2023

Fermion sampling: a robust quantum computational advantage scheme. — Quantum sampling is a popular family of protocols for near-term quantum devices. For example, the famous Google quantum supremacy experiment of 2020 and the boson sampling experiment conducted last year at the University of Science and Technology of China fall into this class. Compared to the random quantum gate sampling used in the Google experiment, the random distribution generated by boson sampling has much more structure, and using this structure, the unitary operation used in such an experiment can be verified by a polynomial number of measurements in the number of bosonic modes. However, boson sampling can only be demonstrated using photonic modes, i.e., it cannot be transferred to a quantum computer with a qubit architecture. This problem motivated us to introduce fermion sampling analogous to boson sampling, which may be suitable for the experimental realization of quantum supremacy [1]. Using the Jordan-Wigner transformation, fermion sampling can also be transferred to a qubit based quantum computer and, analogously to boson sampling, can be verified by a number of measurements scaling polynomially with the number of qubits.

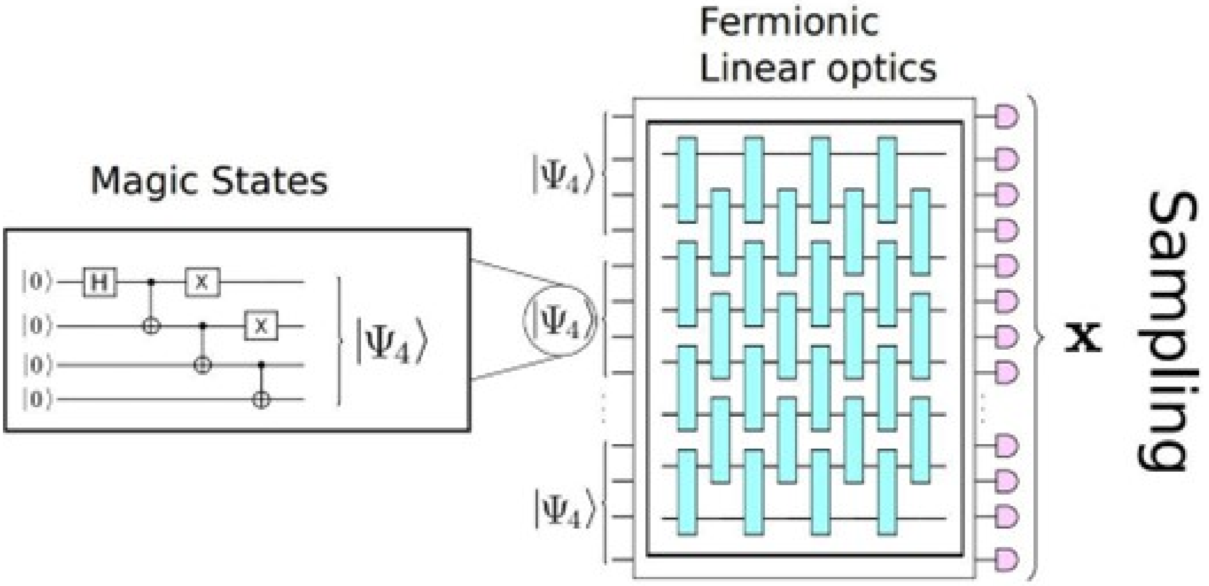

Figure 1. Fermion sampling set-up: a tensor product of magic states is transformed by a fermionic linear optical unitary and measured in the computational basis producing the binary samples. The decomposition of the fermionic linear optical unitary into elementary nearest neighbor gates can be realized in a brickwall layout.

The specific set-up of the fermion sampling protocol is the following: a suitable input state, which is equivalent to an N-fold tensor product of Bravyi's non-Gaussian magic state, is transformed via a Fermionic Linear Optical transformation V and is measured in the computational basis that produces the samples (Fig. 1). From a quantum complexity theory point of view, we provided strong hardness guarantees. In particular, using low-dimensional continuous symmetry groups that underpin these classes of quantum circuits, we proved the so-called anticoncentration property and the robust average-case hardness of computation of output probabilities. Taken together, these findings provide hardness guarantees comparable to the paradigm of random circuit sampling and boson sampling. We should also mention that these fermionic linear optical circuits are also relevant for quantum chemistry and many-body physics, and have been successfully implemented in superconducting architectures.

Tensor network models of AdS/qCFT. — The study of critical quantum many-body systems through conformal field theory (CFT) is one of the pillars of modern quantum physics. Certain CFTs are also understood to be dual to higher-dimensional theories of gravity via the anti-de Sitter/conformal field theory (AdS/CFT) correspondence. To reproduce various features of AdS/CFT, a large number of discrete models based on tensor networks have been proposed. Some recent models, most notably including toy models of holographic quantum error correction, are constructed on regular time-slice discretizations of AdS (Fig. 2.). In Ref. [2], we showed that the symmetries of these models are well suited for approximating CFT states, as their geometry enforces a discrete subgroup of conformal symmetries. Based on these symmetries, we introduced the notion of a quasiperiodic conformal field theory (qCFT), a critical theory less restrictive than a full CFT and with characteristic multi-scale quasiperiodicity. We obtained holographic code states and their renormalization group flow as specific implementations of a qCFT with fractional central charges and argued that their behavior generalizes to a large class of existing and future models. Beyond approximating CFT properties, we showed that these can be best understood as belonging to a paradigm of discrete holography.

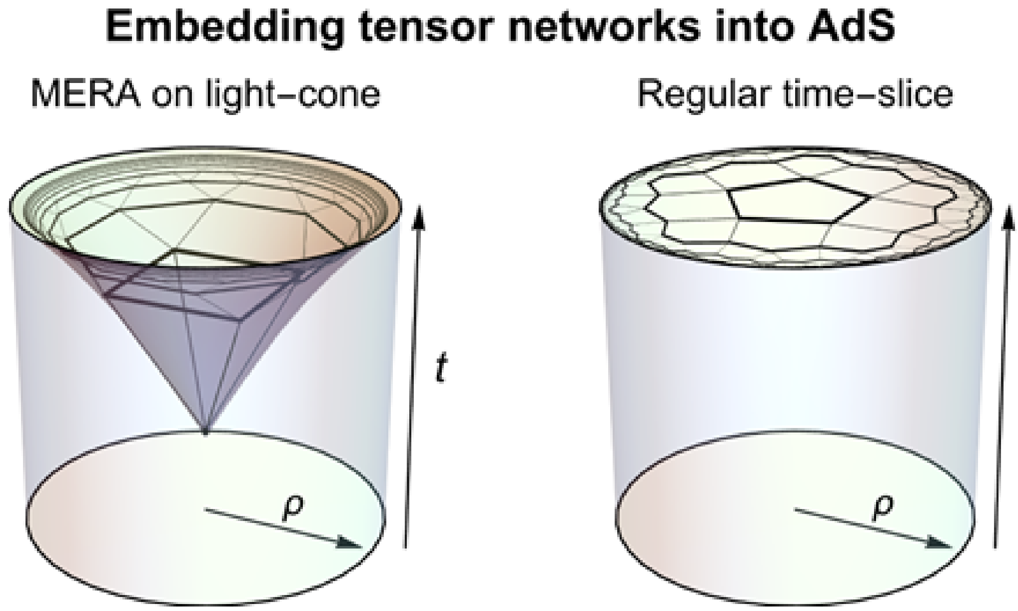

Figure 2. Embedding two tensor networks into 2+1-dimensional anti-de Sitter (AdS) spacetime: The multi-scale entanglement renormalization ansatz (left figure) can be identified with the symmetries of a discretized AdS lightcone, whereas regular tilings naturally discretize slices at constant time (right figure).

References:

[1] DOI: 10.1103/PRXQuantum.3.020328

[2] DOI: 10.22331/q-2022-02-03-643

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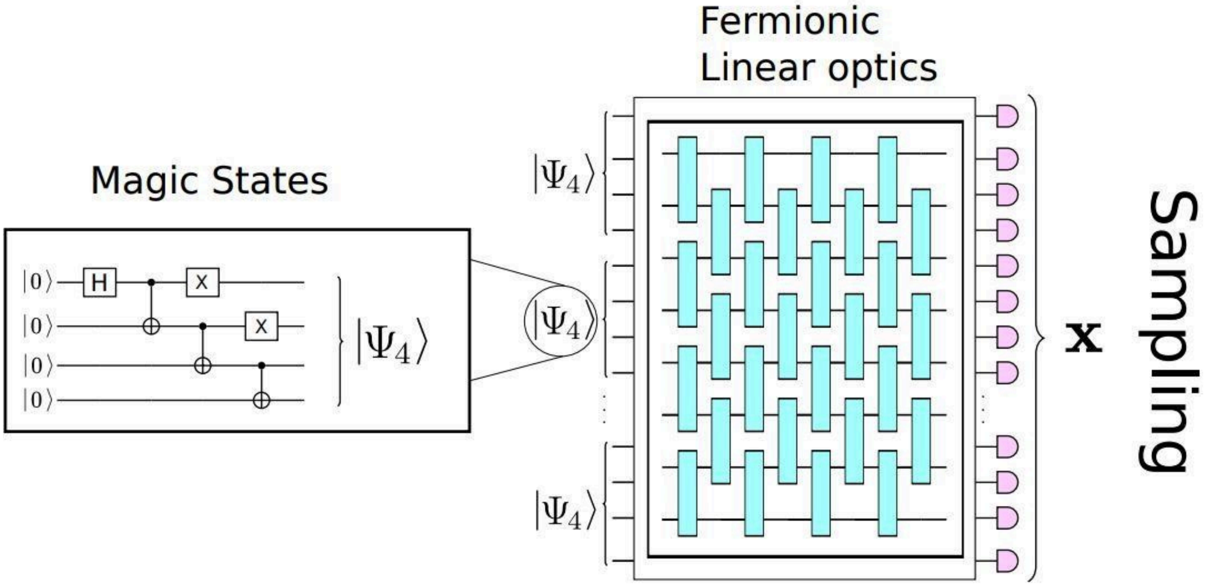

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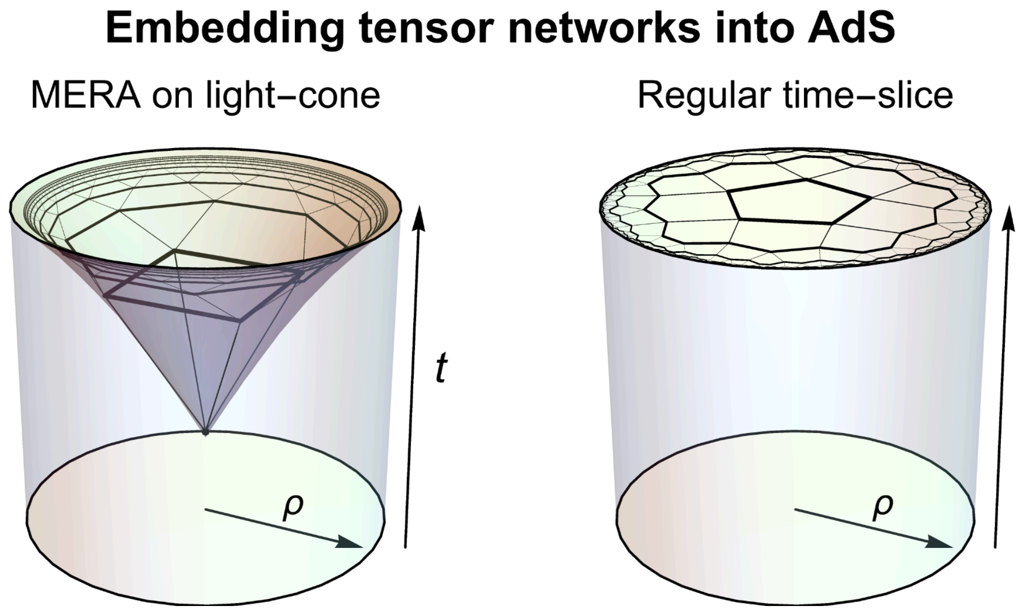

Figure 2. Embedding two tensor networks into 2+1-dimensional anti-de Sitter (AdS) spacetime: The multi-scale entanglement renormalization ansatz (left figure) can be identified with the symmetries of a discretized AdS lightcone, whereas regular tilings naturally discretize slices at constant time (right figure).

2020

Short title of the following text. — Conformal field theories are one of the pillars of modern quantum physics, suited for describing critical quantum many-body systems. In our recent paper [1], we discussed how aspects of conformal field theory (CFT) can be captured in terms of simple toy models of tensor networks. Specifically, we introduced the concept of a quasi-regular conformal field theory (qCFT) defined from a discretely broken subset of conformal symmetries. We realized these symmetries on the level of boundary states of a tensor network on a regular hyperbolic tiling, extending geometrical insights from the anti-de Sitter/conformal field theory (AdS/CFT) correspondence to the discrete setting.

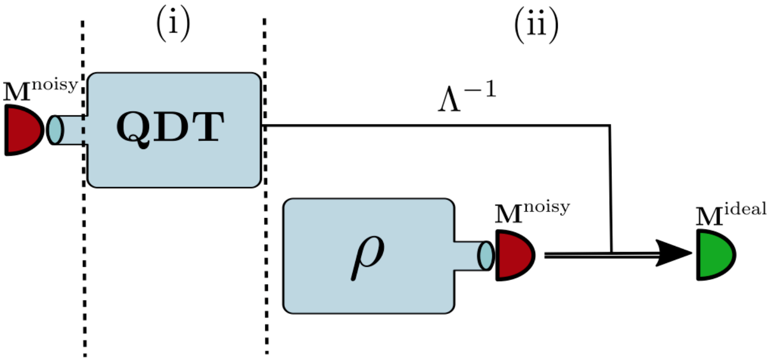

Figure 1. *AdS embeddings of tensor networks. The multi-scale entanglement renormalization ansatz (MERA) corresponds to a light-cone embedding (a), while regular discretizations such as the Majorana dimer network with {5,4}-tiling, corresponding to the hyperbolic pentagon code, can be identified with a time slice (b). The Majorana dimer states with {5,4}-tiling at the first (c) and the second inflation (d) layers are shown on the Poincaré disk.*

Central to the AdS/CFT correspondence is a precise relationship between the curvature of an AdS spacetime and the central charge of the dual conformal on its boundary. Our work shows that such a relationship can also be established for tensor network models of AdS/CFT based on regular bulk geometries, leading to an analytical form of the maximal central charges exhibited by the boundary states. We explicitly identified a class of tensors based on Majorana dimer states, depicted in Fig. 1., that saturate these bounds in the large curvature limit, while also realizing perfect and block-perfect holographic quantum error correcting codes. These systems exhibit a large range of fractional central charges, tunable by the choice of bulk tiling. Our approach thus provides a precise physical interpretation of tensor network models on regular hyperbolic geometries and establishes quantitative connections to a wide range of existing models.

Mitigation of readout noise in near-term quantum processors. — We proposed a simple scheme to reduce readout errors in experiments on quantum systems with finite number of measurement outcomes. Our method, described in Ref. [2], relies on performing classical post-processing which is preceded by Quantum Detector Tomography, i.e., the reconstruction of a Positive-Operator Valued Measure (POVM) describing the given quantum measurement device. If the measurement device is affected only by an invertible classical noise, it is possible to correct the outcome statistics of future experiments performed on the same device, as illustrated schematically in Fig. 2.

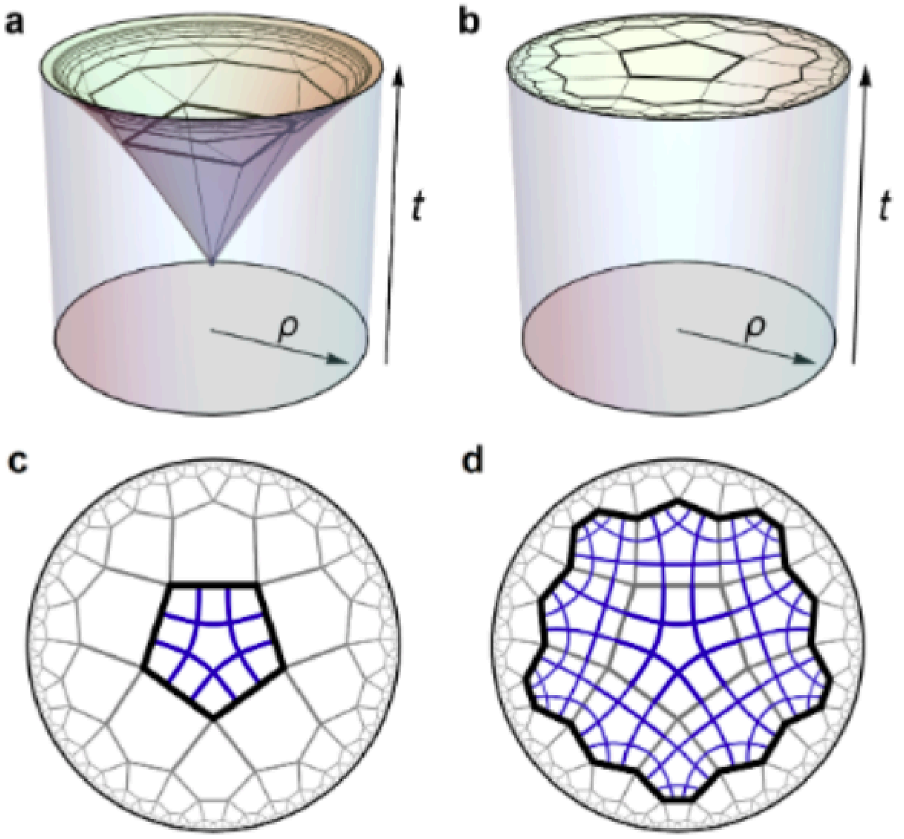

Figure 2. Schematic representation of our readout error mitigation procedure. (i) In the first stage, one performs the tomography of a noisy detector (red semicircle). (ii) In the next stage, when measuring an arbitrary quantum state ρ, one employs a post-processing procedure on the measured statistics through the application of the inverse of a stochastic noise map obtained in the quantum detector tomography. This gives access to the statistics that would have been obtained in an ideal detector (green semicircle).

To support the practical applicability of this scheme for near-term quantum devices, we characterize measurements implemented in IBM's and Rigetti's quantum processors. We find that for these devices, based on superconducting transmon qubits, classical noise is indeed the dominant source of readout errors. Moreover, we analyze the influence of the presence of coherent errors and finite statistics on the performance of our error-mitigation procedure. Applying our scheme on the IBM's 5-qubit device, we observe a significant improvement of the results of a number of single- and two-qubit tasks including Quantum State Tomography (QST), Quantum Process Tomography (QPT), the implementation of non-projective measurements, and certain quantum algorithms (Grover's search and the Bernstein-Vazirani algorithm).