
# Abstract Booklet

## Quantum Computing User Forum

## July 18-19, 2023

*Hosted by the Oak Ridge Leadership Computing Facility at Oak Ridge National Laboratory*

OAK RIDGE National Laboratory

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# 2023 Quantum Computing User Forum

The Quantum Computing User Forum brings together users to discuss common practices in the development of applications, software, and simulations for quantum computing devices and systems. The forum is hosted by the Quantum Computing Institute and the Oak Ridge Leadership Computing Facility at Oak Ridge National Laboratory. The forum highlights the results from a broad variety of projects supported by the Quantum Computing User Program which enables more than 400 users to access state-of-the-art quantum computing systems. This program is supported by the US Department of Energy, Office of Science, Advanced Scientific Computing Research program office.

This booklet contains abstracts for the forum's keynote talks, invited talks, and poster sessions to be presented July 18-19. For more information about this event please visit https://www.olcf.ornl.gov/calendar/quantum-computing-user-forum-2023/

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## *1. KEYNOTE TALKS*

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| **Kim, Jungsang** | IonQ |

### PRACTICAL USE CASES FOR QUANTUM COMPUTERS

Recent progress in constructing high performance quantum computers capable of executing deep quantum circuits have stimulated the exploration of various quantum application use cases. Quantum computer systems with high levels of connectivity among the qubits and high-fidelity gate operations allow implementation of a wide range of quantum algorithms to be executed on real hardware. Using the high-performance quantum computers available at IonQ such as IonQ Aria and IonQ Forte, we have developed, executed and tested various quantum algorithms for real-world use cases, and validated the benefits of quantum approach in many of them. I will outline the architectural designs of IonQ quantum computers that make it attractive for executing quantum algorithms, discuss how we characterize the performance, and share examples of real-world problems we tackled using these systems.

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| **McCaskey, Alex** | NVIDIA |

### DEFINING THE QUANTUM-ACCELERATED SUPERCOMPUTER

Supercomputing architectures based on GPU acceleration have greatly improved our scientific computing workflows and applications over the past decade. Quantum computing has recently been proposed as a potential addition to this heterogeneous compute architecture, serving as another node-level accelerator to continue problem scalability in domains such as quantum many-body physics and artificial intelligence. As stand-alone quantum processing units (QPUs) continue to evolve and improve, the applied computational science community is left to wonder - how do we build, program, and deploy large-scale quantum-classical heterogeneous architectures that incorporate both GPUs and QPUs? In this talk, we will demonstrate how NVIDIA is leveraging its current suite of multi-GPU platforms to define and deploy the NVIDIA quantum platform. We will highlight three components specifically that together constitute this quantum platform: (1) the cuQuantum multi-GPU quantum computer simulation libraries, (2) the CUDA Quantum programming model and compilation platform, and (3) the DGX Quantum tightly-coupled quantum-classical compute node. This talk will present the NVIDIA vision for quantum computing and how it fits into existing heterogeneous computing, how we are accelerating quantum algorithms research and development today with NVIDIA GPU platforms, and our vision for GPU-accelerated error correction and fault-tolerance.

| Sheldon, Sarah | IBM |
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**WHAT CAN YOU DO WITH A NOISY QUANTUM COMPUTER**

The proven speedups of canonical quantum algorithms like factoring and phase estimation over their classical counterparts has motivated work towards realizing quantum computers. To achieve these speedups we need fault tolerance, which is beyond the capabilities of today's quantum hardware. At the same time state-of-the-art noisy quantum systems are approaching a scale and quality that is hard to simulate classically. This begs the question: is there anything we can do before fault tolerance? This talk will describe a path to studying interesting problems on near-term quantum devices through error suppression and error mitigation techniques, including recent results demonstrating high quality measurements on a 127-qubit IBM Quantum system using these noise reduction techniques.

| Stutz, Russell | Quantinuum |
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**RECENT PROGRESS ON H-SERIES HARDWARE**

Quantum computers are just beginning to reach performance levels that allow users to run select programs that are difficult, or even impossible, to replicate on classical computers. The challenge will be finding useful problems that these new machines can solve that are beyond the reach of classical computers. This effort will take a collaboration between hardware providers, middleware experts, and quantum algorithm designers to continue improving the performance of the machines, squeezing the most performance out of every available qubit, and reducing the resource requirements for algorithms of interest. The Oak Ridge National Laboratory Quantum Computing User Program allows for these groups to collaborate and push to solve these grand challenges in quantum computing. Here we will discuss the latest Quantinuum quantum computer, the system model H2, detailing its current performance, upgrade plans, and distinguishing features to help the user community better understand how to maximize the usefulness of these machines.

## *2. INVITED TALKS*

| **Balewski, Jan** | Lawrence Berkeley National Laboratory |
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### QUANTUM-PARALLEL VECTORIZED DATA ENCODINGS AND COMPUTATIONS ON TRAPPED-IONS AND TRANSMONS QPUS

Compact data representations in quantum systems are crucial for the development of quantum algorithms for data analysis. In this study, we present two innovative data encoding techniques, known as QCrank and QBArt, which exhibit significant quantum parallelism via uniformly controlled rotation gates. The QCrank method encodes a series of real-valued data as rotations of data qubits, resulting in increased storage capacity. On the other hand, QBArt directly incorporates a binary representation of the data within the computational basis, requiring fewer quantum measurements and enabling well-established arithmetic operations on binary data. We showcase various applications of the proposed encoding methods for various datatypes. Notably, we demonstrate quantum algorithms for tasks such as DNA pattern matching, Hamming weight computation, complex value conjugation, and the retrieval of an O(400) bits image, all executed on the Quantinuum trapped-ion QPU. Furthermore, we employ several cloud-accessible QPUs, including those from IBMQ and IonQ, to conduct supplementary benchmarking experiments.

| **Chen, Senrui** | University of Chicago |
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### THE LEARNABILITY OF PAULI NOISE

Understanding quantum noise is a major challenge for scaling up quantum computing systems. Despite recent developments in quantum noise characterization methods, the fundamental question of what information about gate noise is self-consistently learnable has been unclear even for a single CNOT gate. In this work, we give a precise characterization about the learnability of Pauli noise associated with Clifford gates using graph theoretical tools, showing that the learnable information corresponds exactly to the cycle space of the pattern transfer graph of a given gate set. We show that a modified version of cycle benchmarking can extract all learnable information of Pauli noise. We experimentally demonstrate Pauli noise characterization of IBM's CNOT gate, where we learn all 14 learnable degrees of freedom and bound the 2 unlearnable degrees of freedom using physical constraints. The implications of these results for quantum error mitigation and potential approaches to overcome the issues will be discussed.

| Chertkov, Eli | Quantinuum |
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**CHARACTERIZING A NON-EQUILIBRIUM PHASE TRANSITION ON A QUANTUM COMPUTER**

Quantum many-body systems can exhibit rich universal behavior at the transition between phases of matter, even for systems far from equilibrium. Probing the dynamics of a quantum system undergoing a non-equilibrium phase transition is a difficult task for a classical computer and one that could be done potentially faster on a quantum computer. In this talk, we present our recent work [1] where we use the Quantinuum H1-1 quantum computer to realize a non-equilibrium phase transition in a dissipative quantum circuit generalization of a classical disease spreading model that is known to possess an absorbing state transition. We use techniques such as qubit-reuse [2] and "error avoidance" based on real-time conditional logic to realize a large-scale quantum simulation (of systems with 73 sites time evolved up to 72 circuit layers) with quantitatively accurate signatures of the critical scaling at the phase transition.

| Claudino, Daniel | Oak Ridge National Laboratory |
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**MODELING SINGLET FISSION ON A QUANTUM COMPUTER**

We demonstrate a practical application of quantum computing by using it to investigate the linear H4 molecule as a simple model for singlet fission. We employ the Peeters-Devreese-Soldatov energy functional to calculate the necessary energetics based on the moments of the Hamiltonian estimated on the quantum computer. To reduce the number of required measurements, we use several independent strategies: 1) reduction of the size of the relevant Hilbert space by tapering off qubits; 2) measurement optimization via rotations to eigenbases shared by groups of qubit-wise commuting Pauli strings; 3) parallel execution of multiple state preparation and measurement operations using all 20 qubits available on the Quantinuum H1-1 quantum hardware. Our results meet the energetic requirements for singlet fission, are in excellent agreement with exact transition energies (for the chosen one-particle basis), and outperform classical methods considered computationally feasible for singlet fission candidates.

| Dasgupta, Samudra | University of Tennessee |
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**ASSESSING RELIABILITY OF NOISY QUANTUM COMPUTING DEVICES**

NISQ (Noisy Intermediate-Scale Quantum) devices, although valuable for testing quantum computing principles, suffer from errors due to factors like decoherence, leakage, and cross-talk. This raises concerns about the reliability and reproducibility of quantum computer outputs. Current NISQ devices are inherently unreliable, and the use of imprecise error-mitigation techniques could worsen reproducibility issues. To assess the reliability of quantum devices, we

examine the similarity of noise processes affecting gate fidelities, duty cycles, and register addressability across different time and space scales. Our analysis of a 127-qubit transmon device reveals inconsistencies in distribution metrics characterizing present-day NISQ device reliability. We also establish an upper bound for observable discrepancy caused by time-varying noise statistics, which can help enhance physical layers for specific applications. Our experimentation shows that the noise statistics of the transmon platform fluctuate over time, with a minimum Hellinger measure of 41% over 18 months, significantly surpassing the required threshold of 2.2%. These findings demonstrate that current NISQ devices lack the ability to consistently reproduce a statistical mean, rendering them unreliable for practical quantum computing. The study emphasizes the importance of reliability as a fundamental feature for evaluating and advancing NISQ devices, urging efforts to address fluctuations and improve stability for more trustworthy results in the field of quantum computing.



| **Dupont, Maxime** | Rigetti |
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**QUANTUM SEASONING OF CLASSICAL COMBINATORIAL OPTIMIZATION SOLVERS**

Classical approaches for solving combinatorial optimization problems are tough competitors for quantum algorithms. In particular, noise in quantum computers remains a challenge in achieving high performance, and developing more sophisticated quantum algorithms is desired.

I will discuss recent works introducing hybrid classical-quantum algorithms for combinatorial optimization providing the performance baseline of classical solvers.



| **Gibbs, Joe** | University of Surrey |
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**LONG-TIME SIMULATIONS FOR FIXED INPUT STATES ON QUANTUM HARDWARE**

Publicly accessible quantum computers open the exciting possibility of experimental dynamical quantum simulations. While rapidly improving, current devices have short coherence times, restricting the viable circuit depth. Despite these limitations, we demonstrate long-time, high-fidelity simulations on current hardware. Specifically, we simulate an XY-model spin chain on Rigetti and IBM quantum computers, maintaining a fidelity over 0.9 for 150 times longer than is possible using the iterated Trotter method. Our simulations use an algorithm we call fixed state Variational Fast Forwarding (fsVFF). Recent work has shown an approximate diagonalization of a short time evolution unitary allows a fixed-depth simulation. fsVFF substantially reduces the required resources by only diagonalizing the energy subspace spanned by the initial state, rather than over the total Hilbert space. We further demonstrate the viability of fsVFF through large numerical simulations and provide an analysis of the noise resilience and scaling of simulation errors.

| Govoni, Marco | Argonne National Laboratory |
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**QUANTUM EMBEDDING THEORIES TO SIMULATE CONDENSED SYSTEMS ON QUANTUM COMPUTERS**

Quantum computers hold promise to improve the efficiency of quantum simulations of materials and to enable the investigation of systems and properties that are more complex than tractable at present on classical architectures. We discuss computational frameworks to carry out electronic structure calculations in solids on noisy intermediate-scale quantum computers using embedding theories. We focus on simulations of point defects in diamond and silicon carbide, which are of interest for the realization of quantum technologies. These examples benefit from the use of the latest developments in high-performance computing architectures, which include pre-exascale capable machines and quantum processors. We discuss the impact of quantum error on the calculation of ground and excited state energies of spin-defects using the variational quantum eigensolver and the quantum subspace expansion method, respectively. We combine a qubit-efficient encoding scheme mapping Slater determinants onto qubits with a modified qubit-coupled cluster ansatz and noise-mitigation techniques. Such strategy leads to a substantial improvement in the scaling of circuit gate counts and in the number of required qubits, and to a decrease in the number of required variational parameters, thus increasing the resilience to noise. Although quantum simulations on quantum architectures are in their infancy, promising results for realistic systems appear to be within reach.

| Hamilton, Kathleen | Oak Ridge National Laboratory |
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**ENTANGLEMENT AS A BENCHMARK FOR NEAR-TERM QUANTUM HARDWARE**

Entanglement is a fascinating property of quantum systems. Generating and controlling these correlations is important for implementing quantum computing tasks. This talk will present results from a volumetric benchmark for near-term quantum platforms based on the generation and verification of genuine entanglement across n-qubits using graph states and direct stabilizer measurements. This benchmark evaluates the robustness of multipartite and bipartite n-qubit entanglement with respect to many sources of hardware noise: qubit decoherence, CNOT and swap gate noise, and readout error. We demonstrate our benchmark on multiple superconducting qubit platforms available from IBM (ibmq_belem, ibmq_toronto, ibmq_guadalupe and ibmq_jakarta) using subsets of $n < 10$ qubits for graph state preparation and stabilizer measurement.

| Illa Subina, Marc | University of Washington |
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**STUDYING DENSE NEUTRINO SYSTEMS WITH QUANTUM COMPUTERS**

In extreme astrophysical environments, such as those found in core-collapse supernovae, neutrino densities are sufficiently high to induce self-interactions between neutrinos. These effects are extremely non-local, and classical methods, such as mean-field models, cannot capture the quantum correlations. While current quantum computers are limited by the number of qubits available, their coherence and gate errors, interesting new properties of these systems are being discovered. In this talk I will discuss how we used Quantinuum trapped ion systems to learn about their multi-body entanglement, as well as IBM superconducting machines to study the effects of collisions.

| Kemper, Alexander | North Carolina State University |
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**A LINEAR RESPONSE FRAMEWORK FOR SIMULATING BOSONIC AND FERMIONIC CORRELATION FUNCTIONS ILLUSTRATED ON QUANTUM COMPUTERS**

Response functions are a fundamental aspect of physics; they represent the link between experimental observations and the underlying quantum many-body state. However, this link is often under-appreciated, as the Lehmann formalism for obtaining response functions in linear response has no direct link to experiment. Within the context of quantum computing, and by using a linear response framework, we restore this link by making the experiment an inextricable part of the quantum simulation. This method can be frequency- and momentum-selective, avoids limitations on operators that can be directly measured, and is ancilla-free. As prototypical examples of response functions, we demonstrate that both bosonic and fermionic Green's functions can be obtained, and apply these ideas to the study of a charge-density-wave material on ibm_auckland. The linear response method provides a robust framework for using quantum computers to study systems in physics and chemistry. It also provides new paradigms for computing response functions on classical computers.

| Klymko, Katie | Lawrence Berkeley National Laboratory |
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**REAL-TIME SUBSPACE METHODS FOR HAMILTONIAN EIGENVALUE ESTIMATION ON QUANTUM HARDWARE**

One of the most promising expected applications of near-term quantum computers lies in the study of static and dynamical properties of quantum many-body systems. Many quantum computing algorithms have been proposed with this goal in mind, with a focus on Hamiltonian eigenvalue extraction, a problem central to chemistry, physics, and materials science. However, the majority of established quantum algorithms require a prohibitively large number of resources

for near-term hardware. Here we show that quantum algorithms relying on real-time evolution for energy eigenvalue determination, which we refer to as variational quantum phase estimation (VQPE), represent an optimal solution for this challenge. Real-time evolution is native to quantum hardware, making these algorithms particularly suited for the near term. Additionally, using a novel transformation we prove that we can drastically reduce the number of measurements needed from quadratic to linear, marking this a significant improvement over previous quantum algorithms based on time evolution. We show that remarkably few time evolution steps, computed on quantum hardware, are needed to converge both ground and excited state energies to experimentally meaningful accuracies. We demonstrate the power of this approach classically on a paradigmatic example of strong correlation, the Cr2 dimer, as well as on quantum hardware for the transverse field Ising model.



| **Li, Ang** | Pacific Northwest National Laboratory |
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**QASMBENCH: A LOW-LEVEL QASM BENCHMARK SUITE FOR NISQ EVALUATION AND SIMULATION**

The rapid development of quantum computing (QC) in the NISQ era urgently demands a low-level benchmark suite and insightful evaluation metrics for characterizing the properties of prototype NISQ devices, the efficiency of QC programming compilers, schedulers and assemblers, and the capability of quantum system simulators in a classical computer. In this NQISRC C2QA supported effort, we fill the gap by proposing a low-level, easy-to-use benchmark suite called QASMBench based on IBM's OpenQASM intermediate representation. It consolidates commonly used quantum routines and kernels from a variety of domains including chemistry, simulation, linear algebra, searching, optimization, arithmetic, machine learning, fault tolerance, cryptography, and so on, trading-off between generality and usability. To analyze these kernels in terms of NISQ device execution, in addition to circuit width and depth, we propose four circuit metrics including gate density, retention lifespan, measurement density, and entanglement variance, to extract more insights about the execution efficiency, the susceptibility to NISQ error, and the potential gain from machine-specific optimizations. For evaluation, we measure the execution fidelity of a subset of QASMBench applications on 12 IBM-Q machines through density matrix state tomography, comprising 25K circuit evaluations. We also compare the fidelity of executions among the IBM-Q machines, the IonQ QPU and the Rigetti Aspen M-1 system, supported by OLCF QCUP. QASMBench is released at: http://github.com/pnnl/QASMBench.



| **Pelofske, Elijah** | Los Alamos National Laboratory |
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**OPTIMIZED TELECLONING CIRCUITS: THEORY AND PRACTICE OF NINE NISQ CLONES**

Although perfect copying of an unknown quantum state is not possible, approximate cloning is possible in quantum mechanics. Quantum telecloning is a variant of approximate quantum cloning which uses quantum teleportation to allow for the use of classical communication to

create physically separate clones of a quantum state. We present results of a of $1 \rightarrow 9$ universal, symmetric, optimal quantum telecloning implementation on a cloud accessible quantum computer - the Quantinuum H1-1 device. The H1-1 device allows direct creation of the telecloning protocol due to real time classical if-statements that are conditional on the mid-circuit measurement outcome of a Bell measurement. In this implementation, we also provide an improvement over previous work for the circuit model description of quantum telecloning, which reduces the required gate depth and gate count for an all-to-all connectivity. The demonstration of creating $9$ approximate clones on a quantum processor is the largest number of clones that has been generated, telecloning or otherwise

| **Smith, Kaitlin** | Infleqtion |
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**MAKING EVERY (NANO)SECOND COUNT DURING QUANTUM COMPUTATION WITH SUPERSTAQ**

Today's quantum computation is a race against the clock: qubits have limited coherence windows, and each moment during quantum program execution presents additional opportunities for qubit state to be altered by various noise channels. Fortunately, quantum software can help defend quantum information from errors during processing, potentially accelerating progress toward utility-scale and accessible quantum computation. In this talk, we present the Superstaq quantum software platform that optimizes the execution of quantum programs by tailoring applications to underlying device physics. Deep optimization can improve program performance by at least 10x compared to prevailing state-of-the-art frameworks, and here, we focus on Superstaq optimizations that boost the resilience of qubits to decoherence during runtime. This is shown first with Superstaq's use of hardware primitives to enable optimized operator decompositions that reduce program critical path durations. Next, we discuss Superstaq's dynamical decoupling routines that mitigate noise during periods of qubit idling unique to an algorithm and device paring. Finally, real quantum machine results are included to demonstrate how Superstaq extracts greater quantum program performance with hardware-tailored optimized decompositions and dynamical decoupling.

| **Suh, In-Saeng** | Oak Ridge National Laboratory |
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**ADVANCED QUANTUM POISSON SOLVER FOR PRACTICAL AND SCALABLE APPLICATIONS**

The Poisson equation plays a crucial role in diverse scientific and engineering domains. Existing quantum algorithms for solving the Poisson equation suffer from accuracy limitations and are restricted to small problem sizes, rendering them impractical. In this study, we propose an advanced quantum algorithm that offers high accuracy and dynamically tunable problem sizes for the Poisson equation solver. By utilizing the finite difference method to convert the equation into a linear system, we employ the HHL algorithm as the foundation of our approach. To ensure

solution accuracy, we introduce an advanced circuit that implements non-truncated eigenvalues through eigenvalue amplification and enhances the precision of controlled rotation angular coefficients, critical components of the HHL algorithm. Consequently, we significantly reduce the relative error while achieving higher success probabilities through increased amplification levels. Our algorithm not only improves solution accuracy but also enables the creation of more practical and scalable circuits by dynamically controlling the problem size on NISQ devices. Simulated and experimental results are presented, along with discussions on error sources. While the current NISQ hardware exhibits CNOT gate errors, our work paves the way for realizing a multidimensional Poisson solver on near-term quantum platforms.

| **Xiaojun, Yao** | University of Washington |
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**QUANTUM SIMULATION OF OPEN QUANTUM SYSTEMS RELEVANT FOR RELATIVISTIC HEAVY ION COLLISIONS**

Relativistic heavy ion collision experiments are currently conducted to probe various properties of the defined phase of nuclear matter, called the quark-gluon plasma (QGP). The QGP only lasts for a very short period of time in the laboratory and one can only probe it indirectly by measuring distributions of particles produced. Useful probes include heavy quarks and jets. Interpreting the experimental data on the heavy quark and jet production and extracting properties of the QGP from these measurements require a thorough understanding on how heavy quarks and jets evolve in the QGP, as open quantum systems. In this talk, I will discuss current limitations of using classical computing to study their in-medium time evolution. I will also explain how quantum computing can help to deepen our understanding of their evolution in the medium. Finally, I will show quantum simulation results of some simple open quantum systems described by gauge theories evolving in a hot medium, which are obtained from both the simulator and real hardware of IBM.

| **Yongxin, Yao** | Ames National Laboratory |
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**COMPARATIVE STUDY OF ADAPTIVE VARIATIONAL QUANTUM EIGENSOLVERS FOR MULTI-ORBITAL IMPURITY MODELS**

Hybrid quantum-classical embedding methods for correlated materials simulations provide a path towards potential quantum advantage. However, the required quantum resources arising from the multi-band nature of $d$ and $f$ electron materials remain largely unexplored. Here we compare the performance of different variational quantum eigensolvers in ground state preparation for interacting multi-orbital embedding impurity models, which is the computationally most demanding step in quantum embedding theories. Focusing on adaptive algorithms and models with 8 spin-orbitals, we show that state preparation with fidelities better

than $99.9\%$ can be achieved using about $2^{14}$ shots per measurement circuit. When including gate noise, we observe that parameter optimizations can still be performed if the two-qubit gate error lies below $10^{-3}$, which is slightly smaller than current hardware levels. Finally, we measure the ground state energy on IBM and Quantinuum hardware using a converged adaptive ansatz and obtain a relative error of $0.7\%$.



| **Kubra, Yeter-Aydeniz** | Mitre |
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**QUANTUM IMAGINARY-TIME EVOLUTION ALGORITHM FOR QUANTUM FIELD THEORIES WITH CONTINUOUS VARIABLES**

There have been recent experimental breakthroughs in continuous variable (CV) photonic quantum computing and programmable photonic quantum computing. This motivated us to develop quantum algorithms using CV quantum computing, which provides a natural platform to study quantum field theories. In this talk, I will present our recent work where we developed a CV quantum imaginary-time evolution algorithm for studying energy levels and corresponding eigenstates of an interacting scalar quantum field theory on a lattice. In this quantum algorithm, only a single qumode is needed for the simulation of the field at each point on the lattice and our quantum algorithm avoids the use of non-Gaussian quantum gates and relies, instead, on detectors projecting onto eigenstates of the photon-number operator.



| **Yu, Kwangmin** | Brookhaven National Laboratory |
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**QUANTUM MULTI-PROGRAMMING FOR GROVER'S SEARCH**

Quantum multi-programming is a method utilizing contemporary noisy intermediate-scale quantum computers by executing multiple quantum circuits concurrently. Despite early research on it, the research remains on quantum gates or small-size quantum algorithms without correlation. In this paper, we propose a quantum multi-programming (QMP) algorithm for Grover's search. Our algorithm decomposes Grover's algorithm by the partial diffusion operator and executes the decomposed circuits in parallel by QMP. We proved that this new algorithm increases the rotation angle of the Grover operator which, as a result, increases the success probability. The new algorithm is implemented on IBM quantum computers and compared with the canonical Grover's algorithm and other variations of Grover's algorithms. The empirical tests validate that our new algorithm outperforms other variations of Grover's algorithms as well as the canonical Grover's algorithm.

| **Zhang, Peng** | Stonybrook University |
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**NOISY-INTERMEDIATE-SCALE QUANTUM POWER SYSTEM TRANSIENT ANALYSIS**

Quantum-empowered electromagnetic transients program (QEMTP) is a promising paradigm for tackling computational burdens in electromagnetic transient simulations for power systems. Nevertheless, no prior studies truly achieve a practical and scalable QEMTP operable on today's noisy-intermediate-scale quantum (NISQ) computers. In this talk, we introduce a NISQ-QEMTP methodology which for the first time transitions the QEMTP operations from ideal, noise-free quantum simulators to real, noisy quantum computers. Further, we present quantum shifted frequency analysis (QSFA) which accelerates QEMTP by exploiting dynamic phasor simulations with larger time steps. If time permits, the speaker will discuss a novel approach to formulating the power system dynamic simulations and how quantum annealing can be used to efficiently evaluate the power system dynamics.

## 3. POSTERS

| Alam, Rizwanul | University of Tennessee |
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### SOLVING MAXCUT WITH QUANTUM IMAGINARY TIME EVOLUTION

We introduce a method to solve the MaxCut problem efficiently based on quantum imaginary time evolution (QITE). We employ a linear Ansatz for unitary updates and an initial state involving no entanglement, as well as an imaginary-time-dependent Hamiltonian interpolating between a given graph and a subgraph with two edges excised. We apply the method to thousands of randomly selected graphs with up to fifty vertices. We show that our algorithm exhibits a 93% and above performance converging to the maximum solution of the MaxCut problem for all considered graphs. Our results compare favorably with the performance of classical algorithms, such as the greedy and Goemans-Williamson algorithms. We also discuss the overlap of the final state of the QITE algorithm with the ground state as a performance metric, which is a quantum feature not shared by other classical algorithms. This metric can be improved by introducing higher-order ansätze and entangled initial states.

| Aly, Esam Eldin | University of Kansas |
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### KU ADVANCED RECONFIGURABLE AND QUANTUM (KUARQ) COMPUTING AND COMMUNICATIONS

With the rapid advancement of quantum computing technology, there is a strong motivation to explore suitable applications for quantum algorithms and quantum computers. For example, High Energy Physics (HEP) is a domain that deals with vast amounts of multidimensional high-resolution data, which poses significant challenges for processing using currently available classical systems. The quantum wavelet transform (QWT) offers a potential solution for reducing data dimensionality. However, QWT requires deep quantum circuits which makes it unsuitable for current quantum hardware that are highly sensitive to external noise and are characterized by short coherence time. Therefore, in our work, we propose optimized QWT circuits in generalized forms that demonstrate their efficacy for multilevel decomposable, multidimensional wavelet operations. In addition, we adopt an innovative approach that combines the strengths of both QWT and Grover's search algorithms to address the computational challenges associated with pattern recognition in multidimensional data. The feasibility of the proposed methods is demonstrated by emulating the quantum algorithms on classical hardware based on field programmable gate arrays (FPGAs) and evaluating them on a high-performance reconfigurable computer (HPRC). Furthermore, we address the encoding challenges involved in classical-to-quantum (C2Q) data conversion, which arise due to high circuit depth in the present solutions. We propose optimized circuits that synthesize arbitrary quantum states from classical data, improving fidelity and reducing circuit complexity. These optimized

circuits achieve 50% lower overall depth compared to previous solutions. We evaluated these methods through simulation in MATLAB, IBM qasm and realistic implementation on an IBM quantum device. We also proposed methods for efficient quantum-to classical (Q2C) data decoding, including optimized QWT-based techniques and a zero-depth technique that employs selective placement of measurement gates to perform the QWT operation. We evaluated these techniques experimentally on a 27-qubit IBM quantum computer. Additionally, we propose a cost effective, classical hardware-accelerated framework for realistic and complete emulation of quantum algorithms. The emulation framework incorporates components for the critical process of C2Q data encoding and Q2C data decoding, as well as architectures for quantum algorithms. Finally, in our research on quantum communications, we focus on enhancing security and extending the communication range. We address these challenges by proposing a novel Free-Space Optical (FSO) communication system that combines chaotic communications with Quantum Key Distribution (QKD). The system employs Lorenz chaotic models for data transmission and synchronization, utilizing both classical and quantum channels. Through experimental evaluations on various quantum devices, we demonstrate the effectiveness of our proposed approaches in real-world scenarios.

Continuing along the above research directions and through our ongoing research in quantum machine learning, quantum image processing, quantum communication, quantum control processors, and evolvable quantum hardware (EQH), we strive to unlock the full potential of this transformative technology for solving complex real-world problems.



| **Bangar, Shikha** | University of Tennessee |
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**EXPERIMENTALLY REALIZABLE CONTINUOUS-VARIABLE NEURAL NETWORK (PART-2)**

Continuous-variable (CV) quantum computing has shown great potential for building neural network models. These neural networks can have different levels of quantum-classical hybridization depending on the complexity of the problem. Previous work on CV neural network protocols required the implementation of non-Gaussian operators in the network. These operators were used to introduce non-linearity, an essential feature of neural networks. However, these protocols are hard to execute experimentally. We built a CV hybrid quantum-classical neural network protocol that can be realized experimentally with current photonic quantum hardware. Our protocol uses Gaussian gates only with the addition of ancillary qumodes. We implemented non-linearity through repeat-until-success measurements on ancillary qumodes. To test our neural network, we studied canonical machine learning and quantum computer problems in a supervised learning setting -- state preparation, curve fitting, and classification problems. We achieved high fidelity in state preparation of single-photon (99.9%), cat (99.8%), and Gottesman-Kitaev-Preskill (93.9%) states, a well-fitted curve in the presence of noise at the cost of less than 1%, and more than 95% accuracy in classification problems. These results bode well for real-world applications of CV quantum neural networks.

This work has been done in collaboration with a fellow grad student (Leanto Sunny), who is also presenting the poster on the same work as Part-1. Please keep our posters together so that we can convey our work efficiently. Here is the reference to the work: Bangar, S., Sunny, L., & Siopsis, G. (2023). Experimentally Realizable Continuous-variable Quantum Neural Networks.



| **Bauer, Nora** | University of Tennessee |
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**NON-ABELIAN ANYONS WITH RYDBERG ATOMS**

We study the emergence of topological matter in two-dimensional systems of neutral Rydberg atoms in Ruby lattices. While Abelian anyons have been predicted in such systems, non-Abelian anyons, which would form a substrate for fault-tolerant quantum computing, have not been generated. To generate anyons with non-Abelian braiding statistics, we consider systems with mixed-boundary punctures. We obtain the topologically distinct ground states of the system numerically using the iDMRG technique. We discuss how these topological states can be created using ancilla atoms of a different type. We show that a system with 2N+2 punctures and an equal number of ancilla atoms leads to N logical qubits whose Hilbert space is determined by a set of stabilizing conditions on the ancilla atoms. Quantum gates can be implemented using a set of gates acting on the ancilla atoms that commute with the stabilizers and realize the braiding group of non-Abelian Ising anyons.



| **Butt, Nouman** | University of Illinois Urbana-Champaign |
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**FAST PARTITIONING OF PAULI STRINGS INTO COMMUTING FAMILIES FOR OPTIMAL EXPECTATION VALUE MEASUREMENTS OF DENSE OPERATORS**

The Pauli strings appearing in the decomposition of an operator can be can be grouped into commuting families, reducing the number of quantum circuits needed to measure the expectation value of the operator. We detail an algorithm to completely partition the full set of Pauli strings acting on any number of qubits into the minimal number of sets of commuting families, and we provide python code to perform the partitioning. The partitioning method scales linearly with the size of the set of Pauli strings and it naturally provides a fast method of diagonalizing the commuting families with quantum gates. We provide a package that integrates the partitioning into Qiskit and use this to benchmark the algorithm with dense Hamiltonians, such as those that arise in matrix quantum mechanics models, on IBM hardware. We demonstrate computational speedups close to the theoretical limit of $(3/2)^m$ relative to qubit-wise commuting groupings, for $m=2,..,6$ qubits

| Chundury, Srikar | North Carolina State University |
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**A NOVEL APPROACH TO SPARSITY IN QUANTUM SIMULATIONS**

We investigate sparsity patterns seen in quantum simulations. Exploiting these patterns, we introduce a specialized data structure to store unitary matrices efficiently. To establish the advantages of our data structure, we perform chain matrix multiplication of unitary matrices involved in quantum circuits from the supermarQ benchmark suite, mimicking a unitary simulation. Our proposed data format offers substantial improvements in both runtime and memory utilization. In contrast to dense formats, which exhibit exponential growth in memory requirements, our data format demonstrates linear growth of memory consumption. For tensor-network simulations, we discover that tensors, when reshaped and stored as matrices in a certain way, exhibit similar sparsity patterns. We develop specialized kernels for tensor operations like reshape, transpose and tensordot using this data structure. We then integrate it with a known tensor-network simulation library called Quimb. Our findings reveal that main computational bottlenecks reside in format conversions and transpose operations. Without further optimization, current simulations are not yet able to match other methods in performance, but we do outperform them in terms of capability of simulating with a larger number of qubits. In summary, our work introduces a novel data structure that leverages sparsity patterns in quantum simulations, resulting in a reduced memory footprint and improved simulation times.

| Clark, Joseph | University of Tennessee |
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**TDAG: TREE-BASED DIRECTED ACYCLIC GRAPH PARTITIONING FOR QUANTUM CIRCUITS**

We propose Tree-based Directed Acyclic Graph (TDAG) partitioning for quantum circuits, a novel quantum circuit partitioning method which partitions circuits by viewing them as a series of binary trees and selecting the tree containing the most gates. TDAG produces results of comparable quality (number of partitions) to an existing method called ScanPartitioner (an exhaustive search algorithm) with an 95% average reduction in execution time. Furthermore, TDAG improves compared to a faster partitioning method called QuickPartitioner by 38% in terms of quality of the results with minimal overhead in execution time.

| Dasgupta, Samudra | University of Tennessee |
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**ADAPTIVE MITIGATION OF TIME-VARYING QUANTUM NOISE**

Spatio-temporal variations in decoherence times within quantum registers can cause program output to be inconsistent. We propose an adaptive algorithm that effectively learns and reduces quantum noise under changing channel conditions. Our findings reveal that this approach can outperform non-adaptive methods by a margin of 4.5 times in the context of probabilistic error cancellation.

| Gopalakrishnan Meena, Muralikrishnan | Oak Ridge National Laboratory |
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**NUMERICAL SOLUTIONS TO IDEAL FLUID FLOW PROBLEMS USING QUANTUM LINEAR SOLVERS**

Numerically solving fluid flow problems poses a significant challenge due to the increasing computational cost associated with complexity of the flows -- such as turbulence, compressibility, chemical reactions, and magnetic effects. Quantum computers, with their computational prowess, offer a unique opportunity to address the computational challenges in accurately simulating fluid flow problems. However, the development of robust and high-fidelity quantum computers capable of handling practical fluid flow problems is still in its early stages. Nevertheless, recent advancements in quantum algorithms have paved the way for quantum counterparts to classical fluid flow solvers. In this study, we leverage quantum algorithms for solving linear systems of equations to tackle continuum problems in fluid dynamics. Specifically, we focus on idealized inviscid potential flows, which have known true solutions. These problems can be formulated as linear systems of equations. To solve these equations, we employ the HHL algorithm, which allows us to find solutions for the system. Using the observables and the complete solution vector from the quantum algorithm, we will compare the obtained solution with the true solution. We will present our ongoing preliminary efforts focused on demonstrating the accuracy, stability, convergence, and computational cost of the quantum solution and the comparison to the true solution. These comparisons will be done to effectively solve the fluid flow problem on specific geometries.

| Gowrishankar, Meenambika | Oak Ridge National Laboratory |
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**LOGICAL ERROR RATES FOR THE VARIATIONAL QUANTUM EIGENSOLVER USING A [[4,2,2]] ENCODED ANSATZ**

Application benchmarks that run on noisy intermediate scale quantum computing (NISQ) devices require techniques for detecting and mitigating errors to assess accuracy and performance. Quantum error detection codes offer a framework in which to encode these computations and track the presence of errors, but the subsequent logical error rate depends on the application circuit as well as the underlying hardware noise. Here we extend recent results using the [[4,2,2]] error detection code to improve the accuracy of computational chemistry calculations by calculating the logical error rate of an encoded variational ansatz. Within the context of the variational quantum eigensolver (VQE), we numerically simulate the mixed state generated by noisy execution of a UCC ansatz circuit for the case of the hydrogen molecule, accounting for variations in circuit parameters due to noise and the underlying noise models. Simulations of the unencoded, encoded, and post-selected states lead to estimates of logical error rate and probabilities for error-free calculations. For the case of one- and two-qubit depolarizing gate noise, we find that the error detection code reduces the logical infidelity by 10% relative to the

unencoded physical rate when the noise parameter is <10%. This yields a corresponding decrease in the estimated energy by 4% (0.04 Ha). We also evaluate the change in the logical state fidelity with circuits modified to account for hardware connectivity constraints for comparison with simulations on hardware.

| **Guar, Bhaskar** | University of Tennessee |
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**NOISE-RESILIENT AND REDUCED DEPTH APPROXIMATE ADDERS FOR NISQ QUANTUM COMPUTING**

The "Noisy intermediate-scale quantum" NISQ machine era primarily focuses on mitigating noise, controlling errors, and executing high-fidelity operations, hence requiring shallow circuit depth and noise robustness. Approximate computing is a novel computing paradigm that produces imprecise results by relaxing the need for fully precise output for error-tolerant applications including multimedia,data mining, and image processing. We investigate how approximate computing can improve the noise resilience of quantum adder circuits in NISQ quantum computing. We propose five designs of approximate quantum adders to reduce depth while making them noise-resilient, in which three designs are with carryout, while two are without carryout. We have used novel design approaches that include approximating the Sum only from the inputs (pass-through designs) and having zero depth, as they need no quantum gates. The second design style uses a single CNOT gate to approximate the SUM with a constant depth of O(1).We performed our experimentation on IBM Qiskit on noise models including thermal, depolarizing, amplitude damping, phase damping, and bitflip: (i) Compared to exact quantum ripple carry adder without carryout the proposed approximate adders without carryout have improved fidelity ranging from 8.34% to 219.22%, and (ii) Compared to exact quantum ripple carry adder with carryout the proposed approximate adders with carryout have improved fidelity ranging from 8.23% to 371%. Further, the proposed approximate quantum adders are evaluated in terms of various error metrics.

| **LaBlond, Tyler** | Oak Ridge National Laboratory |
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**TISCC: A SURFACE CODE COMPILER AND RESOURCE ESTIMATOR FOR TRAPPED-ION PROCESSORS**

We introduce the Trapped-Ion Surface Code Compiler (TISCC), which is a software tool that can generate circuits for a universal set of surface code patch operations in terms of a native trapped-ion gate set. To accomplish this, TISCC manages an internal representation of a trapped-ion system where a repeating pattern of trapping zones and junctions is arranged in an arbitrarily large rectangular grid. TISCC utilizes a realistic trapped-ion hardware model and, in compiling operations into hardware instructions, it explicitly accounts for the movement of ions between trapping zones and ensures validity of the _nal circuit by resolving junction conicts. The TISCC hardware model is able to count space-time resources required for operations by tracking the

nominal time at which each operation should occur in the _nal hardware circuit. Surface code operations are compiled by instantiating one or several surface code patches on the grid and using methods to generate transversal operations over data qubits, rounds of error correction over stabilizer plaquettes, and/or merge operations between pairs of logical qubits. Patches can additionally be deformed through corner movements, which allow for the patch rotation required subsequent to a transversal Hadamard gate. These methods have been combined to compile a universal lattice surgery-based instruction set. TISCC output has been veri_ed using the Oak Ridge Quasi-Cli_ord Simulator (ORQCS). As an application, TISCC resource estimates have been used in combination with Lattice Surgery Compiler (LSC) to estimate the space-time resources needed for large quantum circuits. Next, we plan to use ORQCS and TISCC in conjunction to calculate error rates for surface code operations.



| **Lyakh, Dmitry** | NVIDIA |
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**CUQUANTUM SDK: A HIGH-PERFORMANCE LIBRARY FOR ACCELERATING QUANTUM SCIENCE**

We present the NVIDIA cuQuantum SDK, a state-of-the-art library of composable primitives for GPU-accelerated quantum circuit simulations. As the size of quantum devices continues to increase, making their classical simulation progressively more difficult, the availability of fast and scalable quantum circuit simulators becomes vital for quantum algorithm developers, as well as quantum hardware engineers focused on the validation and optimization of quantum devices. The cuQuantum SDK was created to accelerate and scale up quantum circuit simulators developed by the quantum information science community by enabling them to utilize efficient scalable software building blocks optimized for NVIDIA GPU-based platforms. The functional building blocks provided cover the needs of both state vector- and tensor network- based simulators, including approximate tensor network simulation methods based on matrix product state, projected entangled pair state, and other factorized tensor representations. By leveraging the enormous computing power of the latest NVIDIA GPU architectures, quantum circuit simulators that have adopted the cuQuantum SDK demonstrate significant acceleration, compared to CPU-only execution, for both the state vector and tensor network simulation methods.

Furthermore, by utilizing the parallel primitives available in the cuQuantum SDK, one can easily transition to distributed GPU-accelerated platforms, including those furnished by cloud service providers and high-performance computing systems deployed by supercomputing centers, extending the scale of possible quantum circuit simulations. The rich capabilities provided by the cuQuantum SDK are conveniently made available via both Python and C application programming interfaces, where the former is directly targeting a broad Python quantum community and the latter allows tight integration with simulators written in any programming language.

| Neelamagam, Ritheshkumar | Georgia Institute for Technology |
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**A CLASSICALLY EFFICIENT QUANTUM SCALABLE FERMI-HUBBARD BENCHMARK**

Some quantum computer benchmarks rely on the performance of random circuits and are generic in nature. Here we instead propose and implement a practical, application-based benchmark. Our protocol calculates the energy of the ground state in the single particle subspace of a 1-D Fermi Hubbard model, a problem which is efficient to solve classically. We provide a quantum ansatz for the problem that is provable able to probe the full single particle subspace for a general length 1-D chain and scales efficiently in number of gates and measurements. Finally, we demonstrate and analyze the benchmark performance on superconducting and ion trap testbed hardware from three hardware vendors and with up to 24 qubits.

| Sander, Aaron | Technical University of Munich |
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**THE MUNICH QUANTUM TOOLKIT (MQT): DESIGN AUTOMATION TOOLS AND SOFTWARE FOR QUANTUM COMPUTING**

Quantum computers are becoming a reality. But designing applications for these devices requires automated, efficient, and user-friendly software tools that cater to the needs of end-users, engineers, and physicists at every level of the design flow. The Munich Quantum Toolkit (MQT) is a collection of design automation tools and software for quantum computing developed at the Chair for Design Automation at the Technical University of Munich. This poster provides an overview of the provided solutions. For each step in the design flow, numbered nodes indicate the correspondingly available software repositories (summarized on the back of this flyer). All software is available as open-source.

| Sunny, Leanto | University of Tennessee |
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**EXPERIMENTALLY REALIZABLE CONTINUOUS-VARIABLE QUANTUM NEURAL NETWORKS - PART 1**

Continuous-variable (CV) quantum computing has shown great potential for building neural network models. These neural networks can have different levels of quantum-classical hybridization depending on the complexity of the problem. Previous work on CV neural network protocols required the implementation of non-Gaussian operators in the network. These operators were used to introduce non-linearity, an essential feature of neural networks. However, these protocols are hard to execute experimentally. We built a CV hybrid quantum-classical neural network protocol that can be realized experimentally with current photonic quantum hardware. Our protocol uses Gaussian gates only with the addition of ancillary qumodes. We implemented non-linearity through repeat-until-success measurements on ancillary qumodes. We evaluated our neural network by applying it to the MNIST image

classification problem, a widely recognized benchmark in both machine learning and quantum computing. Impressively, our network achieved a classification accuracy exceeding 95% for this task. These results bode well for real-world applications of CV quantum neural networks.

| **Wang, Yan** | Oak Ridge National Laboratory |
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**GROUND STATE PREPARATION FOR HIGHLY FRUSTRATED MAGNETIC CLUSTERS ON DIGITAL QUANTUM COMPUTERS**

With the utility-scale fault-tolerant quantum computing still being decade away, one of the most promising quantum utilities on current noisy hardware is to solve quantum chemistry and physics problems because of the direct map from the quantum particles and their interactions to the qubits and their entangling gates and also thanks to the rapidly improved qubit quality and error-mitigation techniques. Understanding quantum spin liquid in frustrated magnetic materials is a longstanding challenge in condensed matter physics and the ground-state phase is highly debated among researchers. Using IBM's hardware and its runtime primitives with the built-in error-mitigation strategies, we apply variational quantum eigensolver (VQE) algorithm to prepare the respective ground states of two 12-site-cluster approximations of these frustrated magnetic materials, specifically a six-pointed star unit cell of the kagome lattice and a cuboctahedron cluster of the so-called kagome on a sphere.

| **Weiwen, Jiang** | George Mason University |
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**SYSTEM-LEVEL OPTIMIZATIONS IN IMPROVING THE ROBUSTNESS OF QUANTUM APPLICATIONS ON THE UNSTABLE QUANTUM DEVICES**

Recently, we have been witnessing the scale-up of superconducting quantum computers; however, the noise of quantum bits (qubits) is still an obstacle for real-world applications to leveraging the power of quantum computing. Although there exist error mitigation or error-aware designs for quantum applications, the inherent fluctuation of noise (a.k.a., instability) can easily collapse the performance of error-aware designs. What's worse, users cannot even be aware of the performance degradation caused by the change in noise. To address both issues, in this poster, we use Quantum Neural Network (QNN) as a vehicle to present a novel compression-aided framework, namely QuCAD, which will adapt a trained QNN to fluctuating quantum noise. In addition, with the historical calibration (noise) data, our framework will build a model repository offline, which will significantly reduce the optimization time in the online adaption process. Results on machine learning datasets show that QuCAD can achieve 16.32% accuracy gain on average in 146 days over a noise-aware training approach; what's more, it increases the number of days that can achieve accuracy larger than 80% from 24 to 100.