QSIM 2023 POSTER SESSIONS

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- *Suggested poster dimensions: 4 feet by 3 feet*
- *Please print before you come to Telluride. There are no printing facilities available in Telluride!*
- *Poster mounting hardware will be provided by the conference venue*
- *Poster sessions are on Tuesday (Aug 8) and Thursday (Aug 10) from 3 pm. Your poster number (in blue) is listed below next to the title. The poster numbers will be marked at the venue. You can mount your poster anytime after lunch.*
- *Please take down your poster after the end of the poster session on each day.*

SESSION 1: TUESDAY, AUGUST 8

[1] *Leveraging Hamiltonian Simulation Techniques to Compile Operations on Bosonic Devices*

Christopher Kang (University of Chicago), Micheline Soley (University of Wisconsin), Eleanor Crane (JQI/QuICS/UMD/NIST & Quantinuum), Steven Girvin (Yale University) and Nathan Wiebe (University of Toronto)

Abstract: Circuit QED enables the combined use of qubits and oscillator modes. Despite a variety of available gate sets, many hybrid qubit-boson (i.e., oscillator) operations are realizable only through optimal control theory (OCT) which is oftentimes intractable and uninterpretable. We introduce an analytic approach with rigorously proven error bounds for realizing specific classes of operations via two matrix product formulas commonly used in Hamiltonian simulation, the Lie--Trotter and Baker--Campbell--Hausdorff product formulas. We show how this technique can be used to realize a number of operations of interest, including polynomials of annihilation and creation operators, i.e., $a^p {a^\dagger}^q$ for integer p, q. We show examples of this paradigm including: state preparation of a fixed photon number in the cavity, simulation of the Jaynes--Cummings Hamiltonian, simulation of a Chi^3 nonlinear material, simulation of the Fermi-Hubbard lattice Hamiltonian, simulation of the Hong-Ou-Mandel effect and more. This work demonstrates how techniques from Hamiltonian simulation can be applied to better control hybrid boson-qubit devices, thus enabling a broader class of simulatable Hamiltonians.

Keywords: Baker-Campbell-Hausdorff, Trotter-Suzuki, Product formulas, circuit QED
Type: Theory

[2] *Ever More Optimized Simulations of Fermionic Systems on a Quantum Computer*

Qingfeng Wang (University of Maryland, College Park), Ze-Pei Cian (University of Maryland, College Park), Ming Li (Atom Computing), Igor Markov (Nova Ukraine) and Yunseong Nam (University of Maryland, College Park)

Abstract: Despite using a novel model of computation, quantum computers break down programs into elementary gates. Among such gates, entangling gates are the most expensive. In the context of fermionic simulations, we develop a suite of compilation and optimization techniques that massively reduce the entangling-gate counts. We exploit the well-studied non-quantum optimization algorithms to achieve up to 24\% savings over the state of the art for several small-molecule simulations, with no loss of accuracy or hidden costs. Our methodologies straightforwardly generalize to wider classes of near-term simulations of the ground state of a fermionic system or real-time simulations probing dynamical properties of a fermionic system.

Keywords: quantum circuit optimization, variational quantum eigensolver, generalized transformation
Type: Theory

[3] *Universality class of the Measurement-induced Phase Transition with a U(1) Conservation Law*

Ahana Chakraborty (Rutgers University, NJ), Kun Chen (Flatiron Institute, NY), Aidan Zabalo (Rutgers University, NJ), Justin Wilson (Louisiana State University, LA) and Jed Pixley (Rutgers University, NJ)

Abstract: We study critical properties of the measurement-induced phase transitions in non-unitary quantum circuit evolving with a U(1) conserved charge. We present a numerical study of the critical behaviour of the entanglement transition and find it is described by a new universality class that is distinct from both the percolation transition and the Haar-random circuit without a conservation law. We provide convincing numerical evidence based on computing the mutual information between two locally coupled Ancilla qubits in the same global charge sector and we estimate the bulk critical exponent. Further, emergent Lorentz invariance at the transition allows us to probe the properties of the underlying (1+1)d conformal field theory via its effective central charge (ceff) and the leading scaling dimensions of the operators. Our numerical analysis predicts that both the bulk critical exponent and ceff have much larger values than those of the percolation or random-Haar circuit and thus uncover distinct signatures of global constraints in the dynamics on the measurement-induced criticality.

Keywords: Non-unitary dynamics in open quantum system, Monitored quantum circuit, Phase transition and criticality, Conformal field theory
Type: Theory

[4] *Noise-resilient Quantum Simulation with Quantum Error Detection Code.*

Dawei Zhong (University of Southern California) and Todd Brun (University of Southern California)

Abstract: Quantum computing promises to offer substantial speed-up in simulating physical systems, but noise in near term quantum devices prohibits people from fully realizing its power. In this work, we propose a procedure to reduce uncertainty coming from noise for quantum simulation tasks based on quantum error detection code. Specifically, we extend the weakly fault-tolerant construction using [[n, n-2, 2]] code and develop a systematic method to construct a general logical exponential map. Together with mid-circuit measurement, this method can be used to detect errors in deep circuits consisting of sequential exponential maps, and thus can be used for dynamical or molecular system simulation after decomposing the overall exponential operator by Trotter–Suzuki formulas. Our work indicates the potential of using quantum error correction code to reduce noise in practical quantum computing tasks before the advent of completely fault-tolerant quantum computers.

Keywords: Noise-resilient Quantum Simulation, Exponential Operation, Quantum Error Detection Code
Type: Theory

[5] *Blind Quantum Tomography on an Ion Trap Quantum Computer.*

Liam Jeanette (University of Maryland) and Dominik Hangleiter (University of Maryland)

Abstract: Quantum state tomography (QST) is a key tool in the development of high-precision quantum devices. QST assumes a highly calibrated measurement device where the errors are well-known. However, calibration of such measurements is limited by the accuracy of state preparation. This creates a `chicken and the egg' cycle, where each must happen before the other. To circumvent this cycle, we need a tomography method which is `blind' to the measurement errors. Here, we implement a novel tomography method (ALS) on a trapped ion quantum computer which recovers the quantum state blindly by distilling the QST problem to the problem of de-mixing a sparse matrix, which has well-known solutions. In addition to recovering the quantum state, the ALS algorithm simultaneously recovers the measurement errors. By artificially injecting various amounts of measurement error, we show that the ALS algorithm consistently recovers the quantum state independent of the error, while other tomography methods fail to recover the state as the errors grow larger. Additionally, we show that a tomographically complete set of data is not required for the ALS algorithm, relaxing the number of quantum measurements necessary to reconstruct the state of the quantum device.

Keywords: Quantum State Tomography, Ion Trap, Measurement Errors
Type: Experiment

[6] *A Quantum Convolutional Neural Network Approach for Object Detection and Classification*

Gowr Namratha (Vellore Institute of Technology), Kandukuri Sai Srirekha (Vellore Institute of Technology) and Radhakrishnan Delhibabu (Vellore Institute of Technology)

Abstract: This paper presents a comprehensive evaluation of the potential of Quantum Convolutional Neural Networks (QCNNs) in comparison to classical Convolutional Neural Networks (CNNs) and Artificial / Classical Neural Network (ANN) models. With the increasing amount of data, utilizing computing methods like CNN in real-time has become challenging. QCNNs overcome this challenge by utilizing qubits to represent data in a quantum environment and applying CNN structures to quantum computers. The time and accuracy of QCNNs are compared with classical CNNs and ANN models under different conditions such as batch size and input size. The maximum complexity level that QCNNs can handle in terms of these parameters is also investigated. The analysis shows that QCNNs have the potential to outperform both classical CNNs and ANN models in terms of accuracy and efficiency for certain applications, demonstrating their promise as a powerful tool in the field of machine learning.

Keywords: Quantum Convolutional Neural Networks, QCNNs, Classical CNN, Artificial Neural Network, ANN, Fully connected neural network, Machine learning, Efficiency, Accuracy, Qubits, Quantum environment
Type: Experiment

[7] *Trapped-Ion Quantum Simulations for Condensed-Phase Chemical Dynamics: Seeking a Quantum Advantage*

Mingyu Kang (Duke University), Hanggai Nuomin (Duke University), Sutirtha N. Chowdhury (Duke University), Jonathon L. Yuly (Princeton University), Ke Sun (Duke University), Jacob Whitlow (Duke University), Jesús Valdiviezo (University of California, Berkeley), Zhendian Zhang (Duke University), Peng Zhang (Duke University), David N. Beratan (Duke University) and Kenneth R. Brown (Duke University)

Abstract: Simulating the quantum dynamics of molecules in the condensed phase represents a longstanding challenge in chemistry. Trapped-ion quantum systems may serve as a platform for the analog-quantum simulation of chemical dynamics that is beyond the reach of current classical-digital simulation. To identify a "quantum advantage" for these simulations, performance analysis of both classical-digital algorithms and analog-quantum simulation on noisy hardware is needed. In this Perspective, we make this comparison for the simulation of model molecular Hamiltonians that describe intrinsically quantum models for molecules that possess linear vibronic coupling, comparing the accuracy and computational cost. We describe several simple Hamiltonians that are commonly used to model molecular systems, which can be simulated with existing or emerging trapped-ion hardware. These Hamiltonians may serve as stepping stones toward the use of trapped-ion simulators beyond the reach of classical-digital methods. Finally, we identify dynamical regimes where classical-digital simulations seem to have the weakest performance compared to analog-quantum simulations. These regimes may provide the lowest hanging fruit to exploit potential quantum advantages.

Keywords: quantum simulation, chemical dynamics, trapped ions
Type: Theory

[8] *Nagaoka Ferromagnetism in 3x3 Arrays and Beyond, a Simple Test Case for Solid State Quantum Simulators*

Yan Li (University of Maryland) and Garnett Bryant (National Institute of Standards and Technology)

Abstract: Nagaoka ferromagnetism (NF) is a long-predicted example of itinerant ferromagnetism in the Hubbard model and has been studied theoretically for many years. Recently, NF was realized experimentally in quantum-dots systems for 2x2 plaquettes. NF occurs when there is one hole and a large onsite Coulomb repulsion, which does not arise naturally in materials. Utilizing the atomically precise fabrication ability of the dopant arrays in Si, it is possible to engineer complex geometries and make highly controllable systems. This makes them good candidates to study NF in different array geometries through analog quantum simulation. Here we describe the theoretical simulations done for 3x3 arrays sand larger NxN array of dopants in Si, such as the 3x3 dopant arrays studied at NIST, and look for the emergence of different forms of ferromagnetism in different geometries. Like the 2x2 plaquettes, we find the existence of NF in perfect 3x3 arrays, as well as NxN arrays. Theoretical simulations are done for arrays more constrained either by special geometries or disorder to see if ferromagnetism will persist. Our results define possible experiments to hunt for different forms of saturated ferromagnetism, which may be used as a simple (but physically interesting) test case for solid-state analog quantum simulators.

Keywords: quantum dots, Nagaoka ferromagnetism, dopant arrays in Si, analog quantum simulators
Type: Theory

[9] *Simulation of the Fermi-Hubbard Model with a Semiconductor Quantum Dot Array*

Matthew Donnelly (University of New South Wales), Sam Gorman (University of New South Wales), Yousun Chung (University of New South Wales), Joris Keizer (University of New South Wales) and Michelle Simmons (University of New South Wales)

Abstract: Semiconductor quantum dots are a promising platform for simulating the Fermi-Hubbard model with the Coulomb interaction providing strong on-site and long-range interactions. Furthermore, the engineering of large hopping energies enables the investigation of phases in the low-temperature, strongly interacting regime such as unconventional superconductivity and anti-ferromagnetism. In this work we describe the use of a large array of phosphorus doped silicon (Si:P) quantum dots to simulate the extended Fermi-Hubbard model on a square lattice. Our atomic-scale fabrication process is particularly well suited for large-scale quantum simulation as we can finely tune the individual Hubbard parameters of each lattice site allowing for quantum simulation of various 2D lattices.

Keywords: Quantum dot arrays, Hubbard Model, 2D lattices
Type: Experiment

[10] *Improved Precision Scaling for Simulating Coupled Quantum-Classical Dynamics*

Sophia Simon (University of Toronto), Raffaele Santagati (Boehringer Ingelheim), Matthias Degroote (Boehringer Ingelheim), Nikolaj Moll (Boehringer Ingelheim), Michael Streif (Boehringer Ingelheim) and Nathan Wiebe (University of Toronto)

Abstract: We provide in this paper a super-polynomial improvement in the scaling with the precision of quantum simulation of coupled classical-quantum simulations, such as molecular dynamics within the Born-Oppenheimer approximation. We achieve this by introducing a framework based on the Koopman-von Neumann formalism to express the Liouville equation of motion as unitary dynamics and then directly use phase kickback from a dynamical quantum simulation to compute the quantum forces acting on the classical particles. We provide a way of simulating the dynamics of these particles without incurring the overheads of measuring gradients and solving the equations of motion for the classical particles on a classical computer, which results in our super-polynomial advantage. We further show that these simulations can be carried out in both the microcanonical and canonical ensembles and used to estimate thermodynamic quantities from the prepared probability density. These improved results suggest that quantum simulation of molecular dynamics will be a significant application for quantum computation.

Keywords: Quantum algorithms, Quantum simulation, Quantum-classical dynamics, Molecular dynamics
Type: Theory

[11] *Composite Quantum Simulations*

Matthew Hagan (University of Toronto) and Nathan Wiebe (University of Toronto)

Abstract: In this paper we provide a framework for combining multiple quantum simulation methods, such as Trotter-Suzuki formulas and QDrift into a single composite channel that builds upon older coalescing ideas for reducing gate counts. The central idea behind our approach is to use a partitioning scheme that allocates a Hamiltonian term to the Trotter or QDrift part of a channel within the simulation. This allows us to simulate small but numerous terms using QDrift while simulating the larger term using a high-order Trotter-Suzuki formula. We prove rigorous bounds on the diamond distance between the composite channel and the ideal simulation channel and show under what conditions the cost of implementing the composite channel is asymptotically upper bounded by the methods that comprise it for both probabilistic partitioning of terms and deterministic partitioning. Finally, we discuss strategies for determining partitioning schemes as well as methods for incorporating different simulation methods within the same framework.

Keywords: randomized compilers, composite simulation, hybridized, trotter, qdrift
Type: Theory

[12] *Fast Quantum Algorithm for Differential Equations*

Mohsen Bagherimehrab (University of Toronto), Kouhei Nakaji (University of Toronto), Nathan Wiebe (University of Toronto) and Alan Aspuru-Guzik (University of Toronto)

Abstract: Partial differential equations (PDEs) are ubiquitous in science and engineering. Prior quantum algorithms for solving the system of linear algebraic equations obtained from discretizing a PDE have a computational complexity that scales at least linearly with the condition number κ of the matrices involved in the computation. For many practical applications, κ scales polynomially with the size N of the matrices, rendering a polynomial-in-N complexity for these algorithms. Here we present a quantum algorithm with a complexity that is polylogarithmic in N but is independent of κ for a large class of PDEs. Our algorithm generates a quantum state that enables extracting features of the solution. Central to our methodology is using a wavelet basis as an auxiliary system of coordinates in which the condition number of associated matrices is independent of N by a simple diagonal preconditioner. We present numerical simulations showing the effect of the wavelet preconditioner for several differential equations. Our work could provide a practical way to boost the performance of quantum-simulation algorithms where standard methods are used for discretization.

Keywords: Quantum Algorithms, Partial Differential Equations, Wavelet representation, Preconditioning
Type: Theory

[13] *Quantum Dynamics between CPTP and HPTP*

Ningping Cao (Institute for Quantum Computing, University of Waterloo), Maxwell Fitzsimmons (Department of Applied Mathematics, University of Waterloo), Zachary Mann (Institute for Quantum Computing, University of Waterloo), Rajesh Pereira (Department of Mathematics and Statistics, University of Guelph) and Raymond Laflamme (Institute for Quantum Computing, University of Waterloo)

Abstract: Quantum channels, also known as completely positive trace-preserving (CPTP) maps, play a critical role in almost all aspects of quantum information. For a system to evolve under CPTP maps, assumptions are made on the correlations between the system and the environment. Hermitian-preserving trace-preserving (HPTP) maps are considered as the local dynamic maps beyond CPTP. In this paper, we provide an answer to the question of what physical maps are in the HPTP realm by two approaches. The first is by stepping out of the CPTP set, which provides us with Semi-Positivity (SP) TP maps. The second way is by stepping inside the HPTP maps, which leads to Semi-Nonnegative (SN) TP maps.

Physical interpretations and geometrical structures are studied for these maps. The non-CP SPTP maps correspond to the quantum non-Markovian process under the CP-divisibility definition ($\Psi = \Xi \circ \Phi^{-1}$, where Ξ and Φ are CPTP). When we remove the invertibility assumption on the preconditioning process Φ, we land in the set of SNTP maps. We prove the following map hierarchy

\begin{equation}

\text{CPTP} \subset \text{PTP} \subset \text{SPTP (under reduction)} \subset \text{SNTP} \subset \text{HPTP}.

\end{equation}

We also prove that the closure $cl(\mathcal{SP})$ of SPTP maps are the set $\mathcal{SN}$ of SNTP maps, i.e. $cl(\mathcal{SP}) = \mathcal{SN}$. It answers an open question -- what kind of dynamics the system will go through when Φ is non-invertible. In this case, the only locally well-defined maps are in $\mathcal{SN}\backslash \mathcal{SP}$; they live on the boundary of $\mathcal{SN}$. Otherwise, the non-local information will be irreplaceable in the system's dynamic.

With the understanding of physical maps beyond CPTP, we prove that the current quantum error correction scheme is still sufficient to correct errors beyond CPTP. In some special cases, non-CP-ness could provide us with more error correction methods with less overhead.

We invite the attendees of QSim to consider the following question: how would the non-CP-ness of quantum dynamics affect quantum simulation methods for open quantum systems?

Keywords: open quantum system, CPTP, HPTP
Type: Theory

[14] *Speed Optimized Two-Qubit Gate in Two-Qutrit System*

Bora Basyildiz (Colorado School of Mines) and Zhexuan Gong (Colorado School of Mines)

Abstract: The speed of entangling quantum gates and other critical two-qubit gates set a speed limit on the operation of quantum circuits. In our work, we simulate commonly used two-qubit gates at record-setting speeds. This is done by using weakly anharmonic transmon qubits, which have accessible higher-level energy states. We used these energy states, specifically the qutrit state, to achieve faster two-qubit gates. We achieve this quantum speed limit by implementing pulse-controlled gates designed using a machine learning-inspired optimal control method, which was previously demonstrated on purely qubit systems. Using our machine learning and qutrit system, we are able to break the previously known speed limits of two-qubit gates in qutrit subsystems.

Keywords: Speed limits, Optimal Control, Machine Learning, Qutrits, Qudits
Type: Theory

[15] *Observation of an Equilibrium Phase Transition in a One-dimensional Trapped Ion Quantum Simulator*

Alexander Schuckert (Joint Quantum Institute, University of Maryland, College Park), Or Katz (Duke Quantum Center, Department of Physics and Electrical and Computer Engineering, Duke University), Lei Feng (Duke Quantum Center, Department of Physics and Electrical and Computer Engineering, Duke University), Arinjoy De (Joint Quantum Institute, University of Maryland, College Park), Eleanor Crane (Joint Quantum Institute, University of Maryland, College Park), Mohammad Hafezi (Joint Quantum Institute, University of Maryland, College Park), Alexey Gorshkov (Joint Quantum Institute, University of Maryland, College Park) and Christopher Monroe (Duke Quantum Center, Department of Physics and Electrical and Computer Engineering, Duke University)

Abstract: Equilibrium phase transitions form the centrepiece of many-body physics as they separate regimes of radically different properties. While such transitions have been observed in two and three dimensions, phase transitions of one dimensional systems at finite temperature or energy away from their ground state have not been explored experimentally. In recent years, quantum simulators have emerged as a tool to study ground state phase transitions. However, preparing equilibrium states beyond the ground state in these simulators has been challenging. Here, we use the intrinsic equilibration in closed quantum many-body systems to prepare equilibrium states in a one-dimensional trapped ion quantum simulator. By preparing initial states with different energies, we study the microcanonical phase diagram and observe a ferromagnetic equilibrium phase transition as well as a crossover from a low-energy polarized paramagnet to a high-energy unpolarized paramagnet in a system of up to 23 spins. Our work demonstrates the ability of quantum simulators to realize and study strongly correlated quantum matter at finite energy density.

Keywords: phase transition, quantum simulation, trapped ions
Type: Experiment

[16] *Advantages of Digital Qubit-Boson Hardware for Quantum Simulation of Lattice Gauge Theories*

Eleanor Crane (JQI/QuICS/UMD/NIST & Quantinuum), Alec Eickbusch (Yale), Teague Tomesh (Princeton), Stefan Kuhn (DESY), Alexander Schuckert (JQI/QuICS/UMD & Quantinuum), Kevin Smith (Yale), John Martyn (MIT), Lena Funke (MIT), Nathan Wiebe (University of Toronto), Isaac Chuang (MIT), Michael DeMarco (MIT) and Steven Girvin (Yale)

Abstract: Quantum simulation of lattice gauge theories (LGTs) has been a subject of intense interest in high energy and condensed matter physics because computing dynamics and ground states is classically hard. However, the infinite Hilbert space bosonic sectors, which cannot be integrated out in higher dimensions, lead to extremely high qubit gate counts, threatening the ability of quantum simulation to address these theories. Extensive progress has recently been made in the fabrication and control of microwave cavity resonators - which naturally host a bosonic Hilbert space - coupled to transmon qubits, however it is unclear whether the currently available hardware would outperform all-qubit hardware. To this end, we must firstly calculate the relative complexity of simulating bosonic operations with qubit-boson hardware vs qubit-only hardware, secondly, due to the lack of compiler, we must design the fermion-boson gates in the mixed qubit-boson hardware, and thridly, we must quantify the effects of noise for deep, multi-qubit/qumode circuits required for high fidelity simulations. Here, we provide an example of an experimental architecture which could be scaled to higher dimensions, for a 1+1D mixed boson-fermion system which efficiently performs ground state preparation for both the Z2 gauge theory coupled to bosonic matter and the Schwinger model and show using 'Bosonic Qiskit' that it would dramatically outperform all-qubit systems, featuring lower gate counts by three orders of magnitude which lead to far higher circuit fidelities and fewer total shots to successfully capture the essential physics of these fermion-boson theories.

Keywords: Boson, circuit QED, Schwinger model, high-energy
Type: Theory

[17] *Antiferromagnetic Bosonic t – J Models and Their Quantum Simulation in Tweezer Arrays*

Lukas Homeier (University of Munich), Timothy Harris (University of Munich; MCQST), Tizian Blatz (University of Munich; MCQST), Ulrich Schollwöck (University of Munich; MCQST), Fabian Grusdt (University of Munich; MCQST) and Annabelle Bohrdt (University of Regensburg; MCQST)

Abstract: Understanding the microscopic origins of the competition between spin- and charge degrees of freedom is a central challenge at the heart of strongly correlated many-body physics. Recently, the combination of optical tweezer arrays with systems exhibiting strong interactions, such as Rydberg atoms or ultracold polar molecules, has opened the door for quantum simulation platforms to explore a wide variety of spin models [1, 2]. A significant next step will be the combination of such settings with mobile dopants, in order to study the physics of doped quantum magnets [3]. Here we present recent numerical results from large-scale density matrix renormalization group (DMRG) calculations to investigate hole-pairing in systems with cylindrical boundary conditions. By introducing antiferromagnetic (AFM) couplings between neighbouring spins, we realize competition between the charge motion and magnetic order similar to that observed in high-Tc cuprates. In the case of only two holes–the simplest instance in which the underlying statistics plays a role–our results indicate a strong tendency for bosonic holes to form stripes, as observed by the emergence of a domain wall in the local spin-spin correlation function. In contrast, identical simulations performed for the standard fermionic t-J model show that fermionic holes prefer to form tightly bound pairs. We also present our recent experimental proposal to realize 2D AFM bosonic t-J models in optical tweezer arrays via encoding the local Hilbert space in a set of three internal atomic or molecular states [4].

[1] A. Browaeys & T. Lahaye, Nat. Phys. 16, 132 (2020).

[2] Bao et al., arXiv:2211.09780 (2022).

[3] Bohrdt et al., Ann. Phys. 435, 168651 (2021).

[4] Homeier et al., arXiv:2305.02322 (2023)

Keywords: t – J model, bosonic statistics, tweezer arrays, DMRG
Type: Theory

[18] *Simulating Markovian Open Quantum Systems Using Higher Order Series Expansion*

Xiantao Li (Penn State University) and Chunhao Wang (Penn State University)

Abstract: We present an efficient quantum algorithm for simulating the dynamics of Markovian open quantum systems. The performance of our algorithm is similar to the previous state-of-the-art quantum algorithm, i.e., it scales linearly in evolution time and poly-logarithmically in inverse precision. However, our algorithm is conceptually cleaner, and it only uses simple quantum primitives without compressed encoding. Our approach is based on a novel mathematical treatment of the evolution map, which involves a higher-order series expansion based on Duhamel's principle and approximating multiple integrals using scaled Gaussian quadrature. Our method easily generalizes to simulating quantum dynamics with time-dependent Lindbladians. Furthermore, our method of approximating multiple integrals using scaled Gaussian quadrature could potentially be used to produce a more efficient approximation of time-ordered integrals, and therefore can simplify existing quantum algorithms for simulating time-dependent Hamiltonians based on a truncated Dyson series.

Keywords: Quantum algorithms, Lindblad evolution, Quantum simulation, Markovian open quantum systems
Type: Theory

[19] *Quantum Simulations in Si:P Devices: Extracting Fermi-Hubbard Model Parameters From Atomistic Tight-Binding Calculations*

Maicol Ochoa (University of Maryland and National Institute of Standards and Technology), Keyi Liu (Joint Quantum Institute and NIST), Michal Zielinski (Quantum Physics Department, Nicolaus Copernicus University, Torun, Poland) and Garnett Bryant (Joint Quantum Institute and National Institute of Standards and Technology)

Abstract: We characterize the single electron energies and wavefunction structure in arrays with two, three, and four phosphorus atoms in silicon by implementing atomistic tight-binding calculations and systematically analyzing wavefunction overlaps. Our model describes the confinement potential in the array by representing each impurity as a screened Coulomb potential with an optimal central-cell correction. In particular, we investigate the energy spectrum as a function of dopant separation and rationalize it by computing overlaps between dopant array and single dopant states. This approach reveals the formation of hybrid forms between single dopant states with well-defined symmetries and the occurrence of energy crossings as a function of dopant separation. Moreover, by resolving the complex single electron energy spectrum, we extract tunneling rates between different dopants and electronic states. Significantly, we find that diagonal and nearest neighbor tunneling are similar in magnitude in a square array. Our analysis also accounts for the energy shift on the on-site energy at each phosphorus atom resulting from the influence of the other dopants. This approach constitutes a solid protocol to map the electron energies and wavefunction structure into Hubbard Hamiltonians as required to realize analog quantum simulations.

Keywords: Quantum analog simulations, Fermi-Hubbard model, dopants in silicon, atomistic tight-binding calculations, solid-state quantum simulators
Type: Theory

[20] *Experimental Verification of Machine Learning for Quantum Many-Body Problems*

Gyungmin Cho (Seoul National University) and Dohun Kim (Seoul National University)

Abstract: The use of machine learning (ML) for analyzing data is proving beneficial in numerous domains. Concurrently, progress in quantum technology has made it possible to gather new kinds of data through quantum computers. In line with these evolutions, a new hybrid algorithm has been developed that leverages data from quantum computers to execute ML on classical computers. This approach is particularly suited for present-day noisy quantum computers that lack quantum error correction, and it expands the scope of problems that can be effectively solved compared to those solvable using only traditional computers. We have employed ML, based on provably efficient algorithms, for problems in many-body physics, such as predicting the properties of the ground state of a particular Hamiltonian and classifying quantum phases. Through experiments on superconducting qubits devices with various error minimizing techniques, we have succeeded in obtaining data with fewer errors from quantum computers. This facilitated the successful execution of ML for a system size encompassing tens of qubits. Our experimental outcomes confirm the scalability and efficiency of the newly developed hybrid ML algorithm.

Keywords: Machine learning, Many-body physics, Hybrid approaches, Quantum error mitigation, SPT phase, Topologically ordered phase
Type: Experiment

[21] *Building a Constraint Based Domain Specific Language for Quantum Computers: NchooseK*

Ellis Wilson (North Carolina State University), Frank Mueller (North Carolina State University) and Scott Pakin (Los Alamos National Laboratory)

Abstract: The domain specific language NchooseK is a way to easily submit combinatorial optimization problems to either quantum annealers or gate based machines. This poster demonstrates the latest additions and compares results of using this language for several NP problems.

Keywords: Optimization, Annealer, Gate model, QAOA, Constraints
Type: Experiment

[22] *Many-Body Resonances in the Avalanche Instability of Many-Body Localization*

Hyunsoo Ha (Princeton University), Alan Morningstar (Stanford University) and David Huse (Princeton University)

Abstract: Many-body localized (MBL) systems fail to reach thermal equilibrium under their own dynamics, even though they are interacting, nonintegrable, and in an extensively excited state. One instability toward thermalization of MBL systems is the so-called "avalanche," where a locally thermalizing rare region is able to spread thermalization through the full system. The spreading of the avalanche may be modeled and numerically studied in finite one-dimensional MBL systems by weakly coupling an infinite-temperature bath to one end of the system. We find that the avalanche spreads primarily via strong many-body resonances between rare near-resonant eigenstates of the closed system. Thus we find and explore a detailed connection between many-body resonances and avalanches in MBL systems.

Keywords: many-body localization, quantum statistical mechanics, disordered system
Type: Theory

[23] *Parallel Entangling Gates and Entanglement-Assisted Benchmark on a Trapped-Ion Quantum Computer*

Yingyue Zhu (University of Maryland, College Park), Nhung H. Nguyen (University of Maryland, College Park), Alaina M. Green (University of Maryland, College Park), Cinthia Huerta Alderete (Los Alamos National Lab) and Norbert M. Linke (University of Maryland, College Park; Duke University)

Abstract: Parallel operations are important for both near-term quantum computers and larger-scale fault-tolerant machines because they reduce execution time and qubit idling. We propose and implement a resource-efficient pairwise-parallel entangling gate scheme for trapped-ion systems, where simultaneous entangling gates are driven on different sets of orthogonal motional modes of an ion chain. We demonstrate the utility and advantage of this scheme by creating a three-qubit GHZ state in one step and by implementing a digital quantum simulation of the dynamics of a 1D transverse-field Ising model. This method effectively extends the available gate depth by up to a factor of two without overhead when no overlapping qubit is involved, apart from additional initial cooling. We also benchmark these parallel gates with an entanglement-assisted benchmark protocol [1].

[1]S. Chen, S. Zhou, A. Seif, and L. Jiang, Phys. Rev. A 105, 032435 (2022)

Keywords: parallel entangling gates, entanglement-assisted benchmark, trapped-ions
Type: Experiment

[24] *Characterizing a Non-Equilibrium Phase Transition on a Quantum Computer*

Eli Chertkov (Quantinuum), Zihan Cheng (University of Texas at Austin), Andrew Potter (University of British Columbia), Sarang Gopalakrishnan (Princeton University), Thomas Gatterman (Quantinuum), Justin Gerber (Quantinuum), Kevin Gilmore (Quantinuum), Dan Gresh (Quantinuum), Alex Hall (Quantinuum), Aaron Hankin (Quantinuum), Mitchell Mattheny (Quantinuum), Tanner Mengle (Quantinuum), David Hayes (Quantinuum), Brian Neyenhuis (Quantinuum), Russell Stutz (Quantinuum) and Michael Foss-Feig (Quantinuum)

Abstract: 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.

[1] E. Chertkov et al. arXiv:2209.12889 (2022).

[2] Matthew DeCross et al. arXiv:2210.08039 (2022).

Keywords: quantum simulation, quantum computation, open quantum system, non-equilibrium phase transition
Type: Experiment

[25] *Self-Supervised Learning with Reconstructive Latent Embeddings for Analyzing Interactions in Diamond Defect*

Kyunghoon Jung (Seoul National University), Jiwon Yun (Delft University), Guido van de Stolpe (Delft University), Tim Taminiau (Delft University) and Dohun Kim (Seoul National University)

Abstract: With defect centers in a diamond as the basis, we develop an analysis model with a neural network for probing spin-spin interactions via constructing a simulated interaction dataset. Our model, trained using dual-attention layers, focuses on both time and pulse aspects of Dynamical-Decoupling signals. We address three scenarios: (1) decomposing overlapped nuclear spin signals with similar periods, (2) identifying split signals induced by nuclear-nuclear interaction, and (3) inferring hyperfine interaction parameters in an external magnetic field-agnostic manner. Experimentally, we conduct measurements of Carr-Purcell-Meiboom-Gill (CPMG) signals by utilizing diverse CPMG unit sequences, successfully discerning nuclear-nuclear interactions, and classifying overlapped signals with ~91% accuracy. Our model also estimates hyperfine interaction parameters with ~93% accuracy. We offer automated Python modules for evaluating CPMG signals under various external magnetic fields, enabling precise derivation of individual spin-spin interaction strengths.

Keywords: Representation Learning, Self-Supervised Learning, NV Center, Hyperfine Interaction
Type: Experiment

[26] *Accreditation of Analogue Quantum Simulators*

Andrew Jackson (The University of Warwick), Theodoros Kapourniotis (The University of Warwick) and Animesh Datta (The University of Warwick)

Abstract: We present the first protocol for accrediting analogue, i.e. continuous-time, quantum simulators. This allows bounds to be placed on the variation distance between noisy and ideal probability distributions generated by measurements on the output state of a simulation: providing a measure on the quality of the quantum hardware.

This protocol rests on 3 pillars: the first is the framework for accreditation established in [Farracin et al. Phys. Rev. A 104, 042603 (2021)]; the second is the result of [Zhou, Aharonov. arXiv:2102.02991], that efficiently reduces a vast array of Hamiltonians to the XY-interaction on a square lattice; and the third is a method developed herein to reverse the direction of an applied time evolution while keeping the error comparable. The end result is a scalable protocol for quantum verification, well suited to near term usage.

Keywords: quantum verification, analogue quantum simulators, quantum accreditation, scalability
Type: Theory

[27] *Quantum Simulation of Polarized Light-Induced Electron Transfer with a Trapped-Ion Qutrit System*

Ke Sun (Duke University), Chao Fang (Duke University), Mingyu Kang (Duke University), Zhendian Zhang (Duke University), Peng Zhang (Duke University), David Beratan (Duke University), Kenneth Brown (Duke University) and Jungsang Kim (Duke University; IonQ Inc.)

Abstract: Electron transfer within and between molecules is crucial in chemistry, biochemistry, and energy science. This study describes a quantum simulation method that explores the influence of light polarization on electron transfer between two molecules. By implementing precise and coherent control among the quantum states of trapped atomic ions, we can induce quantum dynamics that mimic the electron-transfer dynamics in molecules. We use three-level systems (qutrits), rather than traditional two-level systems (qubits), to enhance the simulation efficiency and realize high-fidelity simulations of electron-transfer dynamics. We treat the quantum interference between the electron coupling pathways from a donor with two degenerate excited states to an acceptor and analyze the transfer efficiency. We also examine the potential error sources that enter the quantum simulations. The trapped-ion systems have favorable scalings with system size compared to those of classical computers, promising access to richer electron-transfer simulations.

Keywords: Qutrits, Electron transfer, Trapped ion
Type: Experiment

[28] *Soliton Versus Single Photon Quantum Dynamics in Arrays of Superconducting Qubits*

Ben Blain (Technology Innovation Institute (TII), Giampiero Marchegiani (Technology Innovation Institute (TII), Juan Polo (Technology Innovation Institute (TII), Gianluigi Catelani (Technology Innovation Institute (TII) and Luigi Amico (Technology Innovation Institute (TII)

Abstract: Superconducting circuits constitute a promising platform for future implementation of quantum processors and simulators. Arrays of capacitively coupled transmon qubits naturally implement the Bose-Hubbard model with attractive on-site interaction. The spectrum of such many-body systems is characterised by low-energy localised states defining the lattice analog of bright solitons. Here, we demonstrate that these bright solitons can be pinned in the system, and we find that a soliton moves while maintaining its shape. Its velocity obeys a scaling law in terms of the combined interaction and number of constituent bosons. In contrast, the source-to-drain transport of photons through the array occurs through extended states that have higher energy compared to the bright soliton. For weak coupling between the source/drain and the array, the populations of the source and drain oscillate in time; for chains of even length, their population remains low at all times, while it can reach half the number of total bosons in odd chains. Implications of our results for actual experimental realisations are discussed.

arXiv:2212.06627 [quant-ph]

Keywords: soliton, superconducting circuits, transmon, transport, boson, photon, dynamics, Bose-Hubbard model
Type: Theory

[29] *Measurement Induced Phase Transition in Random Quantum Circuits with Various Measurement Models*

Kemal Aziz (Rutgers University), Jed Pixley (Rutgers University) and Ahana Chakraborty (Rutgers University)

Abstract: Competition between entangling dynamics and collapsing measurements in quantum many-body systems can induce a Measurement Induced Phase Transition (MIPT) between phases with distinct entanglement structure. MIPTs in random quantum circuits are described by non-unitary Conformal Field Theories (CFTs) with central charge c=0. We study the properties of these CFTs in Haar Dual Unitary circuits subject to various measurement models by computing the Lyapunov exponents, central effective charge, and bulk critical exponents. Specifically, we compute these quantities in two models of weak measurements, a measuring device modeled as a continuous Gaussian probe and a softened version of the standard projective measurement, at various measurement strengths. We find that circuits undergoing softening measurements are within the same universality class of those with projective measurements (to our numerical accuracy), whereas we cannot rule out that Gaussian measurements belong to a distinct universality class. We also study circuits with open boundaries and a dephasing channel at a boundary spin, allowing us to extract the surface free energies and largest conformal weight associated with corrections to the free energy density of an infinite strip.

Keywords: Measurement Induced Phase Transition, Open Quantum Systems, Weak Measurements, Random Quantum Circuits, Conformal Field Theory
Type: Theory

[30] *Leveraging Code-Switching techniques for an Efficient Variational Hamiltonian Ansatz*

Abhinav Anand (Duke University) and Kenneth Brown (Duke University)

Abstract: Efficiently simulating the dynamics of Hamiltonians given as sums of Pauli operators is a crucial task in quantum computing. While various methods have been proposed to reduce the complexity of quantum circuits for Hamiltonian simulation, there remains room for further improvement. In this study, we introduce a novel circuit design inspired by code switching to further reduce the circuit complexity of Hamiltonian simulation. Our approach involves partitioning the Pauli operators into mutually commuting clusters and finding Clifford unitaries that diagonalize each cluster. We then design an ansatz that uses these Clifford unitaries for efficient switching between the clusters, complemented by a layer of parameterized single qubit rotations for each individual cluster. By conducting numerical simulations, we demonstrate the effectiveness of our method in accurately determining the ground state energy of different quantum chemistry Hamiltonians. Our results highlight the applicability and potential of our approach for designing problem-inspired ansatz for various quantum computing applications.

Keywords: Hamiltonian Simulation, Variational Quantum Algorithm, Variational Hamiltonian Ansatz
Type: Theory

[31] *Simulating Energy Transport with a Problem-Tailored Trace Estimator: Application on Noisy Quantum Computers*

I-Chi Chen (Iowa State University), Klee Pollock (Iowa State University), Yong-Xin Yao (Ames National Laboratory), Peter Orth (Saarland University) and Thomas Iadecola (Iowa State University)

Abstract: The high-temperature transport of conserved quantities like spin and charge in strongly interacting quantum many-body systems is a topic of substantial recent theoretical investigation. One important open question is to understand the timescales for the emergence of hydrodynamic behavior, as quantified by the dynamical critical exponent z. The transport of energy, however, has been much less well studied, even though it is the most generic conserved quantity in Hamiltonian dynamics and is therefore of fundamental importance in studying such dynamics with local probes. We study the infinite-temperature transport of energy in the mixed-field Ising model using cloud-accessible superconducting quantum processors and classical simulation techniques. Instead of preparing Haar-random states to sample from the infinite-temperature distribution, which requires deep quantum circuits, we compute dynamics for a small ensemble of product states with zero energy expectation value. Using both generic and problem-tailored quantum error mitigation techniques, we obtain results for the dynamical exponent that are consistent with classical simulations.

Keywords: Quantum dynamics, Quantum simulation, Quantum transport
Type: Theory

[32] *Linear Combination of Hamiltonian Simulation for Non-Unitary Dynamics With Optimal State Preparation Cost*

Dong An (University of Maryland), Jin-Peng Liu (University of California, Berkeley) and Lin Lin (University of California, Berkeley)

Abstract: We propose a simple method for simulating a general class of non-unitary dynamics as a linear combination of Hamiltonian simulation (LCHS) problems. LCHS does not rely on converting the problem into a dilated linear system problem, or on the spectral mapping theorem. The latter is the mathematical foundation of many quantum algorithms for solving a wide variety of tasks involving non-unitary processes, such as the quantum singular value transformation. The LCHS method can achieve optimal cost in terms of state preparation. We also demonstrate an application for open quantum dynamics simulation using the complex absorbing potential method with near-optimal dependence on all parameters.

Keywords: Quantum ODE algorithm, Hamiltonian simulation, Open quantum system
Type: Theory

[33] *Doping an Antiferromagnet: From hole pairing to stripe formation*

Timon Hilker (Max Planck Institute of Quantum Optics)

Abstract: Unraveling the origins of unconventional superconductivity and charge order in doped antiferromagnets is one of the driving forces behind quantum simulations with Fermions in optical lattices. In these strongly correlated materials, the frustration between hole motion and magnetic order can generate an attraction between hole dopants leading to the pairing of holes and the formation of stripes.

With our lithium quantum gas microscope, we implement Hubbard models with a large control over system parameters and parallel spin- and density-resolved read-out on every site. Here, I am presenting our recent observation of hole pairs and signatures of stripes in mixed-dimensional systems. This setting, where hole motion is restricted to one dimension while spin order is two-dimensional, boosts interaction effects by reducing kinetic energy. We observe a strong attraction between pairs of holes and study 3rd and 4th-order correlation functions between spins and holes probing the properties of the emerging stripes. The underlying optical superlattice, in addition, provides a promising starting point for quantum gates.

Keywords: Neutral atoms in Optical lattices, Fermi Hubbard model, Magnetism, Doping, Charge order, High-temperature superconductivity
Type: Experiment

[34] *FermiQP- A Fermion Quantum Processor*

Andreas von Haaren (Max Planck Institute of Quantum Optics), Robin Groth (Max Planck Institute of Quantum Optics), Janet Qesja (Max Planck Institute of Quantum Optics), Maximilian Schattauer (Max Planck Institute of Quantum Optics), Er Zu (Max Planck Institute of Quantum Optics), Gleb Neplyakh (Max Planck Institute of Quantum Optics), Immanuel Bloch (Max Planck Institute of Quantum Optics), Timon Hilker (Max Planck Institute of Quantum Optics) and Philipp Preiss (Max Planck Institute of Quantum Optics)

Abstract: FermiQP is a demonstrator for a novel approach to combine quantum simulation and computation on a single platform, using ultracold fermionic lithium in an optical lattice.

In its analog mode, it will operate as a quantum simulator for the Fermi-Hubbard model with additional control over the starting configuration. As a quantum-gas-microscope, the experiment will feature single-site-resolved imaging and spin-resolved state detection.

In the digital mode, it will serve as a fully programmable quantum computer with single qubit gates implemented as Raman rotations between hyperfine states and controlled collisions between atoms in the superlattice as two-qubit gates. Tweezer-based resorting techniques will enable entangling operations across the entire lattice.

We are building the experiment using a single-chamber design with the goal of reducing cycle times.

Keywords: Ultracold atoms, Quantum simulation, Quantum computation, Hybrid quantum computation, Fermi-Hubbard model
Type: Experiment

SESSION 2: THURSDAY, AUGUST 10

[35] *Towards Near-Term Quantum Simulation of Materials*

Laura Clinton (Phasecraft Ltd.), Toby Cubitt (Phasecraft Ltd.), Brian Flynn (Phasecraft Ltd.), Filippo Maria Gambetta (Phasecraft Ltd.), Joel Klassen (Phasecraft Ltd.), Ashley Montanaro (Phasecraft Ltd.), Stephen Piddock (Phasecraft Ltd.), Raul A. Santos (Phasecraft Ltd.) and Evan Sheridan (Phasecraft Ltd.)

Abstract: Simulation of materials is one of the most promising applications of quantum computers. On near-term hardware the crucial constraint on these simulations is circuit depth. Many quantum simulation algorithms rely on a layer of unitary evolutions generated by each term in a Hamiltonian. This appears in time-dynamics as a single Trotter step, and in variational quantum eigensolvers under the Hamiltonian variational ansatz as a single ansatz layer. We present a new quantum algorithm design for materials modelling where the depth of a layer is independent of the system size. This design takes advantage of the locality of materials in the Wannier basis and employs a tailored fermionic encoding that preserves locality. We analyse the circuit costs of this approach and present a compiler that transforms density functional theory data into quantum circuit instructions -- connecting the physics of the material to the simulation circuit. The compiler automatically optimises circuits at multiple levels, from the base gate level to optimisations derived from the physics of the specific target material. We present numerical results for materials spanning a wide structural and technological range. Our results demonstrate a reduction of many orders of magnitude in circuit depth over standard prior methods that do not consider the structure of the Hamiltonian. For example our results improve resource requirements for Strontium Vanadate (SrVO_3) from 864 to 180 qubits for a 3x3x3 lattice, and the circuit depth of a single Trotter or variational layer from 7.5x10^8 to depth 884. Although this is still beyond current hardware, our results show that materials simulation may be feasible on quantum computers without necessarily requiring scalable, fault-tolerant quantum computers, provided quantum algorithm design incorporates understanding of the materials and applications.

Keywords: quantum simulation, variational quantum eigensolver, time dynamics simulation, correlated electronic systems, material science
Type: Theory

[36] *Tiling the Way to Large Scale Quantum Simulation of Spin Lattices*

Karunya Shailesh Shirali (Department of Physics, Virginia Tech), John S Van Dyke (Department of Physics, Virginia Tech), George S. Barron (Department of Physics, Virginia Tech), Nicholas J. Mayhall (Department of Chemistry, Virginia Tech), Edwin Barnes (Department of Physics, Virginia Tech) and Sophia E. Economou (Department of Physics, Virginia Tech)

Abstract: Quantum computers are a natural platform for studying many-body interacting electronic systems due to their ability to access an exponential space of states compared to classical computers. Adaptive variational quantum simulation algorithms dynamically construct wavefunction ansätze from a pool of operators tailored to the problem Hamiltonian. The operator pool is vital to the efficiency and scalability of the calculations, since it constitutes the set of building blocks from which the wavefunction is built. We present the operator tiling technique to design efficient operator pools for strongly correlated lattice Hamiltonians for arbitrarily large problem instances. We run an adaptive variational calculation on a small instance of the problem using a large, computationally inefficient operator pool and `tile' the operators chosen by the algorithm to build efficient pools for larger problem instances. This technique makes use of the natural translation symmetry in many condensed matter physics problems. We demonstrate this technique on one and two dimensional quantum spin systems, and show that the resulting state preparation circuits are significantly shorter compared to existing methods.

Keywords: adaptive variational calculation, strongly correlated, scalable quantum simulation, quantum spin model
Type: Theory

[37] *Potential Quantum Advantage for Simulation of Fluid Dynamics*

Xiangyu Li (Pacific Northwest National Laboratory), Xiaolong Yin (Colorado School of Mines), Nathan Wiebe (University of Toronto), Jaehun Chun (Pacific Northwest National Laboratory), Gregory K Schenter (Pacific Northwest National Laboratory), Margaret S Cheung (Pacific Northwest National Laboratory) and Johannes Heinrich Georg Muelmenstaedt (Pacific Northwest National Laboratory)

Abstract: Numerical simulation of turbulent fluid dynamics needs to either parameterize turbulence—which introduces large uncertainties—or explicitly resolve the smallest scales—which is prohibitively ex- pensive. Here we provide evidence through analytic bounds and numerical studies that a potential quantum exponential speedup can be achieved to simulate the Navier–Stokes equations governing turbulence using quantum computing. Specifically, we provide a formulation of the lattice Boltz- mann equation for which we give evidence that low-order Carleman linearization is much more accurate than previously believed for these systems and that for computationally interesting exam- ples. This is achieved via a combination of reformulating the nonlinearity and accurately linearizing the dynamical equations, effectively trading nonlinearity for additional degrees of freedom that add negligible expense in the quantum solver. Based on this we apply a quantum algorithm for simu- lating the Carleman-linerized lattice Boltzmann equation and provide evidence that its cost scales logarithmically with system size, compared to polynomial scaling in the best known classical algo- rithms. This work suggests that an exponential quantum advantage may exist for simulating fluid dynamics, paving the way for simulating nonlinear multiscale transport phenomena in a wide range of disciplines using quantum computing.

Keywords: Navier-Stokes equation, Carleman linearization, quantum PDE solver, quantum advantage
Type: Theory

[38] *Isometric Tensor Network Optimization for Extensive Hamiltonians Has No Barren Plateaus*

Qiang Miao (Duke University)

Abstract: There are no barren plateaus in the energy optimization of isometric tensor network states (TNSs) for extensive Hamiltonians with finite-range interactions. Specifically, we consider matrix product states, tree tensor network states, and the multiscale entanglement renormalization ansatz. The variance of the energy gradient, evaluated by taking the Haar average over the TNS tensors, has a leading system-size independent term and decreases according to a power law in the bond dimension χ. For a hierarchical TNS with branching ratio b, the variance of the gradient with respect to a tensor in layer τ scales as $(b\eta)^\tau$, where η is the second largest eigenvalue of the Haar-average doubled layer-transition channel and decreases algebraically with increasing bond dimension. The scaling properties bear implications for efficient initialization.

Keywords: Barren plateaus, Tensor network states, Extensive Hamiltonians
Type: Theory

[39] *Network-Based Methods to Assess Robustness of Neural Quantum States*

Brandon Barton (Colorado School of Mines), Cecilia Diniz Behn (Colorado School of Mines), Lincoln Carr (Colorado School of Mines) and Zhe-Xuan Gong (Colorado School of Mines)

Abstract: We investigate an original application of graph theory and complex network analysis to assess the robustness of neural network quantum states. To demonstrate our methods, we focus on understanding the performance of restricted Boltzmann machine neural networks used to approximate ground states of the transverse field Ising model. Specifically, we analyze several neural network parameters, including complex-valued bias vectors and the weight matrix, both during the learning process and across critical parameters in the Hamiltonian. During training, we observe a correlation between the model's accuracy and the natural connectivity of the weight matrix, a spectral graph measure of connectedness that serves as a network robustness measure. Furthermore, our analysis of the neural network's parameters and underlying graph structure across the quantum phase transition enables us to characterize the model's ordered and disordered phases. These findings contribute to understanding important structural features in neural networks used to approximate quantum many-body states.

Keywords: Neural Quantum States, Graph Analysis, Complex Systems
Type: Theory

[40] *Quantum Simulations of Hamiltonian Dynamics*

Michelle Wynne Sze (Quantinuum), Nathan Fitzpatrick (Quantinuum) and David Muñoz Ramo (Quantinuum)

Abstract: Quantum electrodynamics plays a significant role in understanding molecular interactions. We exploit the recent developments in quantum computing, which may aid classical computational chemistry and physics, to study systems of light-matter interaction — Jaynes-Cummings and Fermi-Hubbard. We demonstrate the implementation of two quantum algorithms to simulate Hamiltonian dynamics, where the initial step is to transform the Hamiltonian H in Pauli terms. First is the Trotter-Suzuki method where the total time evolution operator exp{-iHt} is expressed as a sequence of shorter time-step operators exp{-iHdt}. The second method expands the exp{-iHt} as a Taylor series up to some order, decomposing it as a linear combination of unitaries (LCU). Considering the compute resources and errors, we find that in some systems the LCU method provides better advantage when studying long-time dynamics over Trotter which may do as well only for short-time dynamics.

Keywords: Trotter, LCU, Quantum simulations, Dynamics
Type: Theory

[41] *A Sharp Phase Transition in Linear Cross-Entropy Benchmarking*

Brayden Ware (Joint Quantum Institute, NIST/University of Maryland), Abhinav Deshpande (California Institute of Technology, Pasadena), Dominik Hangleiter (Joint Center for Quantum Information and Computer Science, NIST/University of Maryland), Pradeep Niroula (Joint Center for Quantum Information and Computer Science, NIST/University of Maryland), Bill Fefferman (Department of Computer Science, University of Chicago), Alexey Gorshkov (Joint Quantum Institute, NIST/University of Maryland) and Michael Gullans (Joint Center for Quantum Information and Computer Science, NIST/University of Maryland)

Abstract: Demonstrations of quantum computational advantage and benchmarks of quantum processors via quantum random circuit sampling are based on evaluating the linear cross-entropy benchmark (XEB). A key question in the theory of XEB is whether it approximates the fidelity of the quantum state preparation.

Previous works have shown that the XEB generically approximates the fidelity in a regime where the noise rate per qudit scales inversely with the number of qudits, and that this approximation breaks down for sufficiently large noise rates. Here, we show that the breakdown of XEB as a fidelity proxy occurs as a sharp, first-order phase transition that occurs at a critical value of the total noise rate. We study this transition using a mapping of second moment properties of random circuits to observables in Ising-like statistical mechanics models and provide a simple explanation for the transition in terms of the spectral properties of the transfer matrix.

Keywords: Linear cross-entropy benchmarking, Random circuit sampling, Phase transition
Type: Theory

[42] *Quantum Simulation with Rydberg Qutrits*

Toonyawat Angkhanawin (Department of Physics, Durham University)

Abstract: Recently, it has been shown that Rydberg atoms can be driven between different Rydberg levels by using microwave lasers. Due to its strong long range dipole-dipole interaction, Rydberg atom has been claimed as one of the most potential platform for quantum simulations with relatively high fidelity. Besides, the Rydberg atoms and their interaction can be used to study many-body phenomena such as quantum phase transition, many-body localization and quantum chaos, etc. We probe the quantum phase by identifying the degeneracy of ground state, calculating the Rydberg probability for each atom in the cluster and computing the density-density correlation. The results has discovered that the system of finite number of atoms can exhibit something called “the finite size effect”. We can reduced such an effect by using the sine deformation of interatomic distance. In addition, It also has been shown that the periodic boundary condition can reduced such an effect efficiently.

Keywords: Quantum simulations, Quantum information, Many-body quantum systems, Rydberg atoms
Type: Theory

[43] *Hardware-Efficient Learning of Quantum Many-Body States*

Katherine Van Kirk (Department of Physics, Harvard University), Jordan Cotler (Department of Physics, Harvard University), Hsin-Yuan Huang (Institute for Quantum Information and Matter and Department of Computing and Mathematical Sciences, Caltech) and Mikhail Lukin (Department of Physics, Harvard University)

Abstract: Efficient characterization of highly entangled multi-particle systems is an outstanding challenge in quantum science. Recent developments have shown that a modest number of randomized measurements suffices to learn many properties of a quantum many-body system. However, implementing such measurements requires complete control over individual particles, which is unavailable in many experimental platforms. In this work, we present rigorous and efficient algorithms for learning quantum many-body states in systems with any degree of control over individual particles, including when every particle is subject to the same global field and no additional ancilla particles are available. We numerically demonstrate the effectiveness of our algorithms for estimating energy densities in a U(1) lattice gauge theory and classifying topological order using very limited measurement capabilities.

Keywords: Tomography of quantum many-body systems, Learning Theory, Classical Shadow Tomography, Machine Learning
Type: Theory

[44] *A Novel Approach to Sparsity in Quantum Simulations*

Srikar Chundury (North Carolina State University), In-Saeng Suh (Oak Ridge National Laboratory) and Frank Mueller (North Carolina State University)

Abstract: 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.

Keywords: Quantum circuit simulation, State vector simulation, Tensor network simulation, Memory footprint, Sparsity patterns, Diagonal format, Unitary matrices, Chain matrix multiplication, Runtime, Memory utilization, Dense formats
Type: Experiment

[45] *Synthesis of Approximate Parametric Circuits for Variational Quantum Algorithms*

Blake Burgstahler (North Carolina State University), Frank Mueller (North Carolina State University) and Scott Pakin (Los Alamos National Laboratory)

Abstract: This work develops a novel approach to exploit synthesized, approximate circuits for the ansatz of variational quantum algorithms (VQA) and demonstrates its effectiveness for NchooseK, a domain-specific language supporting quantum-based solving of constraint-based problems. Synthesis is generalized to produce parametric circuits of short depth in close approximation of the original circuit offline. This removes synthesis from the critical path (online) between repeated quantum circuit executions of VQA while reducing circuit depth, thereby resulting in higher fidelity results than the baseline without synthesis. Simulation (noise-free and noisy) indicate improvements of 98% on average and at best obtaining viable solutions when the baseline could not, all with an average change in depth of less than 15%.

Keywords: Algorithms, VQA, Synthesis, Noise-reduction
Type: Experiment

[46] *Solving Relativistic Bound-State Problems in QCD with a Fault-Tolerant Quantum Computer*

Mason Rhodes (Sandia National Laboratories), Michael Kreshchuk (Lawrence Berkeley National Laboratory) and Andrew Landahl (Sandia National Laboratories)

Abstract: We show how to use a fault-tolerant quantum computer to solve relativistic bound-state problems in ab initio (3+1)D quantum chromodynamics (QCD) non-perturbatively. We use a formulation of QCD in a frame of reference moving at the speed of light (the "light front frame") to simplify the relevant calculations. To showcase our approach, we work out a detailed resource estimate for the T-count complexity for the problem of predicting the mass of a specified hadron. We apply our estimates to a variety of hadronic particles, including the color-flavor-spin singlet sexaquark (udsuds), a particle that could be the source of dark matter if its mass is in the range of 1870 to 1890 MeV/c2, as argued by Farrar, Wang, and Xu. Computing the mass of this particle, whose size is predicted to be an extremely compact 0.1 fm because of all the symmetries it possesses, is beyond the reach of the best classical computers today using lattice gauge theory methods.

Keywords: Fault-tolerant quantum computing, Ground state energy estimation, Light-front quantization, QCD, Dark Matter
Type: Theory

[47] *Composite QDrift-Product Formulas for Quantum and Classical Simulations in Real and Imaginary Time*

Matthew Pocrnic (University of Toronto), Matthew Hagan (University of Toronto), Dvira Segal (University of Toronto), Nathan Wiebe (University of Toronto) and Juan Carrasquilla (Vector Institute and University of Toronto)

Abstract: Recent work (Hagan and Wiebe, 2022) has shown that it can be advantageous to implement a composite channel that partitions the Hamiltonian H for a given simulation problem into subsets A and B such that $H=A+B$, where the terms in A are simulated with a Trotter-Suzuki channel and the B terms are randomly sampled via QDrift. Here we show that this approach holds in imaginary time, making it a candidate classical algorithm for quantum Monte-Carlo calculations. We upper-bound the diamond distance on both imaginary-time QDrift and Composite channels. Another recent result (Haah et. al, 2021) demonstrated that simulation of Hamiltonians containing geometrically local interactions for systems defined on a finite lattices can be improved by decomposing H into subsets that contain only terms supported on that subset of the lattice using a Lieb-Robinson argument. Here, we provide a quantum algorithm by unifying this with the composite approach into ``local composite channels" and upper bound the diamond distance. We provide exact numerical simulation cost analysis on these algorithms by counting the number of gates of the form $e^{-iH_j t}$ and $e^{-H_j \beta}$ to meet a certain error tolerance ϵ.

Keywords: quantum simulation, quantum algorithms, quantum monte carlo, classical simulation of quantum
Type: Theory

[48] *Quantum Monte Carlo simulations of Rydberg Atom Arrays*

Ejaaz Merali (University of Waterloo) and Roger Melko (University of Waterloo)

Abstract: Arrays of Rydberg atoms are a powerful platform to realize strongly-interacting quantum many-body systems. A common Rydberg Hamiltonian is free of the sign problem, meaning that its equilibrium properties are amenable to efficient simulation by quantum Monte Carlo (QMC). In this paper, we develop a Stochastic Series Expansion QMC algorithm for Rydberg atoms interacting on arbitrary lattices. We describe a cluster update that allows for the efficient sampling and calculation of physical observables for typical experimental parameters, and show that the algorithm can reproduce experimental results on large Rydberg arrays in one and two dimensions. We will also discuss limitations of this scheme, particularly on some frustrated lattices where glassy behavior has recently been detected, as well as efficiency comparisons against experimental setups as the system size grows. Finally, we will show recent work developing more effective QMC methods to simulate large Rydberg arrays.

Keywords: quantum monte carlo, rydberg atom arrays, exact simulations
Type: Theory

[49] *Going Beyond Gadgets: The Importance of Scalability for Analogue Quantum Simulators*

Dylan Harley (University of Copenhagen), Ishaun Datta (Stanford University), Frederik Ravn Klausen (University of Copenhagen), Andreas Bluhm (Univ. Grenoble Alpes), Daniel Stilck França (Univ. Lyon), Albert Werner (University of Copenhagen) and Matthias Christandl (University of Copenhagen)

Abstract: We propose a theoretical framework for analogue quantum simulation to capture the full scope of experimentally realisable simulators, motivated by a set of fundamental criteria first introduced by Cirac and Zoller. Our framework is consistent with Hamiltonian encodings used in complexity theory, is stable under noise, and encompasses a range of possibilities for experiment, such as the simulation of open quantum systems and overhead reduction using Lieb-Robinson bounds. We discuss the requirement of scalability in analogue quantum simulation, and in particular argue that simulation should not involve interaction strengths that grow with the size of the system. We develop a general framework for gadgets used in Hamiltonian complexity theory, which may be of interest independently of analogue simulation, and in particular prove that size-dependent scalings are unavoidable in Hamiltonian locality reduction. However, if one allows for the additional resource of intermediate measurements, we demonstrate a scheme that circumvents the locality reduction no-go theorem using the quantum Zeno effect. Our gadget framework opens the door to formalise and resolve long-standing open questions about gadgets. We conclude with a discussion on universality results in analogue quantum simulation.

Keywords: analogue, analog, gadget, scalability, quantum channels, framework, Hamiltonian complexity theory, Lieb-Robinson, Quantum Zeno effect, Universality
Type: Theory

[50] *Autotuning Quantum Dot Devices in the Slow Tunneling Regime via Reinforcement Learning*

Chanung Park (Department of Physics and Astronomy, Seoul National University), Kyunghoon Jung (Department of Physics and Astronomy, Seoul National University) and Dohun Kim (Department of Physics and Astronomy, Seoul National University)

Abstract: As a quantum computing platform, quantum dot (QD) devices have their strength in scalability, but the complexity of their tuning increases with the number of QDs. Recently, autotuning methods using machine learning have been suggested to handle this task, with some successful results, but mostly considered single or double QD devices. Here, we consider autotuning of three or more QD devices. For three or more QDs, “latching” may happen when the tunneling time of electron is large compared to the gate voltage scanning time. We simulate QD devices with latching to draw their stability diagrams. Using the stability diagram dataset, we train a neural network by reinforcement learning to auto-tune quantum dot devices.

Keywords: Quantum dot, Autotuning, Reinforcement learning
Type: Experiment

[51] *Improved Quantum Carleman Solver*

Pedro C.S. Costa* (Centre for Quantum Technology, Transport for New South Wales and Macquarie University), Philipp Schleich* (University of Toronto and Macquarie University), Mauro E.S. Morales (University of Technology Sydney), Dominic W. Berry (Macquarie University)

*=equal contribution

Abstract: The solution of nonlinear differential equations is of large interest to the general scientific community. In this study, we present several improvements on existing algorithms based on the Carleman linearisation technique.

By using a high-precision technique for the solution of the linearised differential equations, we achieve, up to constant factors, logarithmic dependence of the complexity on the error and linear dependence on time. We further thoroughly discuss a rescaling technique which can considerably reduce the cost of amplitude amplification in the case of high-order nonlinearities and we provide new error bounds on Carleman linearisation in the rescaled dynamics. We apply our results on a class of discretised reaction-diffusion equations using higher-order finite differences for the spatial resolution.

As in the case of linear differential equations, we can expect an exponential improvement over classical approaches in the scaling with respect to the dimension.

Keywords: quantum simulation, quantum chemistry, fault-tolerant quantum simulation algorithms
Type: Theory

[52] *Probing Quantum Fluids Through Manybody Ramsey Interferometry.*

Gabrielle Roberts (University of Chicago), Andrei Vrajitoarea (University of Chicago), David Schuster (Stanford University) and Jonathan Simon (Stanford University)

Abstract: A central challenge of modern quantum science is understanding strongly correlated quantum matter. Inspired by Feynman, one way to approach the problem is to recreate the physics of interest in pristine analog quantum simulators. In recent years, superconducting circuits have proven to be a rich testbed for modeling and probing many-body phenomena. We construct and characterize strongly interacting quantum fluids in a 1D Bose-Hubbard circuit consisting of capacitively coupled transmon qubits. We deterministically prepare fluid eigenstates of our system using particle-by-particle assembly and adiabatic control of lattice site detuning. This state preparation technique is reversible; combining it with a many-body interferometry experiment, we prepare cat states of quantum fluids, and then localize the information about energy differences of these highly entangled and delocalized states into one qubit for measurement. We then use this manybody Ramsey to explore the system's thermodynamic properties, probing the chemical potential and compressibility of the fluids at different filling fractions.

Keywords: superconducting circuits, Bose-Hubbard, quantum fluid, transmon qubits
Type: Experiment

[53] *Uncovering Local Quasi-Integrability in Quantum Many-Body Dynamics*

Oles Shtanko (IBM Quantum), Derek Wang (IBM Quantum), Haimeng Zhang (IBM Quantum), Nikhil Harle (IBM Quantum), Alireza Seif (IBM Quantum), Ramis Movassagh (IBM Quantum) and Zlatko Minev (IBM Quantum)

Abstract: The quantum dynamics of interacting many-body systems is difficult to simulate and understand. However, the intricacies of these complex systems can be unraveled by discovering symmetries, conservation laws, and integrability. Here, using up to 124 qubits of a fully programmable quantum computer, we uncover local integrability in one- and two-dimensional Floquet spin lattices in a regime previously inaccessible to such detailed analysis. We first verify the existence of a disorder-induced ergodicity-breaking regime, in which charge transport is localized, via an anomaly in the spectrum of the one-particle density matrix. We then demonstrate that this localized regime stems from hidden local integrals of motion, which we faithfully reconstruct, providing a detailed portrait of the integrable dynamics of the system. Our results demonstrate a general strategy for extracting valuable information from large-scale quantum simulations on noisy quantum computers.

Keywords: local integrals of motion, quantum simulation, Floquet dynamcis, noisy quantum devices, superconducting qubits
Type: Experiment

[54] *Estimating Eigenenergies from Quantum Dynamics: A Unified Noise-Resilient Measurement-Driven Approach*

Yizhi Shen (Lawrence Berkeley National Laboratory), Daan Camps (Lawrence Berkeley National Laboratory), Aaron Szasz (Lawrence Berkeley National Laboratory), Siva Darbha (Lawrence Berkeley National Laboratory), Katherine Klymko (Lawrence Berkeley National Laboratory), David Williams–young (Lawrence Berkeley National Laboratory), Norm Tubman (NASA Ames Research Center) and Roel Van Beeumen (Lawrence Berkeley National Laboratory)

Abstract: Ground state energy estimation in physics and chemistry is one of the most promising applications of quantum computing. In this paper, we introduce a novel measurement-driven approach that finds eigenenergies by collecting real-time measurements and post-processing them using the machinery of dynamic mode decomposition (DMD). We provide theoretical and numerical evidence that our method converges rapidly even in the presence of noise and show that our method is isomorphic to matrix pencil methods developed independently across various scientific communities. Our DMD-based strategy can systematically mitigate perturbative noise and stands out as a promising hybrid quantum-classical eigensolver.

Keywords: Quantum algorithms and computation, Quantum algorithms for chemical calculations, Quantum simulation
Type: Theory

[55] *Realizing an Exactly Solvable Spin Chain with Trapped Yb-171+*

Emma Stavropoulos (Duke Quantum Center, Duke University, Durham, NC 27701; Department of Physics, Duke University, Durham, NC 27708), Will Morong (Joint Quantum Institute, University of Maryland and NIST, College Park, MD 20742), Katherine Collins (Joint Quantum Institute, University of Maryland and NIST, College Park, MD 20742), Arinjoy De (Duke Quantum Center, Duke University, Durham, NC 27701; JQI, University of Maryland and NIST, College Park, MD 20742), Tianyu You (Duke Quantum Center, Duke University, Durham, NC 27701; Dept of Elec and Comp Eng, Duke University, Durham, NC 27708), Alexander Kozhanov (Duke Quantum Center, Duke University, Durham, NC 27701; Dept of Elec and Comp Eng, Duke University, Durham, NC 27708) and Christopher Monroe (Duke Quantum Center, Duke; Dept of Physics, Duke; JQI, UMD/NIST; Dept of ECE, Duke; IonQ Inc., College Park, MD 20740)

Abstract: We simulate spin chains in a controllable Yb-171+ trapped ion platform. Increasing the Mølmer-Sørensen detuning adjusts the spin-spin interaction in an Ising-like Hamiltonian that obeys power-law decay (r^(-α)). Trotterization and Floquet engineering generate average Hamiltonians for n=2 and n=3 spin components (XY and Heisenberg-like models respectively). On four ions, we select an inverse square law regime (α=2) to realize the Haldane-Shastry model, a quantum integrable Heisenberg-like chain. Additionally, dynamical decoupling enhances coherence by averaging out noise via global pulses.

Keywords: trapped ion, spin chain, quantum simulation, Ytterbium, Yb-171+, Haldane-Shastry, Heisenberg model, dynamical decoupling, Floquet engineering, long-range, exactly solvable, quantum integrable
Type: Experiment

[56] *DMRG Study of t-J Excitons*

Nicholas Pomata (University of Maryland College Park), Christopher Baldwin (University of Maryland College Park) and Mohammad Hafezi (University of Maryland College Park)

Abstract: We apply DMRG on the excitonic charge sector to determine the properties of an excitonic bound state in the t-J model on the square lattice. Using finite-size calculations on a cylinder of with 6, we estimate the gap for several values of the coupling. We additionally investigate the corresponding Fermi-Hubbard systems and consider the parallel problem on an infinite cylinder.

Keywords: exciton, DMRG, bound state, t-J model, Mott insulator, matrix product state, antiferromagnetism
Type: Theory

[57] *Extended Reservoir Approach for Quantum Transport and non-Markovian Dynamics*

Gabriela Wojtowicz (Jagiellonian University), Marek M. Rams (Jagiellonian University), Michael Zwolak (National Institute of Standards and Technology) and Justin Elenewski (MIT Lincoln Laboratory)

Abstract: Recent progress in semiconductor technology brings attention to quantum transport in fermionic systems. Quantum transport is a paradigm example of a non-equilibrium process induced by the environment. However, it is extremely difficult to study analytically and numerically due to infinitely large systems and the non-negligible memory effect. Efficient research of quantum transport requires effective numerical approximations.

Extended reservoirs enable addressing strong coupling and non–linear response for non-Markovian environments. It provides a framework for capturing macroscopic environments, such as metallic electrodes, which drive a current through a finite lattice.

I will discuss and comment on the approach in the context of tensor network methods.

Keywords: quantum transport, fermionic model, non-Markovian effects, extended reservoir approach, non-equilibrium steady state, tensor networks, strong coupling
Type: Theory

[58] *Capturing the Quantum Phases of Matter Realized on a 256-Atom Rydberg Array with Data-Enhanced Variational Monte Carlo*

Megan Moss (University of Waterloo, Perimeter Institute), Sepehr Ebadi (Harvard University), Annabelle Bohrdt (Harvard University) and Roger Melko (University of Waterloo, Perimeter Institute)

Abstract: Programmable Rydberg atom arrays are a fast-emerging quantum platform, bringing together long coherence times, high-fidelity operations, and large numbers of interacting qubits deterministically arranged in flexible geometries. Today's Rydberg array devices are already demonstrating their utility as quantum simulators for studying phases and phase transitions in quantum matter. In this paper, we show that unprocessed experimental data from projective measurements in the Rydberg occupation basis can be used to enhance in silico simulations of quantum matter, by improving the performance of variational Monte Carlo simulations. Using powerful autoregressive wavefunctions based on recurrent neural networks (RNNs), we focus on data for across the disordered-to-checkerboard transition in a 16x16 square lattice array [S. Ebadi et al. Nature 595, 227–232 (2021)]. We find that unsupervised pre-training on experimental data provides a robust improvement in convergence time for an RNN wavefunction subsequently trained through the variational principle, despite real-world noise in the experimental data. Our work hints at the promise of autogregessive language models like the RNN, which can be optimized both from experimental data as well as through a Hamiltonian-guided variational loss function. In addition to using today's quantum computing outputs to provide value for problems of practical interest to the condensed matter and quantum information communities, this hybrid strategy will be well-suited to leverage data from even larger devices with limited measurement shot rates in the near future.

Keywords: Quantum Simulation, Rydberg Atom Arrays, Quantum Phase Transition, Machine Learning, Variational Monte Carlo
Type: Theory

[59] *Quantum Metrology Enhanced by Indefinite Causal Order*

Márcio Taddei (ICFO - The Institute of Photonic Sciences) and Manuel Gessner (Universidad de Valencia-CSIC)

Abstract: Quantum indefinite causal order includes a series of phenomena where inside each lab (Alice's, Bob's, possibly more) there is a well-defined causal order, but between the labs the order need not be defined.

There are foundational questions pertaining to this topic, such as that of whether some of the mathematical objects of the theory (process matrices) correspond to actual physical processes and, if so, how to interpret them. However, at the same time there are cases, typically related to the so-called quantum switch, that have a clear physical interpretation and have been experimentally realized. These instances of indefinite causal order have been shown to provide quantum advantages to tasks intrinsic to quantum algorithms, such as the identification of unitary operators in a black-box scenario with fewer queries.

Here, we will present a work in progress where we probe advantages of using a quantum switch for quantum metrological tasks. Quantum metrology has shown advantage over metrology using only classical resources, e.g. by using entangled states for phase discrimination. Here we aim at advantages of using indefinite causal order over the use of fixed-order quantum resources -- as typical for quantum indefinite causal order.

The Quantum Fisher Information, which measures the maximal sensitivity of a system under quantum measurements and can be directly related to measurement precision, will be crucial in this work. We investigate the case of single- and multiparameter estimation on qubit systems, and describe some no-go results as well as cases where an advantage can be seen.

Keywords: Quantum indefinite causal order, Quantum switch, Quantum metrology, Quantum Fisher information
Type: Theory

[60] *A Dual-Element Neutral Atom Array for Quantum Information Processing*

Bob Bao (University of Chicago), Haley Nguyen (University of Chicago), Conor Bradley (University of Chicago), Kevin Singh (University of Chicago), Shraddha Anand (University of Chicago), Vikram Ramesh (University of Chicago), Ryan White (University of Chicago) and Hannes Bernien (University of Chicago)

Abstract:. The ability to control, probe, and connect large, coherent quantum systems allows us to explore potential applications that are powered by quantum effects, such as quantum computation. A particularly promising platform for such systems is laser-trapped 2D arrays of neutral atoms, which can be excited to high-n electronic states (Rydberg states) to introduce interactions. These Rydberg states have high coherence times and large interaction ranges, making them well-suited as a resource for generating entanglement. In the Bernien Lab, we are developing a new dual-species optical tweezer array experiment with rubidium and cesium atoms, improving upon the current setup in terms of vacuum level, optical access, tweezer generation technology etc. Building upon our recent demonstration of global Rydberg interspecies interactions, the new setup aims to enhance control over single atoms using a fiber-coupled micro lens array, with the intention of achieving a fully-programmable quantum processor.

Keywords: Dual-Species Neutral Atom Array, Rydberg Atoms, Quantum Information Processing
Type: Experiment

[61] *Boson-Assisted Quantum Error Correcting Codes*

Omid Khosravani (Duke University)

Abstract: In order to do large scale quantum computations it is necessary to correct errors. Quantum error-correcting codes based on qubits were originally designed to correct errors on two-level quantum systems and were later extended to correct errors on bosonic systems with Gottesman-Kitaev-Preskill (GKP) code. Bosonic and spin systems are typically subject to noise models of different nature. Here, we present a hybrid code that involves both bosons and spins and propose a fault-tolerant protocol for its realization with trapped-ions.

Keywords: quantum error correcting codes, heterogeneous quantum computation, quantum control, noise
Type: Theory

[62] *Efficient Quantum Algorithms for Quantum Optimal Control*

Xiantao Li (Penn State University) and Chunhao Wang (Penn State University)

Abstract: In this paper, we present efficient quantum algorithms that are exponentially faster than classical algorithms for solving the quantum optimal control problem. This problem involves finding the control variable that maximizes a physical quantity at time T, where the system is governed by a time-dependent Schrodinger equation. This type of control problem also has an intricate relation with machine learning. Our algorithms are based on a time-dependent Hamiltonian simulation method and a fast gradient-estimation algorithm. We also provide a comprehensive error analysis to quantify the total error from various steps, such as the finite-dimensional representation of the control function, the discretization of the Schr\"odinger equation, the numerical quadrature, and optimization. Our quantum algorithms require fault-tolerant quantum computers.

Keywords: Quantum algorithm, Optimal control, Hamiltonian simulation
Type: Theory

[63] *Hamlib: a Library of Hamiltonians for Benchmarking Quantum Algorithms and Hardware*

Katie Klymko (NERSC, Lawrence Berkeley National Laboratory), Daan Camps (NERSC, Lawrence Berkeley National Laboratory), Nicolas Sawaya (Intel) and Norm Tubman (NASA Ames)

Abstract: In order to characterize and benchmark computational hardware, software, and algorithms, it is essential to have many problem instances on-hand. This is no less true for quantum computation, where a large collection of real-world problem instances would allow for benchmarking studies that in turn help to improve both algorithms and hardware designs. To this end, here we present a large dataset of qubit-based quantum Hamiltonians. The dataset, called HamLib (for Hamiltonian Library), is freely available online and contains problem sizes ranging from 2 to 1000 qubits. HamLib includes problem instances of the Heisenberg model, Fermi-Hubbard model, Bose-Hubbard model, molecular electronic structure, molecular vibrational structure, MaxCut, Max-k-SAT, Max-k-Cut, QMaxCut, and the traveling salesperson problem. The goals of this effort are (a) to save researchers time by eliminating the need to prepare problem instances and map them to qubit representations, (b) to allow for more thorough tests of new algorithms and hardware, and (c) to allow for reproducibility and standardization across research studies.

Keywords: Hamiltonians, Benchmarking, Algorithms
Type: Theory

[64] *Observation of Nagaoka Ferromagnetic Bubbles in a Triangular Lattice Quantum Gas Microscope*

Anant Kale (Harvard University), Muqing Xu (Harvard University), Lev Kendrick (Harvard University), Youqi Gang (Harvard University), Richard Scalettar (University of California, Davis), Martin Lebrat (Harvard University) and Markus Greiner (Harvard University)

Abstract: Quantum gas microscopy with fermionic atoms has proven to be a powerful tool for gaining insights into the phase diagram of the Fermi-Hubbard model in regimes that are challenging to approach numerically and theoretically. Even less is known about the quantum phases of the Hubbard model beyond the usual square lattice. Introducing magnetic frustration in the system by switching to non-bipartite lattices is believed to lead to intriguing phases such as chiral spin liquids, stripe phases and unconventional superconductors. Here we report on an experimental realization of a quantum gas microscope with a tunable optical lattice which can realize triangular, square, and as well as honeycomb connectivities. Combined with a digital micromirror device, this lattice can also realize Lieb and kagome connectivities. The dynamical tunability of the lattice also facilitates full spin- and density- resolved imaging, as well as adiabatic state preparation of low-entropy strongly correlated quantum phases. We also report on our first results with this tunable lattice in which we investigate the local magnetic order in an anisotropic triangular lattice Fermi Hubbard model as a function of geometric frustration and charge doping.

Keywords: Fermi-Hubbard, Magnetic frustration, Quantum gas microscope
Type: Experiment

[65] *False Vacuum Decay in Rydberg Atom Quantum Simulators: Classical Emulation Over the Parameter Space*

Siva Darbha (Lawrence Berkeley National Laboratory), Katherine Klymko (Lawrence Berkeley National Laboratory), Daan Camps (Lawrence Berkeley National Laboratory), Mark Hirsbrunner (Lawrence Berkeley National Laboratory), Jan Balewski (Lawrence Berkeley National Laboratory), Yizhi Shen (Lawrence Berkeley National Laboratory), Roel Van Beeumen (Lawrence Berkeley National Laboratory), Milan Kornjaca (QuEra Computing), Fangli Liu (QuEra Computing), Pedro Lopes (QuEra Computing) and Shengtao Wang (QuEra Computing)

Abstract: The expansion and cooling of the universe may have caused it to settle into a false vacuum state. A false vacuum would decay into the true vacuum through nucleation and potentially produce an observable signature. The phenomenon of false vacuum decay is difficult to probe in its field-theoretic form in physical cosmology, but it can be investigated more easily in analogue quantum simulators with strongly-coupled matter. Recent work has examined false vacuum decay in spin chains with the ferromagnetic Ising model and XXZ ladder, determining the relevant parameter range and quantifying the features of some important observables. We investigate false vacuum decay in Rydberg atom chains with the antiferromagnetic Rydberg Hamiltonian, using local detuning to achieve confinement and nucleation. We use classical emulation to examine the decay dynamics over a broad space of waveform inputs, notably studying the Neel order parameter. We constrain the parameter range for false vacuum decay and characterize the dynamics at the core and boundary of this regime.

Keywords: Quantum simulation, False vacuum decay, Rydberg atoms
Type: Theory

[66] *Efficient Multi-Qubit Gates for Simulating Chemical Dynamics in Trapped-Ion Quantum Computers*

Aj Rasmusson (Indiana University), Thomas Burkle (Indiana University) and Phil Richerme (Indiana University)

Abstract: Simulating the dynamics of quantum chemical systems is a promising application of quantum computers. While most quantum algorithms and experimental demonstrations have focused on calculations of electronic structure in molecules, a recently developed protocol [1] proposed techniques to simulate nuclear dynamics in a Hydrogen-bonded system and was recently demonstrated in a trapped-ion quantum computer [2]. Here we propose a more efficient decomposition of Hamiltonians which describe proton transfer in chemical systems using multi-qubit gates and single qubit rotations. Leveraging the all-to-all connectivity of global Molmer-Sorensen interactions in trapped-ion systems, we show an efficient decomposition into layers of global multi-qubit gates and local single qubit rotations. We present a thorough study of the experimental feasibility of our approach and comparison against more common universal gate sets available in generic quantum computers. Our proposal offers the potential to perform efficient simulation of quantum chemical dynamics on trapped-ion quantum simulators well into the regime of classical intractability.

[1] D. Saha et al, J. Chem. Theory Comput. 17, 6713 (2021)

[2] P. Richerme, et al., arXiv:2204.08571 (2022)

Keywords: quantum simulation, trapped ion, quantum chemistry, nuclear dynamics, multi-qubit gates, n-body interactions, pulse-level optimization
Type: Theory

[67] *High-fidelity parallel entangling gates on a neutral atom quantum computer*

Marcin Kalinowski* (Harvard), Simon J. Evered* (Harvard), Dolev Bluvstein* (Harvard), Sepehr Ebadi (Harvard), Tom Manovitz (Harvard), Hengyun Zhou (Harvard/QuEra), Sophie H. Li (Harvard), Alexandra A. Geim (Harvard), Tout T. Wang (Harvard), Nishad Maskara (Harvard), Harry Levine (Harvard), Giulia Semeghini (Harvard), Markus Greiner (Harvard), Vladan Vuletić (MIT), and Mikhail D. Lukin (Harvard)

Abstract: The ability to perform entangling quantum operations with low error rates in a scalable fashion is a central element of useful quantum information processing. Neutral atom arrays have recently emerged as a promising quantum computing platform, featuring coherent control over hundreds of qubits and any-to-any gate connectivity in a flexible, dynamically reconfigurable architecture. The major outstanding challenge has been to reduce errors in entangling operations mediated through Rydberg interactions. Here we report the realization of two-qubit entangling gates with 99.5% fidelity on up to 60 atoms in parallel, surpassing the surface code threshold for error correction. Our method employs fast single-pulse gates based on optimal control, atomic dark states to reduce scattering, and improvements to Rydberg excitation and atom cooling. We benchmark fidelity using several methods based on repeated gate applications, characterize the physical error sources, and outline future improvements. Finally, we generalize our method to design entangling gates involving a higher number of qubits, which we demonstrate by realizing low-error three-qubit gates. By enabling high-fidelity operation in a scalable, highly connected system, these advances lay the groundwork for large-scale implementation of quantum algorithms, error-corrected circuits, and digital simulations.

Keywords: Rydberg Atom Arrays, Quantum Computing, High-Fidelity Quantum Gates

Type: Experiment