Evaluating the Practical Limits of Zero-Noise Extrapolation in NISQ Devices

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Abstract

The accuracy of computational results is severely constrained by noise in the Noisy Intermediate-Scale Quantum (NISQ) region, where current quantum computers operate. Error mitigation strategies have become a viable substitute as full quantum error correction is not possible on current hardware. Zero-Noise Extrapolation (ZNE) is a popular method that attempts to estimate noise-free results by deliberately raising the noise and then extrapolating back to the zero-noise limit.

In this project, I study the usefulness and constraints of Zero-Noise Extrapolation in relation to a Variational Quantum Eigensolver (VQE) then compare the convergence behaviour of noiseless and noisy VQE under a fixed measurement shot budget using numerical simulations. The results indicate significant trade-offs that need to be taken into account when implementing error mitigation approaches on near-term quantum devices, as noise causes fluctuations and distorts the energy estimates.

1 Introduction

Although existing quantum hardware is still very flawed, quantum computing has the potential to offer computational advantages for some situations. These devices, also known as Noisy Intermediate-Scale Quantum (NISQ) devices, are impacted by a number of noise sources, such as measurement errors, decoherence, and poor gate operations. Because of this, the results of quantum algorithms run on these kinds of devices frequently differ greatly from their perfect theoretical predictions.

Offering a long-term solution to noise, quantum error correction necessitates a significant overhead in terms of extra qubits and circuit depth. Because of this, it is not feasible with the gear available today. As a temporary solution, error mitigation techniques have been devised to lessen the effect of noise without explicitly fixing hardware-level errors.

The purpose of this project is to investigate the practical limits of Zero-Noise Extrapolation by exploring how noise influences the convergence behavior of a Variational Quantum Eigensolver under actual situations.

2 Noise in NISQ Devices

Noise in NISQ devices arises from several sources, including gate imperfections, decoherence due to environmental interactions, and measurement errors. These effects accumulate as circuit depth increases, which strongly limits the reliability of quantum computations in the NISQ era.

3 Variational Quantum Eigensolver

The Variational Quantum Eigensolver is a hybrid quantum-classical algorithm designed to approximate the ground-state energy of a Hamiltonian. A parameterized quantum circuit is repeatedly executed to estimate expectation values, which are then optimized using a classical algorithm. Due to its reliance on repeated measurements, VQE is particularly sensitive to noise and shot statistics.

4 Methodology

A small two-qubit system is used to keep the analysis simple and computationally efficient. A shallow parameterized ansatz is chosen to reflect the limitations of NISQ hardware. A fixed measurement shot budget is enforced per optimization step to ensure a fair comparison between noiseless and noisy scenarios.

Noise is modeled using depolarizing errors applied to single-qubit rotation gates, with a base error rate defining the noise strength.

5 Results

5.1 Noiseless VQE Convergence

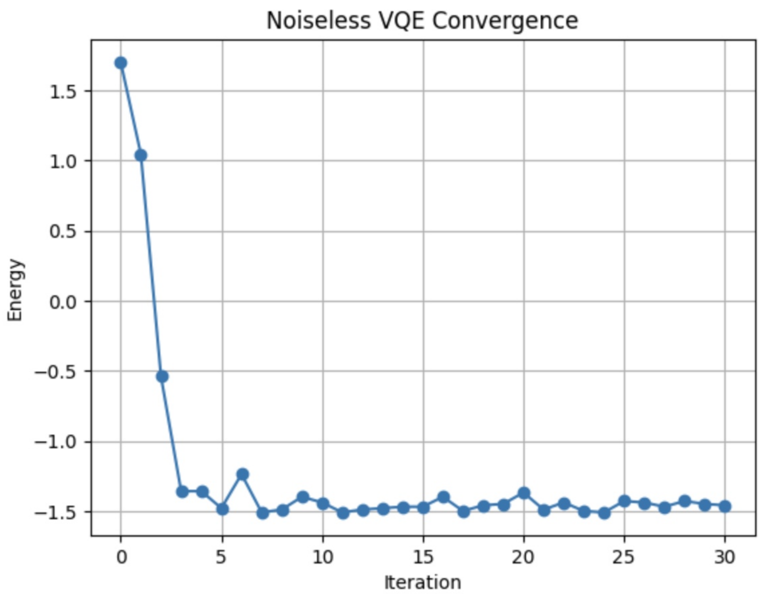

Figure 1: Convergence of the Variational Quantum Eigensolver in the noiseless case. The energy decreases rapidly during the initial iterations and stabilizes near the ground-state energy, providing a reference baseline.

Figure 1 shows that the VQE converges quickly in the absence of noise, serving as a baseline for comparison.

5.2 Effect of Noise on VQE

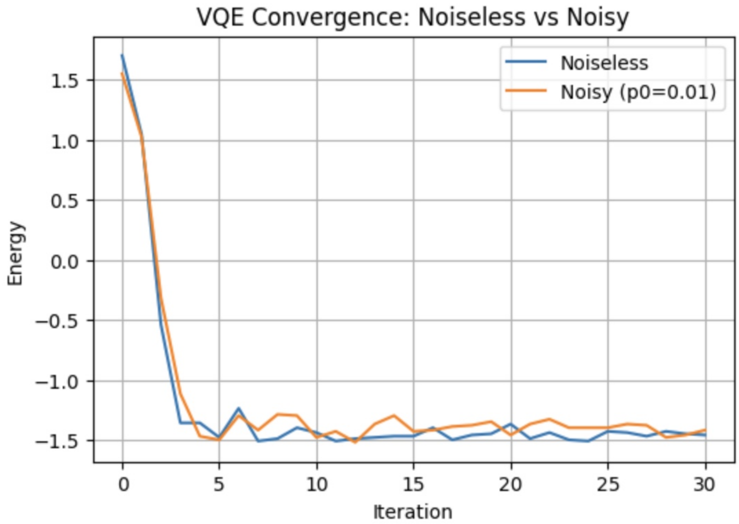

Figure 2: Comparison of VQE convergence in the noiseless case and in the presence of depolarizing noise with base error rate $p_0 = 0.01$. Noise introduces fluctuations and biases the energy estimate.

As shown in Figure 2, noise leads to increased fluctuations and a bias in the energy estimates, while still allowing the algorithm to converge.

6 Limitations

This study has several limitations that should be considered when interpreting the results. First, the analysis is restricted to small problem sizes and shallow circuits, which were chosen to remain compatible with the limitations of NISQ devices. As a result, the findings may not directly extend to larger systems or deeper circuits, where noise effects are expected to be more severe.

Second, the effectiveness of Zero-Noise Extrapolation depends strongly on the available measurement shot budget. In this work, a fixed number of shots is divided across multiple noise-scaled circuits, which increases statistical fluctuations. This introduces a trade-off between reducing systematic noise and increasing statistical uncertainty, limiting the accuracy of the extrapolated results at higher noise levels.

Finally, the noise model used in this project is a simplified depolarizing noise model. Real quantum hardware may exhibit more complex and correlated noise behavior, which could further reduce the effectiveness of error mitigation techniques such as Zero-Noise Extrapolation. These limitations highlight that while ZNE can be useful in certain regimes, it is not a universal solution for mitigating noise in near-term quantum devices.

7 Conclusion

This project investigated the impact of noise on the Variational Quantum Eigensolver in the NISQ regime by comparing noiseless and noisy executions under a fixed measurement shot budget. The results clearly show that noise affects both the convergence behavior and the accuracy of the energy estimates, even for shallow circuits and small problem sizes.

These findings highlight that while variational algorithms remain usable on near-term quantum devices, their performance is strongly limited by noise and finite sampling effects. In particular, the trade-off between systematic noise reduction and increased statistical fluctuations must be carefully considered when applying error mitigation techniques. Overall, this study emphasizes the importance of understanding practical noise limitations when running quantum algorithms on current hardware.

References

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