Breaking the Chain: Geometry-Native State Preparation with ASPIRE

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***Abstract*—Loading data into quantum computers is a key bottleneck that threatens end-to-end quantum advantage. Quantum-circuit compilers for structured states like matrix product states (MPS) are a critical enabler to manage this in quantum chemistry, finance, and many-body quantum simulation. Approximate preparation of MPS typically relies on layered sequential staircases of nearest-neighbor gates. We present Adaptive State Preparation by Iterative Removal of Entanglement (ASPIRE), an algorithm that approximately compiles state-preparation circuits by selecting gates based on the state's underlying entanglement geometry and the available connectivity of the target quantum processor. Our protocol scores candidate qubit pairs on the removability of their entanglement and identifies layers of parallelised long-ranged gates that remove the most entanglement. We demonstrate our protocol empirically across a range of settings, illustrating its success for preparing Hamiltonian ground states and multivariate amplitude-encoded functions, and accounting for qubit connectivity, hardware noise, and both NISQ and early-fault-tolerant settings. Throughout, ASPIRE typically achieves higher fidelities than existing methods for states with long-ranged entanglement, even when classical optimisation is accounted for. Our investigation positions ASPIRE as a competitive, resource-frugal state preparation protocol, with particular promise for applications tolerant to imperfect fidelity such as preparation of guide states for quantum phase estimation.**

***Index Terms*—quantum state preparation, matrix product states, tensor networks, quantum circuit compilation, qubit connectivity, entanglement geometry, noise resilience**

I. Introduction

Loading a generic state into an N-qubit register costs a number of gates exponential in N [1], enough to erase an end-to-end quantum speed-up [2]. Matrix product states (MPS) avoid this for structured data, such as ground states from the density matrix renormalization group (DMRG) [3], guide states for quantum phase estimation (QPE) [4], and multivariate functions [5].

The standard approximate compiler is the matrix product disentangler (MPD) of Ran [6], refined by gate optimization [7]. Its layers are staircases of gates between neighbors in the MPS ordering, which spread correlation by about one site per layer. Yet a snake-mapped 2D lattice places most bonds at long range in the chain, and processor coupling graphs are rarely one-dimensional.

II. ASPIRE

ASPIRE builds the circuit from the entanglement geometry of the target and a connectivity matrix K listing the pairs the device can couple (Fig. 1). Each layer (I) scores every pair admitted by K by its removable quantum mutual information per native gate, (II) discards pairs below a threshold, (III) selects the maximum-weight set of disjoint pairs, (IV) applies their gates to the MPS, and (V) recomputes and repeats until no pair survives or the budget is spent. The inverted circuit prepares the target.

For a pair (i, j) with reduced density matrix ρ_{ij}, the gate that minimizes $S(\rho_i)+S(\rho_j)$ maps the eigenvectors of ρ_{ij}, in decreasing order of eigenvalue, onto the computational basis. One 4×4 eigendecomposition gives both the gate and the correlation R_{ij} it removes [8]. Step (III) is an exact maximum-weight matching, and each layer's scan costs $\mathcal{O}(N^2\chi^3)$ at bond dimension χ.

The total correlation $T = \sum_a S(\rho_a)$ of the disentangled state is its relative-entropy distance to the product states. A layer of disjoint gates lowers T by exactly the sum of what each gate removes, and T bounds the infidelity, $\varepsilon \leq T$, so ASPIRE descends on a bound on its own error.

III. Results

For the 10×10 transverse-field Ising (TFIM) ground state, the unoptimized MPD stalls near $\varepsilon = 1.2 \times 10^{-1}$ while ASPIRE reaches 1.6×10^{-2} at the same T-gate count, 7.7 times lower (Fig. 2). Under a snake of width L_x the vertical bonds sit at spans up to $2L_x - 1$, out of the MPD's reach. Optimization at an equal classical budget does not close the gap; from 5×5 to 10×10 the unoptimized advantage grows linearly with N. Optimized to convergence on 7×2 lattices, ASPIRE ends 2.8 to 9.8 times lower on the Heisenberg ground state and at least 54 times lower on the TFIM; on random MPS the MPD leads narrowly or ties.

On a 30-qubit heavy-hex patch [9] preparing a kicked-Ising state [10], ASPIRE uses only native couplers while the MPD pays SWAPs (Fig. 3). Under depolarizing noise each curve reaches a floor, and at each of the three error rates ASPIRE's is lower and reached in fewer native gates, and admitting only high-scoring gates helps further as noise grows.

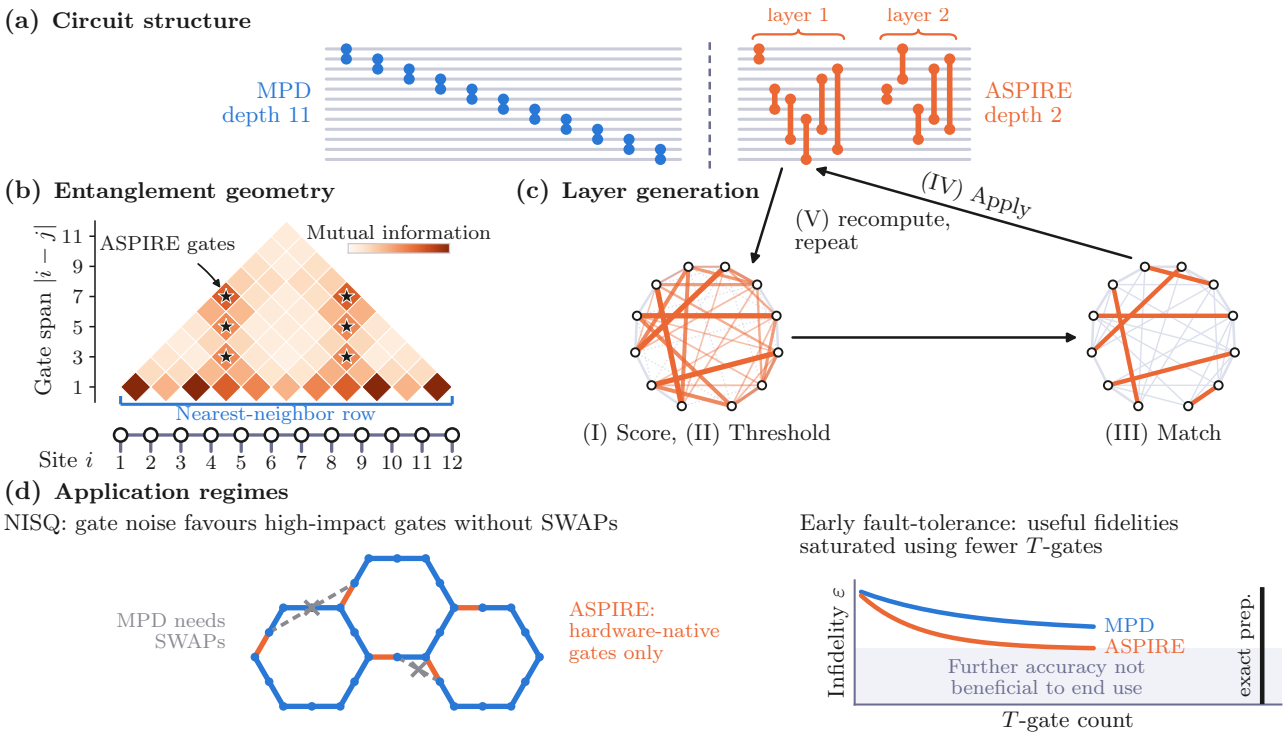


Fig. 1. Overview of ASPIRE. (a) Circuit structure of the MPD (blue) and ASPIRE (orange) at equal gate count. (b) Pairwise mutual information of a 4×3 Heisenberg ground state against MPS site and gate span; the MPD reaches only the bottom row. (c) One ASPIRE layer, steps (I) to (V). (d) The NISQ and early fault-tolerant regimes.

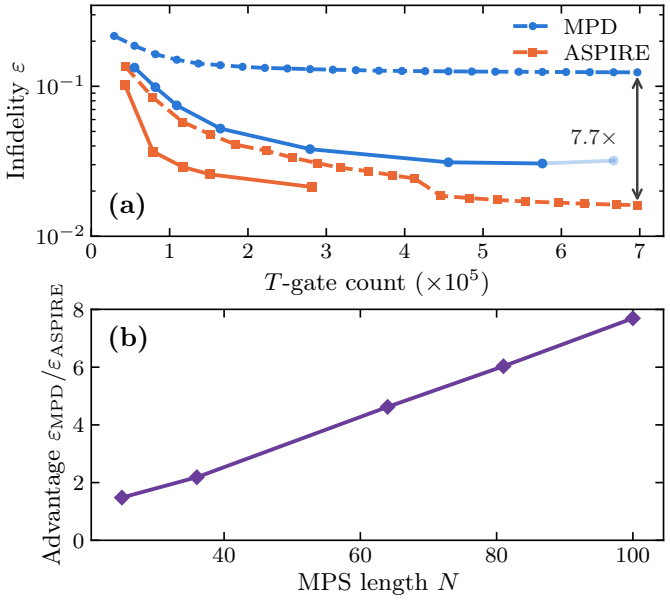


Fig. 2. 10×10 TFIM ground state ($N = 100$, $h = 2$). (a) Infidelity against T-gate count. Dashed: as constructed. Solid: optimized at an equal budget of 5×10^{12} operations per point. (b) Advantage $\varepsilon_{\mathrm{MPD}}/\varepsilon_{\mathrm{ASPIRE}}$ at $\varepsilon_{\mathrm{ASPIRE}} = 1.61 \times 10^{-2}$ against MPS length N.

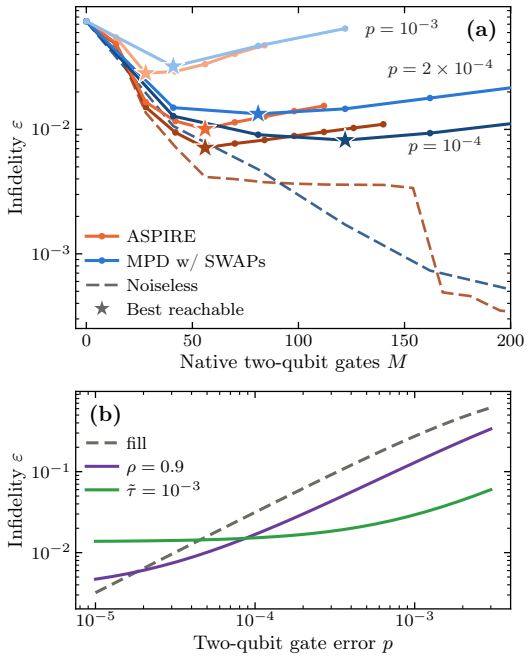


Fig. 3. Kicked-Ising state on a 30-qubit heavy-hex patch. (a) Infidelity against native two-qubit gates at depolarizing rates $p = 10^{-3}$, 2×10^{-4} and 10^{-4} (light to dark), noiseless dashed. The MPD is charged 1.4 times its logical gate count for routing SWAPs; stars mark the best reachable infidelity. (b) Final infidelity of three ASPIRE admission rules against p.

In the quantics encoding of a multivariate function with serial bits, cross-variable correlation sits at span $\approx n$ for n bits per variable. At the gate count of eight MPD layers,

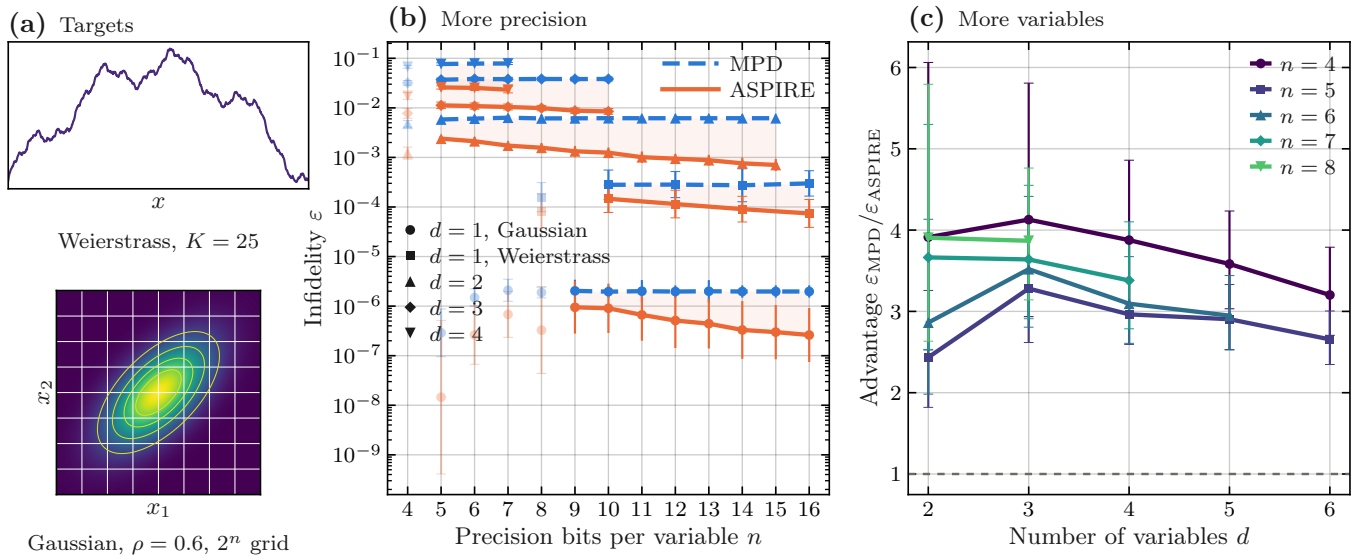


Fig. 4. Correlated Gaussian ($\rho = 0.6$) in the quantics encoding with serial bit order, at the gate count of eight MPD layers; 16 seeds. (a) The Weierstrass and Gaussian targets. (b) Infidelity against precision bits per variable n. (c) Advantage against the number of variables d.

added precision leaves the MPD flat while ASPIRE keeps descending, widening the separation from 3.9 times at $n = 4$ to 8.8 times at $n = 15$ (Fig. 4).

IV. Conclusion

ASPIRE compiles an MPS from the entanglement geometry of the state and the coupling graph of the device. For states with long-range entanglement it reaches lower infidelity than the MPD at equal gate count, before and after optimization, with a gap that grows with problem size on 2D lattices and multivariate functions.

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