Quantum science needs mathematicians

Bert de Jong
Director Quantum Systems Accelerator
Director MACH-Q Program

wadejong@lbl.gov

Quantum is already used in every day life

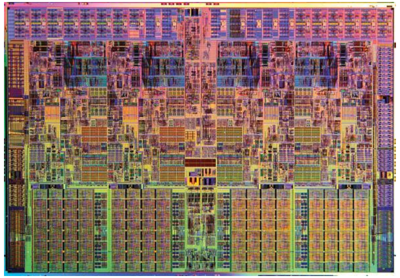
MRI

Lighting

GPS with atomic clocks

Optical fibers in telecom

Lasers



Ubiquitous transistors

Ingredients that make quantum *quantum*

Interference

Superposition

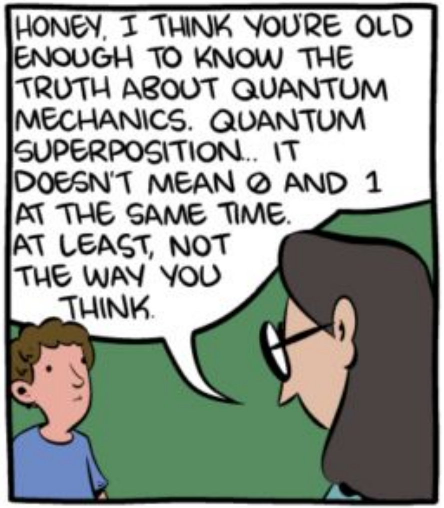
Qubit

Measurement

Entanglement

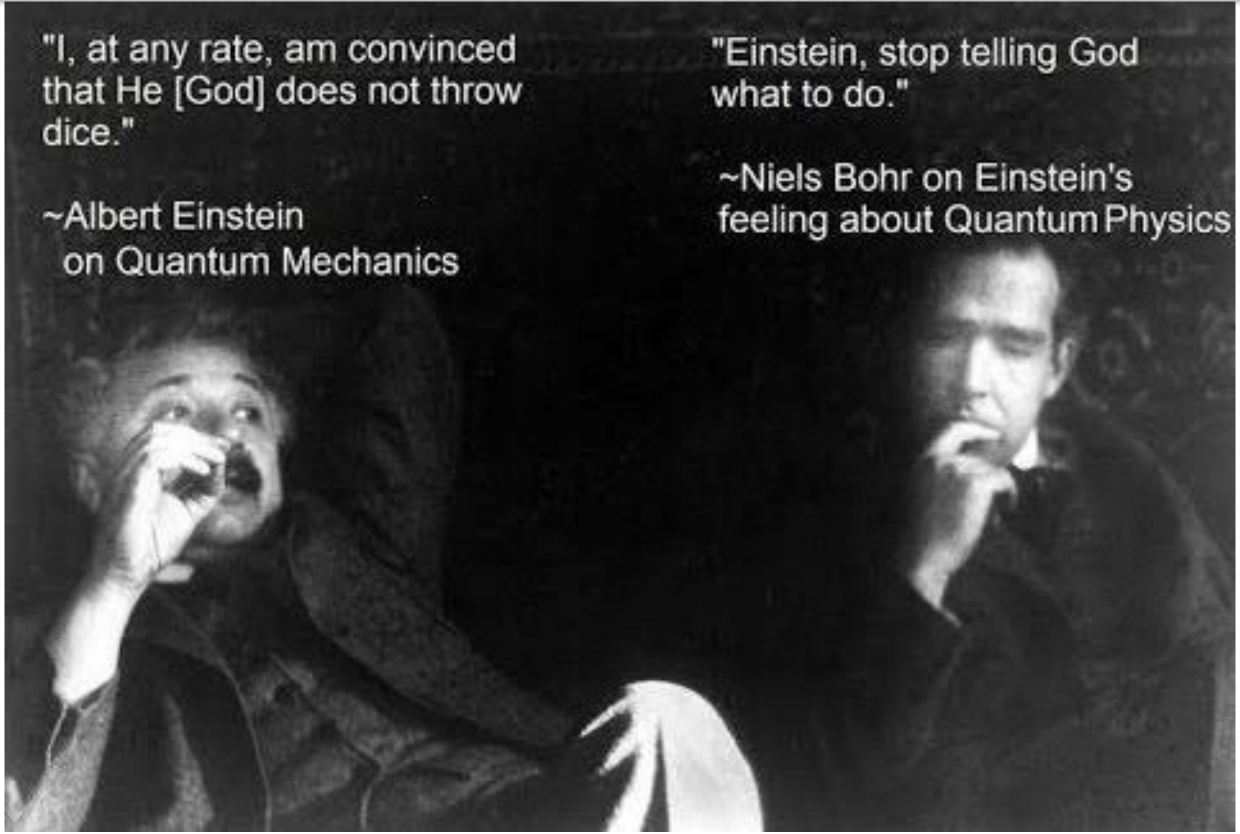
This is the one that makes it "Quantum." The rest is just math.

Superpostion and Schrödinger's Cat



- You can only MEASURE either dead or alive, not both
- How you measure (which basis) determines if you get information or gibberish
- No copying of quantum information is possible

Einstein did not like this uncertainty



"I, at any rate, am convinced that He [God] does not throw dice."

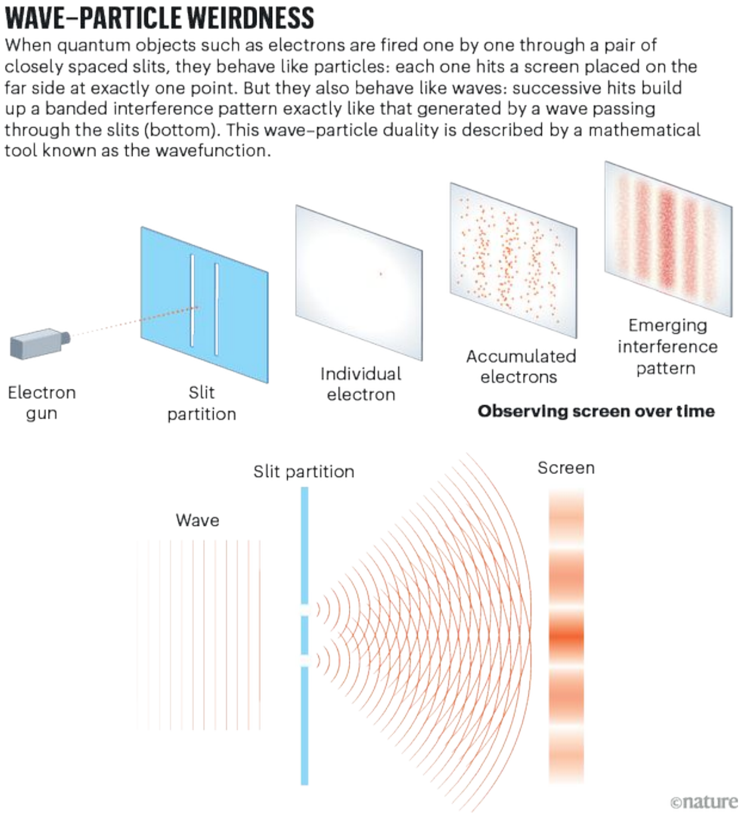
~Albert Einstein
on Quantum Mechanics

"Einstein, stop telling God what to do."

~Niels Bohr on Einstein's feeling about Quantum Physics

Niels Bohr’s office in Copenhagen

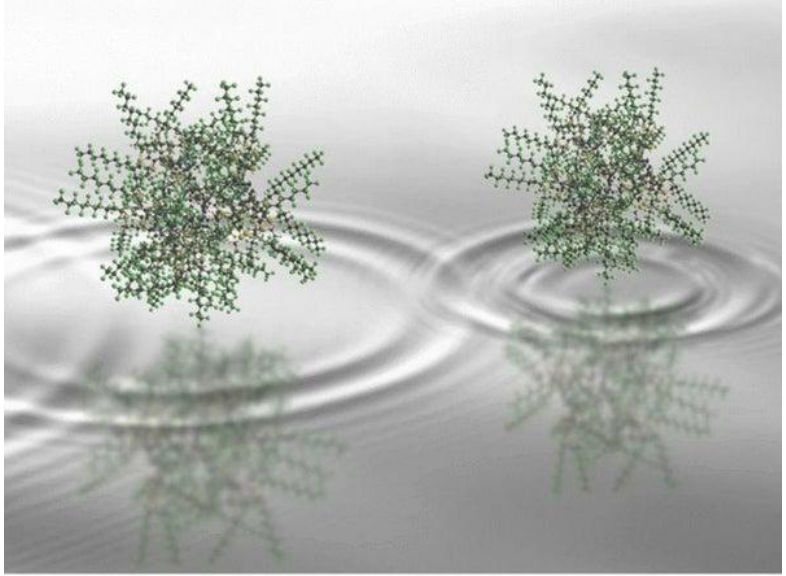
Two-slit experiment proved superposition and uncertainty



WAVE–PARTICLE WEIRDNESS

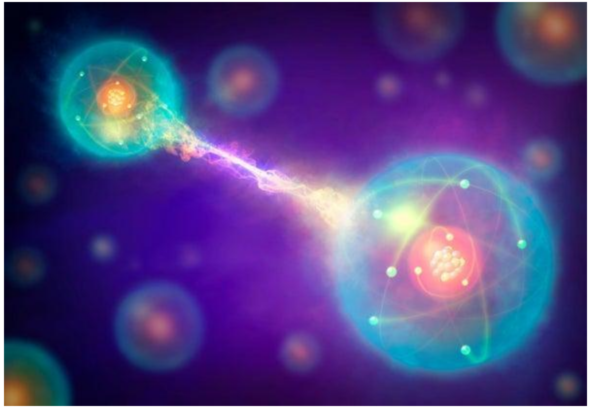
When quantum objects such as electrons are fired one by one through a pair of closely spaced slits, they behave like particles: each one hits a screen placed on the far side at exactly one point. But they also behave like waves: successive hits build up a banded interference pattern exactly like that generated by a wave passing through the slits (bottom). This wave–particle duality is described by a mathematical tool known as the wavefunction.

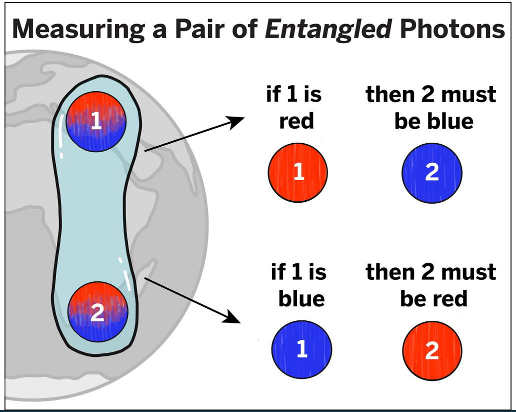
Even large proteins show quantum behavior



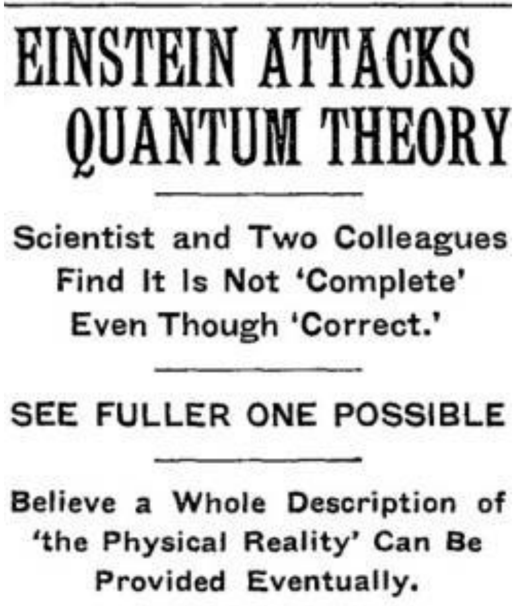
Credit: Yaakov Fein Universität Wien

Entanglement is what makes quantum powerful





Measuring a Pair of *Entangled* Photons

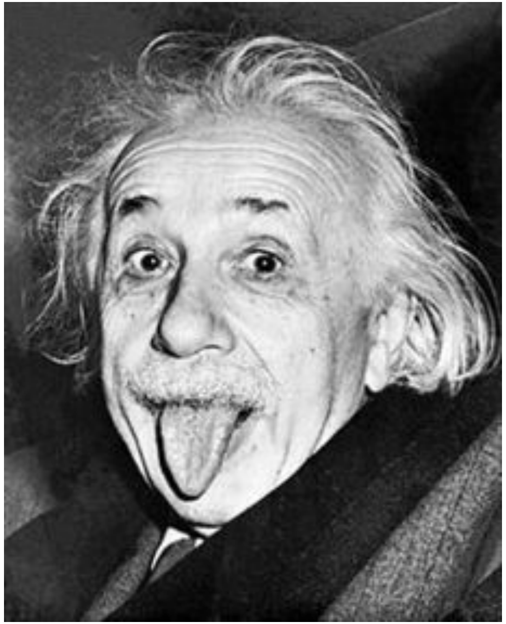


EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

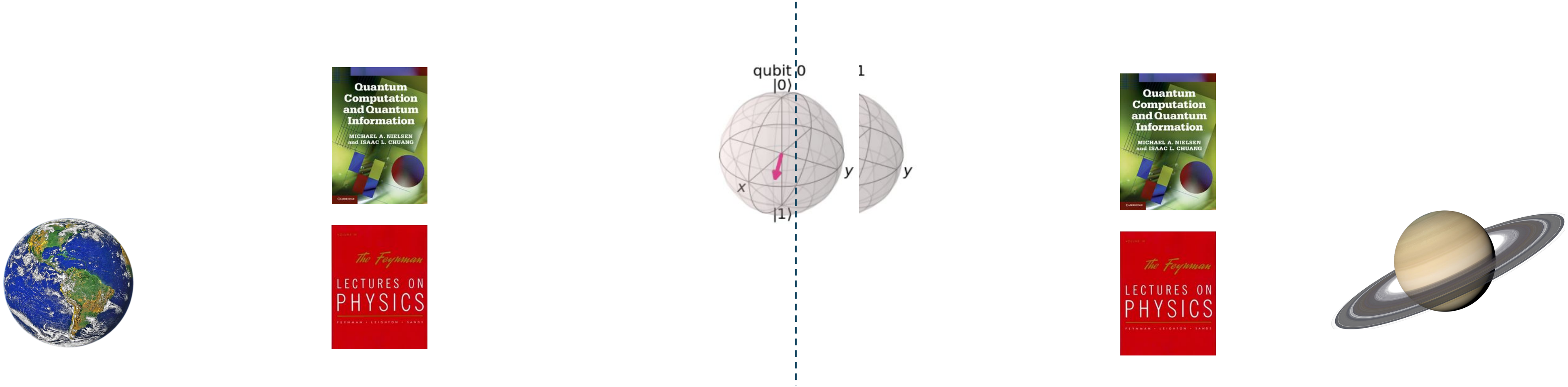
SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.



Einstein called it “spooky action at a distance”

Entanglement and quantum correlations

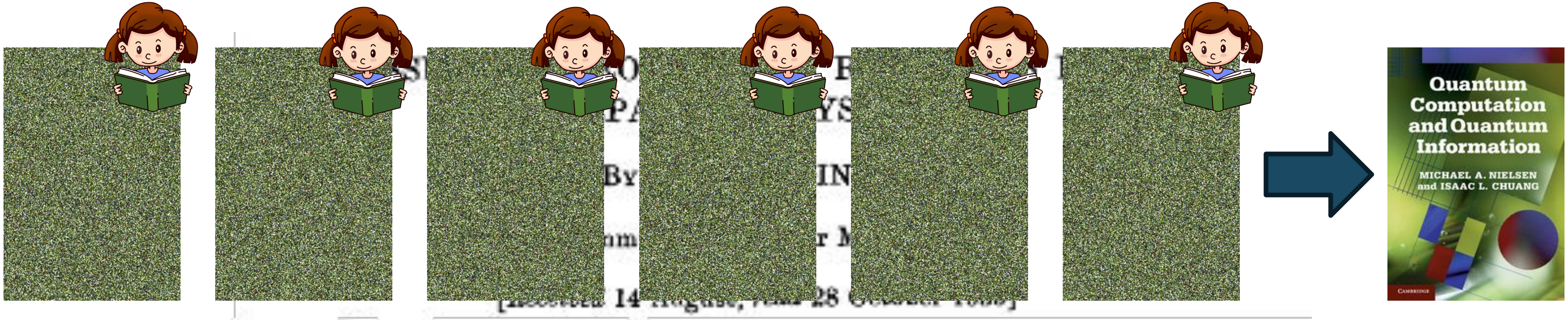


Quantum information can be stored *nonlocal*

and is stored in *quantum correlations* between qubits

Based on Preskill (CalTech) Wolfgang Pauli Lecture 2024

Entanglement and quantum correlations



[Received 14 August, read 28 October 1935]

the best possible knowledge of a *whole* does not necessarily include the best possible knowledge of all its *parts*,

Proceedings of the Cambridge Philosophical Society

Classically

Collective measurement

(reading of all pages in quantum book at the same time)

Not so with quantum information in a quantum book

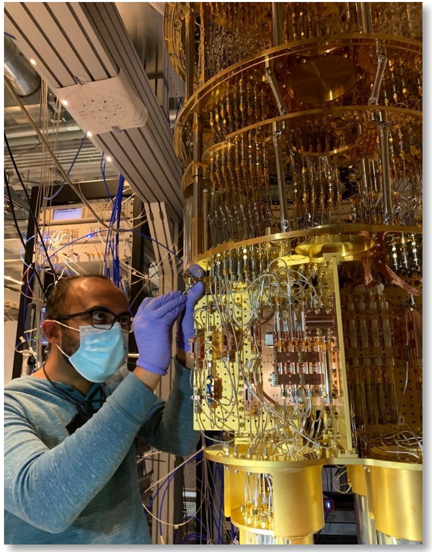
reveals the information contained in the qubits

Based on Preskill (CalTech) Wolfgang Pauli Lecture 2024

Twentieth century quantum revolution

Quantum computing

Next-level simulations

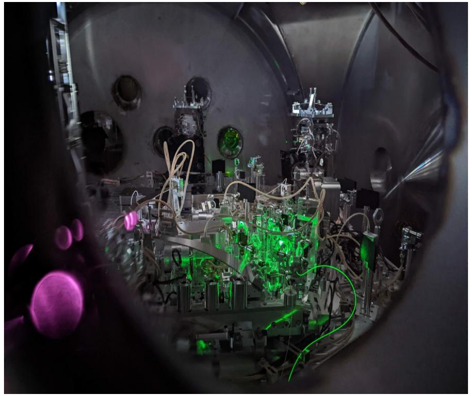


Quantum networks

Secure data communication

Quantum sensors

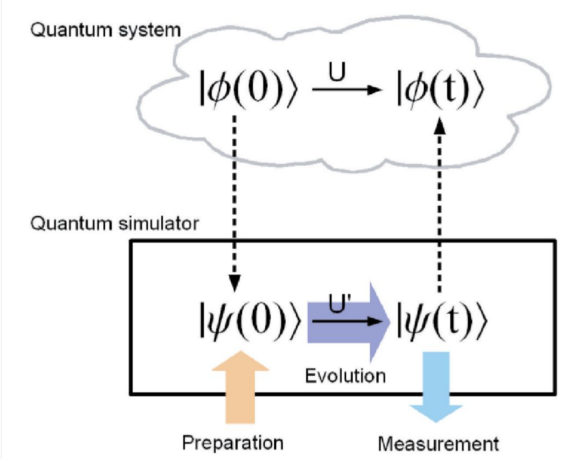
From materials to gravitational waves

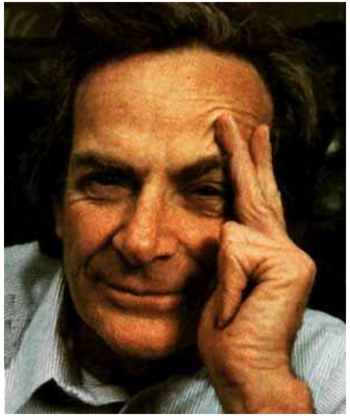


Credit: Georgia Mansell/LIGO Hanford

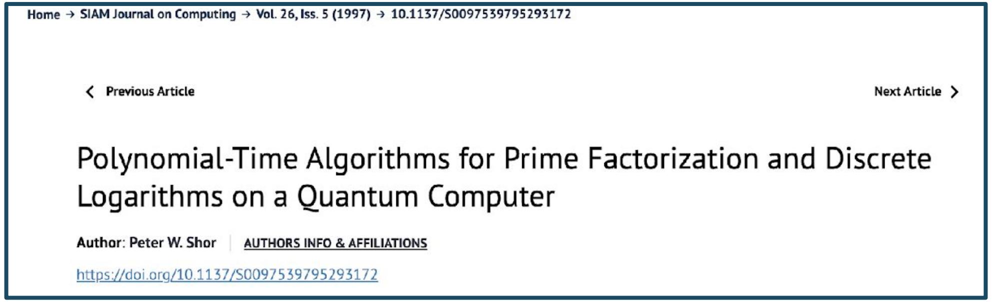
Feynman proposed idea of universal quantum simulators

Simulating evolution of a quantum system on a classical computer in an efficient way is impossible (Feynman, 1982)





Shor developed factorization algorithm with quantum advantage



Home → SIAM Journal on Computing → Vol. 26, Iss. 5 (1997) → 10.1137/S0097539795293172

< Previous Article

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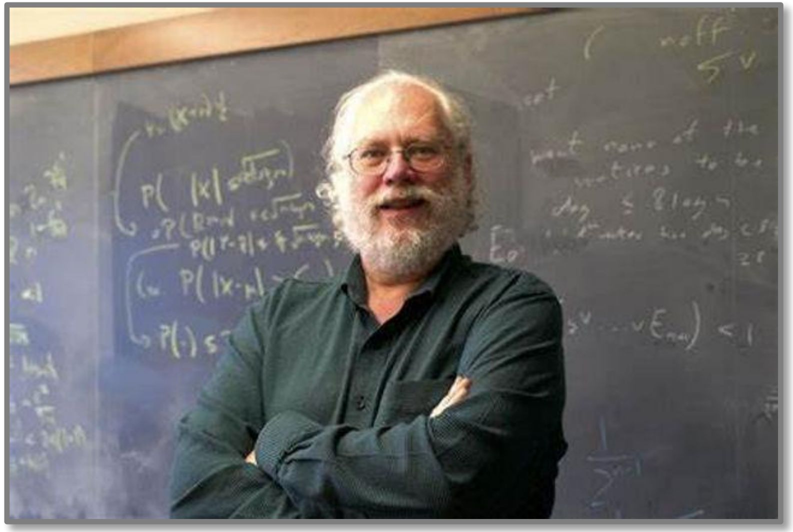
Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer

Author: Peter W. Shor | AUTHORS INFO & AFFILIATIONS

https://doi.org/10.1137/S0097539795293172

SIAM J. Sci. Statist. Comput. 26 (1997) 1484



Information content of quantum computers is key

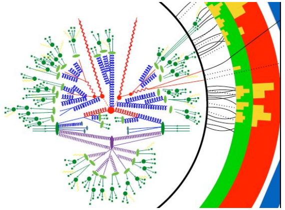
- 2^n complex coefficients describe the state of a composite quantum system with n qubits

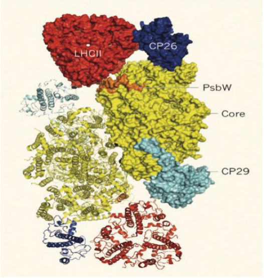
- 100 qubits = 2^{100} states

- Quickly reaches number of particles in the universe

Accelerating DOE discovery science with quantum computing

Algorithmic speedups over classical computing





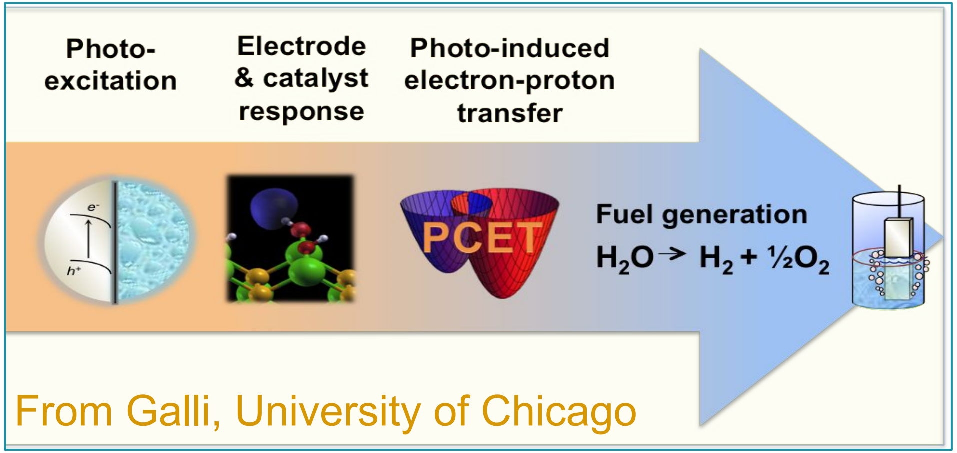
Quantum simulation

Efficient optimization algorithms

“Unbreakable” encryption protocols

Quantum computing advantage for molecular sciences

Chemisty - Photo-induced catalysis of water

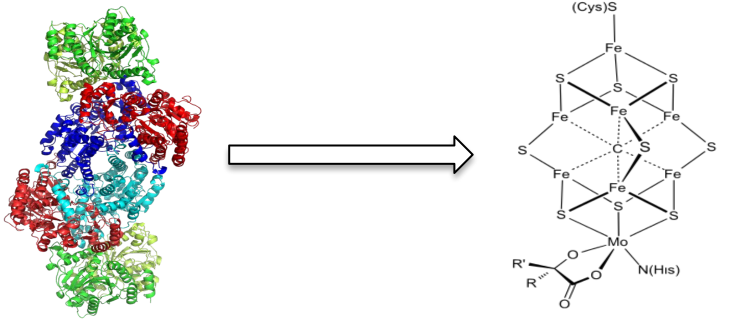


From Galli, University of Chicago

Biology - Nitrogenase enzyme

$$N_2 + 3\ H_2 \rightarrow 2\ NH_3$$

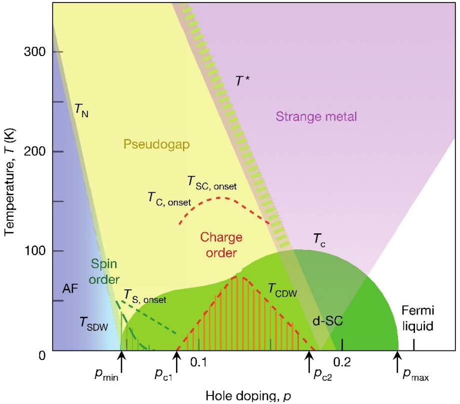
"FeMoco"



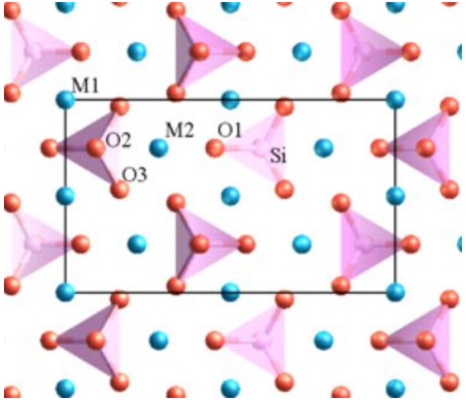
Nature's answer to Haber Process

Single energy calculation is inaccessible, even at exascale!
Quantum computer requires ~100-200 ideal qubits for solution

Electron correlation drives many materials technologies



Taken from Keimer et al., Nature 2015



Superconductivity in MRI magnets and wires for current transmission

Strongly correlated materials in battery materials

Accurate solutions are challenging to impossible on classical computers

Quantum advantage exploring fundamental laws of physics

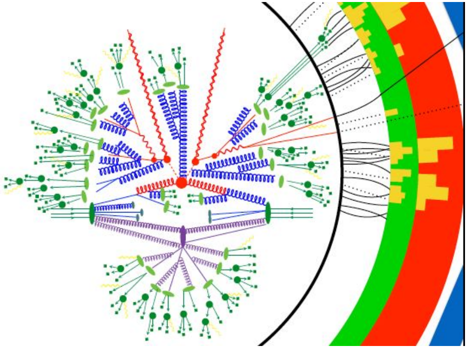
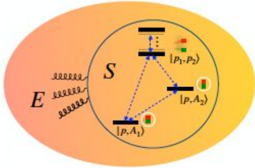
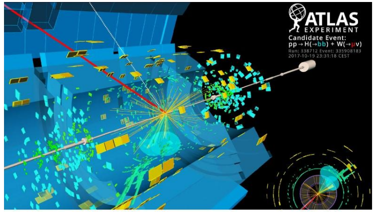


Image inspired by JHEP 02 (2009) 007, Courtesy Nachman (LBNL)





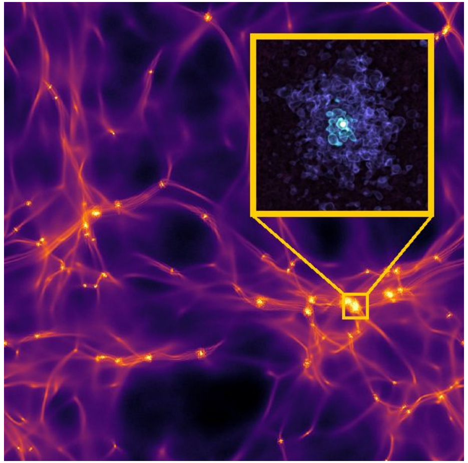
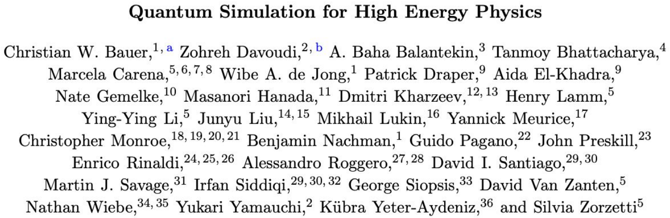


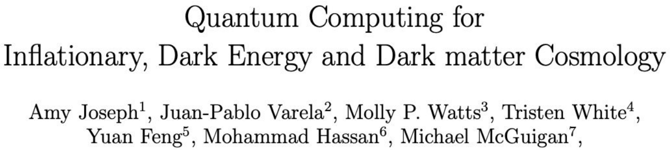
Image from arXiv:2101.05821



Quantum Simulation for High Energy Physics

Christian W. Bauer,[1, a] Zohreh Davoudi,[2, b] A. Baha Balantekin,[3] Tanmoy Bhattacharya,[4]
Marcela Carena,[5, 6, 7, 8] Wibe A. de Jong,[1] Patrick Draper,[9] Aida El-Khadra,[9]
Nate Gemelke,[10] Masanori Hanada,[11] Dmitri Kharzeev,[12, 13] Henry Lamm,[5]
Ying-Ying Li,[5] Junyu Liu,[14, 15] Mikhail Lukin,[16] Yannick Meurice,[17]
Christopher Monroe,[18, 19, 20, 21] Benjamin Nachman,[1] Guido Pagano,[22] John Preskill,[23]
Enrico Rinaldi,[24, 25, 26] Alessandro Roggero,[27, 28] David I. Santiago,[29, 30]
Martin J. Savage,[31] Irfan Siddiqi,[29, 30, 32] George Siopsis,[33] David Van Zanten,[5]
Nathan Wiebe,[34, 35] Yukari Yamauchi,[2] Kübra Yeter-Aydeniz,[36] and Silvia Zorzetti[5]

PRX Quantum **4**, 027001 (2023)



Quantum Computing for
Inflationary, Dark Energy and Dark matter Cosmology

Amy Joseph[1], Juan-Pablo Varela[2], Molly P. Watts[3], Tristen White[4],
Yuan Feng[5], Mohammad Hassan[6], Michael McGuigan[7],

arXiv:2105.13849

Speedup not only factor for quantum advantage

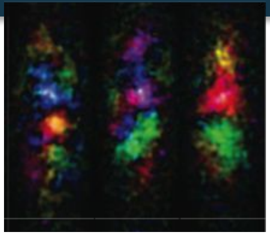
Power: 20 MW + 10 MW for cooling
Cost: US$600M (estimated cost)
Space: 2225 m^2 (7,300 sq ft)
24,000 house holds

Quantum computers could solve **larger problems faster** compared to classical computing hardware

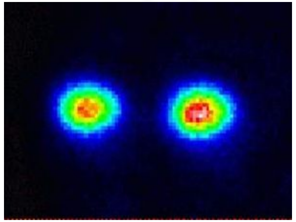
Quantum computers potentially **cheaper and use less energy** than classical computers, increasing accessibility to large scale computing

Quantum computers come in many flavors

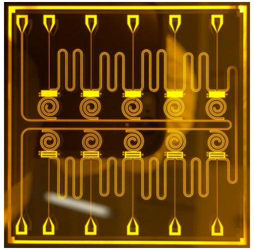
Currently Leading in the Field



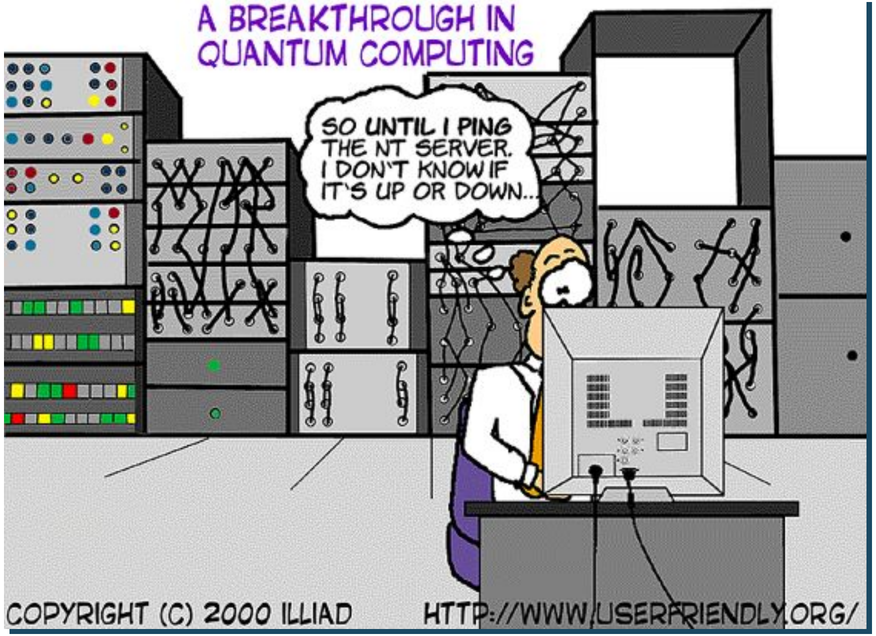
ATOMS

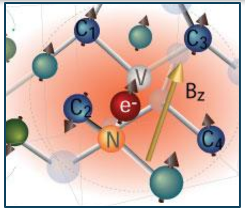


IONS

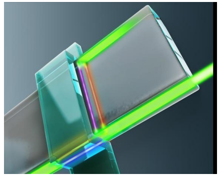


SUPERCONDUCTING

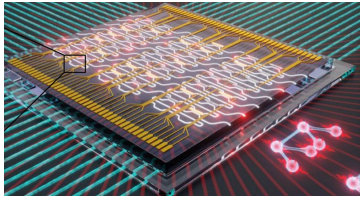




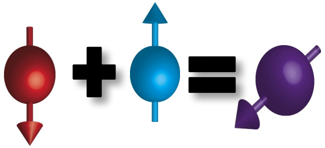
SOLID STATE (spins)



MAJORANA QUASI-PARTICLE



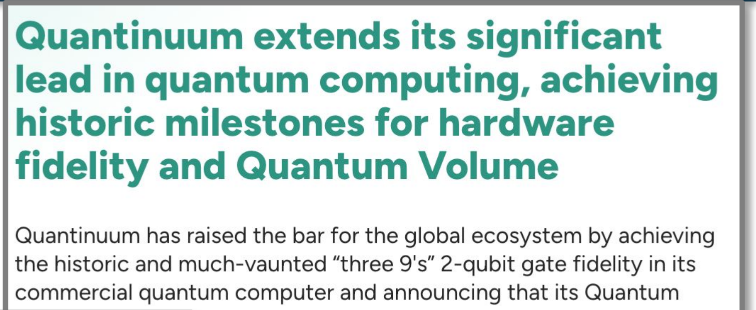
PHOTONS



ELECTRONS SPIN UP + SPIN DOWN

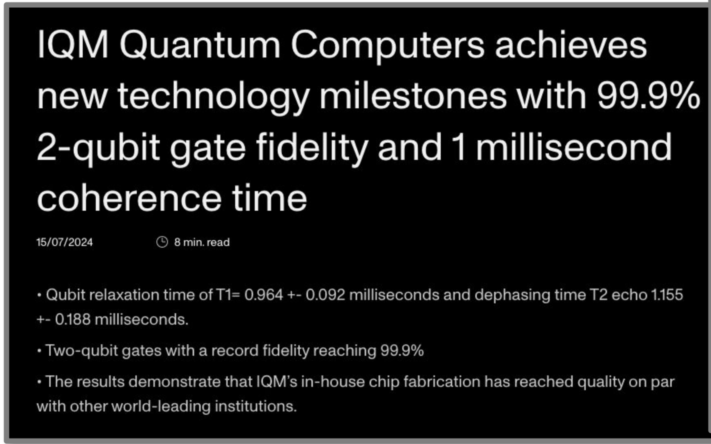
Quantum systems are getting higher gate fidelities

Different technologies achieve 99.9% fidelity on 2-qubit entangling gates



Quantinuum extends its significant lead in quantum computing, achieving historic milestones for hardware fidelity and Quantum Volume

Quantinuum has raised the bar for the global ecosystem by achieving
the historic and much-vaunted "three 9's" 2-qubit gate fidelity in its
commercial quantum computer and announcing that its Quantum
ssed one million – exponentially higher than its
ors.



IQM Quantum Computers achieves new technology milestones with 99.9% 2-qubit gate fidelity and 1 millisecond coherence time

15/07/2024 ◷ 8 min. read

- Qubit relaxation time of T1= 0.964 +- 0.092 milliseconds and dephasing time T2 echo 1.155 +- 0.188 milliseconds.
- Two-qubit gates with a record fidelity reaching 99.9%
- The results demonstrate that IQM's in-house chip fabrication has reached quality on par with other world-leading institutions.

PHYSICAL REVIEW LETTERS

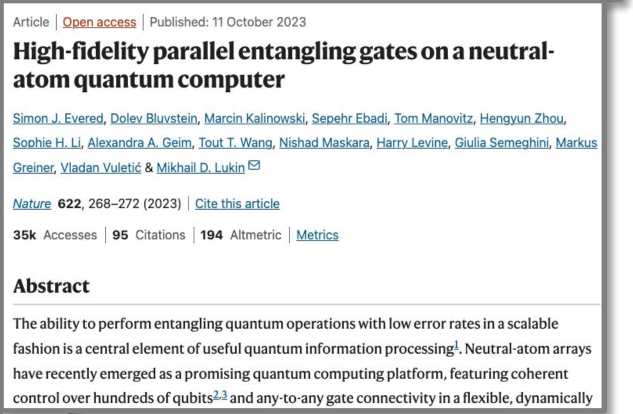
High-Fidelity, High-Scalability Two-Qubit Gate Scheme for Superconducting Qubits

Yuan Xu, Ji Chu, Jiahao Yuan, Jiawei Qiu, Yuxuan Zhou, Libo Zhang, Xinsheng Tan, Yang Yu, Son
Fei Yan, and Dapeng Yu

Phys. Rev. Lett. **125**, 240503 – Published 9 December 2020

ABSTRACT

High-quality two-qubit gate operations are crucial for scalable quantum information proce
the gate fidelity is compromised when the system becomes more integrated. Therefore, a
rate, easy-to-scale two-qubit gate scheme is highly desirable. Here, we experimentally de
new two-qubit gate scheme that exploits fixed-frequency qubits and a tunable coupler in
superconducting quantum circuit. The scheme requires less control lines, reduces cross t
and simplifies calibration procedures, yet produces a controlled-Z gate in 30 ns with a hig
99.5%, derived from the interleaved randomized benchmarking method. Error analysis sh
gate errors are mostly coherence limited. Our demonstration paves the way for large-scale
implementation of high-fidelity quantum operations.



Article | Open access | Published: 11 October 2023

High-fidelity parallel entangling gates on a neutral-atom quantum computer

Simon J. Evered, Dolev Bluvstein, Marcin Kalinowski, Sepehr Ebadi, Tom Manovitz, Hengyun Zhou, Sophie H. Li, Alexandra A. Geim, Tout T. Wang, Nishad Maskara, Harry Levine, Giulia Semeghini, Markus Greiner, Vladan Vuletić & Mikhail D. Lukin ✉

Nature **622**, 268–272 (2023) | Cite this article

35k Accesses | **95** Citations | **194** Altmetric | Metrics

Abstract

The ability to perform entangling quantum operations with low error rates in a scalable fashion is a central element of useful quantum information processing[1]. Neutral-atom arrays have recently emerged as a promising quantum computing platform, featuring coherent control over hundreds of qubits[2,3] and any-to-any gate connectivity in a flexible, dynamically

Quantum systems get new operation capabilities

Demonstrating a Continuous Set of Two-Qubit Gates for Near-Term Quantum Algorithms

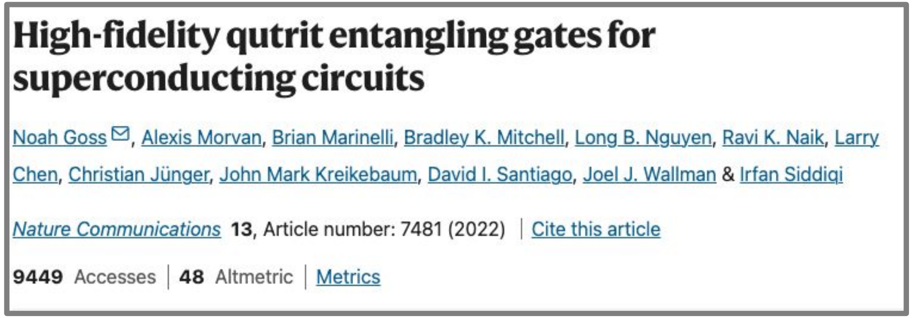
B. Foxen *et al.* (Google AI Quantum)
Phys. Rev. Lett. **125**, 120504 – Published 15 September 2020

ABSTRACT

Quantum algorithms offer a dramatic speedup for computational problems in material science and chemistry. However, any near-term realizations of these algorithms will need to be optimized to fit within the finite resources offered by existing noisy hardware. Here, taking advantage of the adjustable coupling of gmon qubits, we demonstrate a continuous two-qubit gate set that can provide a threefold reduction in circuit depth as compared to a standard decomposition. We implement two gate families: an imaginary swap-like (iSWAP-like) gate to attain an arbitrary swap angle, θ, and a controlled-phase gate that generates an arbitrary conditional phase, ϕ. Using one of each of these gates, we can perform an arbitrary two-qubit gate within the excitation-preserving subspace allowing for a complete implementation of the so-called Fermionic simulation (fSim) gate set. We benchmark the fidelity of the iSWAP-like and controlled-phase gate families as well as 525 other fSim gates spread evenly across the entire $\mathrm{fSim}(\theta, \phi)$ parameter space, achieving a purity-limited average two-qubit Pauli error of 3.8×10^{-3} per fSim gate.

- ✔ New types of two-qubit gates
- ✔ Multi-qubit gates
- ✔ Parallel gates
- ✔ Qutrit operations
- ✔ Mid-circuit measurement

….

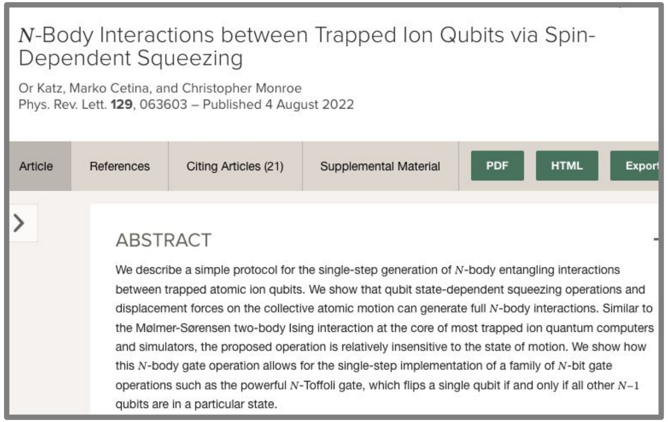


High-fidelity qutrit entangling gates for superconducting circuits

Noah Goss ✉, Alexis Morvan, Brian Marinelli, Bradley K. Mitchell, Long B. Nguyen, Ravi K. Naik, Larry Chen, Christian Jünger, John Mark Kreikebaum, David I. Santiago, Joel J. Wallman & Irfan Siddiqi

Nature Communications **13**, Article number: 7481 (2022) | Cite this article

9449 Accesses | **48** Altmetric | Metrics



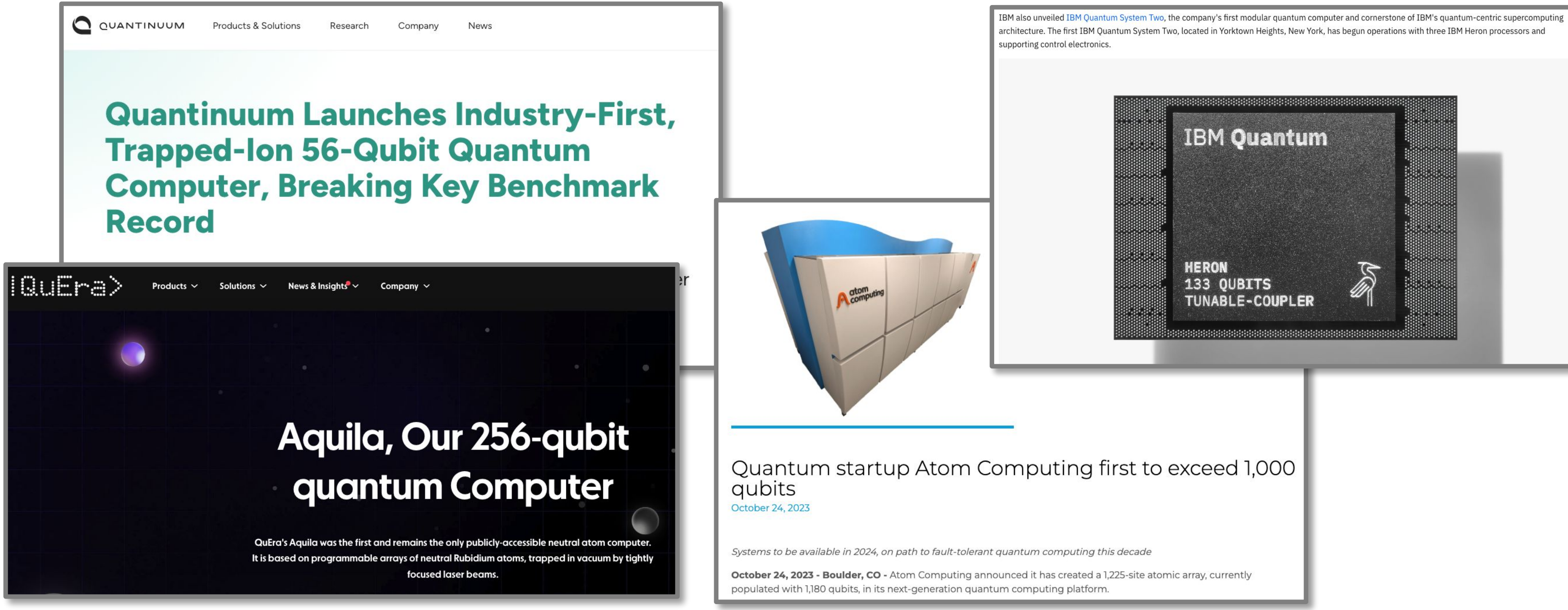
N-Body Interactions between Trapped Ion Qubits via Spin-Dependent Squeezing

Or Katz, Marko Cetina, and Christopher Monroe
Phys. Rev. Lett. **129**, 063603 – Published 4 August 2022

ABSTRACT

We describe a simple protocol for the single-step generation of N-body entangling interactions between trapped atomic ion qubits. We show that qubit state-dependent squeezing operations and displacement forces on the collective atomic motion can generate full N-body interactions. Similar to the Mølmer-Sørensen two-body Ising interaction at the core of most trapped ion quantum computers and simulators, the proposed operation is relatively insensitive to the state of motion. We show how this N-body gate operation allows for the single-step implementation of a family of N-bit gate operations such as the powerful N-Toffoli gate, which flips a single qubit if and only if all other $N-1$ qubits are in a particular state.

Number of qubits in quantum systems is growing



Quantinuum Launches Industry-First, Trapped-Ion 56-Qubit Quantum Computer, Breaking Key Benchmark Record

Aquila, Our 256-qubit quantum Computer

QuEra's Aquila was the first and remains the only publicly-accessible neutral atom computer. It is based on programmable arrays of neutral Rubidium atoms, trapped in vacuum by tightly focused laser beams.

Quantum startup Atom Computing first to exceed 1,000 qubits

October 24, 2023

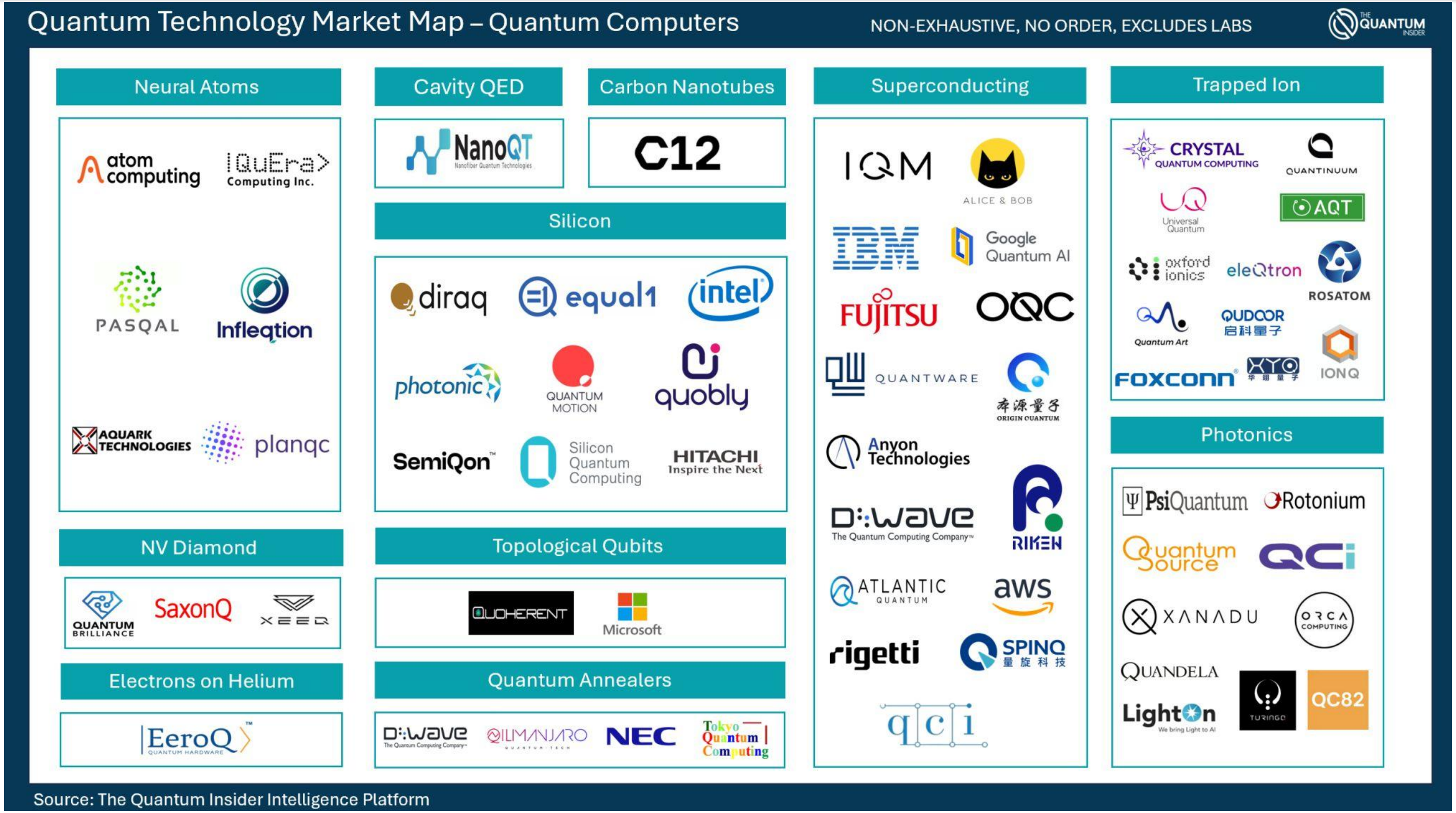
Systems to be available in 2024, on path to fault-tolerant quantum computing this decade

October 24, 2023 - Boulder, CO - Atom Computing announced it has created a 1,225-site atomic array, currently populated with 1,180 qubits, in its next-generation quantum computing platform.

IBM also unveiled IBM Quantum System Two, the company's first modular quantum computer and cornerstone of IBM's quantum-centric supercomputing architecture. The first IBM Quantum System Two, located in Yorktown Heights, New York, has begun operations with three IBM Heron processors and supporting control electronics.

Challenging our ability to simulate and validate

Sprawling quantum industry with great job opportunities



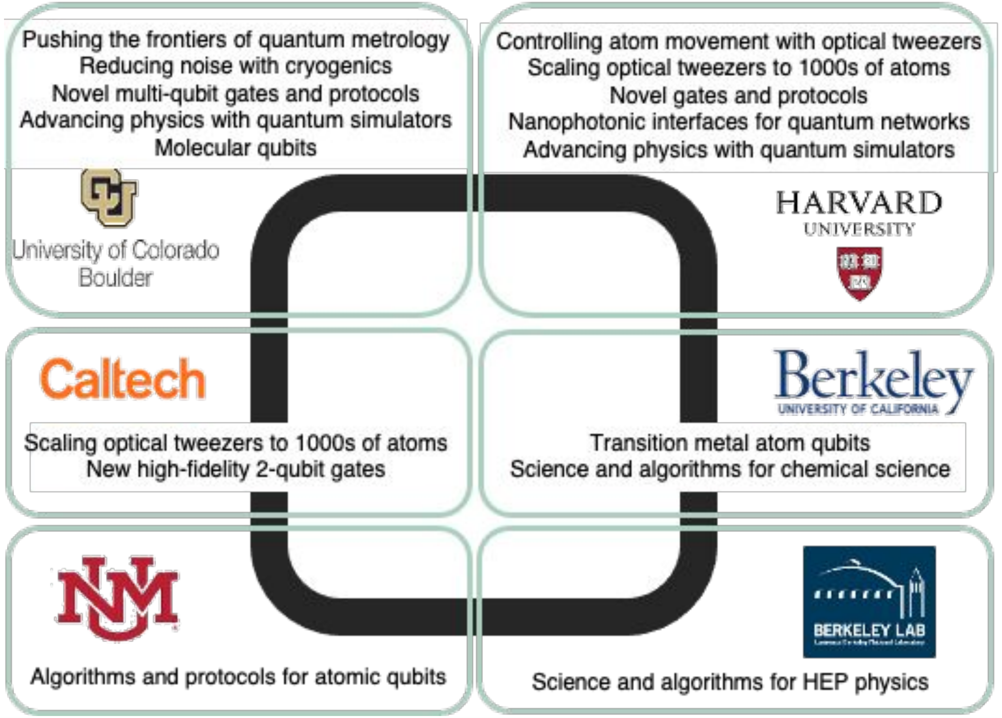
Quantum Technology Market Map – Quantum Computers

NON-EXHAUSTIVE, NO ORDER, EXCLUDES LABS

Source: The Quantum Insider Intelligence Platform

Quantum Systems Accelerator is solving big challenges with integrated teams

QSA integrates researchers with complementary skills from six institutions to create useful quantum systems based on neutral atoms



Pushing the frontiers of quantum metrology
Reducing noise with cryogenics
Novel multi-qubit gates and protocols
Advancing physics with quantum simulators
Molecular qubits

University of Colorado Boulder

Controlling atom movement with optical tweezers
Scaling optical tweezers to 1000s of atoms
Novel gates and protocols
Nanophotonic interfaces for quantum networks
Advancing physics with quantum simulators

HARVARD UNIVERSITY

Caltech

Scaling optical tweezers to 1000s of atoms
New high-fidelity 2-qubit gates

Berkeley
UNIVERSITY OF CALIFORNIA

Transition metal atom qubits
Science and algorithms for chemical science

Algorithms and protocols for atomic qubits

BERKELEY LAB

Science and algorithms for HEP physics

2021

Two qubit gate fidelities at ~95%
Limited qubit coherence
No mid-circuit operations
Limits on scaling
No modules and interconnects

QSA's integrated atoms team has made revolutionary advances

2024

Two qubit gate fidelities at ~99.7%
1200 second lifetimes
3000 second lifetime with cryogenics
Mid-circuit operations available
Scaling to 1000s of atoms
Science with 256 atoms
Metrology beyond quantum limit
First attempts at interconnects

Challenges to achieving useful quantum computers

Almost enough good qubits for specialized quantum use

Coherence - available compute time - very short (10s-100s of ops), driven by noise and errors

Advances in algorithms, software tools and compilers are needed to make quantum computing broadly approachable

Designing better qubits is hard

Moving towards quantum advantage for science

Hardware technology

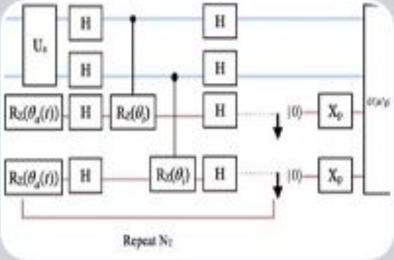
Scientific algorithms and software

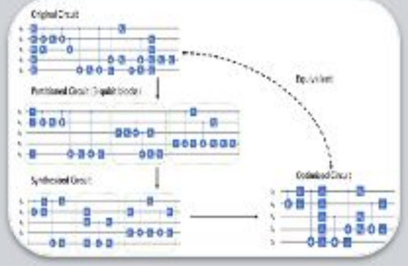
- Increasing qubit count
- Increasing lifetimes
- Increasing fidelity and reducing errors

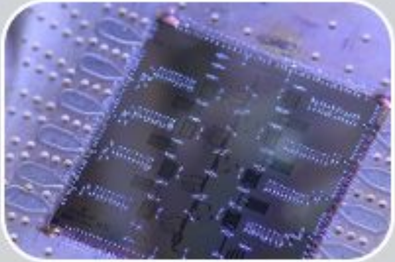
- Reducing qubit count
- Decreasing operation counts
- Incorporating error resiliency

Mathematics is needed everywhere!!!

Applied mathematics critical across the quantum stack







Developing Novel Algorithms and Software to Advance Science with Quantum

Programming Tools and Control Protocols to Harness the Power of Quantum Computers

Designing and Building Prototype Quantum Processors, Controls, and Sensors

Building Prototype Quantum Network and Quantum Computing Testbeds

Designing chips and control systems with AMR and electromagnetics solvers

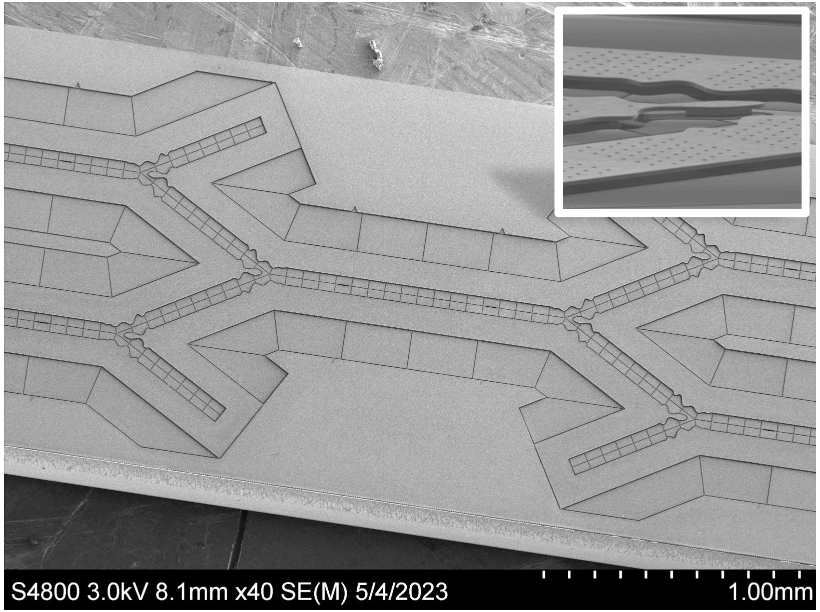
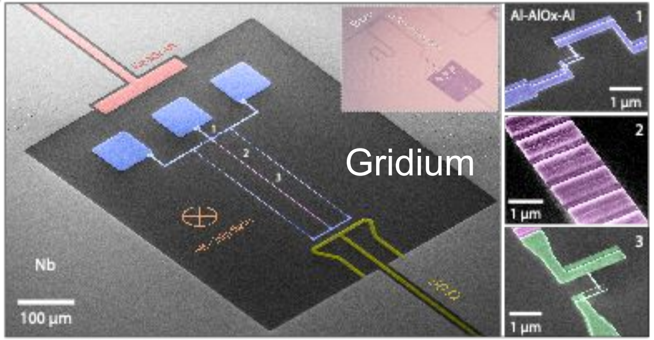
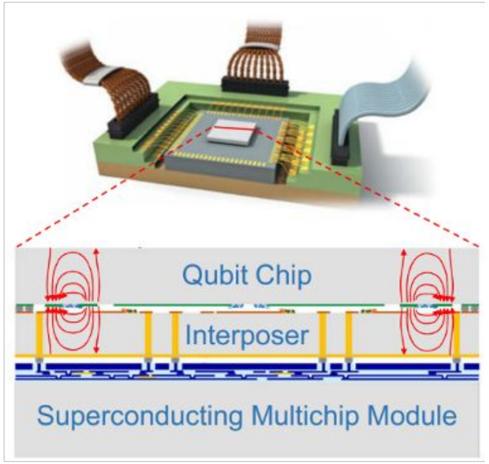
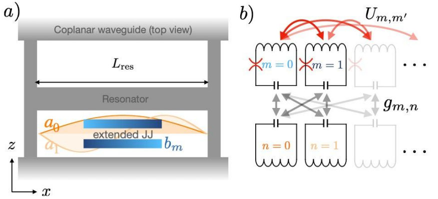


Image of ENCHILADA ion trap

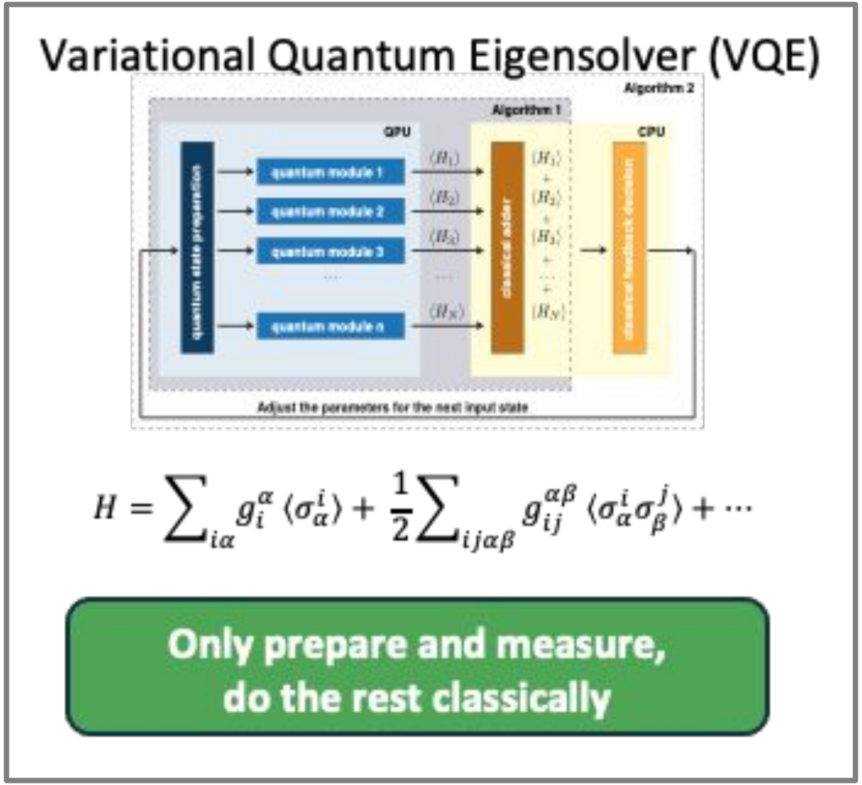
Manuscript on arXiv:2403.00208 (2024)







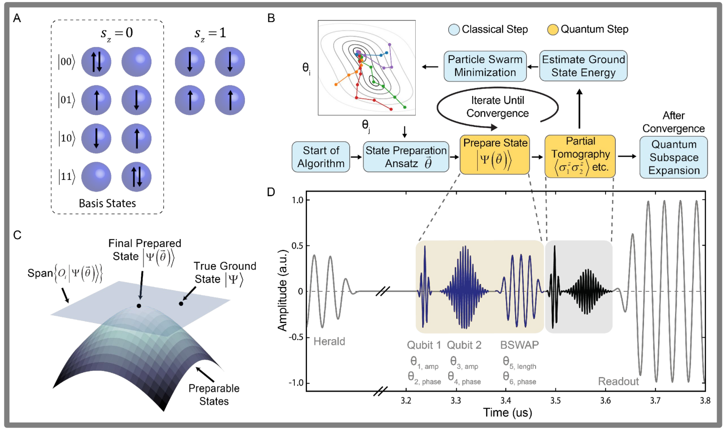
Optimization challenges are everywhere

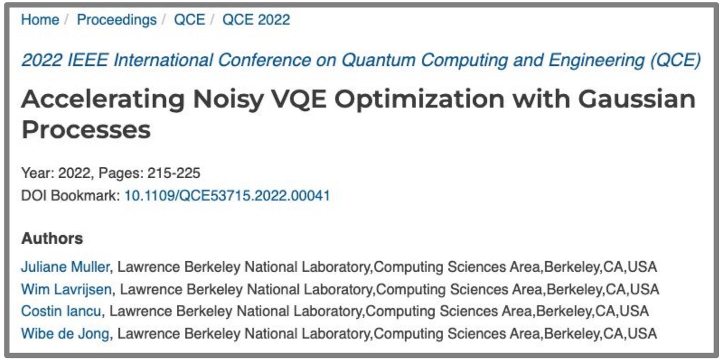


Variational Quantum Eigensolver (VQE)

$$H = \sum_{i\alpha} g_i^{\alpha} \langle \sigma_\alpha^i \rangle + \frac{1}{2}\sum_{ij\alpha\beta} g_{ij}^{\alpha\beta} \langle \sigma_\alpha^i \sigma_\beta^j \rangle + \cdots$$

Only prepare and measure, do the rest classically





Home / Proceedings / QCE / QCE 2022

2022 IEEE International Conference on Quantum Computing and Engineering (QCE)

Accelerating Noisy VQE Optimization with Gaussian Processes

Year: 2022, Pages: 215-225
DOI Bookmark: 10.1109/QCE53715.2022.00041

Authors

Juliane Muller, Lawrence Berkeley National Laboratory,Computing Sciences Area,Berkeley,CA,USA
Wim Lavrijsen, Lawrence Berkeley National Laboratory,Computing Sciences Area,Berkeley,CA,USA
Costin Iancu, Lawrence Berkeley National Laboratory,Computing Sciences Area,Berkeley,CA,USA
Wibe de Jong, Lawrence Berkeley National Laboratory,Computing Sciences Area,Berkeley,CA,USA

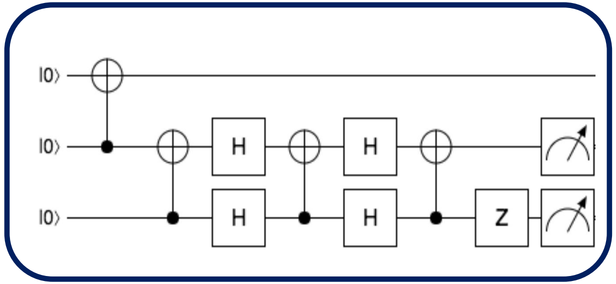
https://scikit-quant.readthedocs.io

Compiling…General Synthesis Problem

Unitary

$$\frac{1}{\sqrt{2^3}}\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & \omega & \omega^2 & \omega^3 & \omega^4 & \omega^5 & \omega^6 & \omega^7 \\ 1 & \omega^2 & \omega^4 & \omega^6 & \omega^8 & \omega^{10} & \omega^{12} & \omega^{14} \\ 1 & \omega^3 & \omega^6 & \omega^9 & \omega^{12} & \omega^{15} & \omega^{18} & \omega^{21} \\ 1 & \omega^4 & \omega^8 & \omega^{12} & \omega^{16} & \omega^{20} & \omega^{24} & \omega^{28} \\ 1 & \omega^5 & \omega^{10} & \omega^{15} & \omega^{20} & \omega^{25} & \omega^{30} & \omega^{35} \\ 1 & \omega^6 & \omega^{12} & \omega^{18} & \omega^{24} & \omega^{30} & \omega^{36} & \omega^{42} \\ 1 & \omega^7 & \omega^{14} & \omega^{21} & \omega^{28} & \omega^{35} & \omega^{42} & \omega^{49} \end{bmatrix}$$

Circuit

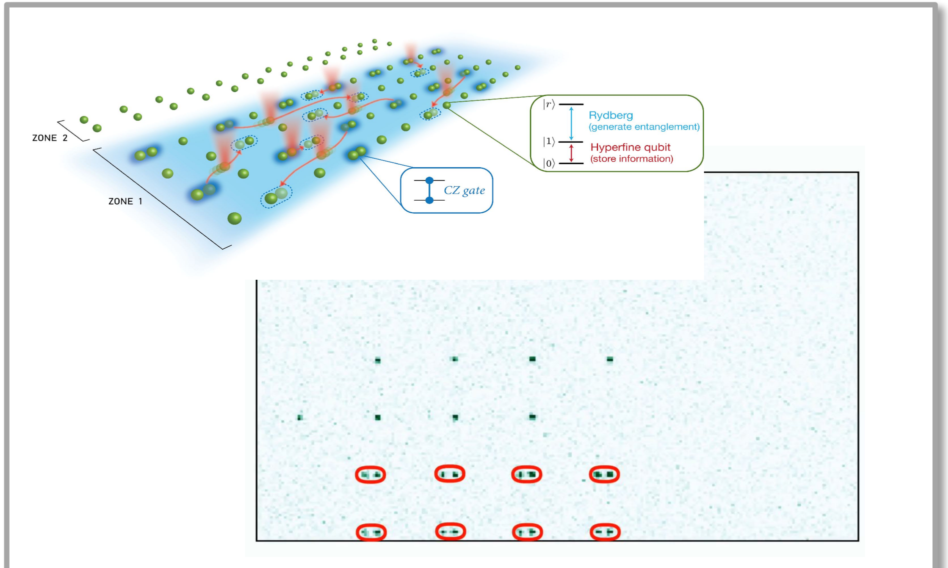


<u>Quantum Compilation:</u> *Given unitary U, find decomposition in terms of gates G from a (universal) fixed gate set*

Enables:

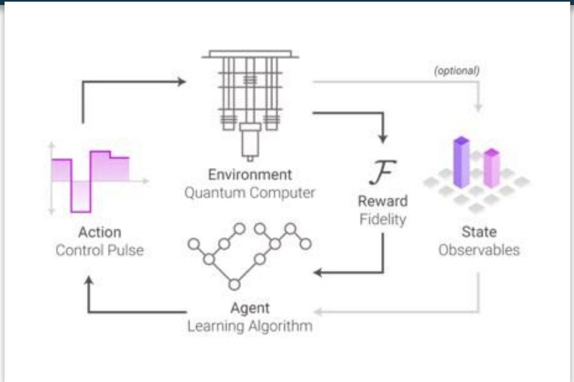
- Algorithm discovery
- Gate set and hardware exploration
- <u>Global circuit optimization</u>

Many opportunities to improve noisy optimization

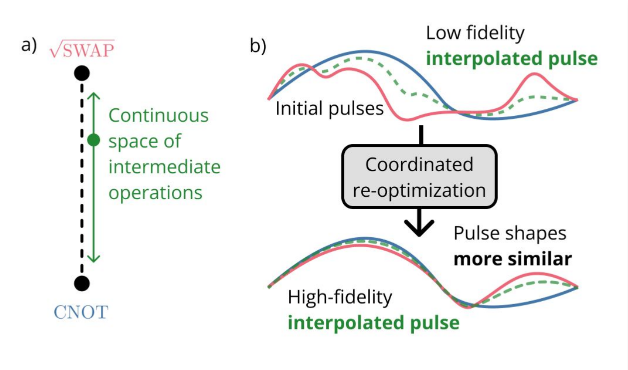


Optimal shuttling of atoms with optical tweezers

Harvard: Bluvstein, Nature 604, 451 (2022)

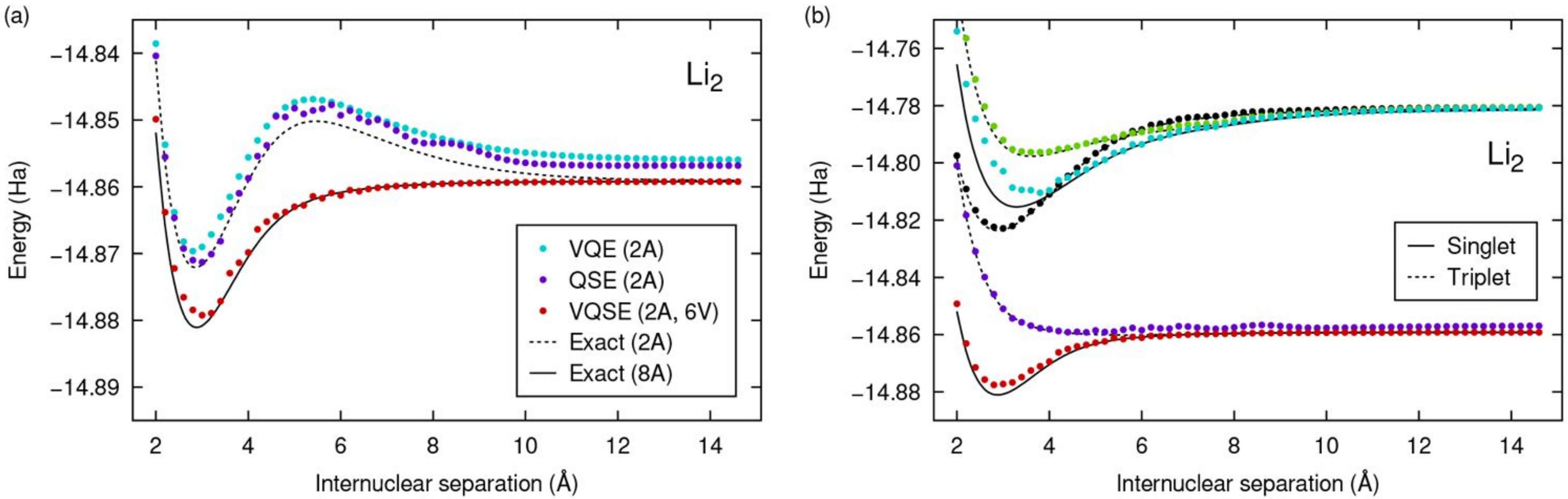


Pulse shaping by Q-CTRL



Chadwick, Chong, QCE23, doi:10.1109/QCE57702.2023.00145

Quantum algorithms rely on applied mathematics



Special care needs to be taken in general eigensolver due to noise in data!

$$HC = SCE$$

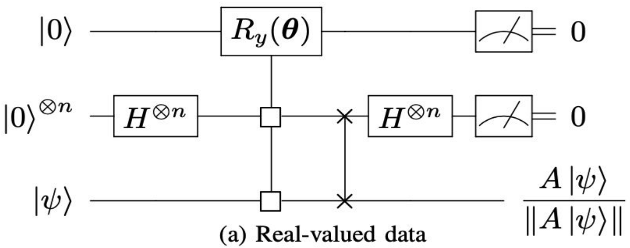
Urbanek, Van Beeumen, et al., J. Chem. Theory Comput. 16, 5425 (2020)

FABLE: Fast Approximate BLock-Encodings

Circuit synthesis tool for block encoded operators

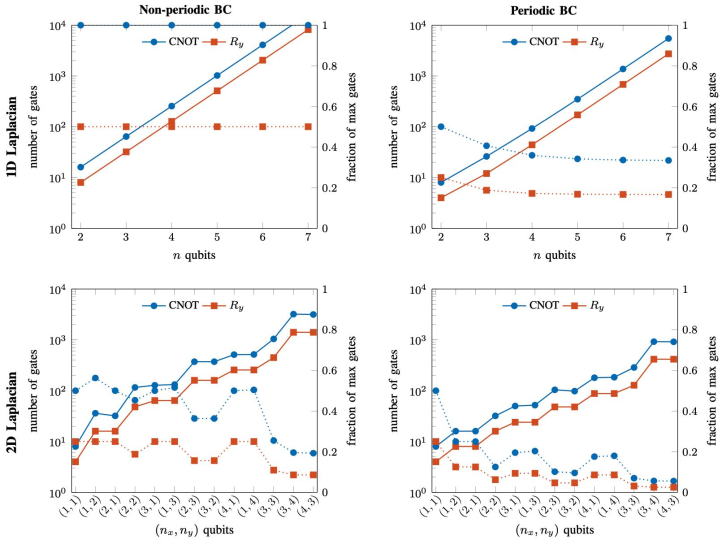
Block encoding: $$U = \begin{bmatrix} A & * \\ * & * \end{bmatrix}$$

- **Non-unitary** evolution on a quantum computer:
  Quantum linear systems, dynamic simulation, ground states, quantum thermodynamics, open quantum systems, …
- FABLE circuits are:
  easy to generate directly in CX, Ry and H gates
  efficiently **compressible**



(a) Real-valued data

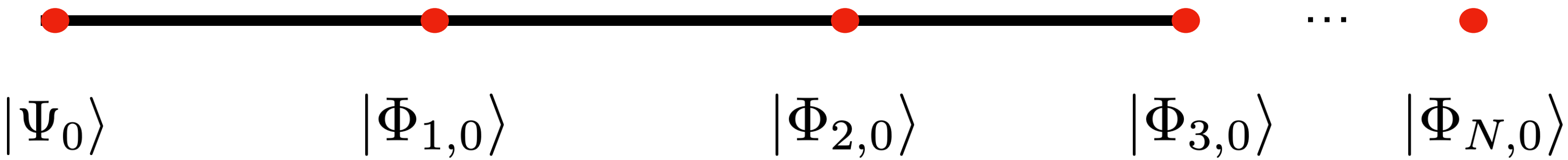
Gate complexities for 1D and 2D Laplacian



Camps, Van Beeumen, QCE22 - DOI:10.1109/QCE53715.2022.00029

Building on Quantum Subspace Expansion: Real-time evolution for eigenvalue extraction

Real time evolution to generate a basis of expansion states: $|\Phi_{j,0}\rangle = e^{-iHt_j}|\Psi_0\rangle$



Initial vector

Use as a basis to solve: $H\Psi = ES\Psi$

$$H_{i,j} = \langle\Phi_i|H|\Phi_j\rangle$$
$$S_{i,j} = \langle\Phi_i|\Phi_j\rangle$$

Possible to extract eigenstates by the cancellation of phases of components of the initial vector.

Promising because unlike imaginary, real time evolution is native to quantum computing.

Klymko, de Jong, Tubman et al., PRX Quantum 3 (2022)

Building on quantum subspace expansion to extract excited states: Variational Quantum Phase Estimation (VQPE)

Original generalized eigenvalue equation:

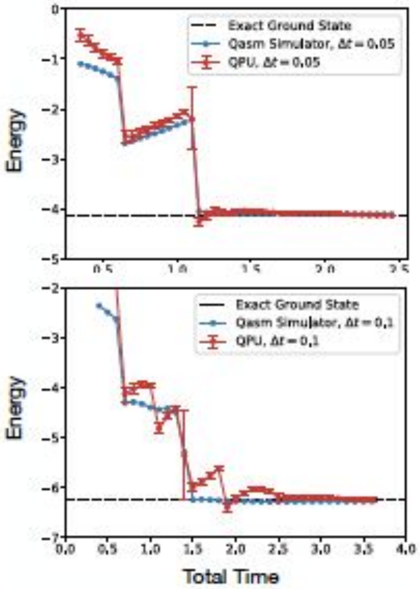
Unitary form:

$$H\mathbf{c} = ES\mathbf{c} \longrightarrow U(\Delta t)\boldsymbol{c} = e^{-iE\Delta t}S\boldsymbol{c}$$

$$U(\Delta t)_{j,k} = \langle \Psi_0 | e^{-iH(\Delta t + t_k - t_j)} | \Psi_0 \rangle \boxed{= S_{j,k+1} = S_{j-1,k}}$$

Autocorrelation Function

Toeplitz structure!



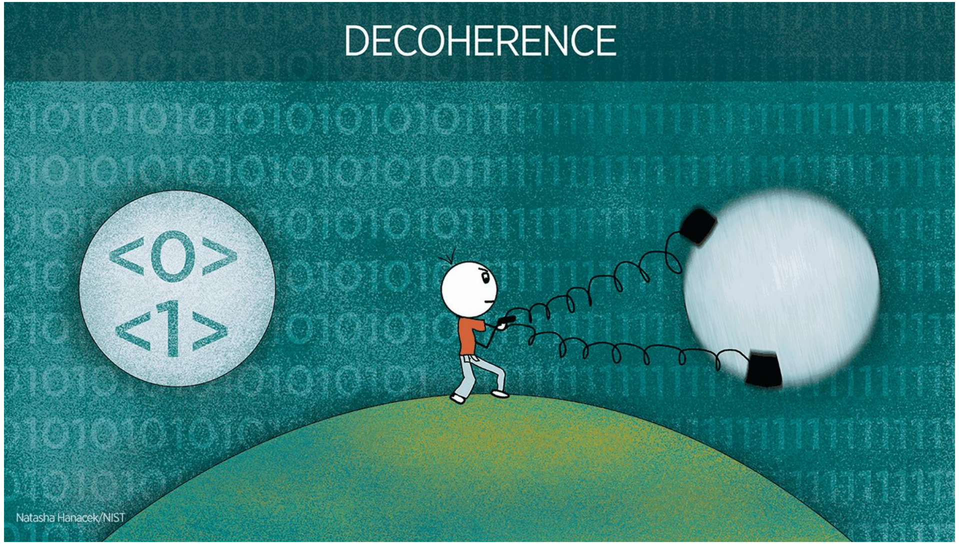
Toeplitz structure means that we only need a ***linear*** number of measurements instead of quadratic

Approach allows extraction of the maximal number of excited states!

Klymko, de Jong, Tubman et al., PRX Quantum 3 (2022)

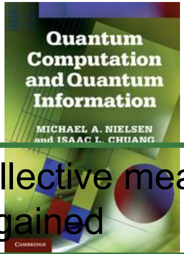
Noise in quantum systems is the biggest nemesis

Credit: N. Hanacek/NIST



<u>Any</u> interaction between the qubits and their environment leads to information loss

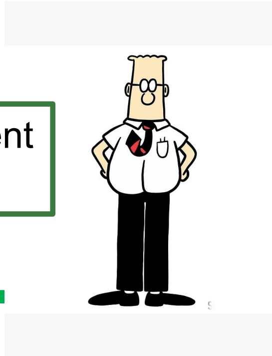
Useful quantum science through error correction



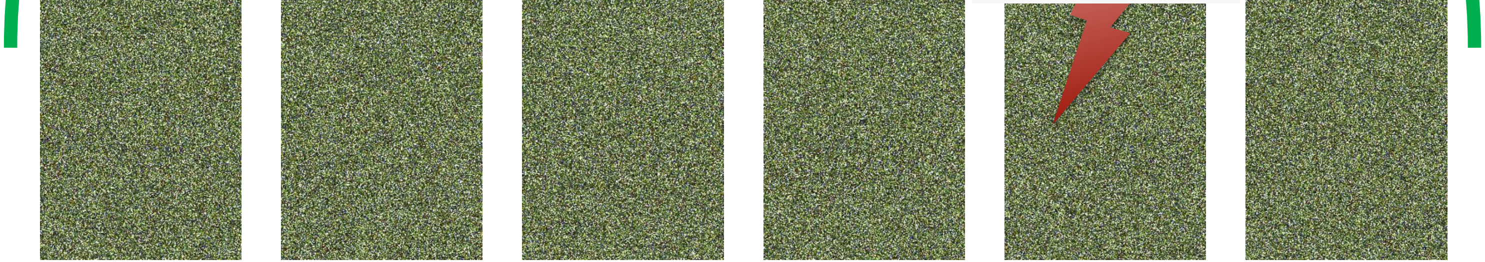
Quantum Computation and Quantum Information

MICHAEL A. NIELSEN and ISAAC L. CHUANG

Repair using collective measurement
No information gained



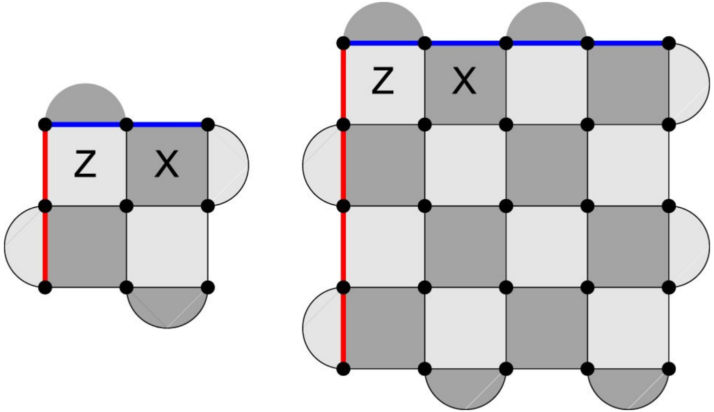
n gained
be reversed



Encode the information in multiple qubits with *nonlocal* correlations

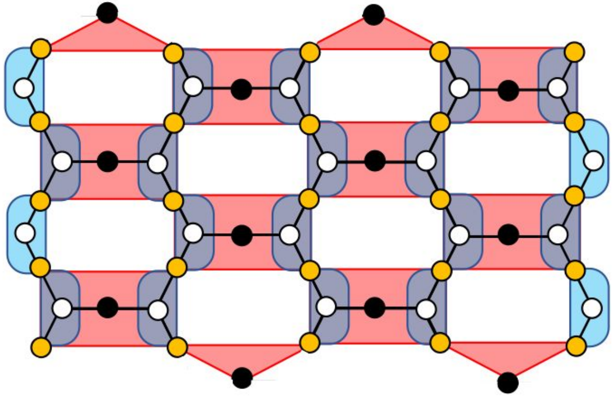
New error correction codes are being developed

Surface code



Bravyi et al., npj Quant. Inf. ***4****, 55 (2018)*

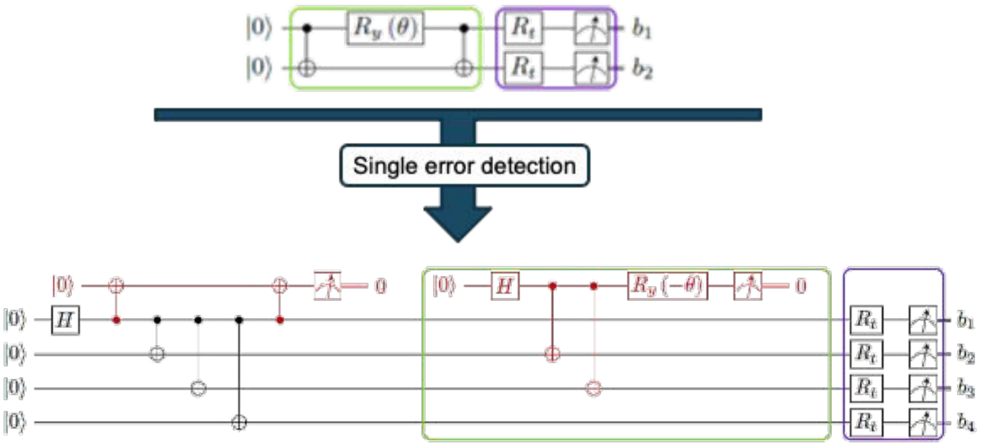
Heavy-Hexagon



Chamberland et al., Phys. Rev. X ***10****, 011022 (2020)*

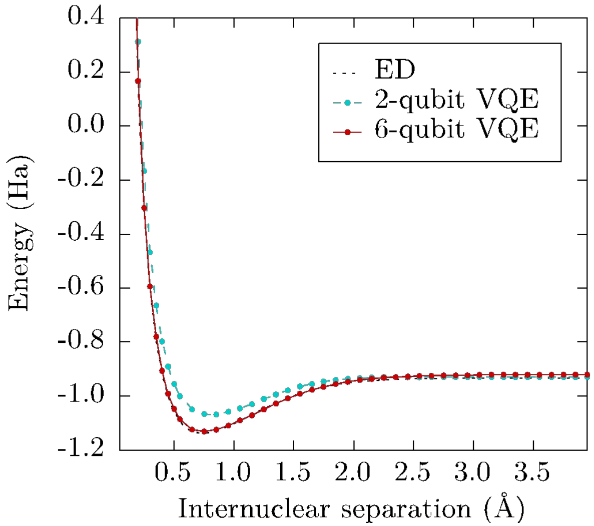
Full error correction (hardware or software) a long-term solution, driven by increases in qubit counts and increases in fidelity

Simple error detection and mitigation works



Single error detection

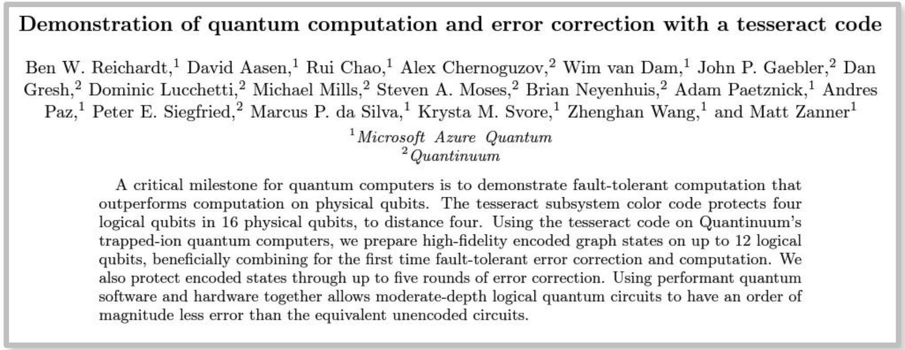
[[4,2,2]] error correction code



2 logical qubit H_2 molecule on 6 qubits with minimal basis

Urbanek et al, Phys. Rev. A 102, 022427 (2020)

First demonstrations of error correction in 2024



Demonstration of quantum computation and error correction with a tesseract code

Ben W. Reichardt,[1] David Aasen,[1] Rui Chao,[1] Alex Chernoguzov,[2] Wim van Dam,[1] John P. Gaebler,[2] Dan Gresh,[2] Dominic Lucchetti,[2] Michael Mills,[2] Steven A. Moses,[2] Brian Neyenhuis,[2] Adam Paetznick,[1] Andres Paz,[1] Peter E. Siegfried,[2] Marcus P. da Silva,[1] Krysta M. Svore,[1] Zhenghan Wang,[1] and Matt Zanner[1]

[1] *Microsoft Azure Quantum*
[2] *Quantinuum*

A critical milestone for quantum computers is to demonstrate fault-tolerant computation that outperforms computation on physical qubits. The tesseract subsystem color code protects four logical qubits in 16 physical qubits, to distance four. Using the tesseract code on Quantinuum's trapped-ion quantum computers, we prepare high-fidelity encoded graph states on up to 12 logical qubits, beneficially combining for the first time fault-tolerant error correction and computation. We also protect encoded states through up to five rounds of error correction. Using performant quantum software and hardware together allows moderate-depth logical quantum circuits to have an order of magnitude less error than the equivalent unencoded circuits.

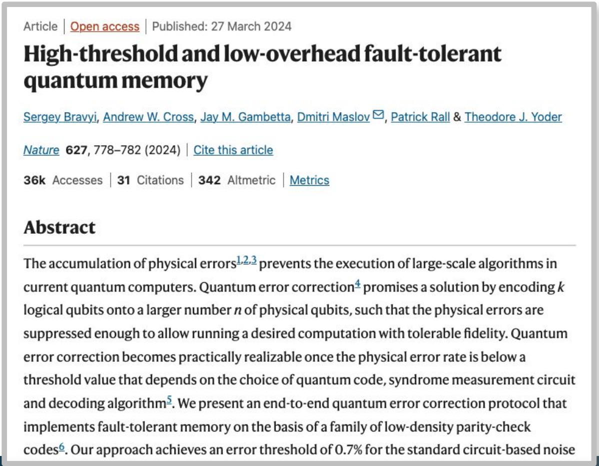
Article | Open access | Published: 06 December 2023

Logical quantum processor based on reconfigurable atom arrays

Dolev Bluvstein, Simon J. Evered, Alexandra A. Geim, Sophie H. Li, Hengyun Zhou, Tom Manovitz, Sepehr Ebadi, Madelyn Cain, Marcin Kalinowski, Dominik Hangleiter, J. Pablo Bonilla Ataides, Nishad Maskara, Iris Cong, Xun Gao, Pedro Sales Rodriguez, Thomas Karolyshyn, Giulia Semeghini, Michael J. Gullans, Markus Greiner, Vladan Vuletić & Mikhail D. Lukin ✉

Nature **626**, 58–65 (2024) | Cite this article

121k Accesses | **122** Citations | **958** Altmetric | Metrics



Article | Open access | Published: 27 March 2024

High-threshold and low-overhead fault-tolerant quantum memory

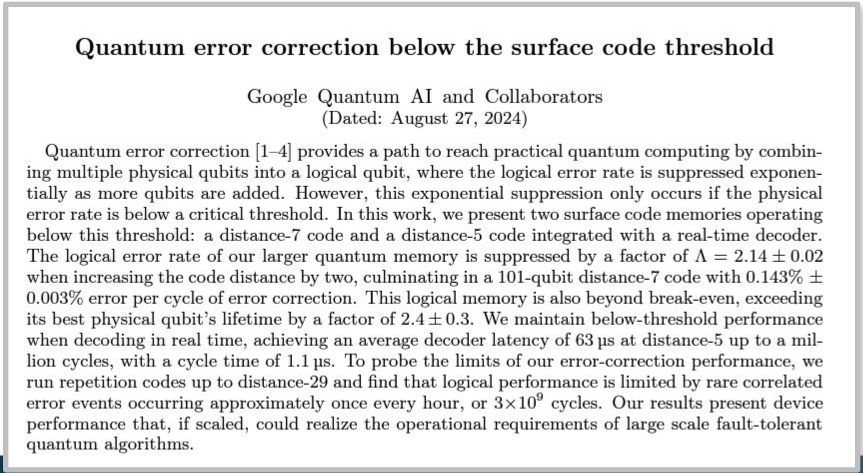
Sergey Bravyi, Andrew W. Cross, Jay M. Gambetta, Dmitri Maslov ✉, Patrick Rall & Theodore J. Yoder

Nature **627**, 778–782 (2024) | Cite this article

36k Accesses | **31** Citations | **342** Altmetric | Metrics

Abstract

The accumulation of physical errors[1,2,3] prevents the execution of large-scale algorithms in current quantum computers. Quantum error correction[4] promises a solution by encoding k logical qubits onto a larger number n of physical qubits, such that the physical errors are suppressed enough to allow running a desired computation with tolerable fidelity. Quantum error correction becomes practically realizable once the physical error rate is below a threshold value that depends on the choice of quantum code, syndrome measurement circuit and decoding algorithm[5]. We present an end-to-end quantum error correction protocol that implements fault-tolerant memory on the basis of a family of low-density parity-check codes[6]. Our approach achieves an error threshold of 0.7% for the standard circuit-based noise



Quantum error correction below the surface code threshold

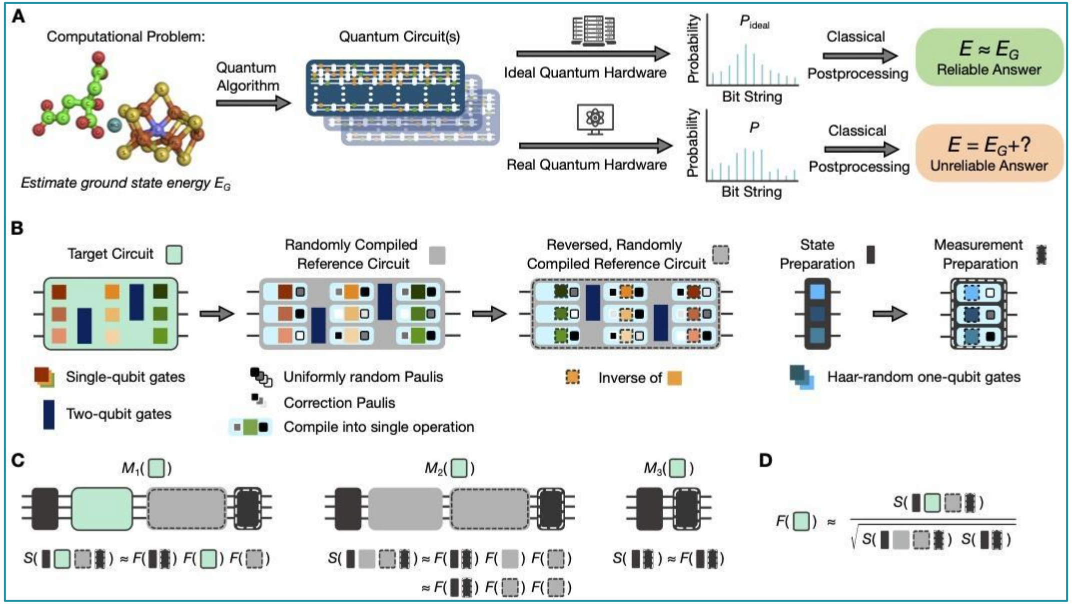
Google Quantum AI and Collaborators

(Dated: August 27, 2024)

Quantum error correction [1–4] provides a path to reach practical quantum computing by combining multiple physical qubits into a logical qubit, where the logical error rate is suppressed exponentially as more qubits are added. However, this exponential suppression only occurs if the physical error rate is below a critical threshold. In this work, we present two surface code memories operating below this threshold: a distance-7 code and a distance-5 code integrated with a real-time decoder. The logical error rate of our larger quantum memory is suppressed by a factor of $\Lambda = 2.14 \pm 0.02$ when increasing the code distance by two, culminating in a 101-qubit distance-7 code with $0.143\% \pm 0.003\%$ error per cycle of error correction. This logical memory is also beyond break-even, exceeding its best physical qubit's lifetime by a factor of 2.4 ± 0.3. We maintain below-threshold performance when decoding in real time, achieving an average decoder latency of 63 µs at distance-5 up to a million cycles, with a cycle time of 1.1 µs. To probe the limits of our error-correction performance, we run repetition codes up to distance-29 and find that logical performance is limited by rare correlated error events occurring approximately once every hour, or 3×10^9 cycles. Our results present device performance that, if scaled, could realize the operational requirements of large scale fault-tolerant quantum algorithms.

Understanding quantum computers through validation

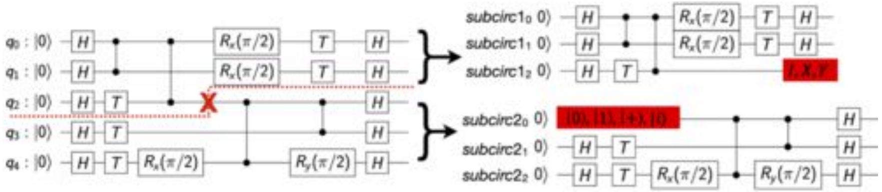
Approach enables verification, by efficiently quantifying how accurately a given computer can implement a given algorithm’s quantum circuits

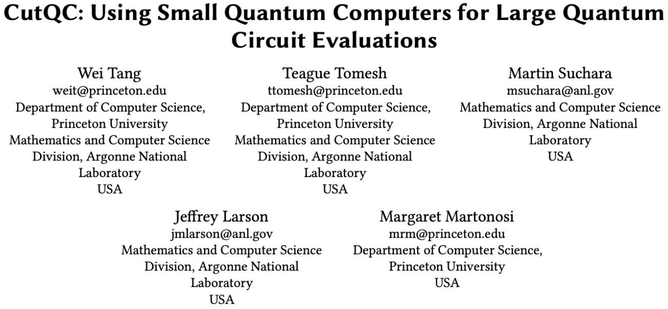


Uses three classes of ”mirror circuits” whose success rates can be efficiently measured

Proctor et al., arXiv:2204.07568

Solving problems beyond the reach of current hardware





CutQC: Using Small Quantum Computers for Large Quantum Circuit Evaluations

Wei Tang
weit@princeton.edu
Department of Computer Science,
Princeton University
Mathematics and Computer Science
Division, Argonne National
Laboratory
USA

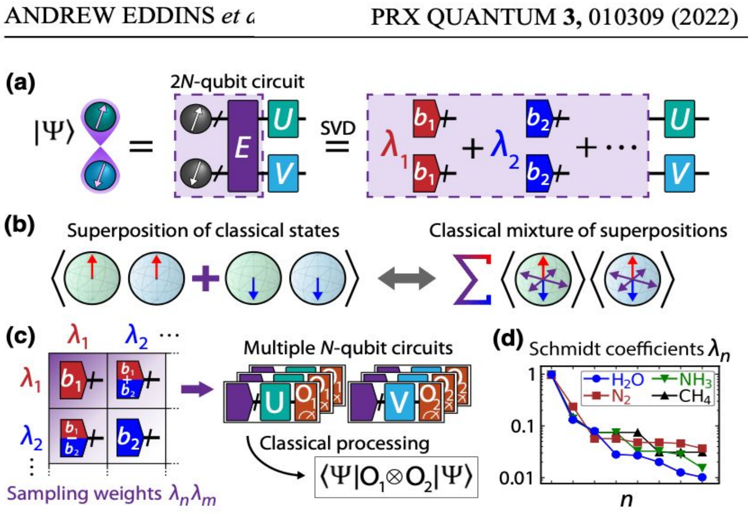
Teague Tomesh
ttomesh@princeton.edu
Department of Computer Science,
Princeton University
Mathematics and Computer Science
Division, Argonne National
Laboratory
USA

Martin Suchara
msuchara@anl.gov
Mathematics and Computer Science
Division, Argonne National
Laboratory
USA

Jeffrey Larson
jmlarson@anl.gov
Mathematics and Computer Science
Division, Argonne National
Laboratory
USA

Margaret Martonosi
mrm@princeton.edu
Department of Computer Science,
Princeton University
USA

ASPLOS 21 - arXiv:2012.02333



ANDREW EDDINS *et a* PRX QUANTUM **3,** 010309 (2022)

Divide-and-conquer, where the cost of stitching the problem back together depends on sparsity

Race to the moon delivered many ancillary technologies

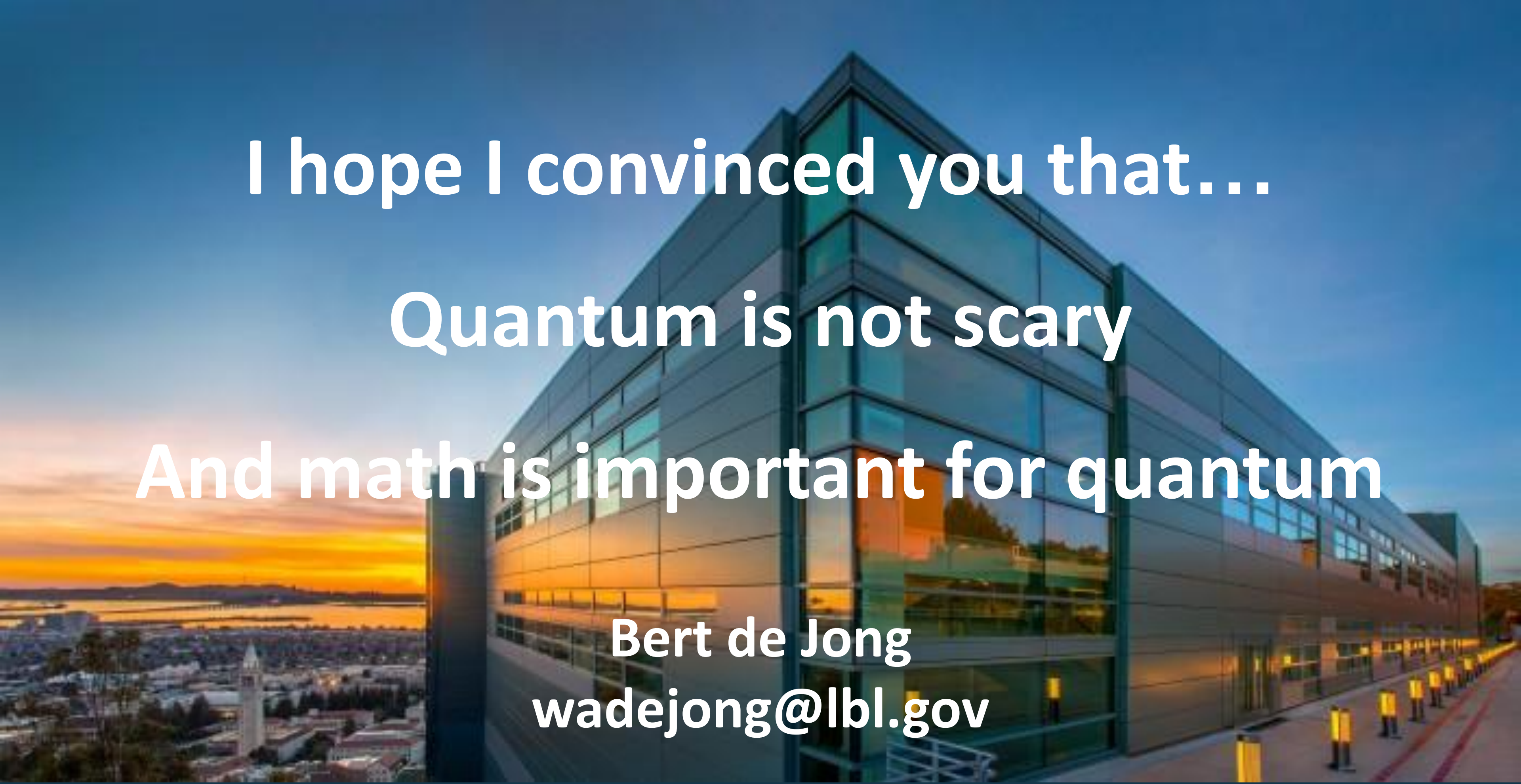
Quantum-inspired algorithms speedup classical computing

Novel quantum hardware technologies find way into classical computing hardware

Better understanding of quantum physics to lead to advances in classical computing

CMOS sensor, using integrated circuits….

Race for a universal quantum computer is already showing impacts beyond quantum computing



I hope I convinced you that…

Quantum is not scary

And math is important for quantum

Bert de Jong
wadejong@lbl.gov