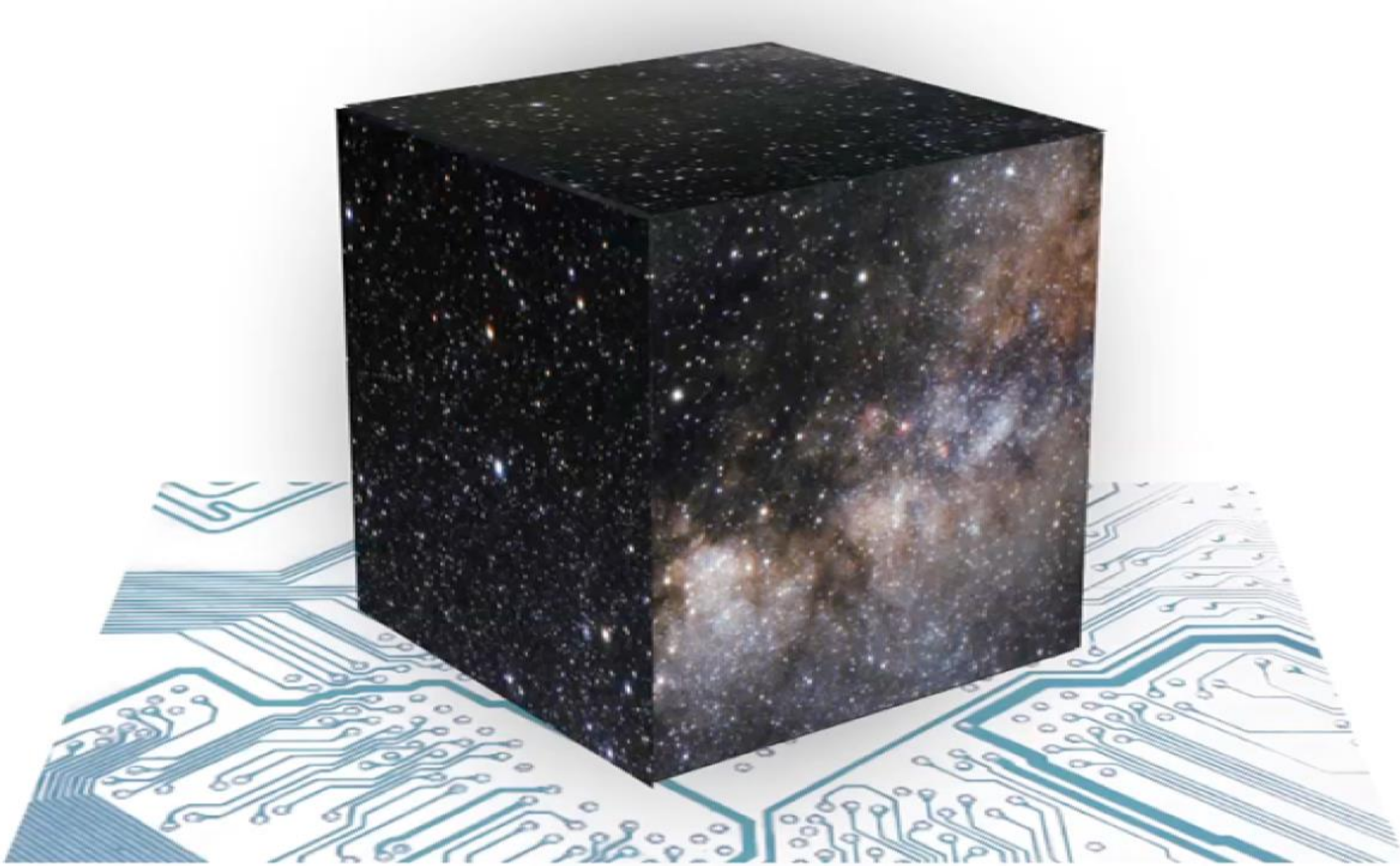
Our Quantum Future



INSTITUTE FOR QUANTUM INFORMATION AND MATTER

John Preskill

APS Global Physics Summit

17 March 2025

@preskill

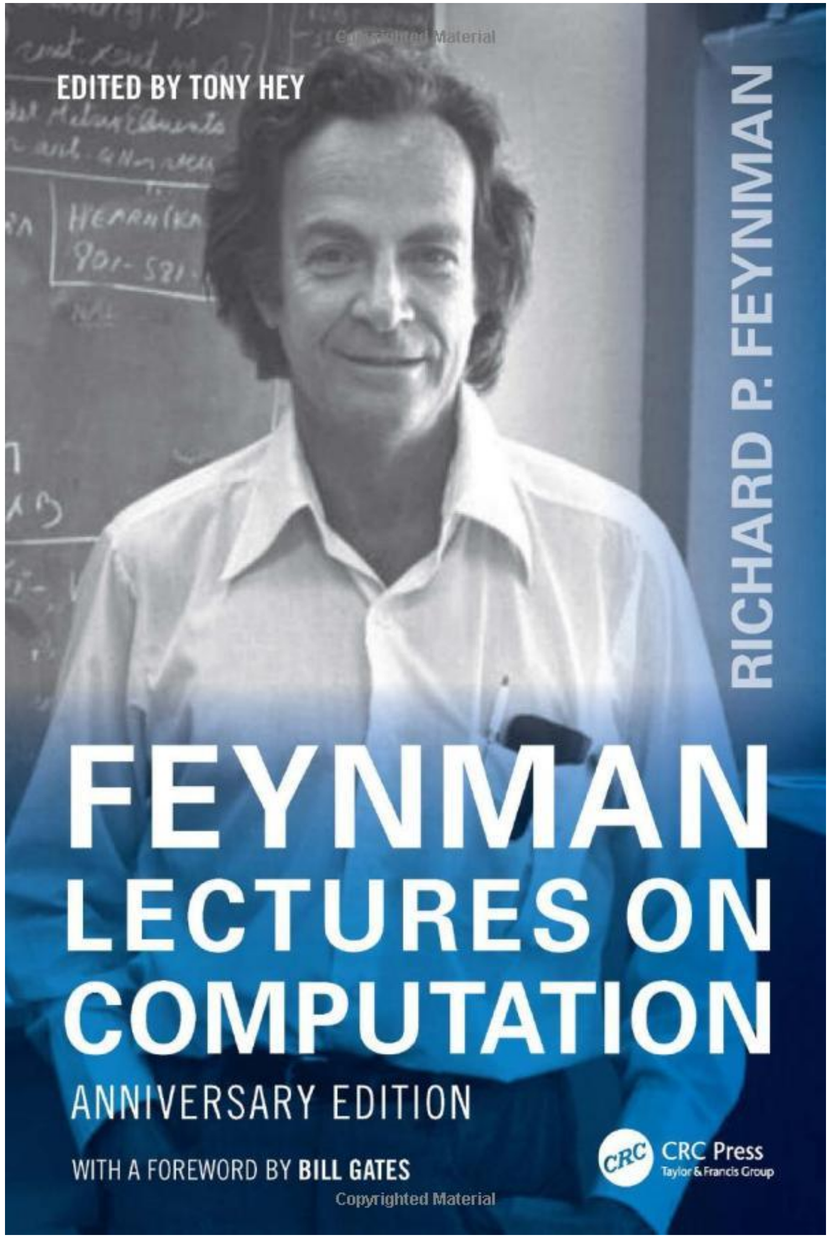
Open Questions

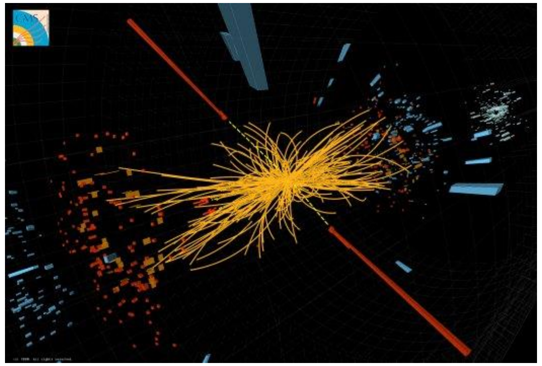
How will we scale up to quantum computing systems that can solve hard problems?

What are the important applications for science and for industry?

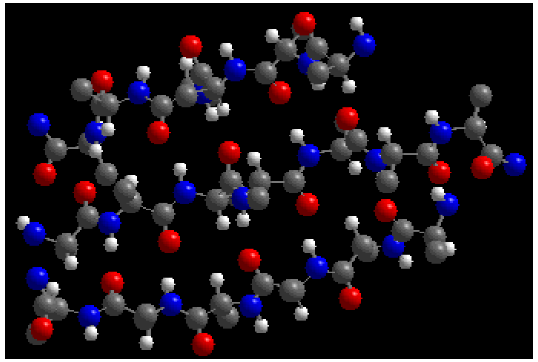
“Nature isn’t classical, dammit, and if you want to make a simulation of Nature, you’d better make it quantum mechanical, and by golly it’s a wonderful problem because it doesn’t look so easy.”

Richard Feynman
Simulating Physics with Computers
May 1981

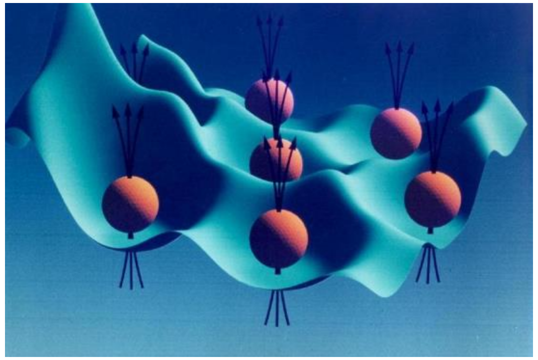




particle collision

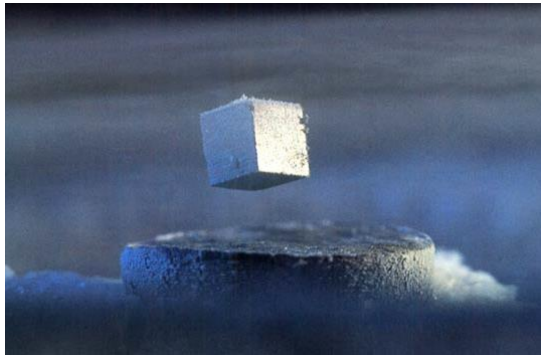


molecular chemistry

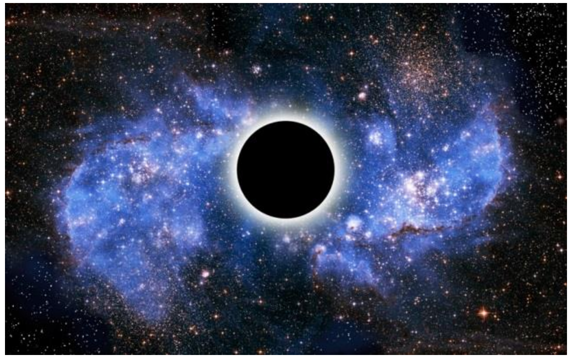


entangled electrons

(We expect that) a quantum computer can simulate efficiently any physical process that occurs in Nature.



superconductor



black hole

early universe

Quantum computing for chemistry and materials

Dirac (1929): "… equations much too complicated to be soluble."

Yet, heuristic classical algorithms are often very successful, and these methods are continually improving.

Quantum computing targets the relatively small "strongly correlated" corner of chemistry and materials science, where such methods falter.

How useful are quantum computers in physically relevant situations that are beyond the reach of classical methods?

Artificial intelligence may drive future progress in (strongly correlated) chemistry and materials science. Eventually, quantum computers can accelerate progress by providing abundant training data.

Noisy Intermediate Scale Quantum (NISQ) Era

What we have now.

NISQ is valuable for scientific exploration. But there is no proposed application of NISQ computing with *commercial* value for which quantum advantage has been demonstrated *when compared to the best classical hardware running the best algorithms for solving the same problems*.

What we can reasonably foresee.

Nor are there persuasive theoretical arguments indicating that commercially viable applications will be found that do *not* use quantum error-correcting codes and fault-tolerant quantum computing.

Fault-tolerant Application Scale Quantum (FASQ) Era

What we want to have.

-- Quantum computers running a wide variety of useful computations.
-- Machines that can execute of order 10^{12} quantum operations ("teraquop machines").
-- This requires improving quantum gate error rates by about 9 orders of magnitude beyond the current state of the art.
-- Quantum error correction and will be essential for crossing the chasm from NISQ to FASQ. We may need devices with millions of physical qubits.

When will we have it?

No one knows. It might take decades.

Megaquop Machine

Logical gate error rate ~ 10^{-6}. Not achievable without QEC.

Error mitigation will continue to be useful in the Megaquop era and beyond.

Beyond classical, NISQ, or analog. E.g., depth 10K and 100 (logical) qubits.

Tens of thousands of high-quality physical qubits.

When will we have it? Less than 5 years? What modality? Rydberg atoms?

What will we do with it? Quantum dynamics?

Commercial as well as scientific applications? [arXiv:2502.17368]

Co-design

Adapt the application and the error correction protocol to the hardware.

Adapt the hardware to the application and the error-correcting code.

Prospects for the next 5 years

Encouraging progress toward scalable fault-tolerant quantum computing.

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

Advances in quantum metrology from improved control of quantum many-body systems.

Prospects for the next 100 years

Past 100 years:

The relatively simple quantum behavior of weakly correlated particles like electrons, photons, etc.

Next 100 years:

The extraordinarily complex quantum behavior of many profoundly entangled particles.