etc. 2021 (superconducting):
Exponential quantum advantage in learning from experiments.
[arXiv:2112.00778]

How many experiments are needed to learn properties of physical systems, with or without access to quantum memory?

For some tasks, we prove that *exponentially fewer* experiments suffice in the “quantum-enhanced” setting.

And we demonstrate this advantage in experiments using up to 40 qubits on the Sycamore processor.

Quantum machine learning circa 2021



Exponential quantum advantage in learning expectation values of observables.

Will quantum technology revolutionize how we acquire and process experimental data to learn about the physical world?

How (quantum) science advances

New ideas and new tools.

Unanticipated discoveries.

Deeper ideas and new questions.

Repeat.

Quantum complexity: an “endless frontier”?

Conclusion

We may have a long road ahead to practical applications, and quantum error correction is most likely the key to getting there.

Exciting prospects for the next 5 years include progress toward fault-tolerant quantum computing and unprecedented opportunities to explore exotic properties of quantum matter.

We face enormous challenges, and basic research advances will be needed to meet them.

A final thought

To achieve great things, we must be optimistic about the future.

But there is a line between setting ambitious goals and fanning inflated expectations.

In the long run, we’ll be better off if we respect that line.