Quantum-Hybrid Generative Flow Networks

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요 약

We propose a hybrid quantum simulation framework that integrates Generative Flow Networks (GFlowNets) with Trotterized quantum circuits for efficient and accurate simulation of the Ising model. By employing GFlowNets to sample intermediate quantum states between Trotter steps, our method significantly reduces circuit depth and mitigates cumulative noise, a major challenge in Noisy Intermediate-Scale Quantum (NISQ) devices. Experimental results on the FakeAlgiers simulator demonstrate that our approach achieves over four orders of magnitude improvement in mean squared error (MSE) compared to baseline simulations. This architecture enables long-time quantum dynamics with enhanced fidelity, offering a scalable strategy for realistic quantum simulations.

Ⅰ. 서 론

Quantum computation has emerged as a promising tool for simulating many-body quantum systems, particularly intractable models like the Ising spin chain. However, the limited fidelity and circuit depth constraints of NISQ-era devices severely degrade the quality of quantum simulations. In this context, techniques such as Trotter-Suzuki decomposition approximate time evolution but remain susceptible to noise as depth increases. To address these challenges, we propose a hybrid methodology wherein Generative Flow Networks are used to interpolate between discrete Trotterized time steps. GFlowNets construct intermediate quantum states by learning a reward-guided stochastic process, thus suppressing noise accumulation and improving accuracy.

Ⅱ. 본론

We target the simulation of the 1D transverse-field Ising model, governed by the Hamiltonian:

$$H = J\sum_{i=1}^{n-1} \sigma_i^z \sigma_{i+1}^z + h\sum_{i=1}^{n} \sigma^x$$

where σ^z and σ^x are Pauli matrices, J controls nearest-neighbor interactions, and h represents the transverse field strength.

To simulate time evolution, we apply Trotter-Suzuki decomposition, splitting the time-evolution operator:

$$e^{-iHt} \approx \left(e^{-iH_A\Delta t} e^{-iH_B\Delta t}\right)^{t/\Delta t}$$

with H_A and H_B representing the spin-spin and field terms respectively. This corresponds to alternating RZZ gates and RX gates on hardware.

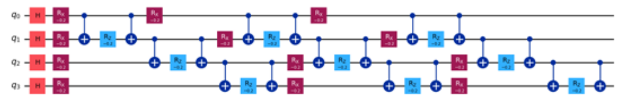

Fig. 1: Quantum Circuit Design for Ising Model Simulation. Example with 4 qubits.

To overcome depth-related noise, we implement a hybrid architecture using FakeAlgiers for coarse steps ($\Delta t = 0.5$), and GFlowNet to interpolate intermediate steps ($\Delta t = 0.1$). GFlowNet uses the reward:

$$R(s,t) = \alpha e^{-\beta E(s)} + (1-\alpha)\mathcal{L}_{\mathrm{clo}}(s,t)$$

Here, E(s) is the classical Ising energy and L_colloc is a collocation loss to match QASM-simulated amplitudes.

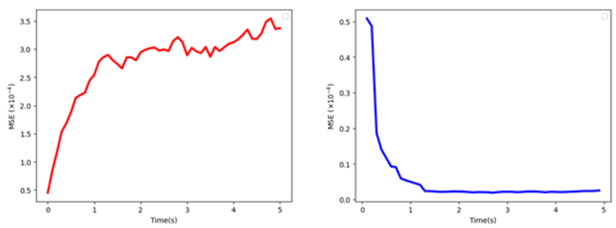

Fig. 2: Comparison of simulation fidelity. (Left) MSE between FakeAlgiers and QASM shows increasing error with time. (Right) GFlowNet-enhanced simulation maintains low MSE throughout evolution.

Experiment Summary:

- Setup: 8-qubit Ising model, J = h = 1.0, T = 5

- Baseline (FakeAlgiers-only): MSE ≈ 3.5×10^{-4}

- Hybrid (Ours): MSE ≈ 10^{-8}

- Optimal α = 0.5 balancing energy fidelity and data consistency.

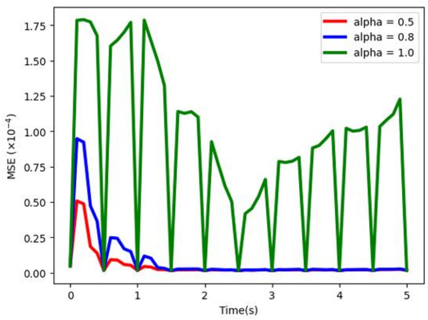

Fig. 3: MSE for different α values, showing optimal fidelity at α = 0.5.

Ⅲ. 결론

In this study, we presented a novel approach to enhancing the accuracy of Ising model simulations on quantum circuits by integrating Generative Flow Networks (GFlowNets). By using GFlowNet to sample intermediate states between Trotter steps, we effectively reduced the depth of quantum circuits and mitigated error accumulation over time. The results show that the GFlowNet-enhanced simulation maintained a lower Mean Squared Error (MSE) compared to simulations conducted solely on the FakeAlgiers simulator, demonstrating improved fidelity with respect to QASM outputs. This work highlights the potential of GFlowNets as a valuable tool for quantum simulations, especially in scenarios where noise and gate fidelity pose significant challenges due to increasing circuit depth. By optimizing intermediate states, GFlowNet provides a promising solution to manage error and maintain high simulation accuracy in long-time evolution studies. Future research could explore the application of this method to more complex quantum models or even experimental quantum devices. Additionally, refining the reward function or exploring adaptive time steps could further enhance the accuracy and efficiency of GFlowNet-integrated simulations.

ACKNOWLEDGMENT

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