Quantum Weirdness: Exploring Quantum Error Correction

Andry Lloyd Paez
San Jose State University

Abstract

Quantum computers are highly susceptible to noise, which can lead to errors that jeopardize computations. Quantum Error Correction (QEC) offers a robust way to protect quantum information from such errors. This project focuses on demonstrating the efficiency of the Shor Code, one of the foundational quantum error-correcting codes. By simulating noisy quantum systems with and without error correction, we highlight the effectiveness of QEC and present results in an accessible manner for audiences new to quantum computing.

Introduction

Quantum computing leverages principles like superposition and entanglement to solve problems that are infeasible for classical computers. However, noise—such as bit-flip and phase-flip errors—poses a significant challenge.

Motivation

This project bridges computational physics and quantum computing to address the problem of noise in quantum systems. By visualizing and simulating the Shor Code, we aim to demonstrate how redundancy in encoding qubits mitigates errors and ensures accurate computations.

Goals

The primary objectives are:

- Simulate noise in quantum systems.
- Implement the Shor Code to correct errors.
- Compare results with and without error correction using visualizations.

Theory

Basics of Quantum Computing

A qubit can exist in a superposition state represented as:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

with $|\alpha|^2 + |\beta|^2 = 1$.

A quantum circuit can be used to visualize these states. The qubits are represented as the wires in the diagram while the other objects represent the gates.

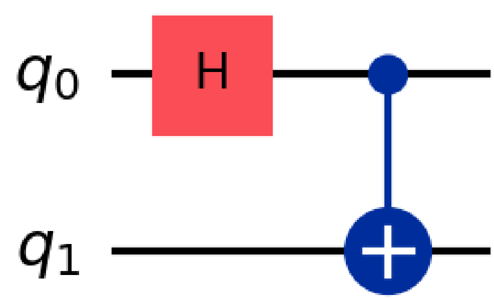

Figure 1: The Bell Circuit

- tensor products
- talk about other types of gates that I won't cover

Quantum Errors

Quantum systems are prone to:

- **Bit-flip errors:** $|0\rangle \rightarrow |1\rangle$ or $|1\rangle \rightarrow |0\rangle$.
- **Phase-flip errors:** Changes in the relative phase of the qubit state.

The Shor Code

The Shor Code encodes one logical qubit into nine physical qubits, correcting both bit-flip and phase-flip errors through redundancy.

Methods

Simulation Setup

Simulations were performed using Qiskit to:

- Generate noisy quantum circuits.
- Implement the Shor Code for error correction.
- Measure outcomes with and without error correction.

Tools

We utilized:

- Qiskit for quantum circuit simulation.
- Matplotlib for visualizations and histograms.
- Python for coding and animations.

Results and Discussion

Noisy Circuit Without Error Correction

Visualization: The histogram in Figure 2 shows a spread of results due to noise.

Figure 2: Measurement results without error correction.

Circuit With Shor Code

Visualization: The histogram in Figure 3 demonstrates how error correction narrows the distribution to the correct outcome.

Figure 3: Measurement results with Shor Code error correction.

Comparison of Results

Analysis: The Shor Code improves accuracy significantly, as shown in the comparative histogram (Figure 4).

Figure 4: Comparison of results with and without error correction.

Conclusion

This project demonstrates the critical role of quantum error correction in mitigating noise and ensuring reliable quantum computations. The Shor Code is an effective method to correct both bit-flip and phase-flip errors, making it a cornerstone for future fault-tolerant quantum computing.

Acknowledgments

Thanks to the instructors, peers, and online resources that supported this project.

References

[1] Chris Bernhardt, *Quantum Computing for Everyone*.

[2] Qiskit Documentation, `https://qiskit.org/documentation/`.

[3] Joschka Roffe, *Quantum error correction: an introductory guide*