QRISE 2024 Mitiq Challenge
Stacking Quantum Error Mitigation Techniques

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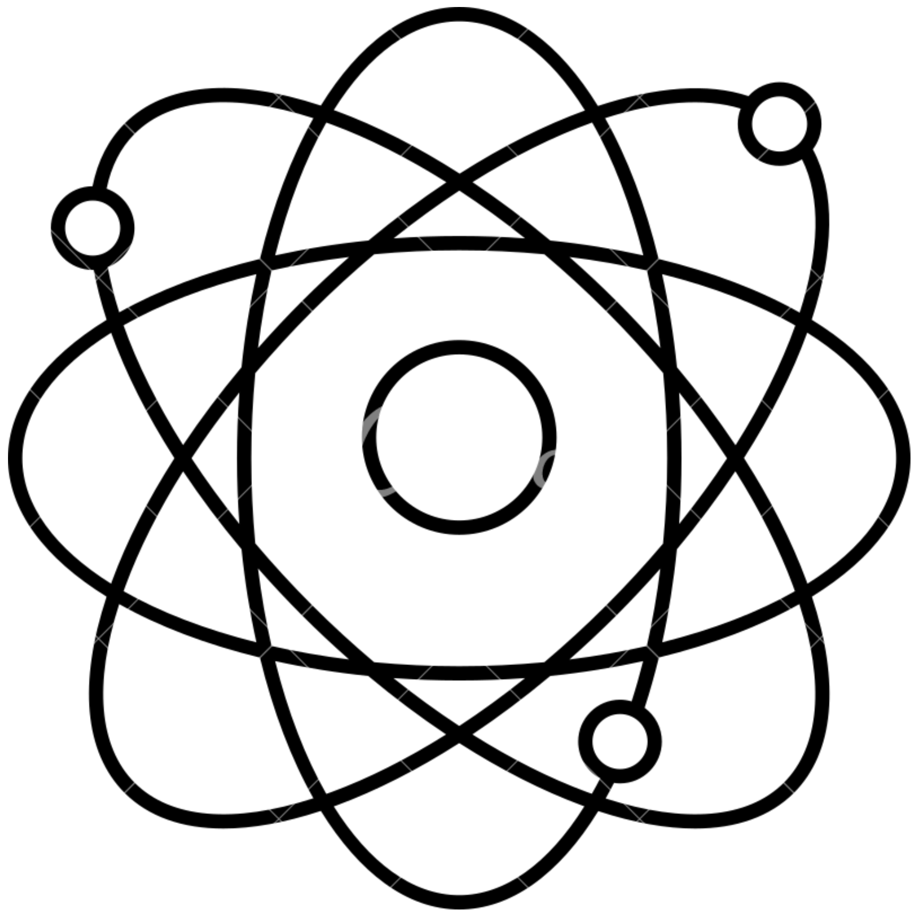

Problem Statement

We had to explore the efficacy of stacking multiple quantum error mitigation techniques leveraging the Mitiq Python toolkit. The goal was to compare different combinations of error mitigation strategies in simulation to achieve the lowest possible error rate.

Different QEM techniques used:

ZNE: Zero-noise extrapolation (ZNE) functions as an error mitigation approach by computing an expectation value across various noise levels. Subsequently, it extrapolates the observed outcomes to deduce the ideal expectation value at the zero-noise threshold.

PEC: Probabilistic error cancellation (PEC) is an error mitigation technique in which ideal operations are represented as linear combinations of noisy operations. In PEC, unbiased estimates of expectation values are obtained by Monte Carlo averaging over different noisy circuits.

DDD: Digital Dynamical Decoupling (DDD) is an error mitigation technique in which sequences of gates are applied to slack windows, i.e. single-qubit idle windows, in a quantum circuit. Such sequences of gates can reduce the coupling between the qubits and the environment, mitigating the effects of noise.

QSE: Quantum Subspace Expansion (QSE) is an error mitigation technique in which we define a small subspace around the output state, then search this subspace for the state with the least amount of error. Regardless of the output state, the same procedure applies. The subspace is defined by a set of operators that act on the output state called the check operators. Subspace expansion can be used in conjunction with a stabilizer code, in which case the stabilizers, or a subset of them, can be used as the check operators.

PEC + DDD + ZNE

We have implemented an error mitigation strategy using PEC + DDD + ZNE. Initially, we defined the 'execute' function to execute a quantum circuit with depolarizing noise and calculate the expectation value of the resulting density matrix. Subsequently, we applied various error mitigation techniques individually, including Probabilistic Error Cancellation (PEC), Zero-Noise Extrapolation (ZNE), and Dynamical Decoupling (DDD), to the circuit. Furthermore, we explored the combined application of these techniques to further enhance error mitigation. The effectiveness of each technique was evaluated by comparing the error between the noisy and ideal expectation values. Additionally, we introduced the 'launch' function to streamline the launch of any specified error mitigation technique with customizable parameters. This comprehensive approach showcases our endeavour to minimize errors and achieve optimal accuracy in quantum computation simulations.

Error without PEC:Circuit3: 0.23111
Error with PEC:Circuit3:   0.02888

Error without ZNE:Circuit3: 0.23111
Error with ZNE:Circuit3: 0.10682

Error without DDD:Circuit3: 0.23111
Error with DDD:Circuit3: 0.23111

Error without COMBINED:Circuit3: 0.23111
Error with COMBINED:Circuit3: 0.02374

In the evaluation of error mitigation techniques, we observed significant improvements in error reduction when employing Probabilistic Error Cancellation (PEC) and a combined approach. Specifically, without PEC, the error rate was 0.23111, which decreased drastically to 0.02888 with PEC applied. Similarly, when employing a combined approach, the error rate reduced from **0.23111 to 0.02374**. However, the effectiveness of Zero-Noise Extrapolation (ZNE) and Dynamical Decoupling (DDD) was less pronounced, with ZNE achieving a reduction from 0.23111 to 0.10682, and DDD maintaining the error rate at 0.23111. These results underscore the importance of combining error mitigation techniques to achieve optimal error reduction in quantum computation simulations.

Future Work

- Stack measurement errors and QSE Mitigation technique.
- Use a variety of circuits (like GHZ, RB) and multitude of errors.
- Investigate sampling in PEC and how to speed it up.
- Run it on non-cirq frontends and real backends.

References

- API-doc
- Noise Scaling Method
- QSE
- PEC
- ZNE
- DDD