Advanced Scientific Computing Research
Quantum Information Science Awards Abstracts

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Quantum Performance Assessment

Robin Blume-Kohout,[1] Kevin Young,[1] Tim Proctor,[1] Kenneth Rudinger,[1] Erik Nielsen,[1] Mohan Sarovar,[1]

Quantum processor technology is advancing at breakneck speed, with labs and companies announcing breakthrough devices regularly. But it's hard to gauge how well any given device actually works. There are few widely-accepted tools for measuring performance. Claims about hardware performance tend to be based on shallow metrics (e.g., number of qubits) or opaque ad-hoc benchmarks. Quantum hardware technology is outracing our ability to test devices and assess their performance.

Our goal, at Sandia's *Quantum Performance Laboratory*, is to provide solutions to this problem by leveraging our expertise and experience in quantum hardware characterization to develop a new and enabling toolbox of methods for testing and evaluating quantum hardware. The core of our program is *research*, to create new frameworks and techniques for performance assessment. But we also want to make our research *usable* by other scientists and engineers, both within and outside the DOE community. We will develop and deploy software tools that implement performance assessment protocols, which will allow quantum hardware developers and the US Government to assess quantum processors that they are developing or considering investing in. We also seek to partner with experimental researchers who are developing and improving qubit hardware, to test our methods and support their progress.

Our plan combines (1) informed R&D to create good metrics and benchmarks, (2) the development of reliable software to implement these techniques, and (3) engagement with experimental hardware developers and researchers to test and use the tools we develop. We intend to build on Sandia's demonstrated capability for characterization of 1- and 2-qubit gates using gate-set tomography (GST) and other protocols. We plan to extend this capability to comprehensive, holistic characterization of multiqubit quantum processors. We will develop protocols to measure the rates of specific errors, and we will determine how specific error modes impact a processor's overall performance. We will develop fair and well-motivated benchmarks to compare and contrast the performance of near-term "testbed-class" quantum processors. These benchmarks will incorporate kernels of promising DOE-relevant quantum algorithms for application-specific benchmarks. We will publish our methodologies, and release open-source implementations of them that can be used straightforwardly by experimentalists. We intend that these methods and their software implementations in the open-source *pyGSTi* package will support continued development of US quantum processors *and* help DOE to understand the performance of cutting-edge quantum hardware. We have already demonstrated this model at a small scale, by using *pyGSTi* to assess the error performance of 1-8 qubit devices. We plan to extend this capability to every form of "performance" that we can identify for testbed-class quantum processors.

We plan to partner with DOE-funded research teams in quantum algorithms to identify quantum algorithms that promise improved solutions to parts of DOE mission-relevant problems, map these algorithms to quantum circuits, and extract key subroutines or "kernels". We will then adapt these kernels to yield *test suites* of quantum circuits that can be run on near-term hardware, and capture its performance in real-world scenarios that are more relevant than how performance on random or contrived quantum circuits.

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[1] Quantum Performance Laboratory, Sandia National Laboratories (Albuquerque, NM and Livermore, CA)

Efficient and Reliable Mapping of Quantum Computations Onto Realistic Architectures

Andrew Childs,[1] Alexey Gorshkov,[1] Michael Hicks,[1] Robert Rand,[1] and Xiaodi Wu[1]

Quantum computers offer the prospect of efficiently solving certain problems that would be intractable for classical computers. Potential applications of quantum computers include several challenges of relevance to the DOE science and energy mission, including simulations of quantum mechanical systems, quantum approaches to approximate optimization, and numerical methods for scientific computing. However, the limited abilities of current quantum hardware make it challenging to realize these benefits with existing devices. The proposed work will develop methods and tools for implementing quantum algorithms as efficiently and reliably as possible on realistic hardware and for evaluating the capabilities of such devices, facilitating computation on near-term quantum processors. Algorithms for quantum computers are typically formulated in an abstract circuit model that allows gates between any two qubits at the same cost. However, realistic quantum processors come with strong constraints on the possible interactions. Mapping a given quantum circuit onto such a realistic device will necessarily incur overhead depending on factors including the system architecture, the underlying quantum computation, and the method used to construct the mapping. Our proposed work aims to develop theoretical and computational tools for addressing this challenge that are efficient, robust, and incur minimal overhead. We will apply these tools to address both research areas suggested in the call for proposals: studying the interplay between architectural and algorithmic choices and quantitatively understanding the potential for near-term quantum devices to address scientific challenges. This work will be organized around three interrelated research thrusts:

Circuit layout. To understand the effect of device architecture on the ability of a quantum processor to carry out quantum computations, it is crucial to develop methods for translating quantum circuits for algorithms of interest into ones that respect a given set of architectural constraints. A key thrust of our proposal is to produce a suite of algorithms for mapping quantum circuits to realistic architectures and implement them in software. Using these tools, we will explore the impact of architectural features on our ability to perform practical quantum computations, providing insights into the design of quantum architectures and evaluating the ability of realistic devices to carry out computations relevant to the DOE science mission.

Effect of interaction range. One of the defining features of any quantum computing platform is the range of available two-qubit interactions, with longer-range interactions allowing for faster computation. Some of the most advanced quantum computing platforms include long-range interactions. The second key thrust of our proposal is to harness such interactions to achieve computational speedups relative to architectures with nearest-neighbor interactions. We will also prove bounds on how quickly a given quantum algorithm can run using interactions of a given range. By combining the protocols and bounds that we develop, we will attempt to determine algorithm implementations for a given architecture that have the shortest possible running time, illuminating the relationship between device architecture and algorithm performance.

Formal methods. The final thrust of our work is the application of formal methods and techniques from the field of programming languages. Our goal is to develop novel tools to ensure that quantum programs are implemented and analyzed properly. Such tools will add confidence to the conclusions of our own analysis of near-term architectures and will also be of general use to the broader community. The result

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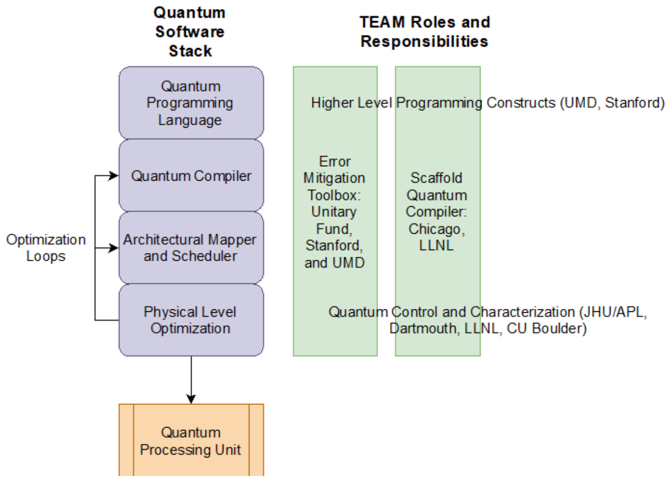
[1] University of Maryland

should be a much greater ability to reliably reason about the complexity and performance of near-term quantum devices.

Tough Errors Are no Match (TEAM): Optimizing the quantum compiler for noise resilience

B. David Clader, Johns Hopkins University Applied Physics Laboratory (Team Director); Fred Chong, University of Chicago (Deputy Team Director); Gregory Quiroz, Johns Hopkins University Applied Physics Laboratory (Noise Characterization and Mitigation - Thrust Area Lead); Will Zeng, Unitary Fund (Quantum Programming and Compilation - Thrust Area Lead); Daniel Appelo, University of Colorado Boulder; Dan Boneh, Stanford University; Pat Hanrahan, Stanford University; N. Anders Petersson, Lawrence Livermore National Laboratory; Lorenza Viola, Dartmouth College; Xiaodi Wu, University of Maryland

Noise in quantum systems poses a challenge for both near term quantum devices as well as for future fault-tolerant quantum computers. To tackle this challenge, this project will integrate a suite of techniques into a toolbox that leverages techniques from quantum characterization and control, probabilistic programming, and approximate computing to improve error robustness in quantum computing hardware. We will integrate characterization and error mitigation strategies into the quantum software stack from the bottom up to optimize and enhance the robustness and scaling of noisy computation. From the top-down, we will investigate whether higher-level programming constructs from the classical domain, such as probabilistic programming or approximate computing, can extend into the quantum domain to further enhance the reliability of noisy quantum computation. While our efforts will focus on near-term noisy intermediate scale quantum (NISQ) computation, our approach will have direct applicability to future fault-tolerant quantum computers as well. Achieving quantum supremacy in the NISQ-era and beyond will require continued reduction in noise levels and optimizations in quantum circuits that consider the underlying hardware constraints, including noise characteristics.



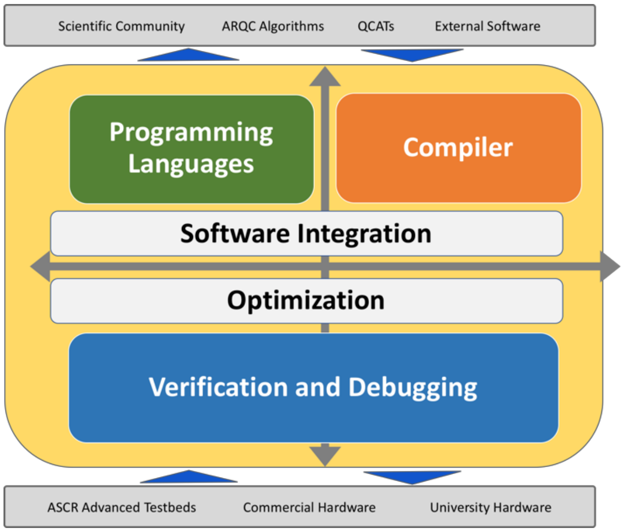
Our research collaboration compromises two thrusts: (1) a noise characterization and mitigation effort and (2) a compiler and computer science thrust. To bridge these two research thrusts, we will build and release an open source hardware-agnostic compiler and software stack that applies these techniques as a toolbox. Since these methods have a large impact on top level performance, it will be important to have a standard toolbox like this to use in the growing amount of hardware and software benchmarking that will be done over the coming years. In order to accomplish the proposed research, we have assembled a diverse team of scientists; this includes team members from the classical and quantum computer science communities working together with experts in quantum characterization and control, applied mathematics, and physics.

Advancing Integrated Development Environments for Quantum Computing through Fundamental Research (AIDE-QC)

W.A. de Jong,[1] T. Humble,[2] M. Sarovar,[3] S. Wild,[4] P. Coles,[5] F. Chong[6]

Recent advances in quantum computing have clarified the potential of the technology to accelerate many key science and engineering applications ranging from quantum chemistry and high-energy physics to machine learning. While these demonstrations remain proof-of-principle, there is a growing need to expand the programmability and testability of these devices. This will require more sophisticated research and development software environments to support the integration of critical concepts with the rapidly changing diverse hardware landscape.

AIDE-QC integrates a multidisciplinary team of five Department of Energy (DOE) laboratories and the University of Chicago to ***address critical aspects of computer science research that accelerate the integration of near-term intermediate-scale quantum (NISQ) devices for scientific exploration.*** These advances include high-level programming languages accessible by domain scientists, novel error - mitigation techniques for near and mid-term hardware devices, and leading-edge platform agnostic compilers supported by classical numerical simulators and robust tools for validation, verification and debugging approaches. ***The goal of AIDE-QC is to develop and deliver open-source computing, programming, and simulation environments that support the large diversity of quantum computing research at DOE***.



Key to the success of the ARQC program is a close relationship between complementary teams focused on software and algorithms research, such as the AIDE-QC and FAR-QC teams. We engage the nascent quantum computing software community by fostering collaboration with the growing use base to discuss ideas and concerns in the broader development of quantum software. We will also be highly engaged with hardware development teams at the DOE laboratories and industrial research labs, as essential partners in co-design of the whole quantum computing infrastructure stack. We will also leverage ASCR's high-performance computing facilities (OLCF, ALCF, NERSC) to establish versatile, scalable and accurate numerical simulators in order to provide a state-of the-art platforms for debugging and testing algorithms and software developed by the research community.

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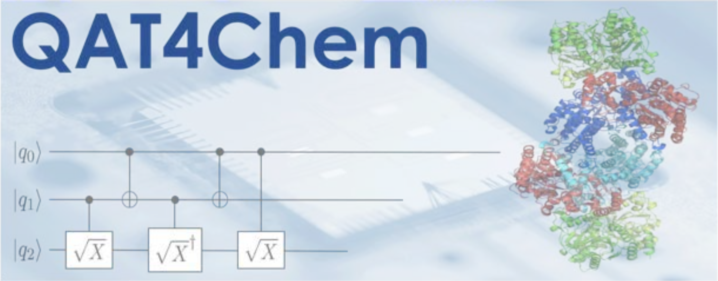
[1] Lawrence Berkeley National Laboratory
[2] Oak Ridge National Laboratory
[3] Sandia National Laboratories
[4] Argonne National Laboratory
[5] Los Alamos National Laboratory
[6] University of Chicago

QAT4Chem - Quantum Algorithms, Mathematics and Compilation Tools for Chemical Sciences

W.A. de Jong,[1] C. Iancu,[1] S. Wild,[2] A. Aspuru-Guzik,[3] N. Yao,[4] B. Whaley,[4] L. Lin[4]

The Quantum Algorithms Team led out of Lawrence Berkeley National Laboratory is an integrated team of quantum algorithm developers, mathematicians, and computer scientists with a ***mission to deliver algorithmic, computational and mathematical advances to enable scientific discovery in chemical sciences on quantum computers.*** Our focus is on quantum chemistry simulations, which are an early exemplar of quantum computing, demonstrating the potential of various types of quantum devices to aid in scientific discovery in the chemical sciences.

Our team demonstrated that quantum error detection improves accuracy of chemical simulations on a quantum computer (https://arxiv.org/abs/1910.00129), and – in partnership with Google - developed an efficient and noise resilient approach to perform measurements for quantum chemistry simulations on near-term quantum computers (https://arxiv.org/abs/1907.13117). To reduce circuit depth generalized swap networks on quantum computers with limited connectivity were shown to work well for a number of different types of algorithms (https://arxiv.org/abs/1905.05118). Thermal states are important for modeling chemical systems. In collaboration with the OVER-QC project have developed a scheme for engineered thermalization of quantum many-body systems in an analogue quantum system (https://arxiv.org/abs/1909.02023). In addition, an approach was developed that allowed us to solve quantum linear system problem with near-optimal complexity (https://arxiv.org/abs/1910.14596), and an artificial quantum spiking neuron was build that relies on the dynamical evolution of two easy to implement Hamiltonians and subsequent local measurements (https://arxiv.org/abs/1907.06269). Finally, applied mathematicians on the team explored the multistart optimization approach within a QAOA framework to improve the performance of quantum machines on important graph clustering problems (https://arxiv.org/abs/1905.08768).



QAT4Chem.lbl.gov

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[1] Lawrence Berkeley National Laboratory
[2] Argonne National Laboratory
[3] University of Toronto
[4] University of California, Berkeley

LLNL Quantum Design and Integration Testbed (QuDIT)

Jonathan L DuBois,[1] Eric T. Holland,[1,2] Yaniv Rosen,[1] Al Castelli,[1] Luis Martinez,[1]
Sean O'Kelley,[1] Yue-Shun Su,[1] Spencer Tomarken,[1] Xian Wu[1]

The LLNL quantum testbed pathfinder effort is focused on exploration, design and demonstration of QC hardware architectures and control interfaces to enable near-term science applications. Our overarching goal is to help bridge the gap between idealized behavior of notional universal quantum computers and current limitations in fabrication, control and characterization of quantum hardware. To this end we treat hardware and software requirements for open quantum system optimal control as the organizing principle for quantum hardware codesign. A starting point on the hardware side of this challenge is realization of quantum systems that are easy to characterize and control. The computational unit cell of our current testbed architecture, the "busmon", consists of multiple long-lived cavity resonance modes coupled together with a planar transmon acting as a bus. The ability to achieve accurate, minimum time, quantum gates for arbitrary unitary operations is a direct consequence of classical control amplitude, bandwidth and fidelity. In our approach a single, numerical waveform optimization combined with off-the-shelf, broadband arbitrary waveform generator enables n-body gate operations at or near a quantum speed limit allowing for fast and accurate entangling operations. Fabrication of the busmon is achieved with well-established and highly reproduceable processes. Specifically, a single step aluminum liftoff process for the transmon devices and conventional high-precision machining for the cavities. The simplicity of the fabrication approach allows us to focus on device control and performance with minimal development of advanced fabrication techniques and results in a platform that effectively maximizes the ratio of accessible quantum volume to the number of parameters required to fully characterize the system. Current efforts are focused on exploiting the relative ease of characterization and control of this system to realize complex many-body gate operations as building blocks for quantum simulation.

This material is based upon work partially supported by the U.S. Department of Energy, Office of Science, Office of Advanced Scientific Computing Research under the Quantum Testbed Pathfinder program and under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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[1] Lawrence Livermore National Lab

[2] Fermilab

Inter-campus network enabled by atomic quantum repeater nodes

Eden Figueroa Barragan,[1] Danton Yu[2]

In this proposal we aim to develop and implement the first agnostic quantum repeater network of quantum light-matter interfaces, at Brookhaven National Lab and Stony Brook University, interconnected using fiber quantum links; this will demonstrate the full potential of quantum repeaters for relaying continuous and discrete variables. This quantum repeater network will be based upon scalable room-temperature quantum memory buffers, bridged to work with entangled photons at telecom wavelengths. The testbed of our ideas will be a grand quantum network connecting several locations in Brookhaven National Laboratory and Stony Brook University on Long Island. By using quantum memories buffers to enhance the swapping of the polarization entanglement of pairs of flying photons, our implementation will take a significant leap in quantum communication by distributing entanglement over long distances without detrimental losses.

Our prototype of a quantum repeater node uses: (I) quantum memories buffers with: a) high efficiency, b) low noise, c) long storage time, d) heralded operation and e) high-duty cycle; (II) frequency conversion devices with: a) high conversion efficiency, b) compatibility with quantum memory buffers, c) low input loss, d) low noise and e) symmetric conversion between atomic and telecom wavelengths; and (III) entangled photon sources with: a) high brightness and production ratio, b) compatible wavelength and bandwidth with atom-based memory buffers or telecom, c) high entanglement fidelity and d) fiber mode compatibility.

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[1] Brookhaven National Laboratory
[2] New Jersey Institute of Technology

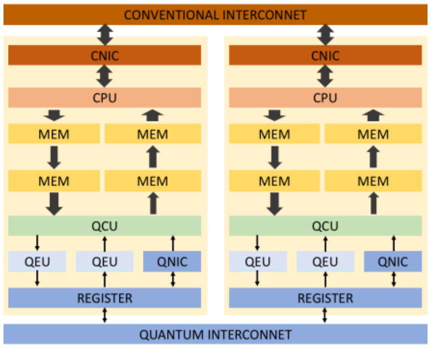
Modeling and Simulation of Quantum High Performance Computing

Travis S. Humble, Quantum Computing Institute, Oak Ridge National Laboratory

We use modeling and simulation to characterize the behavior of quantum high-performance computing (HPC) systems. These calculations estimate the time, energy, complexity, and accuracy of both near-term and future quantum HPC. By modeling integration of novel quantum processing units (QPUs) with conventional computer architectures, we identify technological bottlenecks and recommend scientific advances necessary for the greatest payoffs from quantum computers. Our results indicate that massively, parallel processing architectures will require real-time, programmable quantum networks to achieve optimal performance, while stand-alone, special purpose machines may be judiciously co-designed for specific scientific applications.

Methodology

Modeling and simulation offer forward looking capabilities for assessing the impact of quantum computing on future scientific infrastructure. We develop models for quantum HPC as a hierarchy of computational devices interconnected by memory systems and networks. Our executable models include the data and instructions for quantum operations as well as the system logic for managing noisy and faulty computational resources. We simulate the operation of the conventional and quantum instructions using a combination of discrete-event and continuous-time simulation methods. We test examples that exercise the complete execution model for both near-term and future fault-tolerant QPUs.



Hierarchical model of quantum HPC system configured for quantum interconnected, massively parallel processing.

Key Insights

A notable insight from our results is that the unreliability of current NISQ devices and the irreproducibility of test programs is a growing crisis for the quantum computing community. Ongoing efforts to advance QPU characterization, verification and validation are essential for reliable modeling, while programming and software techniques to robustly mitigate hardware errors have yet to be realized. In addition, the performance of current NISQ QPUs operating in sampling mode is undercut by the bandwidth and latency of the calling process. Multiplexing and pipelining instructions lack natural analogs in the quantum domain and manifest as technological bottleneck for future architectures. Overcoming this bottleneck with traditional, multi-node parallelism is a temporary solution as the best quantum algorithms require coherent quantum memory across QPUs.

Representative Publications

- Quantum supremacy using a programmable superconducting processor, Nature (2019)
- Establishing the Quantum Supremacy Frontier with a 281 Pflop/s Simulation, arxiv (2019)
- Quantum Computing Circuits and Devices, IEEE Design & Test (2019)
- Cryogenic Electronics and Quantum Information Processing, IRDS (2019)
- Simulated Execution of Hybrid Quantum Computing Systems, SPIE (2018)
- High-performance Computing with Quantum Processing Units, ACM JETC (2017)

This work supported by the Department of Energy, Office of Science, Early Career Research Program.

DOE ASCR QAT Project: Heterogeneous Digital-Analog Quantum Dynamics Simulations

ORNL: Pavel Lougovski (Lead); University of Washington: Martin Savage

Enabling simulations of large-scale many-body systems is a long-standing problem in scientific computing. Recent progress in designing digital and analog quantum simulation algorithms hints at the exciting possibility of performing simulations that are beyond the reach of all existing and future classical supercomputers. Despite the tremendous progress, there is still a gap between the resources required by state-of-the-art quantum algorithms and the resources offered by available and near-future quantum hardware.

The main goal of this project is to bridge the gap between quantum algorithms and hardware by developing a novel algorithmic approach to quantum simulations. Our approach combines individual algorithmic strengths of analog and digital quantum simulations and it is heterogeneous across quantum hardware, classical and quantum algorithms. For specific scientific domain applications, we focus on designing hardware-efficient quantum algorithms for simulating the dynamics of nuclear, strongly-correlated electron, and lattice gauge quantum field systems.

To accomplish our objective, we have assembled a multidisciplinary team of computer scientists, applied mathematicians, scientific application domain experts, and quantum computing researchers. As part of this project our team develops and analyzes quantum simulation algorithms for computing: i) the binding energy of light nuclei; ii) spin lattice systems dynamics; iii) lattice gauge quantum field dynamics.

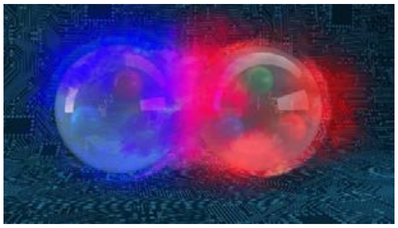


Figure 1. Quantum simulations of the deuteron [Phys. Rev. Lett. **120** 210501 (2018)]

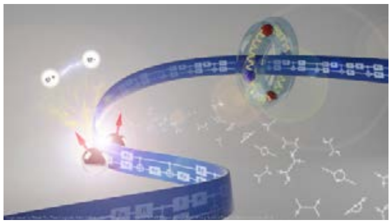


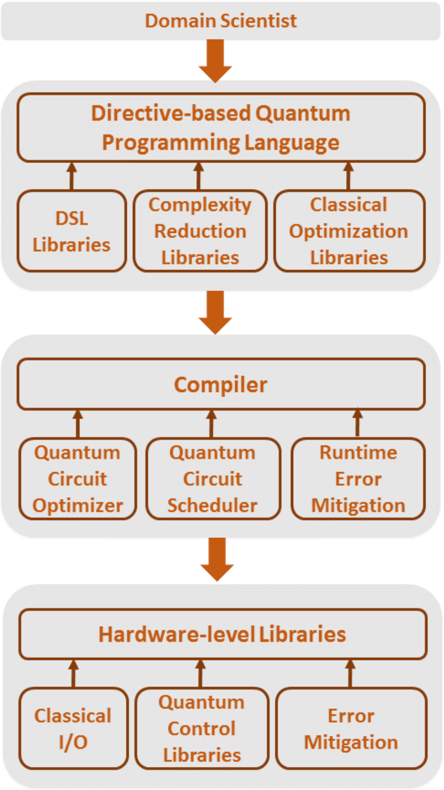
Figure 2. Quantum simulations of the Schwinger model [Phys. Rev. A **98** 032331 (2018)]

Project Publications in 2019

1. Alex Shaw, Natalie Klco, Pavel Lougovski, Jesse Stryker, Nathan Wiebe, “Resource-Adaptable Quantum Algorithms for Scalable Simulation of the Schwinger Mode” preprint (2019)
2. Alessandro Roggero, Andy C. Y. Li, Joseph Carlson, Rajan Gupta, Gabriel N. Perdue, “Quantum Computing for Neutrino-nucleus Scattering”, preprint arXiv:1911.06368 (2019)
3. Eugene F. Dumitrescu, Pavel Lougovski ”Hamiltonian Assignment for Open Quantum Systems” preprint arXiv:1911.11092 (2019)
4. T. Keen, T. Maier, S. Johnston, P. Lougovski “Quantum-classical simulation of two-site dynamical mean-field theory on noisy quantum hardware” preprint arXiv:1910.09512 (2019)
5. Hsuan-Hao Lu, Andrew M Weiner, Pavel Lougovski, Joseph M Lukens “Quantum Information Processing with Frequency-Comb Qudits” IEEE Photonics Technology Letters (2019) doi: 10.1109/LPT.2019.2942136
6. Natalie Klco, Jesse R. Stryker, Martin J. Savage, “SU(2) non-Abelian gauge field theory in one dimension on digital quantum computers” preprint arXiv:1908.06935 (2019)
7. Ana Martin, Lucas Lamata, Enrique Solano, Mikel Sanz, “Digital-analog quantum algorithm for the quantum Fourier transform” preprint arXiv:1906.07635 (2019).
8. Natalie Klco, Martin J. Savage, “Minimally-Entangled State Preparation of Localized Wavefunctions on Quantum Computers” preprint arXiv:1904.10440 (2019)
9. Alessandro Roggero, Alessandro Baroni, “Short-depth circuits for efficient expectation value estimation” arXiv preprint arXiv:1905.08383 (2019)

DOE ASCR QCAT Project: Software Stack and Algorithms for Automating Quantum-Classical Computing

ORNL: Pavel Lougovski (Lead); Georgetown University: James Freericks; UMD: Zohreh Davoudi; USC: Itay Hen; JHU Applied Physics Lab: Gregory Quiroz



For a long time, developing real-world applications for quantum computing (QC) has been a prerogative of a select few quantum information specialists with access to experimental hardware. Cloud QC pioneered by IBM and Rigetti, as well as the ongoing efforts by DOE ASCR to create testbeds, are poised to change this predisposition and bring QC within the reach of domain scientists. However, to create and execute a quantum simulation algorithm, software tools are needed that address multiple aspects of QC : (i) translation of the problem at hand from a domain-specific language (DSL) into the language of qubits and quantum circuits, (ii) optimization of the resulting circuits to meet hardware constraints, (iii) implementation of rudimentary error mitigation strategies at runtime, and (iv) postprocessing of measurement results. As a result, the wide adoption of QC by the research community is complicated by *the problem of translating scientific applications into functional quantum programs that return accurate results when executed on real-world faulty quantum hardware.*

This project addresses this problem by developing an open-source algorithm and software stack that will automate the process of designing, executing, and analyzing the results of quantum algorithms, thus enabling new discovery across many scientific domains. Prompted by limitations on algorithms and models of computation imposed by available and near-term quantum hardware – noisy quantum gates, limited qubit connectivity, and short circuit depth to name a few – we focus the stack on implementing a hybrid quantum-classical model of computation for various types of quantum hardware with particular emphasis on scientific applications in quantum field theory, nuclear physics, condensed matter, and quantum machine learning.

Project Publications in 2019

- Alex Shaw, Natalie Klco, Pavel Lougovski, Jesse Stryker, Nathan Wiebe, “Resource-Adaptable Quantum Algorithms for Scalable Simulation of the Schwinger Mode” preprint (2019)
- Indrakshi Raychowdhury and Jesse R. Stryker,“Loop-String-Hadron Dynamics in SU(2) Lattice Gauge Theory” preprint (2019)
- Eugene F. Dumitrescu, Pavel Lougovski ”Hamiltonian Assignment for Open Quantum Systems” preprint arXiv:1911.11092 (2019)
- T. Keen, T. Maier, S. Johnston, P. Lougovski “Quantum-classical simulation of two-site dynamical mean-field theory on noisy quantum hardware” preprint arXiv:1910.09512 (2019)
- Paraj Titum, Mohammad F. Maghrebi, ”Non-equilibrium criticality in quench dynamics of infinite-range spin models” preprint arXiv:1909.12311
- Tiffany M. Mintz, Alexander J. McCaskey, Eugene F. Dumitrescu, Shirley V. Moore, Sarah Powers, and Pavel Lougovski “QCOR: A Language Extension Specification for the Heterogeneous Quantum-Classical Model of Computation” preprint arXiv:1909.02457 (2019)
- Zohreh Davoudi, Mohammad Hafezi, Christopher Monroe, Guido Pagano, Alireza Seif, Andrew Shaw, “Towards analog quantum simulations of lattice gauge theories with trapped ions” preprint arXiv:1908.03210 (2019)

Scalable Architectures for Hybrid Quantum/Classical Networking

Joseph M. Lukens[1]

This project will develop practical fiber-optic quantum communication networks for connecting devices in quantum information. Advances in quantum communication networks are critical to realize the full potential of the scientific applications of quantum information science, especially those that rely on distributed quantum information processing such as quantum sensing, distributed quantum computing, quantum key distribution, and quantum cloud computing—just to name a few. Such applications face stringent networking requirements because of their unique quantum properties. For example, quantum states cannot be amplified or measured without destroying the information they carry, so that many conventional classical networking approaches cannot be applied in the quantum domain. To realize true quantum communication networks, then, systems for control, routing, and managing quantum information between separated quantum nodes need to be developed. Three foundational challenges facing quantum network development are: (1) the successful coexistence of quantum and classical data on existing telecommunications infrastructure; (2) scalable network nodes that can optically process and route quantum information in real time; and (3) transduction, the ability to convert the quantum information from stationary network nodes into optical photons suited for traversing the network.

In this project, we propose to overcome the above technical challenges by researching, developing, and testing a new generation of photonic quantum communication network technologies (hardware, software, and protocols) that exploit the dual the nature of light (particle and wave) to transmit quantum information over long distances. The ultimate goal is to develop quantum communication systems that leverage existing optical network technologies and that can coexist with classical networks in the same fiber-optic telecommunication infrastructure. We will concentrate on three research goals. First, we will design and experimentally test a complete fiber-optic network supporting coexistent quantum and classical communications. By drawing on both frequency-based quantum information processing and classical all-optical signal processing, the design will push the limits of speed, spectral efficiency, and fidelity. Second, we will address the crucial requirement of scalability by designing novel photonic integrated circuits that can realize required optical processing capabilities on chip. Such circuits should facilitate compact, low-cost quantum network nodes and should also improve raw performance. Third, we will develop devices for controlling, reading out, and converting quantum information from leading quantum technologies.

Upon successful completion, this project will deliver protocols, designs, and physical systems for hybrid quantum and classical networking, attaining hitherto missing functionalities for network processing nodes and flexible interfaces for edge nodes. As new devices come online, whether quantum or classical in nature, these network designs should be able to accommodate their distinct properties in a standard, overarching framework.

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[1] Oak Ridge National Laboratory

Realization of a Quantum Slide Rule for 1+1 Dimensional Quantum Field Theories Using Josephson Superconducting Circuits

Vladimir E. Manucharyan[1]

We explore a new regime of quantum electrodynamics (QED) where a single photon acquires a finite life time due to spontaneous decay into many lower-frequency photons. This phenomenon is a hallmark of ultra-strong coupling between a sufficiently non-linear quantum system (the quantum impurity) and a continuum of gapless 1D bosonic modes. While this situation is impossible in atomic physics, it is ubiquitous in the bosonic description of strongly-correlated 1D electronic systems and, more generally in conformal boundary quantum field theories. We created a superconducting circuit (the quantum slide rule) which synthesizes the dynamics of two key quantum impurity models: the boundary sine-Gordon model and the Kondo model. Physically our system is a long section of a high-impedance transmission line (the bosons) connected to a single small capacitance Josephson junction (the BSG impurity) or to a fluxonium qubit (the Kondo impurity). The many-body correlation functions of these two quantum impurity problems can be extracted from the measured inelastic spectrum of microwave photons, which implements a quantum simulation of a classically difficult computational problem.

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[1] University of Maryland (College Park)

Quantum Scientific Computing Open User Testbed (QSCOUT)

Peter Maunz,[1] Andrew Landahl,[1] Kenneth Brown,[2] Matthew G. Blain,[1] Susan M. Clark,[1] Daniel Lobser,[1]
Richard P. Muller,[1] Melissa C. Revelle,[1] Kenneth M. Rudinger,[1] Christopher G. Yale[1]

The Quantum Scientific Computing Open User Testbed (QSCOUT) is a testbed laboratory whose purpose is to assess the potential of near-term quantum hardware to address scientific computing applications of interest to the U.S. Department of Energy (DOE) and its Advanced Scientific Computing Research (ASCR) program.

QSCOUT is realized as a trapped-ion system to leverage its unique architectural advantages. Trapped-ion systems enable highly connected qubit layouts (up to all-to-all connections), they feature a reconfigurable qubit arrangement that can be adapted to different algorithms, they offer the highest fidelity single- and two-qubit gates, they admit multiple ways to scale to large processors, and there is a path for them to execute coherent operations networked beyond a single processor. All-to-all connectivity can significantly reduce the number of gates required to execute a quantum circuit. The reconfigurability of the system has important consequences for algorithm and software design. These advantages also enable trapped-ion processors to emulate other quantum processors, allowing one to explore the impacts limited qubit connectivity has on other platforms. High fidelity operations enable larger algorithms without the need to employ error correcting codes.

Here, we present the hardware design of the QSCOUT testbed system as well as its expected capabilities and low-level programmability features. At the assembly level, we provide an Extensible Quantum Assembly Language (xQASM) having a predefined library of native gates and open-source pulse sequences that implement them. Because it is extensible, users are free to define new gates in xQASM and corresponding new pulse sequences for them. This will enable users to optimize the QSCOUT testbed for specific algorithmic inquiries and innovate new error suppression paradigms all the way down to the pulse level.

The trapped ion quantum system designed for the QSCOUT testbed is currently being integrated and characterized. We have trapped ytterbium-171 ions in the system, established qubit state preparation and state detection and have achieved qubit coherence times exceeding 8 seconds.

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Integrated Platform for Quantum Photonic Networks

Emilio Nanni,[1] Paul Welander,[1]Amir Safavi-Naeini,[1]Jelena Vuckovic[1], Martin Fejer[1]

Quantum Information Science (QIS) has incredible potential to drive scientific discovery forward, leading to new capabilities and scientific tools to transform our understanding of nature and advance U.S. energy, economic, and national security interests. Delivering this potential requires achieving the goals and challenges set forth in the National Strategic Overview for QIS. In particular, networks that transport quantum information will play a key role interfacing quantum computers, devices and sensors. Our program seeks to create the platform needed for the nodes of this network. These nodes will serve as the gateway between a diverse array of rapidly evolving quantum subsystems and optical networks that move photons with different temporal and spectral properties over long distances. The essential requirements for these systems are ultra-low loss, efficient and tailorable quantum frequency conversion, and the capability to interface with qubits and memories. We set out to realize the networking hardware needed for ultra-low-loss and high-bandwidth connections between quantum systems, interfacing with telecom photonic networks and emitters, while being sufficiently versatile and extensible to operate with the multitude of different encodings and frequencies essential to QIS.

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[1] SLAC

Fundamental Algorithmic Research for Quantum Computing (FAR-QC)

Ojas Parekh (Director)[1], Pavel Lougovski (Deputy Director)[2], Wibe de Jong[3], Rolando Somma[4], Jeff Larson[5], Andrew Childs[6], John Preskill[7], James Whitfield[8], Itay Hen[9]

Quantum computing is unique among Beyond Moore's Law computing contenders in that it leverages quantum mechanics to offer potentially exponential resource advantages over technologies relying only on classical physics. A few beacons, such as Shor's famous quantum algorithm for integer factorization, suggest applications where quantum computing may offer a tremendous advantage. However, the scope of such applications is currently limited, and in many cases achieving a quantum advantage requires restrictive assumptions. We will build on our previous and ongoing work as part of the ASCR QAT/QCAT programs to: (i) develop novel quantum, classical, and hybrid quantum-classical algorithms to advance basic capabilities in quantum simulation, optimization, and machine learning, and (ii) provide rigorous resource scaling estimates for fundamental quantum algorithmic primitives.

Anticipation of the noisy intermediate-scale quantum (NISQ) era has sparked unprecedented interest in quantum computing. Executing quantum algorithms on NISQ hardware is essential to fulfilling the promise of quantum computing. Yet, there is no guarantee that encouraging results gleaned from empirical assessments of NISQ devices imply sustained performance advantages over classical computing as quantum processing matures and scales. Rigorous asymptotic analysis of quantum algorithms presents a means of mitigating this risk. Our effort will deliver quantum algorithms that offer provable asymptotic advantages over the best-known or best-possible classical counterparts. Our high-level algorithms will serve as a template for implementations on emerging and future quantum architectures. We will engage in complementary coordination with other ARQC teams that are focused on more practical aspects of quantum algorithm implementation, to adapt and optimize our high-level algorithms for NISQ devices.

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[1] Sandia National Laboratories
[2] Oak Ridge National Laboratory
[3] Lawrence Berkeley National Laboratory
[4] Los Alamos National Laboratory
[5] Argonne National Laboratory
[6] University of Maryland
[7] California Institute of Technology
[8] Dartmouth College
[9] University of Southern California

Quantum Transduction and Buffering Between Microwave Quantum Information Systems and Flying Optical Photons in Fibers

Matt Eichenfield[1]

Quantum systems have the potential to revolutionize computing by implementing quantum algorithms that solve problems much faster than corresponding classical algorithms, even if running on future supercomputers. However, many of the most promising candidate systems for quantum bits, also known as "qubits," utilize electromagnetic fields at microwave frequencies for quantum information processing. These fields cannot easily be distributed over conventional wiring without incurring significant loss that degrades the quantum entanglement necessary to encode the quantum information. Moreover, there is currently no quantum memory technology available for buffering the quantum information produced by these systems that would allow them to communicate effectively over a large network. To enable efficient transmission and buffering, the Nanoscale Optical and Acoustic Physics Group at Sandia National Labs will develop new piezoelectric nano-optomechanical systems, which are designed to tightly couple single quanta of the electromagnetic field (photons) and mechanical vibrations (phonons). The initial microwave photon qubits will be converted to optical photon qubits at frequencies used in conventional telecommunications networks with an intermediate quantum buffer based on confined phononic qubits. This system will allow two-way buffered quantum communication between microwave qubits over existing optical networks. Sandia will demonstrate 1) two-way buffered quantum communication over optical fiber using microwave qubits operating at different microwave frequencies and 2) strong coupling between discrete-variable microwave qubits and continuous-variable oscillators intrinsic to the system to create novel hybrid continuous-variable/discreet-variable quantum states. This project supports the goals of the National Quantum Initiative Act by enhancing the ability to scale some of the most promising quantum information processing technologies; it also supports the specific goal of the DOE Office of Science's Advanced Scientific Computing Research Program to develop a transparent optical quantum network for enabling quantum science applications and, eventually, a quantum internet.

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[1] Sandia National Laboratories

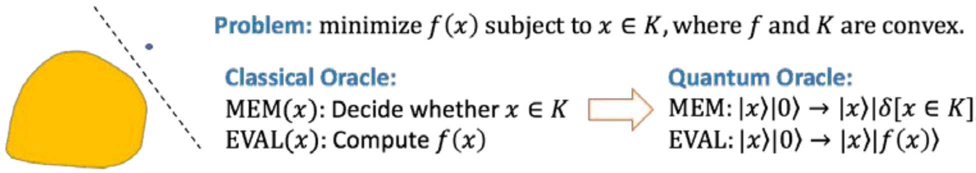
QOALAS

Quantum Optimization and Learning and Simulation

SNL: Ojas Parekh (Lead); LANL: Rolando Somma; CalTech: John Preskill;
UMD: Andrew Childs

The QOALAS Quantum Algorithms Team explores the impact of quantum computing in three interrelated areas underpinning the DOE mission: quantum simulation, optimization, and machine learning. Our work leverages connections among these areas to fuel new applications of quantum information processing to science and technology. We are an interdisciplinary team of theoretical physicists and theoretical computer scientists from Caltech, Los Alamos Lab, Microsoft Research, NIST, Sandia National Labs, and the University of Maryland.

Quantum Simulation. Quantum computers offer a natural approach to efficiently simulating the dynamics of quantum systems, a fundamental physical problem intractable for classical computers. We have produced stronger bounds on the performance of quantum simulations as well as new quantum approaches for eigenvalue estimation and time-dependent Hamiltonian simulation. We have introduced the Quantum Singular Value Transformation, a new framework unifying many previous quantum simulation and machine learning algorithms.



Problem: minimize $f(x)$ subject to $x \in K$, where f and K are convex.

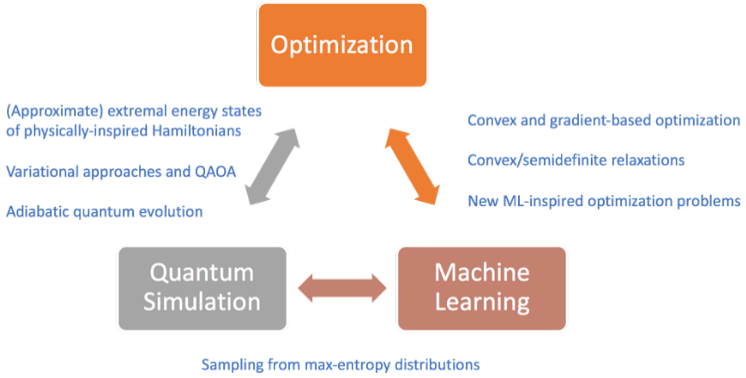
Classical Oracle:
MEM(x): Decide whether $x \in K$
EVAL(x): Compute $f(x)$

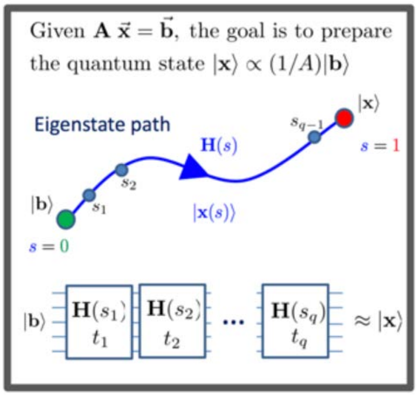
Quantum Oracle:
MEM: $|x\rangle|0\rangle \rightarrow |x\rangle|\delta[x \in K]\rangle$
EVAL: $|x\rangle|0\rangle \rightarrow |x\rangle|f(x)\rangle$

New quantum algorithm for convex optimization using $\tilde{O}(n)$ oracle queries vs $\tilde{O}(n^2)$ classically [arXiv:1809.01731]

Optimization. We seek to understand how quantum resources may be used to reap gains in speed or solution quality over current classical approaches. We have developed new quantum techniques for rigorously approximating ground states of physically motivated quantum Hamiltonians. Our work connects widely used techniques in discrete optimization to central topics in condensed matter physics. We have also recently developed some of the first quantum algorithms for convex optimization and volume estimation (e.g., see figure above).

Machine learning. Linear algebraic kernels are a fundamental ingredient in machine learning and serve as a building block for advanced quantum machine learning algorithms. We have designed a new quantum algorithm for solving linear systems, inspired by adiabatic quantum computing, that is much simpler than previous approaches with comparable performance (see figure below).





Given $\mathbf{A}\,\vec{\mathbf{x}} = \vec{\mathbf{b}}$, the goal is to prepare the quantum state $|\mathbf{x}\rangle \propto (1/A)|\mathbf{b}\rangle$

A simpler quantum linear system solver [arXiv:1805.10549]

Towards Hybrid Continuous/Discrete Variable All-Optical Quantum Repeaters for Quantum-Classical Coexistence in Optical Fiber Networks

Nicholas A. Peters,[1] Saikat Guha,[2] Linran Fan,[2] Paul Toliver[3]

This project will determine architectural foundations for future transparent, all-optical networks with quantum repeater backbones. The network will contain coexisting quantum and classical optical traffic and hybrid continuous variable (CV) and discrete variable (DV) components to maximize quantum information throughput and efficiency. To facilitate this quantum-classical coexistence network, our approach seeks to develop the concepts and building blocks for hybrid CV/DV encoded all-optical one-way quantum repeater networks. The key networking building blocks that this project will provide are CV and DV quantum light sources compatible with telecom fiber networks (including both squeezed light and discrete entangled photons), a control plane harness that supports development and testing of coexistence between quantum and classical network components, proof-of-principle hybrid network protocols, including hybrid teleportation, and a blueprint for a hybrid quantum repeater backbone. As it is all optical, this approach in principle requires no quantum memory. During the first 2 years, a transparent optical quantum network emulator will also be developed to test control plane and hybrid protocol designs. The control plane harness will be compatible with and can be deployed in other US Department of Energy (DOE) quantum networks starting in year 3 of the project. The end result will be a proof-of-principle hybrid CV/DV network that coexists with classical traffic and a clear path forward to the future with quantum repeater-based, hybrid coexistence networks. This project will play a vital role in enabling the next generation of DOE networks by augmenting the conventional parts with communications capabilities between quantum information devices, from quantum sensors to networked quantum computers

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[1] Oak Ridge National Laboratory
[2] University of Arizona
[3] Perspecta Labs

Methods and Interfaces for Quantum Acceleration of Scientific Applications (MIQASA)

Raphael Pooser,[1] Sophia Economou,[2] Ken Brown[3]

The MIQASA project explores the design and development of quantum computing for scientific applications in chemistry, nuclear physics, quantum field theory, and machine learning. The project has several major goals: 1) To determine the feasibility of running scientific applications of interest to DOE on near-term quantum computer (QC) hardware. 2) To foster industry relationships and benchmark multiple QCs for DOE applications. This goal requires suitable metrics that can accurately communicate the potential utility of these machines. Providing benchmarks and metrics also helps hardware developers target future performance for scientific applications, thus seeding the codesign loop. 3) To foster academic partnerships and engage in educational outreach. We achieve this goal by partnering with universities on this project, by speaking in public forums at universities, and by maintaining a set of resources for the community, such as specification sheets developed by our partners at Duke that help researchers understand the metrics we derive under this project.

We benchmark QCs that are available today and gather metrics into an easy to understand format. Benchmarks consist of assessing quantum gate performance, larger collections of gates that represent computational primitives, and the applications themselves, which are suitable benchmarks in this early, pre-fault tolerant era of QC. In order to run these benchmarks and applications, we also study how to efficiently program quantum computers. We automate tasks such as error mitigation, qubit tapering, variational optimization, and qubit selection and placement. Examples of benchmarks from each of the above categories are:

- Gate constructions, including the design of waveforms. We simulate RF pulse controls for transmon qubits using Virginia Tech's simulator to produce faster two-qubit gates, and subsequently test these on real hardware. Our project is integrating these gate constructions into higher level algorithms on hardware using OpenPulse in partnership with IBM.
- Algorithmic Primitives: We use machine learning to train quantum registers to prepare specific wavefunctions and encode information in probability amplitudes. Our machine learning benchmarks test a machine's capability to perform basic primitive operations in hybrid algorithms. We also produce benchmarks which test the computational power of random gate constructions, which provides a supremacy benchmark.
- Applications: We test multiple scientific applications in order to determine the suitability for QCs to run them now or in the future, and to determine what, if any, quantum advantage is to be had. In some cases the advantage may come from accuracy rather than execution speed. Examples include nuclear bound states, field theories, and a chemistry benchmarking suite.

When taken in aggregate, these benchmark categories paint a holistic picture of a QC's performance potential. When benchmarks represent scalable algorithm implementations, and gate benchmarks indicate low noise, high performance is a leading indicator of quantum advantage in the future. Our benchmarks indicate key performance metrics for next generation devices to improve in order to reach scalable implementations. The end result is a determination of the feasibility to run scientific applications on current and near-future hardware in the NISQ era and beyond.

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[1] Oak Ridge National Laboratory

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Optimization, Verification, and Engineered Reliability of Quantum Computers (OVER-QC)

Mohan Sarovar,[1] James Whitfield,[2] Patrick Coles,[3] Deepak Kapur[4]

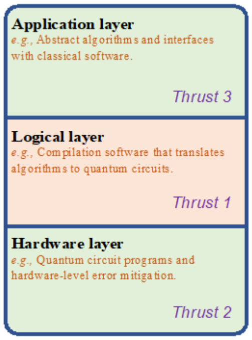
Quantum technologies, especially quantum computers, show great promise for revolutionizing high-performance computing and simulation. As prototype quantum computers come online, it is becoming clear that obtaining useful output from such devices will require layers of sophisticated classical software that provide interpretation and analysis of the quantum computer's state and output. We will develop critical components in this “software stack” with a particular focus on enabling near-term Noisy Intermediate-Scale Quantum (NISQ) technologies. We have identified three critical needs for near-term quantum computing platforms, and the project is structured around three thrusts that address these needs:

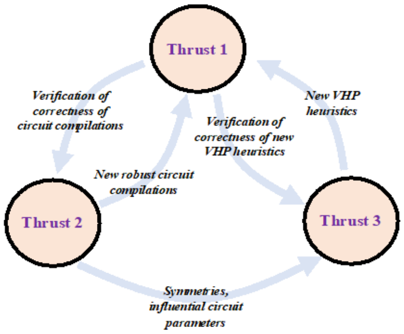
Thrust 1: develop capabilities to verify and certify translations of abstract quantum algorithms to quantum circuit programs;

Thrust 2: develop tools to identify the reliable information that can extracted from near-term devices in the absence of fault-tolerant operation;

Thrust 3: develop interfaces for variational hybrid quantum-classical processors (VHPs) that enable applications by connecting classical algorithms to quantum co-processors.

The following figure illustrates how these thrusts fit into the conventional picture of a quantum computing software stack, and how the outcomes of each thrust inform the other ones.





A key aspect of the proposed research is that we will not only develop software tools targeted for use with near-term quantum computers, but we will also invest significant effort into understanding the reliability and computational power of near-term devices. In particular, we will address two key questions, (1) is it possible to engineer the dynamics of NISQ devices so that they have robust algorithmic properties in the presence relevant error models, and (2) what is the real computational advantage posed by algorithms running on NISQ devices, and specifically, what level/type of noise permits some computational advantage over classical algorithms and heuristics for the same tasks. Answering these questions will not only guide the development of quantum algorithms tailored to near-term quantum devices, but it will also reveal the fundamental computational potential of non-fault-tolerant quantum devices.

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[1] Sandia National Laboratories

[2] Dartmouth College

[3] Los Alamos National Laboratory

[4] University of New Mexico

The Advanced Quantum Testbed

Irfan Siddiqi,[1] Jonathan Carter,[1] William Oliver[2]

We propose the establishment of a collaborative research facility for the advancement of quantum computation based on superconducting circuits. This facility will develop and implement quantum algorithms co-designed for noisy, intermediate-scale quantum hardware with a focus on computational problems relevant to the scientific computing mission of the DOE, including applications in optimization, materials science, and cosmology. Our technology strategy maintains the state-of-the-art by drawing from multiple hardware and software resources and by transitioning specific advances in basic quantum information science research programs (and fledgling industry) to the testbed, where quantum algorithms can then be executed and refined. We aim to move quantum algorithms beyond single, academic, proof-of concept demonstrations to a broad range of informative and impactful calculations. Testbed users will have full access to the hardware (including detailed data concerning architecture, operation, limitations, and imperfections), participate in its evolution, and share results to maximize the utility of nascent quantum hardware. An on-site catalyst team, experts in quantum hardware and software, will advance the basic science mission of the testbed and interact with a broad community of users to help them make effective use of our resources.

Over the past year, the Advanced Quantum Testbed (AQT), took its first steps toward becoming a unique facility for quantum computation, bridging a key gap between highly exploratory academic research efforts and highly specialized instances of commercially available cloud-based and physical resources. We deployed a dilution refrigerator capable of housing and controlling up to 128 qubits. We made significant advances in microwave hygiene of qubit chips via careful modeling of the electromagnetics of the chip. We started to develop 3D integration of qubit control and readout for scalability. We made significant progress in developing a full qubit control stack from microwave pulse generation to firmware to an instruction-set architecture. We have started to develop a tunable coupler for fast, high-fidelity, two-qubit gates and made significant progress in materials processing for high-coherence quantum processors. On the experimental front, we demonstrated genuine scrambling between two qutrits (three-level systems) in a transmon-based digital quantum processor. In addition, we demonstrated average recovery fidelity of 54 percent, well above the expected classical fidelity of 33 percent, thus demonstrating clear quantum advantage.

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[2] Massachusetts Institute of Technology, Lincoln Laboratory

Illinois-Express Quantum Networks

Panagiotis Spentzouris,[1] Greg Kanter,[2] Joaquin Chung,[3] Nikolai Lauk[4]

Quantum technologies, based on quantum superposition, quantum entanglement and fundamental quantum metrology, create new opportunities in powerful computation, unparalleled precision sensing capabilities, and distributed secure communications. In alignment with the U.S. National Quantum Initiative goals on quantum communication technologies, the Illinois-Express Quantum Network (IEQNET), led by Fermi National Accelerator Laboratory, will develop and demonstrate operation of transparent optical quantum networks designs in the greater Chicago metropolitan area.

IEQNET brings together academic researchers from Northwestern University and Caltech, small businesses (NuCrypt, HyperLight), and the INQNET AT&T/Caltech consortium. The INQNET consortium is linked to the National Institute of Standards and Technology Quantum Economic Development Consortium (QED-C), led by SRI International.

The proposed quantum network architecture includes existing Fermilab Quantum Network (FQNET) nodes and proposed university campus nodes at Northwestern, both in Evanston and at the medical school campus in downtown Chicago. The project will benefit from existing research and development collaborations with quantum networking experts at the University of Calgary and will leverage existing conventional network infrastructure (Starlight) and experience from ESnet, the Energy Sciences high-speed computer network serving DOE scientists and their collaborators worldwide, managed by Lawrence Berkeley National Laboratory.

The IEQNET quantum network will be designed to coexist with classical networks in the same optical fiber transmission system.

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[1] Fermi National Accelerator Laboratory
[2] Northwestern University
[3] Argonne National Laboratory
[4] California Institute of Technology