Preparing for Scalable Quantum Computing at NERSC

NERSC

ICS 2025

June 8, 2025

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NERSC
nersc.gov/quantum

Summary and Outline of the Talk

NERSC is developing quantum applications and algorithms, building benchmarking tools, and evaluating the infrastructure needed to integrate quantum computing into NERSC's scientific workload.

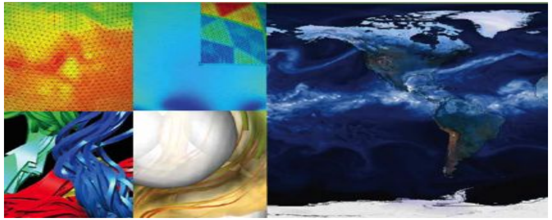
Outline:

- Introduction to NERSC
- Quantum workload analysis
- NERSC's quantum team and strategy
- Pathfinding efforts for quantum: developing benchmarking tools
- NERSC's quantum user program
- Developing tools with the Berkeley Lab quantum environment

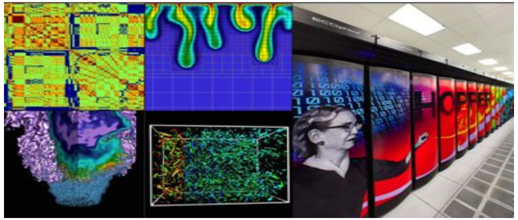
NERSC is the Mission HPC Facility for DOE Office of Science Research

U.S. DEPARTMENT OF ENERGY | Office of Science

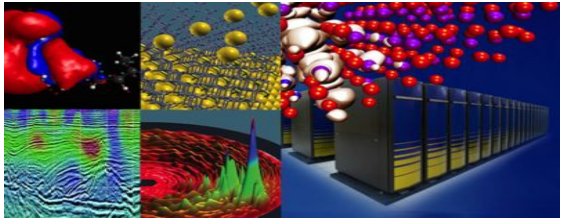
Largest funder of physical science research in the U.S.



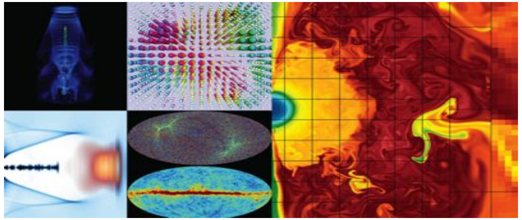
Biological and Environmental Research



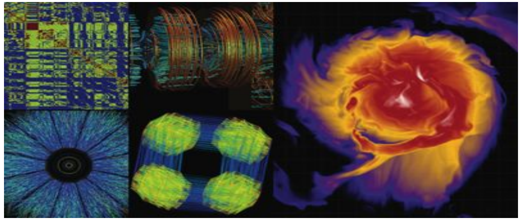
Computing



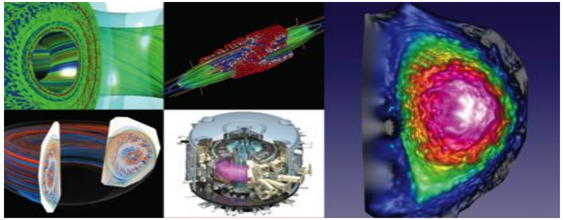
Basic Energy Sciences



High Energy Physics

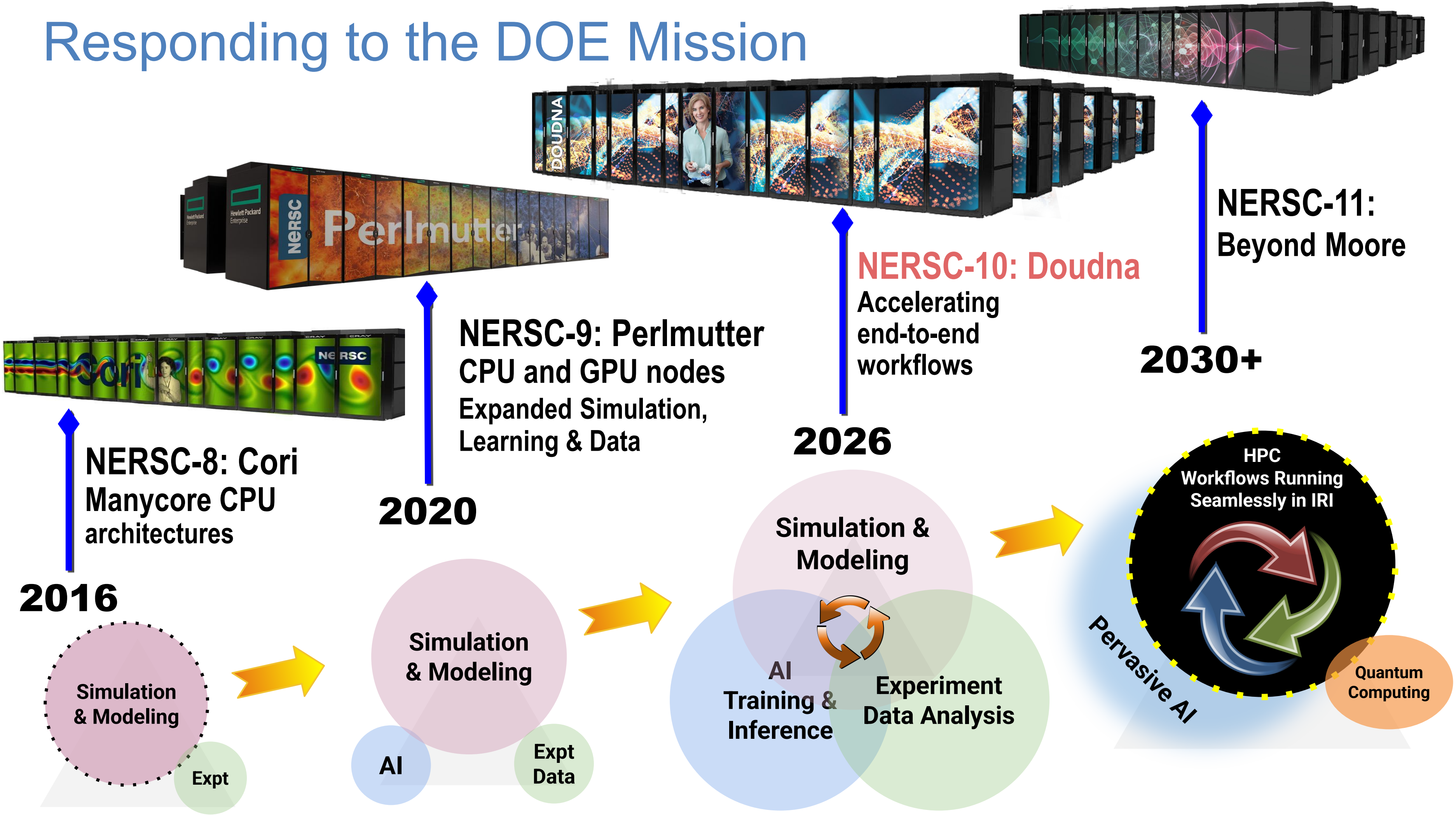


Nuclear Physics



Fusion Energy, Plasma Physics

Responding to the DOE Mission



The Doudna Supercomputer

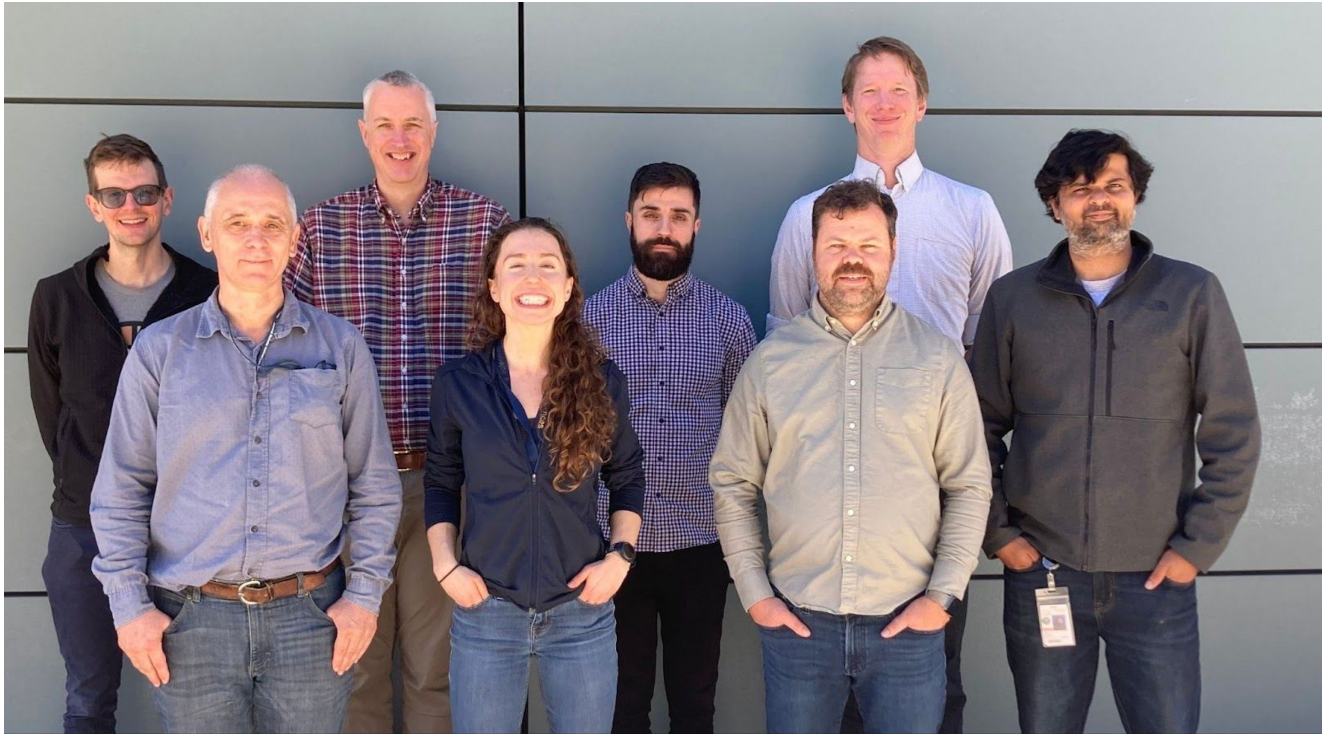
- The *Doudna* supercomputer will have thousands of NVIDIA Rubin GPUs and provide more than ten times the performance of *Perlmutter*, NERSC's current flagship supercomputer.
- *Doudna* will be built using cutting-edge technology:
  - Dell Integrated Rack Scalable Systems and PowerEdge servers
  - Dell ORv3 direct liquid-cooled server technology
  - NVIDIA Vera-Rubin CPU-GPU platform
  - High-speed NVIDIA Quantum-X800 InfiniBand networking platform
- *Doudna* will be a key tool for research across the DOE Office of Science mission space, powering scientific discovery in areas like fusion energy, advanced materials design, fundamental physics, biomolecular design, quantum computing, and more.
- *Doudna* is designed to accelerate scientific research by enabling the seamless incorporation of AI, simulations, and data analysis for the near-real-time processing of data from experimental facilities like telescopes and fusion energy research facilities.

May 29, 2025

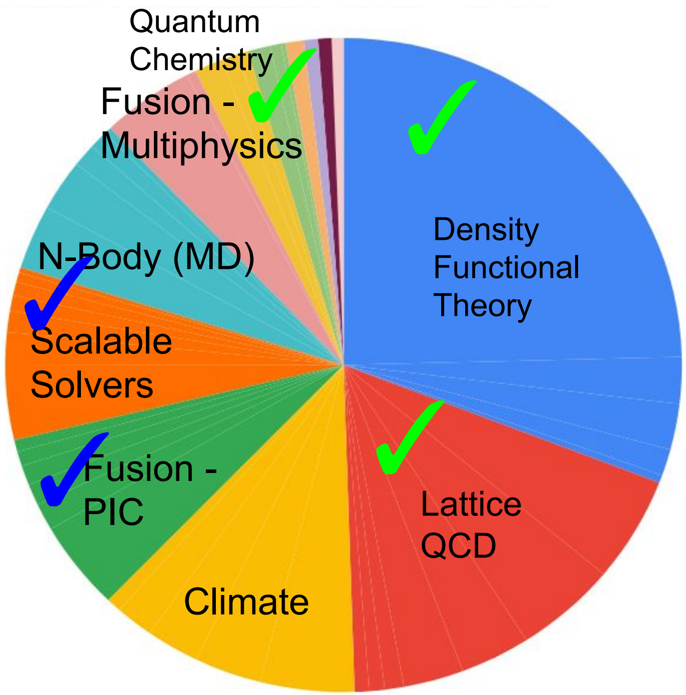
DOE Announces New Supercomputer Powered by Dell and NVIDIA to Speed Scientific Discovery

Named in honor of Jennifer Doudna, the Berkeley Lab-based biochemist who was awarded the 2020 Nobel Prize for Chemistry in recognition of her work on the gene-editing technology CRISPR.

Quantum Team at NERSC



NERSC Workload Analysis Drives Quantum Computing Requirements



✓ Quantum mechanical problem
Quantum algorithms proposed

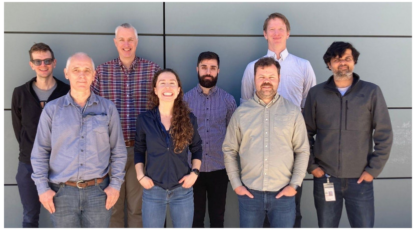
>50% of cycles

✓ non-Quantum mechanical problem
Quantum algorithms proposed

20% of cycles

What is **not** on the pie chart?
Growth areas for quantum technologies!

Quantum Strategy Reflect's NERSC Mission



Pathfinding:

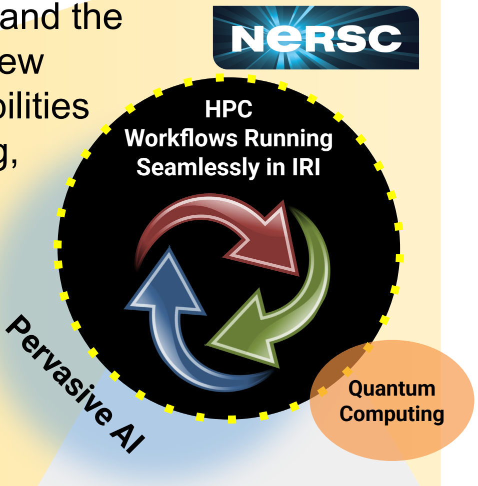
Understand how quantum computing will complement future NERSC workloads and enable new science applications & modes of discovery

Early User & Vendor Exploration:

Deep engagements with vendors and users at small scale to explore capabilities, requirements & best practices for the broad user community

Broad User Impact:

Develop users and the workforce for new quantum capabilities through training, tutorials, and access to classical and quantum technologies



hardware	software	algorithms	people/support

Ensure users have access to state-of-the-art quantum computing resources for scientific discovery

Quantum @ NERSC Pathfinding and Early User & Vendor Exploration Activities

Pathfinding R&D

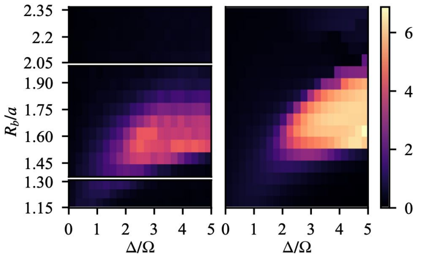
Application Development

Benchmarking

Resource Evaluation

Vendor Collaboration

|QuEra> R&D Partnership



User Programs

[Quantum Computing Access @ NERSC (QCAN)]()

- 2022 QIS @ Perlmutter

Quantum Information Science @

30+ Teams and Publications

- 2024 Neutral Atoms |QuEra>
- 2025 Superconducting Qubits

IBM

Simulation of Quantum Systems

NVIDIA Collaboration: Developing with CUDA-Q quantum software development toolkit on Perlmutter

Xanadu

NESAP Collaboration: Quantum machine learning workflows with PennyLane on Perlmutter

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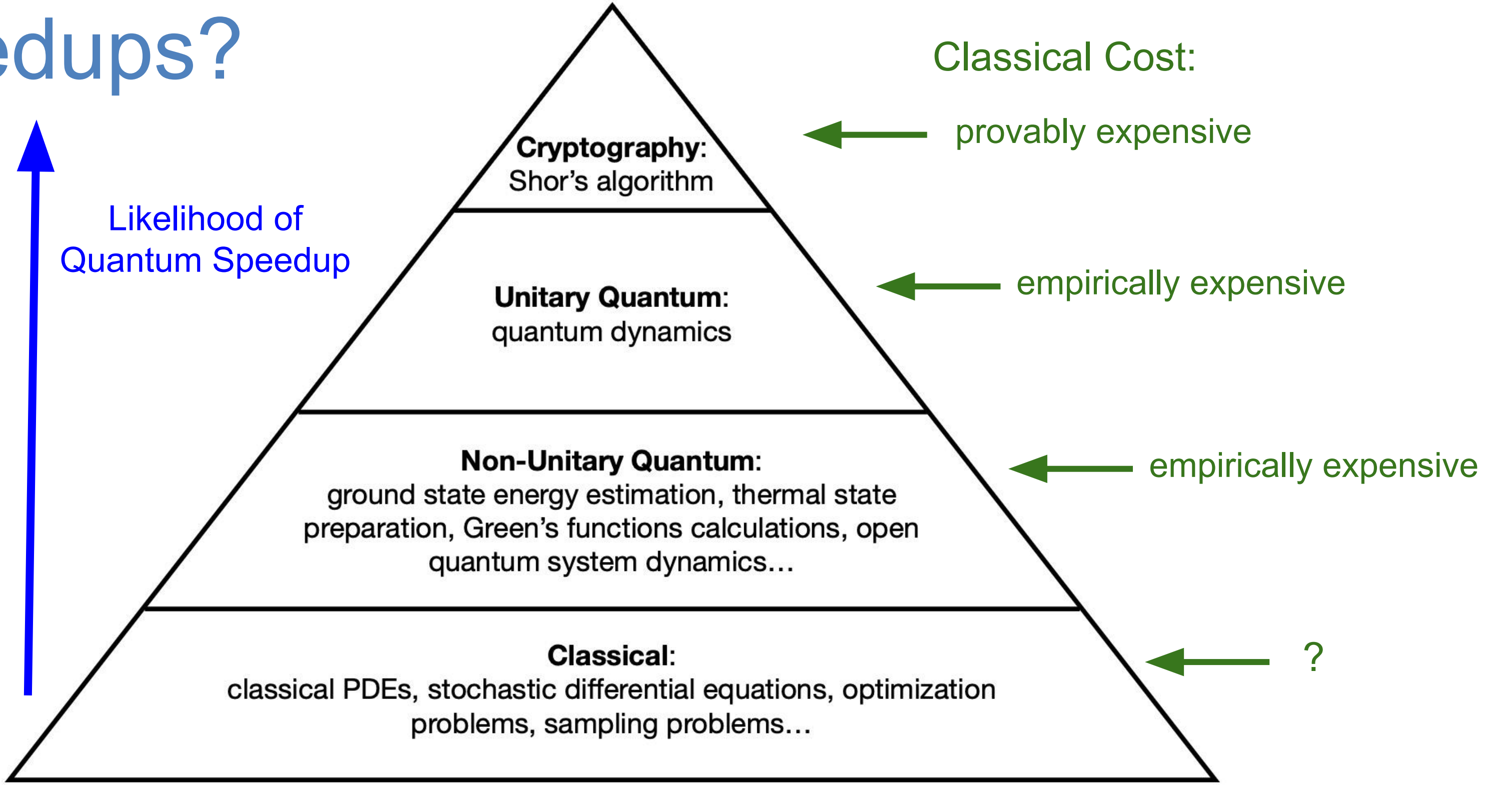
What Do We Currently Know about Quantum Speedups?



Inspired by Lin Lin

How Can We Effectively Benchmark New Quantum Algorithms and Hardware?

- New algorithm papers are put on the arXiv every day, but are often not run on a standard set of examples – how useful are they?

- Hardware updates are being introduced quickly, and new technologies are being introduced, but it's often unclear how to compare them

HamLib: A Library of Hamiltonians for Benchmarking Quantum Algorithms and Hardware

Commonality between all qubit technologies and quantum computational models: **solve a computational problem through Hamiltonian evolution and encode the problem in the Hamiltonian**

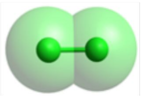
- Explicitly: adiabatically or through analog quantum computation
- More subtly: the circuit model
- Different types of encodings possible

HamLib: A Library of Hamiltonians for Benchmarking Quantum Algorithms and Hardware

- Project led by Intel and NERSC, including Sandia, NASA, LBL, Texas A&M, Oxford
- One of the first quantum benchmarking data sets available
- Independently integrated into Pennylane software from Xanadu
- Published *(Quantum 8 (2024): 1559)* in December 2024, 20+ citations

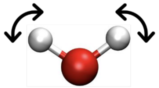
Physical Sciences

Chemistry



Electronic structure
Hydrogen clusters
Diatomics
Bond breaking
Transition metals

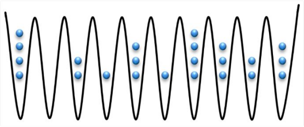
Vibrational structure
Diatomics
Triatomics
Tetratomics
Num. atoms > 4



Physics models

Models
Transverse-field Ising
Heisenberg
Fermi-Hubbard
Bose-Hubbard

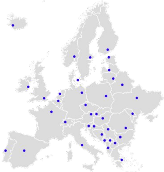
Lattices
1D chains
2D square, hex, triag
2D square ribbons
3D cubic



Combinatorial Optimization

Discrete optimization

Max-k-Cut
Random reg. graphs
Erdos-Renyi graphs
COLOR02 library

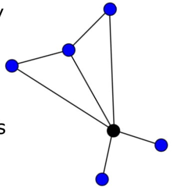


Traveling Salesman
Random planar
TSPLib

Binary opt. & related

MaxCut & QMaxCut
Random regular graphs
Erdos-Renyi graphs
Biq Mac library
CI-QuBe library

Max-k-SAT
Random instances
SATLib



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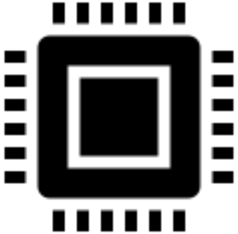
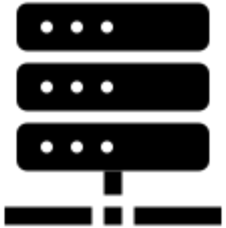
HamLib: A Library of Hamiltonians for Benchmarking Quantum Algorithms and Hardware

3-20 qubits
For testing on early quantum hardware



10-40 qubits
For running on simulators



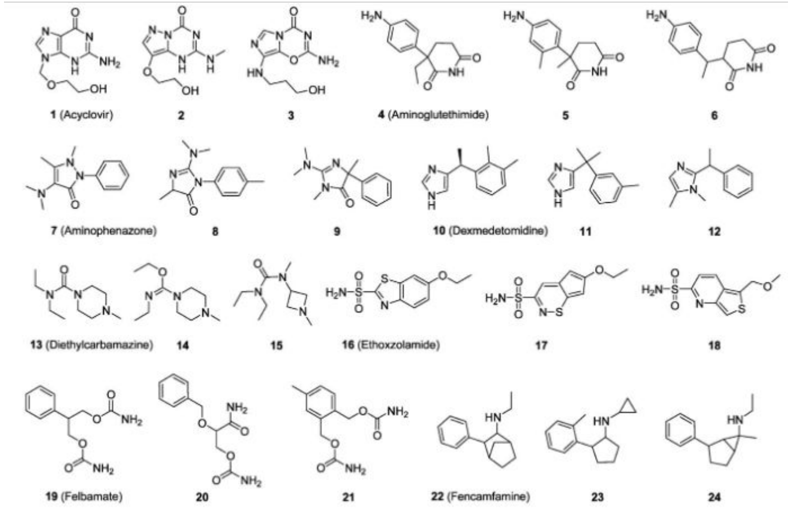
40-1000 qubits
For medium-term algorithm analysis

Want thousands of problem instances

Analogy: Classical Libraries for Benchmarking

Deep learning on images

Molecular datasets

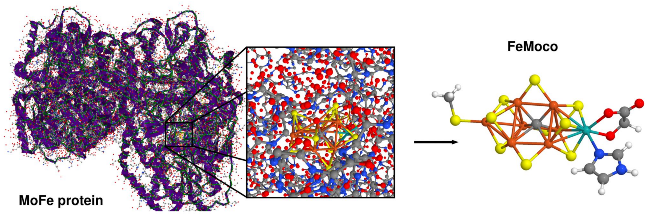


(QM9)

syncedreview.com/2020/06/23/google-deepmind-researchers-revamp-imagenet

Savings in the Problem Preparation Pipeline

Chemistry example:



FeMoco, *PNAS*, 2017

Collect experimental geometries

Choose basis

Solve Hartree-Fock

Choose active space

Create 2nd-quant Hamiltonian

Qubit Ham (e.g. Jordan-Wigner)

Compile Suzuki-Trotter circuit

Run quantum circuit

Choose circuit ansatz

Run VQE

Productivity savings due to HamLib

Characteristics of a Good Hamiltonian Library

- "Well-spaced" 2-, 4-, 6-, …, 100- qubit problems
- Inclusion of "real-world" problems
- Already mapped to qubits

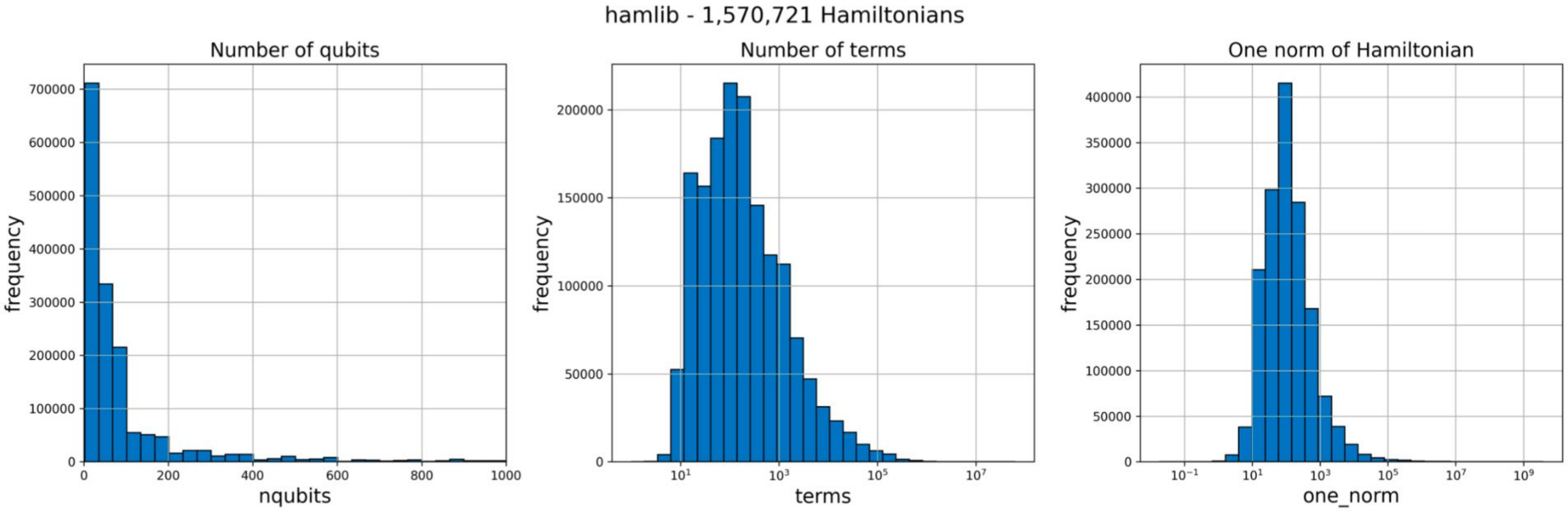
A few practical details:

- The dataset mainly contains qubit Hamiltonians (with minimal auxiliary data)
- Files are zipped as HDF5 and represented using represented using OpenFermion's QubitOperator class
- All provided in a Pauli representation using multiple different encodings

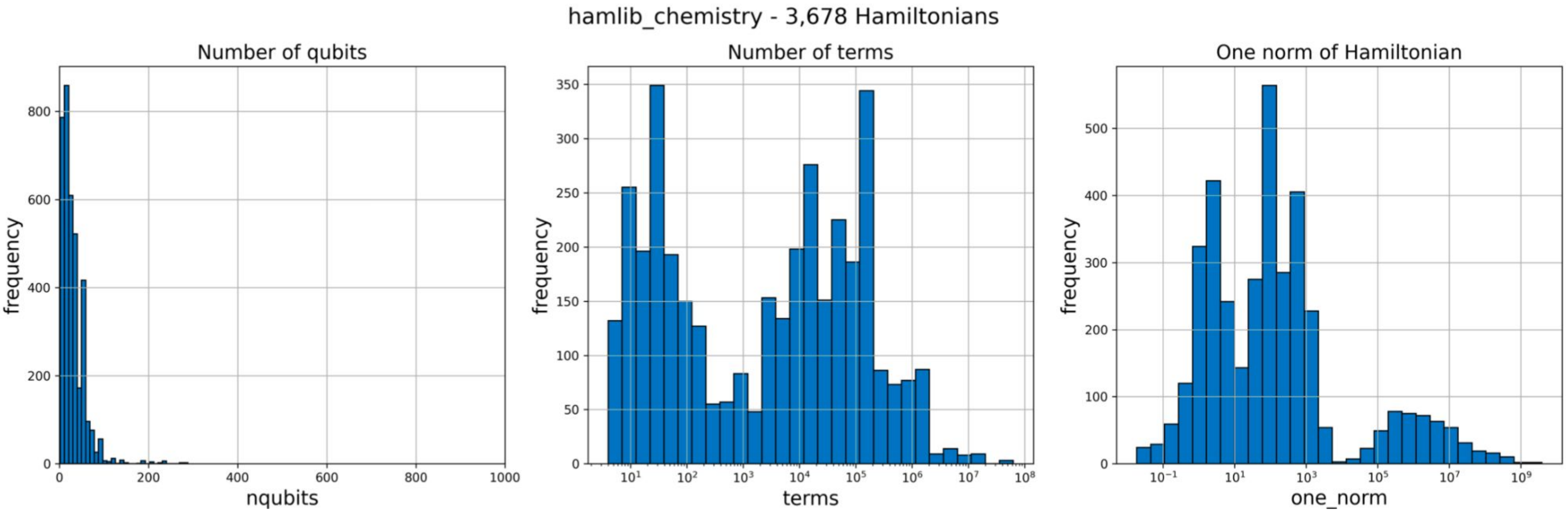
$$H_{\text{encoded}} = \sum_i c_i \bigotimes_k \{\sigma_{ik}\}$$

- Stored on NERSC servers https://portal.nersc.gov/cfs/m888/dcamps/hamlib/

Hamlib Stats



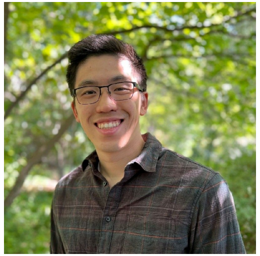
Hamlib Chemistry Stats



HamLib Team


Nicolas Sawaya


Daniel Marti-Dafcik


Yang Ho


Daniel Tabor


David Bernal


Alicia Magann


Pradeep Dubey


Anne Matsuura

Nathan Bishop


Bert de Jong


Simon Benjamin


Ojas Parekh


Norm Tubman


Katie Klymko


Daan Camps

intel labs

UNIVERSITY OF OXFORD

Sandia National Laboratories

ATM

NASA

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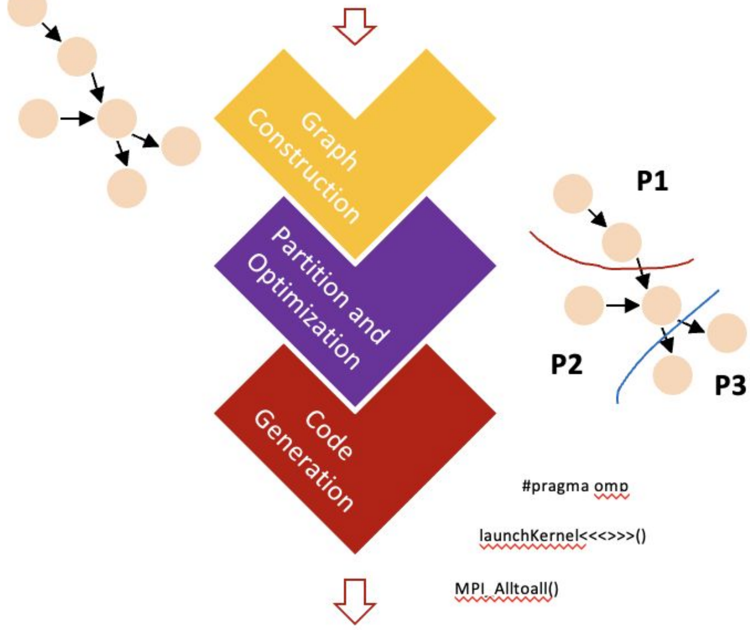
Library for Optimizing Quantum Circuits Simulations

Doru Thom Popovici, Harlin Li, Naoki Yoshioka, Naoto Aoki, Nobuyasu Ito, Daan Camps, Katie Klymko, Anastasiia Butko

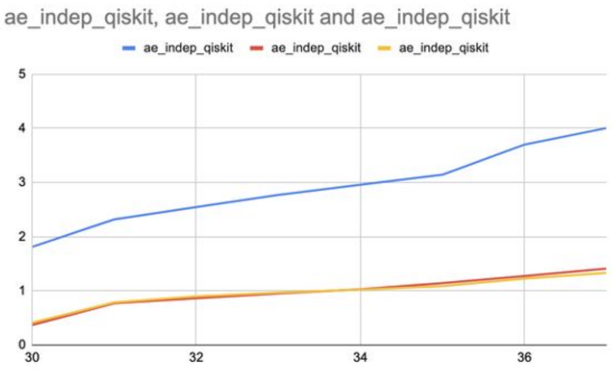
- **Graph Construction**
  - Create a **dependency graph** between the gates
- **Partition and Optimization**
  - Partition the graph into **clusters** to better utilize the **memory hierarchy**
  - Construct a **hierarchical representation**
- **Generation of Efficient Implementation**
  - Generate **efficient code** C++/cuda/hip

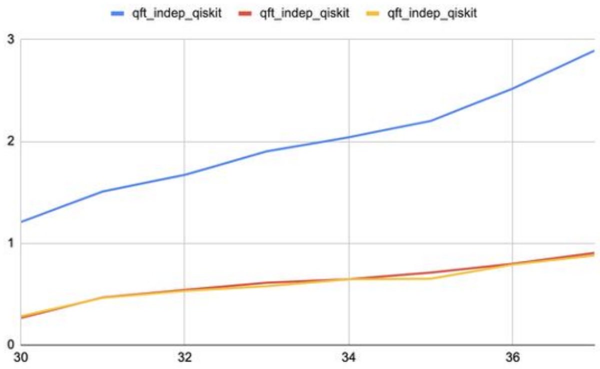
Input: Flat list of gates

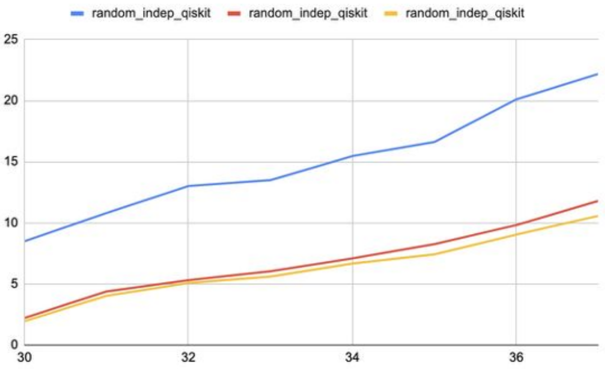


Output: Optimized implementation

Preliminary Results: Execution Time on Perlmutter







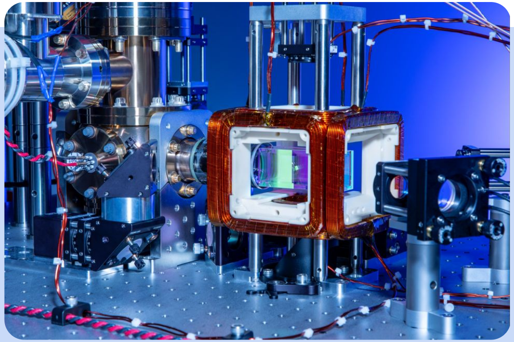
We start with 30 qubits on 4 GPUs

The blue plot represents the execution of the simulation without optimizations for the local computation

The red and orange plots show our optimized implementation that better map to the memory hierarchy of the GPU

NERSC's R&D Partnership with QuEra Computing: First DOE Lab To Partner with a Neutral Atom Vendor

- Boston-based quantum computing startup focused on **neutral atom hardware** out of Harvard and MIT researchers
- Current hardware is Aquila, an analog quantum computer with 256 qubits in a **reconfigurable 2D geometry** ("Dynamically Field-Programmable Neutral Atom Array Processors")
- R&D collaboration has been focused on **application development** and understanding the resources needed to use current and future neutral atom systems for science applications

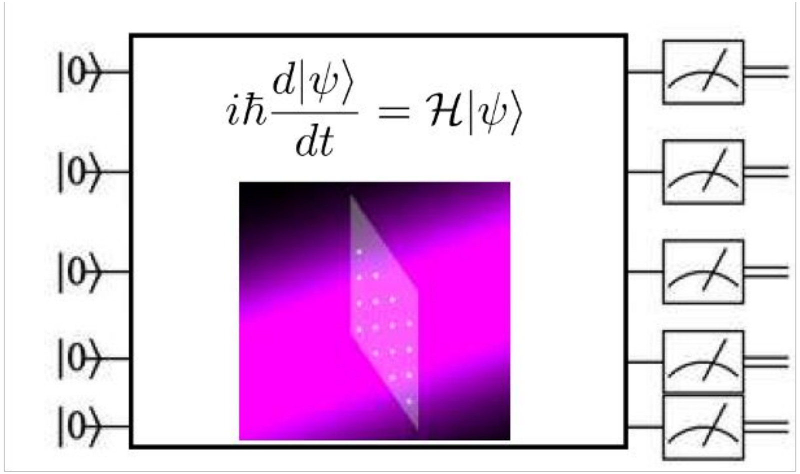


Engagement themes:

Year 1 (2023-24): Initial hardware explorations for accelerating science applications. Expertise development.

Year 2 (2024-25): Large-scale experiments for expertise and use-case demonstration. User program established.

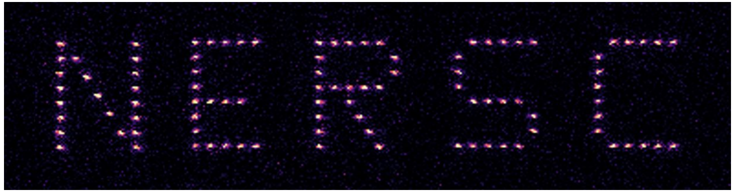
Aquila: QuEra's Neutral Atom Analog Computer



[2] Henriet et al, Quantum 4, 327 (2020).

Some technical specifications:

- Rb atom
- Maximum qubits: 256
- Maximum duration: 4-20 microseconds
- Field of View: (75-100, 76) microns
- Minimum spacing: 2-4 microns



[1] Aquila v1.0 (2023) https://arxiv.org/abs/2306.11727

Hamiltonian and Rydberg Interactions

$$H = \frac{\Omega(t)}{2}\sum_j \hat{\sigma}_{x,j} - \sum_j \Delta_j(t)\hat{n}_j + \sum_{j<k} V_{jk}\hat{n}_j\hat{n}_k$$

Rydberg interaction

$$V_{jk} = \frac{C_6}{r_{jk}^6} \text{ : van der Waals}$$

$\Longrightarrow$ Entangle atoms

Detuning

$\hat{n}_j = |1\rangle\langle 1|_j$: Number operator

$\Delta_j = \Delta_{\text{glob}} + \Delta_{\text{loc},j}$: Detuning field

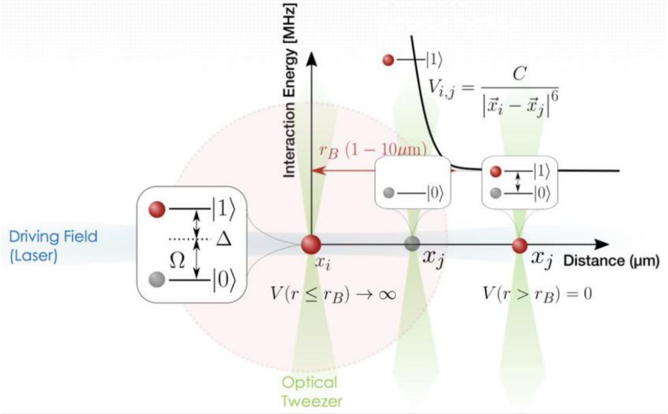
Global Local

Rabi drive

$\hat{\sigma}_{x,j} = |0\rangle\langle 1|_j + |1\rangle\langle 0|_j$: Pauli-X

Ω : Rabi frequency

Rydberg blockade :

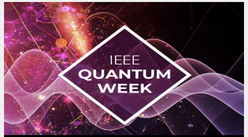


Blockade radius $R_b = (C_6/\Omega)^{1/6}$

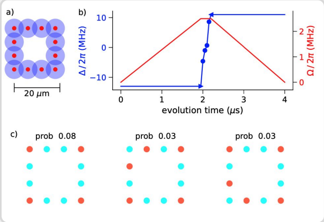
$r_{jk} < R_b \implies$ Joint excitations suppressed

Progress Towards Quantum Application Development with QuEra

Solving optimization problems with neutral atoms



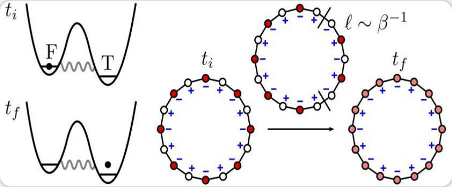
Best paper award 2024



2024 IEEE International Conference on Quantum Computing and Engineering (QCE)

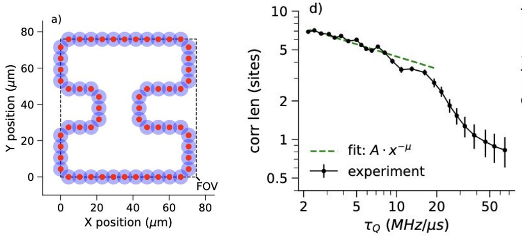
Quantum dynamics for cosmology and high energy physics

- *Physical Review B* 110 (15), 155103
- *Physical Review B* 110 (15), 155114



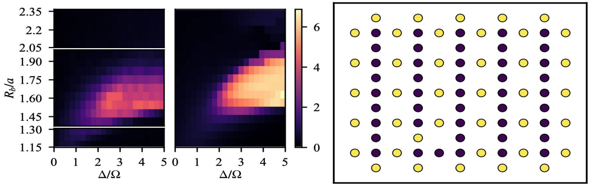
Coarsening dynamics and statistics of defect formation in quantum materials

Paper in preparation



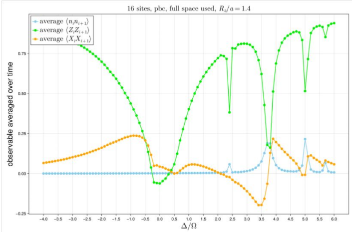
Probing ground state phase diagrams for materials

Paper in preparation

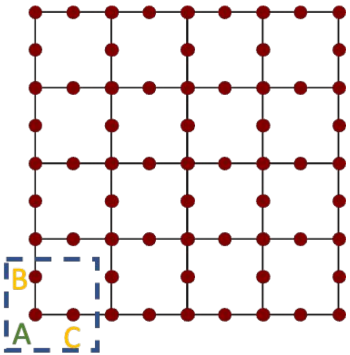


Dynamical quantum phase transitions in condensed matter

Paper in preparation

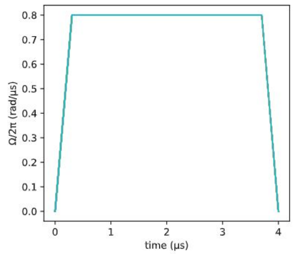


Probing the Phase Diagram of the Lieb Lattice

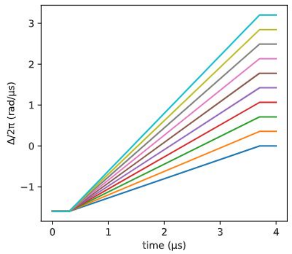


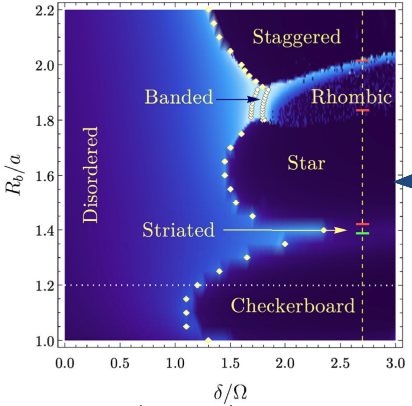
In condensed matter physics and materials science, computing the ground state phase diagram tells us how important materials behave under different conditions.

Rabi frequency

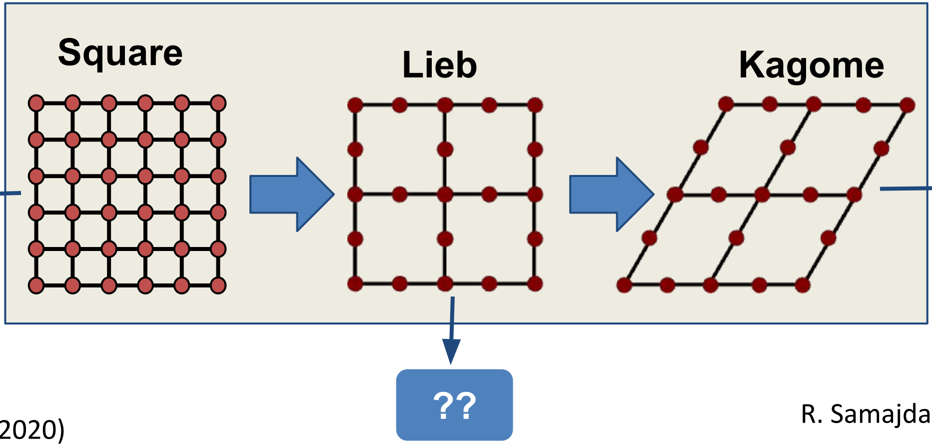


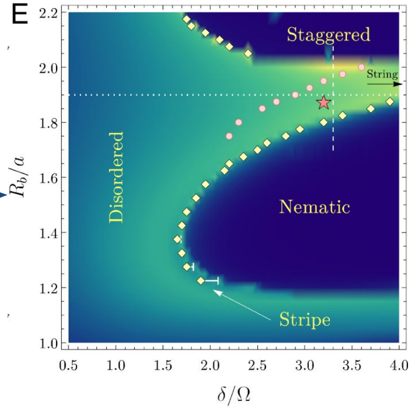
Detuning





R. Samajdar et. al., PRL 124:103601 (2020)

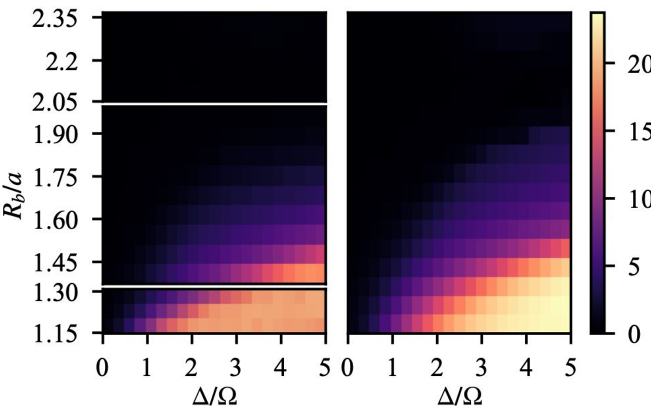




R. Samajdar et. al., PNAS 118:2015785118 (2020)

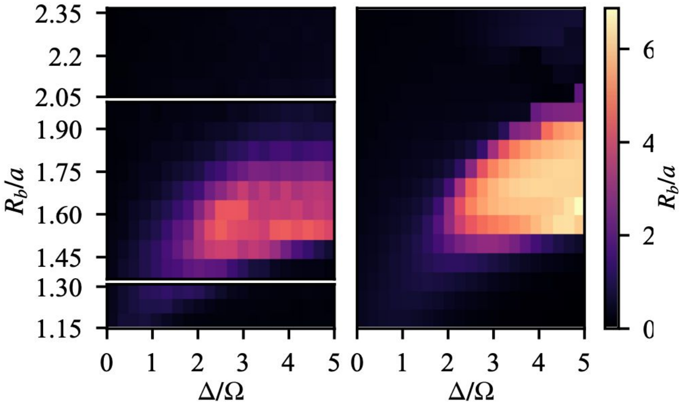
Comparison of Phases Between Aquila and Perlmutter

Symmetric phase



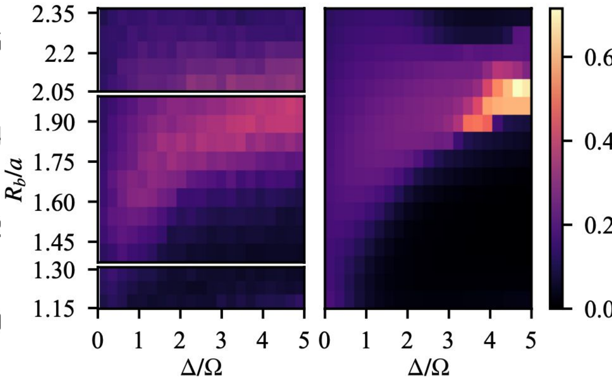
Aquila Perlmutter

Collinear phase

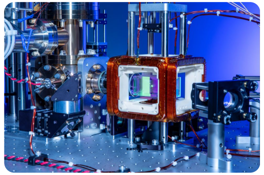


Aquila Perlmutter

Star phase



Aquila Perlmutter



Atom lattices of 85-133 on Aquila

NERSC |QuEra> Computing Inc.

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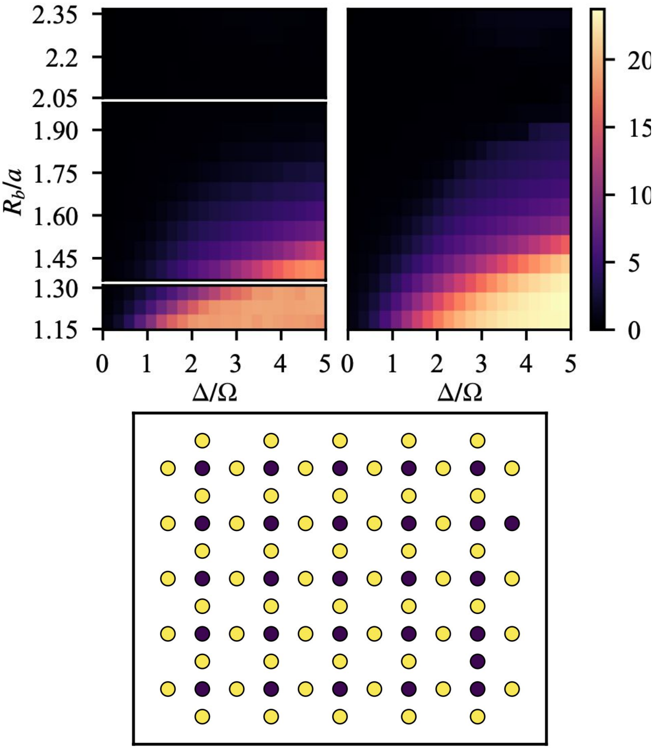
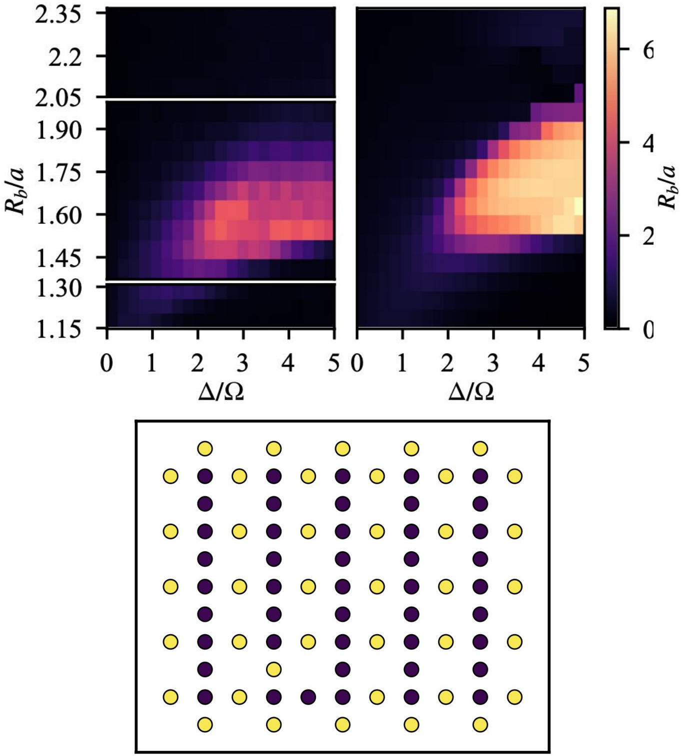
Comparison of Phases Between Aquila and Perlmutter

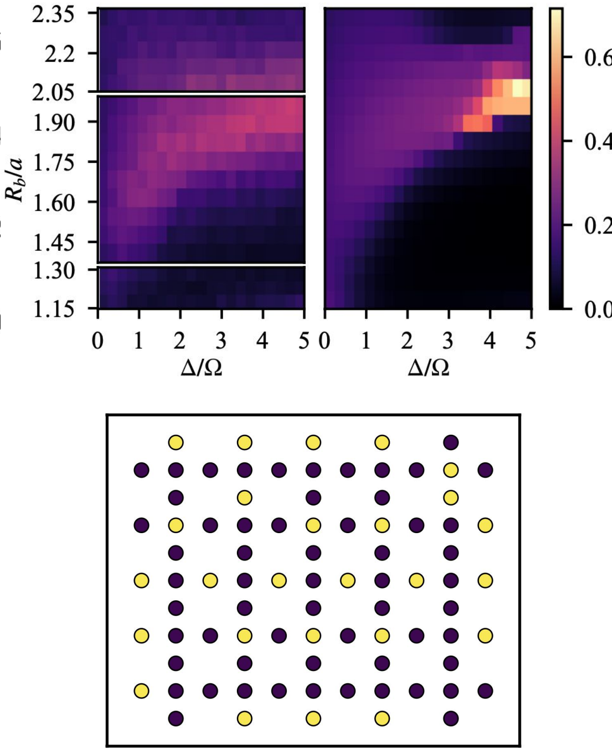
Symmetric phase



Collinear phase



Star phase

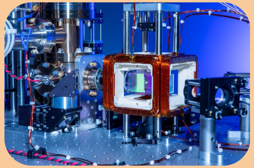


Quantum Computing Access @ NERSC (QCAN)

Quantum Information Science on Perlmutter

- **Early user exploration** through access to NERSC's classical resources
- 10+ teams selected per year on a rolling basis
- 30+ publications
- Started January 2022

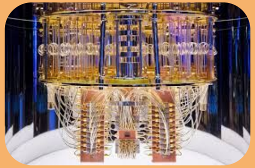
Neutral Atoms



Access through QuEra Computing

- **Close collaborations** between NERSC, science teams, and hardware vendor
- Up to 25h of QC usage per selected team
- 20 teams applied, 3 selected
- Started October 2024

Superconducting Qubits



Access through IBM

- **Broader access** to quantum hardware for a subset of NERSC users (up to 15 projects)
- Support from IBM team
- IBM Quantum Network: community of users
- Started January 2025

We are adapting access based on advancements in quantum hardware, algorithms and software development, and increased understanding of users' needs.

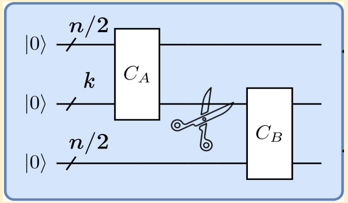
QIS@Perlmutter: Science Highlights 2022-2025

Perlmutter GPU hours dedicated for research in areas that include quantum simulation, error mitigation, chemistry, materials science, condensed matter physics, and optimization: ***accelerating quantum simulations at supercomputing scale.***

Users have access to NVIDIA tools like CUDA-Q.

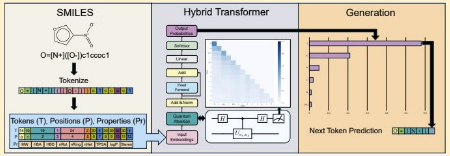
30+ Project Teams, 30+ Publications

PI: Lee J. O'Riordan (Xanadu)



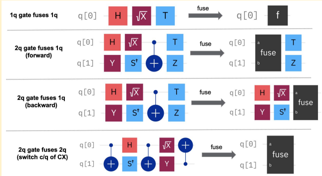
Fast Quantum Circuit Cutting
Lowe et al., Quantum 2023

PI: Marwa Farag (NVIDIA)

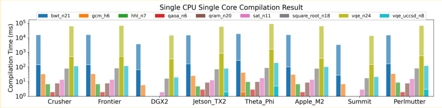


Hybrid Transformer Architecture
Smaldone et al, *arXiv*:2502.19214

PI: Ang Li (PNNL)

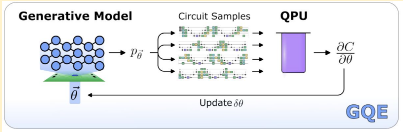


Gate Fusion
Li et al., 2023 arXiv:2310.17739



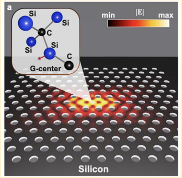
Quantum Transpiler
Hua et al., 2023 arXiv:2308.07581

PI: Kouhei Nakaji (University of Toronto)



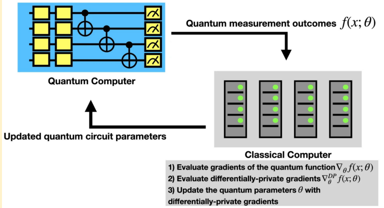
Generative Quantum Eigensolver
Nakaji et al., *arXiv*:2401.09253

PI: Liang Tan (LBL)



All-silicon Quantum Light Source
Redjem et al., Nature Comm. 2023

PI: Shinjae Yoo (BNL)



Quantum Machine Learning
Watkins et al., Scientific Reports 2023

QCAN QuEra Project Awardees

Dr. Huan-Hsin Tseng

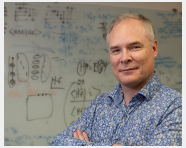
Brookhaven National Laboratory

Maximum Independent Set Problems

The MIS problem is **NP-hard** and has **broad applicability**, including in high-energy and condensed-matter physics. This project proposes to develop and implement an **improved MIS algorithm** on the Aquila neutral atom quantum computer.

Dr. Bert de Jong

BERKELEY LAB



Spin Transport in 2D Lattices

Spintronics uses spin transport in solid-state devices for efficient information processing and storage. This project proposes to carry out an **experiment of spin transport on Aquila.**

Prof. Lex Kemper

NC STATE UNIVERSITY

Information Scrambling in Negatively Curved Spaces

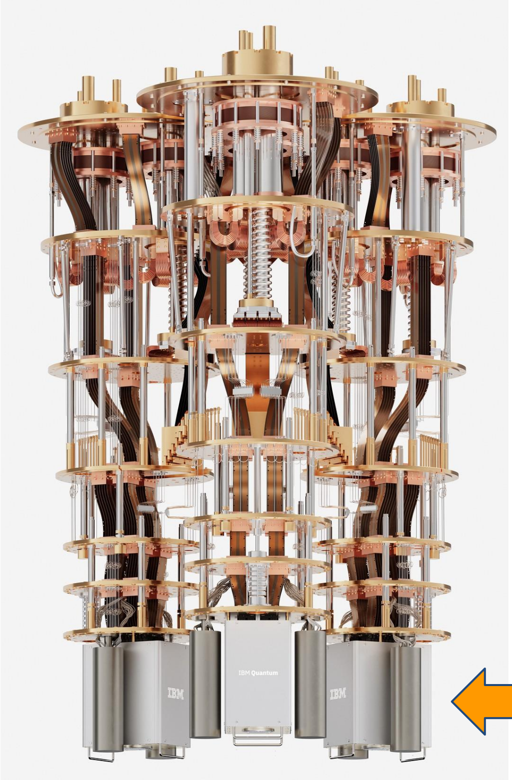
Models of quantum gravity that exhibit AdS/CFT correspondence, are **notoriously difficult to classically simulate.** The results will elucidate information scrambling and dynamics in curved spaces

NERSC IBM Quantum Hub Opened in 2025

LBL employees and selected external users will get access to access multiple IBM quantum processor systems, all with 100+ qubits, and new systems as they come online

Credit: Christopher Tirrell from IBM

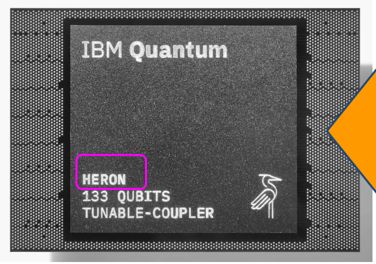
Utility-scale Quantum Processor from IBM

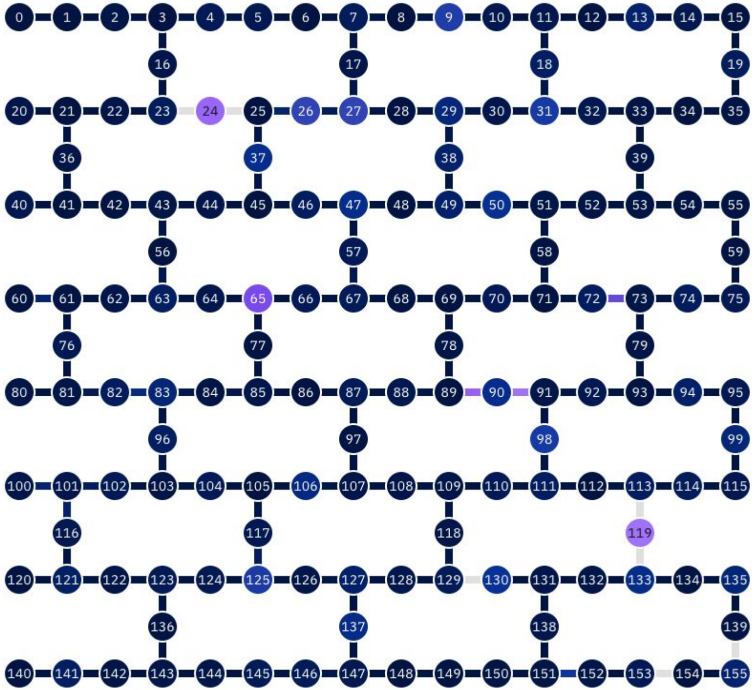


Credit: Christopher Tirrell from IBM

133 qubits
variable couplers

latest
technology





NERSC Benefits from LBNL's Quantum Research Community & Interacts with Broader DOE Efforts

Berkeley Lab-led Quantum Centers, Testbeds, and Facilities

QUANTUM SYSTEMS ACCELERATOR Catalyzing the Quantum Ecosystem	MOLECULAR FOUNDRY	AQT	QUANT-NET
National QIS Research Center to catalyze national leadership for co-design of algorithms, quantum devices, and engineering solutions.	Extensive toolset for the exploration of new materials through synthesis, fabrication, characterization, and simulation.	DOE Testbed that provides users with full-stack access to an advanced quantum computation system based on superconducting circuits.	DOE Testbed that will enable quantum entanglement distribution between Berkeley Lab and UC Berkeley with optical fiber.

DOE Quantum Programs

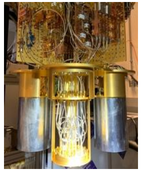
Oak Ridge Leadership Computing Facility Quantum Computing User Program

QPL Quantum Performance Laboratory

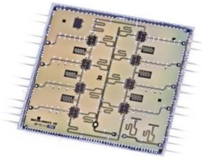
NERSC Quantum events have participants from PNNL, LLNL, ORNL, SNL, and BNL

Full Stack Superconducting Quantum Computing Platforms

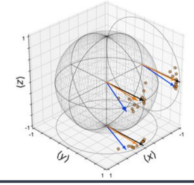
aqt.lbl.gov



Cryogenic Platform
Bluefors dilution fridge with 160 RF lines, operating at 10 mK. Modular and extensible cryopackaging, developed in partnership with Bleximo, mitigates crosstalk, provides control and readout for 128 qubits, and can accommodate multiple chips.



Superconducting Quantum Processors
Current chip is an 8-qubit transmon ring design with high-coherence qubits (T_1 and T_2 >100 μs). A novel 8-qubit QPU with arbitrary dynamically reconfigurable (up to all-to-all) qubit-qubit connectivity will soon be available.



Software Stack
Open programming stack and flexible user interface, with demonstrated tailoring and mitigation of coherent errors to improve algorithmic performance. Can support non-standard user software needs.

Commercial and Custom Controls
Cutting-edge controls equipment capable of fast feedback and on-the-fly state detection, which can accommodate custom user needs. Both commercial Zurich Instrument solutions and an in-house custom modular solution called QubiC are available.

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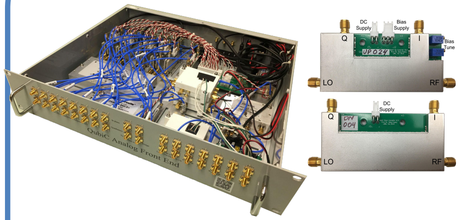
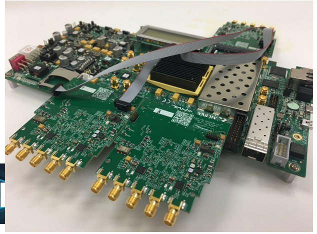
QubiC: Open-source FPGA-based Quantum Bit Control System

U.S. DEPARTMENT OF ENERGY
Office of Science

QubiC 1.0



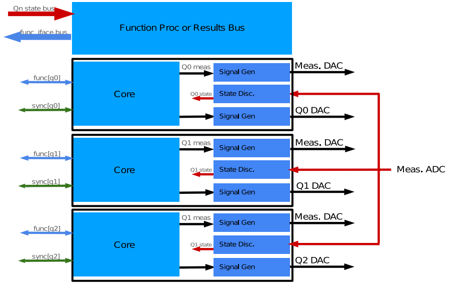
- Started in 2018 by Gang Huang, based on VC707.
- Auxiliary RF components, firmware, software, calibration protocols published & **open-sourced**.
- Low-cost DACs-ADCs



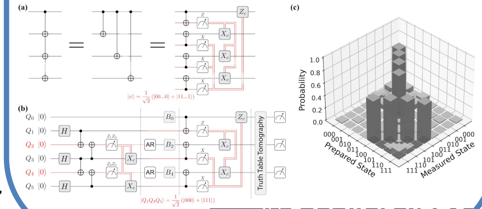
QubiC 2.0

- Based on ZCU216 RFSOC
- 10 GSPS allows direct generation up to ~10 GHz in 2nd Nyquist Zone
- AC- and DC-coupled AFEs
- Adopted by multiple groups
- Used for various co-design projects
- QubiCSV: data management and visualization

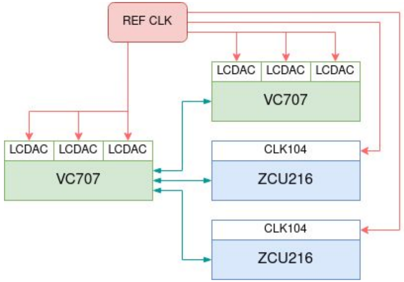
Distributed Processor



- Novel Architecture on FPGA to enable Mid-Circuit Measurement and Feedforward
- Flexible Function Proc enables arbitrary logic



Multi-Platform Sync



- 2x VC707 and 2x ZCU216 synchronized thru ref clk
  - 24-ch 16-bit DAC @ 1 GSPS
  - 32-ch 14-bit DAC @ 8 GSPS
- RMS jitter < 10ps
- Next step: decision distribution

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QubiC: Open-source FPGA-based Quantum Bit Control System

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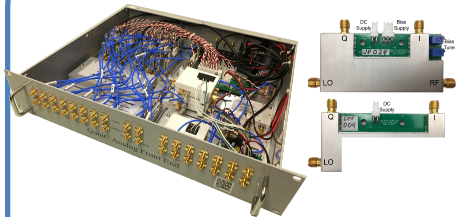
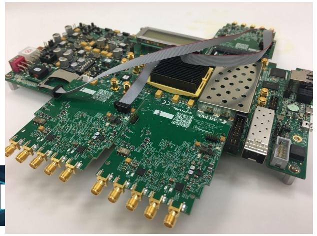
Office of Science

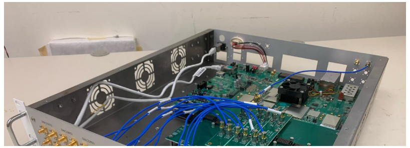
QubiC 1.0



- Started in 2018 by Ga Huang, based on VC7
- Auxiliary RF compone firmware, software, calibration protocols published & **open-so**
- Low-cost DACs-ADCs

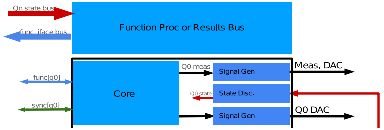


QubiC 2.0

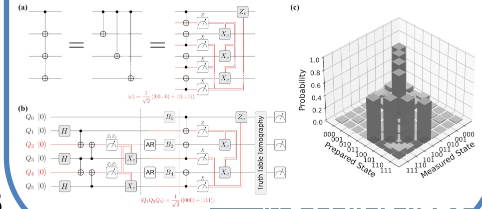


- AC- and DC-coupled AFEs
- Adopted by multiple groups
- Used for various co-design projects
- QubiCSV: data management and visualization

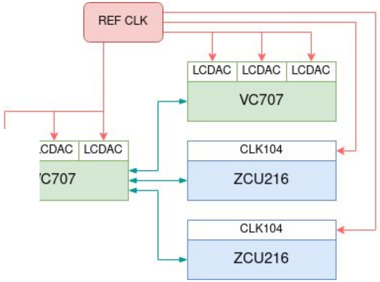
Distributed Processor



arbitrary logic



Multi-Platform Sync



- C707 and 2x ZCU216 hronized thru ref clk
- -ch 16-bit DAC @ 1 GSPS
  - 32-ch 14-bit DAC @ 8 GSPS
- RMS jitter < 10ps
- Next step: decision distribution

Open source repos
https://gitlab.com/LBL-QubiC

Get Involved
https://go.lbl.gov/qubicsignup

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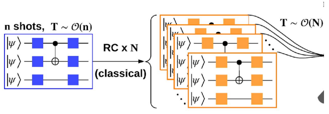
QubiC: Hardware Efficient Randomized Compiling

U.S. DEPARTMENT OF ENERGY
Office of Science

The Problem:

- Quantum Processors suffer from both coherent and stochastic noise.
- Coherent noise is much more problematic than stochastic noise.
- Thankfully, there is Randomized Compiling to help us convert coherent noise to stochastic noise.
- Unfortunately, Randomized Compiling is very expensive in terms of classical steps (compilation and upload), often saved for final runs.



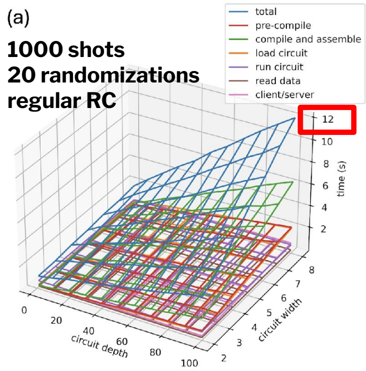
The Solution: Bypass Compilation

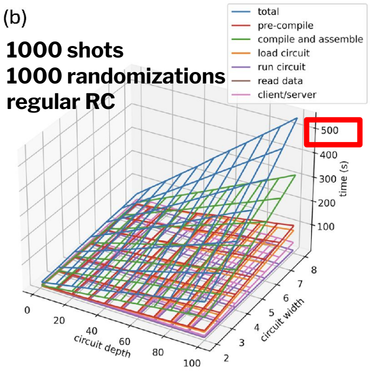
1. Randomly select twirling Pauli on FPGA from {I, X, Y, Z}
2. Look up the "undoing Pauli" through a 2-qubit gate in a 4x4 element table:

$$P_i,\ P_j \rightarrow P'_i,\ P'_j$$

3. Single-qubit gate combination around U3:
   Given:
   $$U3 = Z(\phi_2)X_{90}Z(\phi_1)X_{90}Z(\phi_0)$$
   We find:
   $$P_i U3 P'_{i-1} = Z(\phi'_2)X_{90}Z(\phi'_1)X_{90}Z(\phi'_0)$$
   where ϕ'_n is given by a 64-element map.

Experimental Results

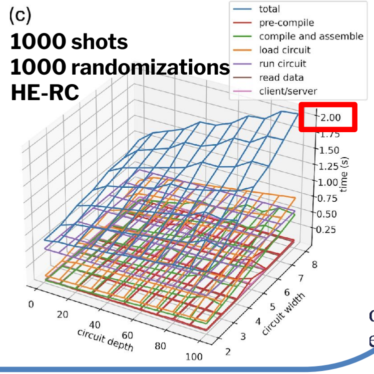




Punchline:

You get RC ***for free***!!!*

* as long as your gate times are longer than 12ns



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QubiC: Hardware Efficient

Science

Hardware-Efficient Randomized Compiling

Neelay Fruitwala,[1,*] Akel Hashim,[2,3,*] Abhi D. Rajagopala,[3] Yilun Xu,[1] Jordan Hines,[2] Ravi K. Naik,[3] Irfan Siddiqi,[2,3,4] Katherine Klymko,[5] Gang Huang,[1,†] and Kasra Nowrouzi[3,‡]

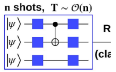
[1] *Accelerator Technology and Applied Physics Division, Lawrence Berkeley National Lab, Berkeley, CA 94720, USA*
[2] *Department of Physics, University of California at Berkeley, Berkeley, CA 94720, USA*
[3] *Applied Math and Computational Research Division, Lawrence Berkeley National Lab, Berkeley, CA 94720, USA*
[4] *Materials Sciences Division, Lawrence Berkeley National Lab, Berkeley, CA 94720, USA*
[5] *National Energy Research Scientific Computing Center, Lawrence Berkeley National Lab, Berkeley, CA 94720, USA*

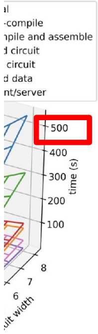
(Dated: June 21, 2024)

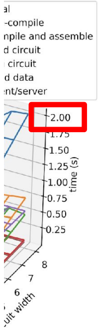
Randomized compiling (RC) is an efficient method for tailoring arbitrary Markovian errors into stochastic Pauli channels. However, the standard procedure for implementing the protocol in software comes with a large experimental overhead — namely, it scales linearly in the number of desired randomizations, each of which must be generated and measured independently. In this work, we introduce a hardware-efficient algorithm for performing RC on a cycle-by-cycle basis on the lowest level of our FPGA-based control hardware during the execution of a circuit. Importantly, this algorithm performs a different randomization per shot with zero runtime overhead beyond measuring a circuit without RC. We implement our algorithm using the QubiC control hardware, where we demonstrate significant reduction in the overall runtime of circuits implemented with RC, as well as a significantly lower variance in measured observables.

The

- Quantum F… from both … stochastic
- Coherent … problemati… noise.
- Thankfully, Randomize… help us cor… noise to st…
- Unfortunat… Compiling … in terms of … compilatio… often save







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QubiC: Parametrized Circuit Execution

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The Problem:

- Many commonly-deployed protocols for benchmarking and mitigation (e.g. RB, CB, RC, etc) consist of 100s-1000s of circuits.
- The classical steps in running these circuits often take the majority of total run time. **Memory** and **upload** are particularly problematic.
- This makes it **expensive** to *characterize* QPUs and *mitigate* noise/errors.

	RC	CB	RB
# Circuits	**1540**	**6000**	**736**
# Unique Circuits	**77**	**21**	**32**
Classical Time (%)	**94**	**68**	**43**

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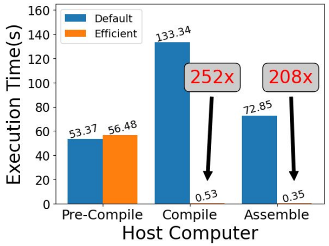
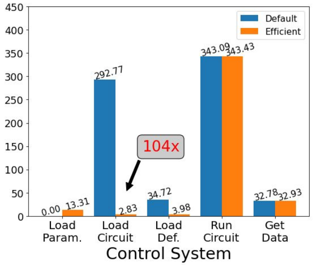
The Solution: RIP & Stitch!

- Note that in all these cases, only a small minority of the total set of circuits are structurally unique! The rest are only off by gate parameters (e.g. phase).
- On the host computer:
  - **R**ead the circuits
  - **I**dentify unique circuits
  - **P**eel off the parameters
- Compile and upload *only* the unique circuits, plus a table of parameters
- At run-time on FPGA: **Stitch** the parameters back in

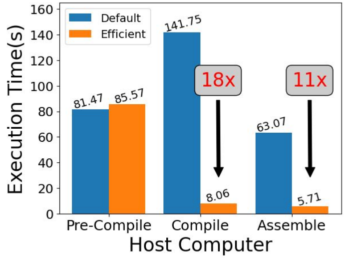
Experimental Results

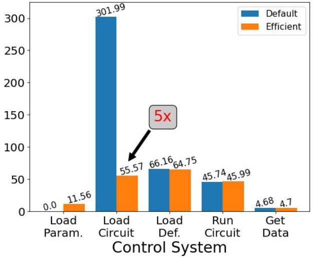
Cycle Benchmarking





Randomized Compiling





	RC	CB	RB
# Circuits	**1540**	**6000**	**736**
# Unique Circuits	**77**	**21**	**32**
Classical Time (%)	**94**	**68**	**43**
Classical Speedup[1]	**255%**	**542%**	**358%**

Office of Science

QubiC: Parametrized Circuit

BER
Bringing :

The Probler

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protocols for benchr
and mitigation (e.g. F
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NERSC

Hardware-Assisted Parameterized Circuit Execution

Abhi D. Rajagopala,[1] Akel Hashim,[1,2] Neelay Fruitwala,[3] Gang Huang,[3] Yilun Xu,[3] Jordan Hines,[4] Irfan Siddiqi,[2,1,5] Katherine Klymko,[6] and Kasra Nowrouzi[1]

[1]*Applied Math and Computational Research Division, Lawrence Berkeley National Lab, Berkeley, CA 94720, USA*
[2]*Quantum Nanoelectronics Laboratory, Department of Physics, University of California at Berkeley, Berkeley, CA 94720, USA*
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Standard compilers for quantum circuits decompose arbitrary single-qubit gates into a sequence of physical $X_{\pi/2}$ pulses and virtual-Z phase gates. Consequently, many circuit classes implement different logic operations but have an equivalent structure of physical pulses that only differ by changes in virtual phases. When many structurally equivalent circuits need to be measured, generating sequences and measuring each circuit is unnecessary and cumbersome since compiling and loading sequences onto classical control hardware is a primary bottleneck in quantum circuit execution. In this work, we developed a hardware-assisted protocol for measuring parameterized circuits on our FPGA-based control hardware, QubiC. This protocol relies on a hardware-software co-design technique in which software identifies structural equivalency in circuits and compiles unique circuits to reduce the overall waveform compilation time. The hardware architecture then performs real-time stitching of the parameters to the circuit before measuring on quantum hardware. This work demonstrates that this protocol speeds up the total execution time for many quantum circuits and algorithms.

Keywords: Quantum Computing, Parameterized Circuits, FPGA

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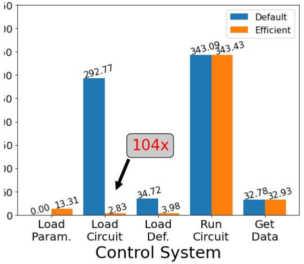

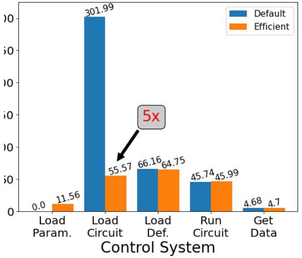

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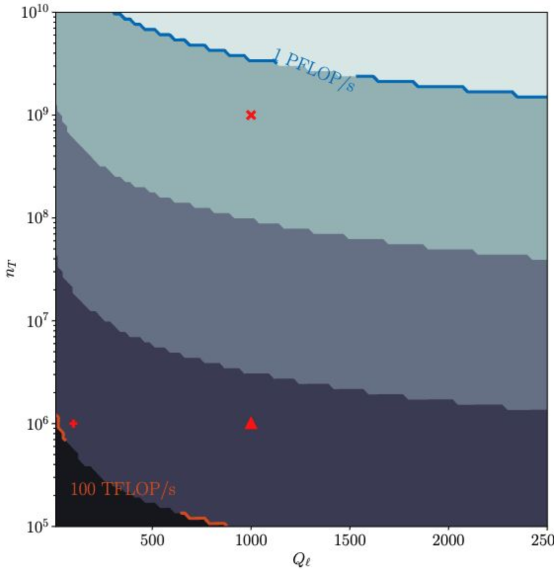
Research to Address the Classical Requirements for Future Quantum Workloads

- NERSC Team awarded best paper at ISC 2024 for “Evaluation of the classical hardware requirements for large-scale quantum computations”

- Paper explores the network latency, network bandwidth between the quantum computer and the HPC system, and compute requirements for applications in physics and chemistry



Above plot shows estimated FLOPs required for real-time decoding as a function of number of logical qubits (x-axis) and depth (y-axis). Red markers show resources required for different large-scale problems from condensed matter physics and quantum chemistry. All problems require less than 1 petaflop of compute.

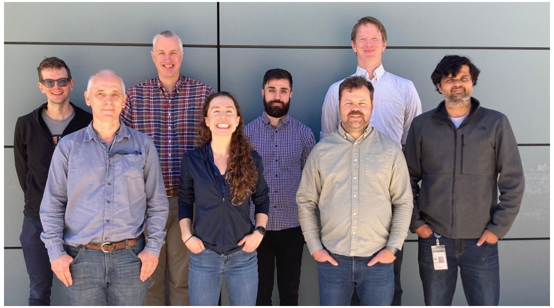
Summary

- The NERSC quantum team is engaging in strategic pathfinding/R&D efforts and collaborations to prepare for future NERSC systems.

- NERSC has a quantum user program designed for both scientific impact and breadth of users which will inform future requirements.

- Understanding the future role of quantum computing in the HPC workload and developing the infrastructure to serve users is a community-wide activity which will require collaboration between NERSC staff, vendors, researchers, users, and the DOE community at-large.

Acknowledgements



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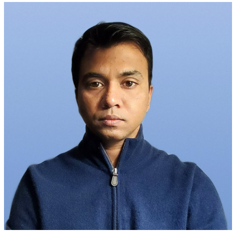

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