Towards quantum simulation of gauge/gravity duality and lattice gauge theory

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Book of Abstracts

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Welcome

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Real time evolution of a SU(2) pure gauge lattice theory on a IBM quantum hardware

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Quantum computers have the potential to expand the utility of lattice gauge theory to investigate non-perturbative particle physics phenomena that cannot be accessed using a standard Monte Carlo method due to the sign problem. Thanks to the qubit, quantum computers can store Hilbert space in a more efficient way compared to classical computers. This allows the Hamiltonian approach to be computationally feasible, leading to absolute freedom from the sign-problem. But what the current noisy intermediate scale quantum hardware can achieve is under investigation. Therefore, in this talk we report the use of a IBM gate-based quantum hardware to perform the time evolution of a SU(2) pure gauge lattice theory in its Hamiltonian formulation. The quantum computer results agree with the exact classical results thanks to the use of various simple error mitigation techniques, like mitigation of measurement error, randomized compiling, zero noise extrapolation and our technique called Self-mitigation. The talk will be based on https://arxiv.org/abs/2205.09247.

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Thermalization and hadronization of SU(N) gauge theories

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We argue that high energy heavy ion collisions at LHC offer the perfect setting to study the information theoretical aspects of thermalization and hadronization of gauge theories. After discussing results from numerical AdS calculations we focus on numerical Hamiltonian simulation of SU(2) on classical computers, as well as first steps to extend the application of AdS/CFT duality to the hadronization phase which is interpreted as a multi-split process.

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Canonical Momenta in Digitized SU(2) Lattice Gauge Theory

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Lattice simulations using the Hamiltonian formulations are becoming increasingly important as they offer potential solutions to long-standing obstacles such as the sign problem. In particular, they are avenues to solving questions requiring real-time dynamics, string breaking, finite fermion densities, or highly curved space-time geometries amongst many others. Hamiltonian formulations of lattice gauge theories are usually studied using tensor networks. However, quantum computing approaches are being developed and investigated with great anticipation as a means of overcoming classical bottlenecks like heavily entangled states requiring large bond dimension in tensor networks.

In this talk, I will present an approach to modeling canonical momenta in digitized SU(2) Lattice Gauge Theory which leads to diagonalized gauge field operators in the discretized theory. I believe that this is a particularly interesting approach for future quantum computing applications as the method is generalizable to arbitrary SU(N) and U(N) theories and ensures that gauge links remain unitary operators, i.e., they can be implemented directly as gates on (universal) quantum devices. Additionally, the proposed discretization schemes retain canonical commutation relations which under naive discretization schemes are broken.

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Simulating fermionic scattering using a digital quantum computing approach (remote)

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Collider experiments play a central role in understanding the subatomic structure of matter, as well as developing and verifying the fundamental theory of elementary particle interactions. However, comprehending scattering processes at a fundamental level in theory remains a significant challenge. The necessarily involved time evolution and the with time rapidly increasing bond dimension in Tensor Networks make simulating the scattering process with this classical method challenging. On the other hand, quantum computers hold great promise to efficiently simulate real-time dynamics of lattice field theories. In this work, we take the first step in this direction towards simulating fermionic scattering using a digital quantum computing approach. Specifically, we propose a method based on Givens rotation to prepare the initial state of the fermionic scattering process, which consists of two fermionic wave packets with opposite momenta. With a time evolution operator based on the underlying Hamiltonian acting on the initial state, the two fermionic wave packets propagate and eventually interact with each other. Using the lattice Thirring model as the test bed, monitoring the particle density and the entropy produced during the scattering process, we observe an elastic scattering between fermions and anti-fermions in the strong interaction region. In addition, we perform a small-scale demonstration on IBM's quantum hardware, showing that our method is suitable for current and near-term quantum devices.

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Towards simulating the large N QCD string on a quantum computer

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I will show that in the strong coupling expansion of large N QCD on a lattice, the dynamics of the confining string can be well approximated by a one dimensional spin chain. I will describe the prospects for simulations of this spin chain in various approximations and dimensions.

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SNAQs - Spin-Network Algorithms for Q-deformed Gauge Theories

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The real-time dynamics of gauge theories is one of the most promising applications for quantum devices where future quantum simulations are expected to provide a practical advantage over classical computers. However, it remains an outstanding challenge to reformulate non-abelian lattice gauge theories in a way that is tailored to quantum information processing.
In this talk, I will present a new approach to this problem using a generalisation of the Kogut-Susskind Hamiltonian formulation, where the defining non-abelian Lie algebra is q-deformed to a quantum group. For the example of pure SU(2) lattice gauge theory in 2+1D, I will demonstrate that this formulation enables a controlled truncation on a finite dimensional Hilbert space that is naturally represented on a register of gauge-invariant spin-network states. Most importantly, the q-deformed Kogut-Susskind formulation preserves symmetry-related properties that allow us to construct efficient quantum circuits for Trotterized real-time evolution by analytically diagonalizing the plaquette operators using local changes of the spin-network basis. Additionally, our approach aligns well with tensor network methods and we numerically find that a simple variational ansatz already captures salient features of the continuum theory. Our work thus points to a new class of efficient quantum and classical algorithms to simulate non-abelian lattice gauge theories.

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Cold-atom quantum simulators of gauge theories

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Gauge theories are a fundamental framework of modern physics and the staple of the Standard Model. Their principal property, gauge symmetry, implements the laws of nature through intrinsic local relations between matter and gauge fields, with Gauss's law from electrodynamics as a paradigmatic example. In recent years, there has been a considerable drive in realizing gauge theories on quantum simulators, which are accessible tunable tabletop devices that can naturally handle entanglement buildup owing to quantum advantage. In this talk, I will first motivate this technology and then discuss recent theoretical and experimental progress in quantum simulators of 1+1D Abelian gauge theories in cold-atom platforms. I will then discuss exotic far-from-equilibrium phenomena that one can probe on such quantum simulators, including particle collisions. I will end by discussing experimental proposals towards advancing quantum simulators of gauge theories to higher spatial dimensions, non-Abelian gauge groups, and towards the lattice quantum field theory limit.

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Real-time dynamics of SYK model on a noisy quantum computer (remote)

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We explore the possibility of simulation of a well-known quantum-mechanical model of quantum gravity on a quantum computer. With the current limitations on the superconducting based hardware, we show that results for return probability and OTOC for small number of Majorana fermions are consistent with those obtained using exact classical methods after applying state-of-the-art error mitigation methods. This talk is based on: https://arxiv.org/abs/2311.17991

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Three ways of calculating mass spectra in the Hamiltonian formalism

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I would like to talk about the calculation methods for mass spectra of composite states of gauge theories in the Hamiltonian formalism.

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Jackiw-Teitelboim gravity with matter on quantum computer

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I will discuss how to put Jackiw-Teitelboim gravity with matter on quantum computer and protocols to explore physics related to wormholes. This talk is based on a work in progress with Rumi Hasegawa.

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Quantum algorithms from algebraic Hilbert spaces.

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The structure of composite operators in gauge quantum field theories with matrix or tensor degrees of freedom is controlled by hidden symmetries which organise the combinatorics of gauge invariants. These include group algebras of symmetric groups and associated natural generalisations. Dualities in string theory, in particular gauge-string duality, motivate the formulation of new classical and quantum algorithms based on structural

properties of these algebras. I will describe an interesting number sequence $k_*(n)$ associated with symmetric groups on n elements, which plays an important role in these
structural properties and determines the complexities of the associated quantum algorithms. The talk will be based on https://arxiv.org/abs/1911.11649 and https://arxiv.org/abs/2303.12154.

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A Quantum Algorithm for Gravitational Wave Parameter Estimation

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Advancements of detector sensitivity in the next generation of gravitational-wave observatories translate into several orders of magnitude larger detection rates and signals of hours of durations that start at a few Hz frequencies. Alongside the exciting sciences are the immediate challenges to prompt and accurate gravitational wave parameter estimation, a crucial part in gravitational-wave astronomy and multimessenger astrophysics. We have developed a quantum algorithm to tackle the challenges, acknowledging that it is not fully prepared for real-world applications. In this talk, I showcase our algorithm's accuracy by inferring the source properties of simulated gravitational waves generated by binary black hole mergers.

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Geometry from Quantum Field Theories — "AdS/CFT" by a conformal flow —

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We develop a framework for the construction of the bulk theory dual to conformal field theory (CFT) without any assumption by means of a flow equation. Using the special flow equation, called the conformal flow, we show that the conformal transformation for a normalized smeared field exactly becomes a part of the general coordinate transformation, which would be the isometry of anti-de Sitter space (AdS). By this bulk construction, we derive BDHM relation and GKP-Witten relation.
We also determine the geometry of the bulk space by the state-dependent metric, which turns out to be the AdS metric for the vacuum state.
Some applications are also discussed.