Proposal - PHYS 550 project

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1 Brief Description

In the recent work *Single Qubit Error Mitigation by Simulating Non-Markovian Dynamics* [Ros+23], the authors present a novel quantum simulation framework capable of implementing general (not necessarily CP) dynamical maps on current quantum hardware.

The core insight of the paper is that any such general trace-preserving, Hermiticity-preserving map Σ can be expressed as a weighted difference of two CPTP maps:

$$\Sigma(\rho) = (1+p)\Lambda_+^*(\rho) - p\Lambda_-^*(\rho),$$

where $\Lambda_\pm^*$ are CPTP maps constructed by augmenting the original CP components with additional Kraus operators to ensure trace preservation. Each $\Lambda_\pm^*$ can in turn be decomposed into a convex combination of two extremal CPTP maps, using results from [KR01], where each extremal map is realized with just two Kraus operators and unitary rotations. This makes them particularly well-suited for efficient implementation on quantum hardware [Wan+13].

Two key applications are demonstrated: (1) reversing a thermal Lindblad evolution to recover the initial state, illustrating a form of *quantum error mitigation*; and (2) simulating time-local master equations with temporarily negative decay rates, representing a class of non-Markovian dynamics.

In this project, we aim to reproduce and build upon the error mitigation strategy. Our primary focus is on experimentally validating their time-reversed simulation protocol for Lindblad-type dissipative dynamics using IBM Quantum hardware. This will enable us to test the effectiveness of their state recovery method in the presence of realistic hardware noise.

2 Intended deliverables

- The results displayed in the paper used the ibmq-lima device. This device has long been replaced with newer devices that are larger and have fewer single-qubit errors. Therefore, we would like to reproduce and compare the results using the newer IBM quantum devices.

- In addition to reproducing the results, we want to further explore the effects on fidelity (after recovery) with varying parameters. In particular, an interesting parameter to explore is time t for which the evolution of the state stops and the recovery process begins. Other parameters to vary are β, ω, γ in the master equation.

3 Further exploration - long term

1. Extension of the protocol to multi-qubit systems.
2. Possible integration with quantum process tomography or machine learning-based noise models to learn the noise map for a specific qubit or operation and use this framework to simulate its inverse.

References

[KR01] C. King and M.B. Ruskai. "Minimal entropy of states emerging from noisy quantum channels". In: *IEEE Transactions on Information Theory* 47.1 (2001), pp. 192–209. DOI: 10.1109/18.904522.

[Wan+13] Dong-Sheng Wang et al. "Solovay-Kitaev Decomposition Strategy for Single-Qubit Channels". In: *Phys. Rev. Lett.* 111 (13 Sept. 2013), p. 130504. DOI: 10.1103/PhysRevLett.111.130504. URL: https://link.aps.org/doi/10.1103/PhysRevLett.111.130504.

[Ros+23] Mirko Rossini et al. "Single-Qubit Error Mitigation by Simulating Non-Markovian Dynamics". In: *Physical Review Letters* 131.11 (Sept. 2023). ISSN: 1079-7114. DOI: 10.1103/physrevlett.131.110603. URL: http://dx.doi.org/10.1103/PhysRevLett.131.110603.