Title: Implementing the ZX-Calculus Quantum Optimization Method for 4 Established Quantum Circuits and Quantifying Its Effectiveness

Intro/Motivation:

Quantum computing has a significant advantage over classical computing when it comes to solving complex problems. Molecular simulation, logistics planning, and advanced cryptography are just a few examples of what quantum computing is revolutionizing with its clever manipulation of subatomic particles. For example, Shor's quantum algorithm can find an integer's prime factors exponentially faster than classic algorithms, due to the entangled nature of qubits and how they allow quantum algorithms to simultaneously process multiple solutions. As the stability of quantum hardware increases, this becomes an imminent threat to RSA encryption if the algorithm is applied to large enough numbers. Measurement-based quantum computing (MBQC) is an implementation of quantum computing that leverages subatomic properties by performing measurements on clusters of photons. Since MBQC is a relatively new method, there is significant potential for optimizing its compilers that map the quantum circuits to hardware.

My proposed research will implement the ZX-calculus optimization technique for measurement-based quantum circuits and evaluate its effectiveness by comparing the performance of four established quantum circuits before and after applying the ZX-calculus optimization. This research proposal is a continuation of a previous research project that I completed, where I performed a literature review on ZX-calculus and assembled an end-to-end method of applying the technique to MBQC. I received William & Mary Monroe Scholar funding and the STEM Bridge 2024-2025 research scholarship to support my previous research and hope to be able to continue this optimization research with the STEM Bridge 2025-2026 research scholarship.

Technical Context for Project Proposal:

The ZX-calculus optimization technique is based on the ZX-diagramming language and set of rewrite rules, where circuit components can be rearranged and simplified to remove unnecessary components (Wetering, 2020). Example translations of quantum gates to ZX-calculus symbols are displayed in Fig. 1. The ZX-calculus optimization algorithm then applies the rules of Fig. 2 to the ZX-form quantum circuit, potentially reducing the number of required gates for computation.

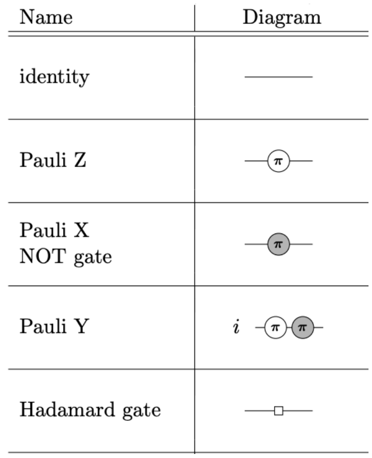

Fig 1. Quantum circuit gates are listed on the left with their corresponding ZX-calculus language symbols on the right. (Wetering, 2020).

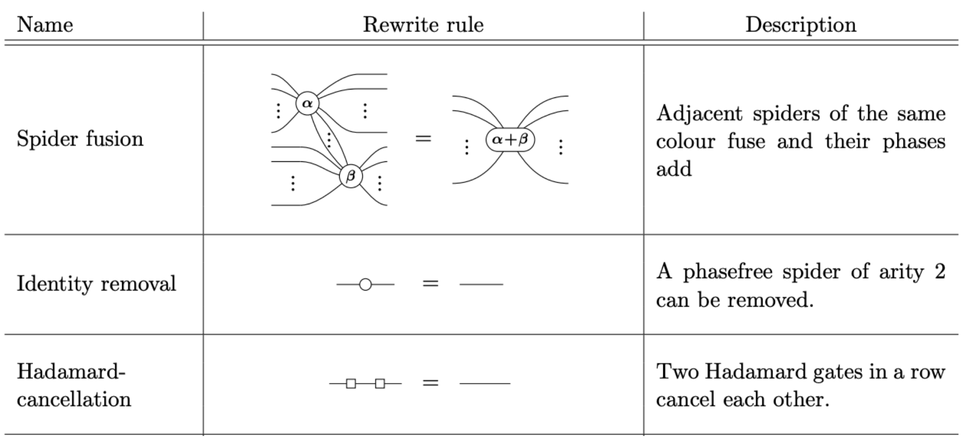

Fig 2. Selected handful of ZX-optimization algorithm rules. These rules are based on the angle-based properties of measurement-based quantum computing, and manipulate the angles of adjacent circuit components. (Wetering, 2020).

The ZX-optimization algorithm leverages the fact that qubit manipulation is implemented through three-dimensional rotations. This can be visualized with the conventional Bloch sphere diagram in Fig. 3.

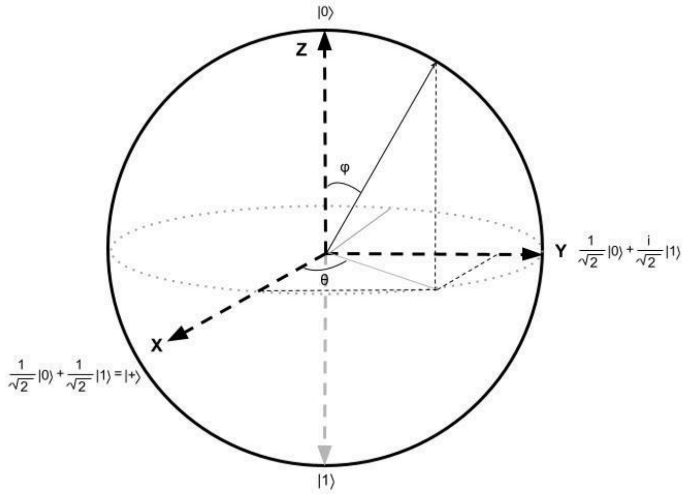

Fig 3. Visualization of the Bloch sphere and key states, a three-dimensional geometric representation of a two-dimensional quantum system. A qubit is in the 0 state if it is oriented in the positive Z direction. A qubit is in the 1 state if it is oriented in the negative Z direction.

For example, two sequential quantum gates of the same type can be merged into a single gate whose rotation sums the two individual rotations. The application of ZX-calculus to measurement-based quantum circuits can be used to reduce the number of qubits needed for the compilers to map the quantum circuits to computational hardware (Li et al., 2023).

Idea of Proposed Project:

The goal of my proposed research is to implement the end-to-end application method of ZX-calculus that I previously assembled, and apply my code to the Shor's algorithm circuit, the Grover's search circuit, the Quantum Fourier Transform circuit, and a predefined teleportation circuit. I will implement these groups with 15, 50, and 100 qubits each, with qubit numbers selected based on the current restrictions of IBM's Qiskit software that I will be using for my research. My goal is to replicate the 40% reduction in 2-qubit gates that researchers recently found the ZX optimization technique to yield (Staudacher et al., 2022).

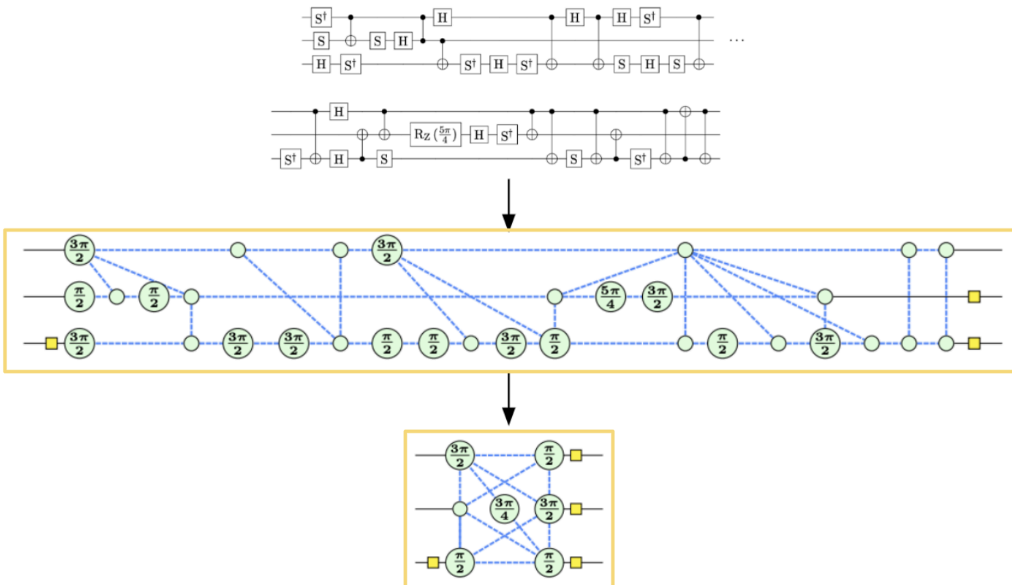

Fig 4: The reduction of gates after applying the ZX-optimization algorithm to an arbitrary circuit is highlighted in yellow. The initial circuit in the sequence is in gate-form, while the following two circuits are in ZX-calculus form. (Staudacher, 2021).

Specific Project Objectives:

- Implement a computer program that builds the measurement-based circuits for Shor's algorithm circuit, Grover's search circuit, the Quantum Fourier Transform circuit, and a predefined teleportation circuit (12 circuits total based on qubit specifications)
- Implement a computer program that transforms input circuits into their ZX-calculus form. This program will also apply the ZX-calculus optimization algorithm to the transformed input circuit.
- Implement an efficient pipeline for applying the ZX-calculus optimization algorithm to each circuit implementation. Pipeline should be optimized to maximize testing time on IBM hardware.
- Build a comprehensive code repository that is able to demonstrate a concrete application of the ZX-calculus optimization algorithm and provide demo scripts for testing.

Timeline of Milestones:

- *Milestone 1*: Review previous literature review on the ZX-calculus method and the selected circuits to implement and optimize.
  Target completion date: June 8th, 2025
- *Milestone 2:* Implement each selected circuit with 15, 50, and 100 qubits each. Also implement the ZX-calculus optimization algorithm locally.
  Target completion date: June 30th, 2025
- *Milestone 3:* Apply the ZX-calculus optimization algorithm to each circuit implementation locally. Run selected optimizations on IBM hardware.
  Target completion date: July 25th, 2025
- *Milestone 4:* Wrap up circuit optimization experiments. Clean up code repository and complete writeup describing experiment results.
  Target completion date: August 1st, 2025

NASA alignment:

My proposed quantum optimization research is most closely aligned with NASA's Science Mission Directorate, as NASA is already studying the applications of quantum technology to its current endeavors. For example, NASA is developing space-based quantum networks for secure information exchange (Stamper-Kurn et al.,2023). NASA's current quantum technology is reliant on photon states, whose extreme fragility have been the main limitation of quantum computation. Applying the ZX-optimization algorithm to current quantum technology has the potential to decrease the number of photons necessary to implement desired computations, which could then improve circuit stability. Thus, my proposed research of applying the ZX-calculus optimization algorithm to quantum circuits could contribute to vital research on the fundamentals of quantum science. This has the potential to advance the accuracy, speed, and computing power of our technology, supporting the performance of NASA's missions in space.

References

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