# QuEra IQuHack 2025 Challenge

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## The Problem

: QuEra's has presented a challenge in the form of a variety of circuits which all have a simple goal of minimizing the cost function given here. Furthermore, the challenge follows strict design rules which requires you to build from a fundamental set of Native Gates which include Z-Rotations, XY-Rotation and a controlled-Z gate. Beyond these design rules there is a quantum computing layout to follow which is built upon a simplified version of a neutral-atom quantum processor with 50 storage sites and 10 pairs within the gate zone. Atoms from the storage zone have to be moved into the pairing within the gate zone to be entangled. Many areas were considered such as how could modifying the arrangement of the circuit produce a more circuit that had global operations instead of several local ones? Was it possible to replace circuit components with ones that included fewer gates? These questions were able to be evaluated throughout the entire 24 hours needed to complete these 5 problems.

## Initial Approach and Thinking

The largest part was trying to get a better grasp of the current optimization techniques available and have attempted to summarize these findings here:
- We found that the simplest modifications was just by changing the order of the gates themselves, where for only one qubit any symbol with the exact same type would be able to commute freely with each other, stating that in terms of the fundamental building blocks of Z, -Z, -X and X.

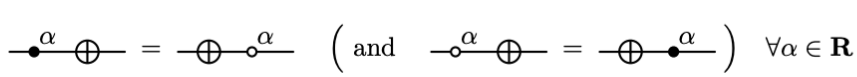


Figure 1:

Figure 1: Sample example for commutating gates

- Regarding CNOT gates under special conditions, they could be rewritten for partially overlapping CNOT gates presented in Fig , reducing the error significantly since it has the largest coefficient. The provided articles also produces a diaganolization of a CNOT representation in terms of Hadamard and a CZ allowing us to code in our native gate set given.

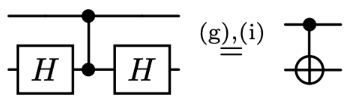


Figure 2:

Figure 2: CNOT represented as the Native Gate Set

Given the initial set of rules, we will be demonstrating a sample on how these transformations were applied to problem 3:

1. All CRZ Gates were translated into a function with a CZ gate along with Hadamard gates. All Hadamards on the same qubit without any control gate between them were essentially canceled out

2. Given the leftover gates, regions were identified with no control gates between the qubits allowing for parallelization of all rotations around the x-axis.

3. Then, parallelism within the CZ gates are checked with only a singular CZ gate which can be run in parallel to make use of the atom shuttling properties

These modifications were provided in the new circuit representation for Fig 3 which uses global gates to lower the total.

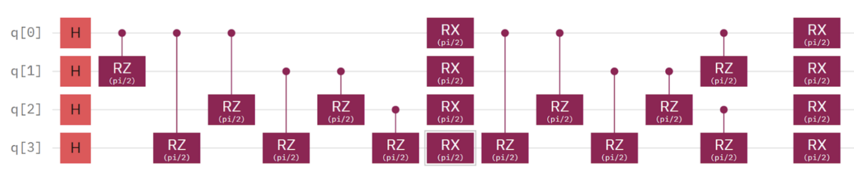


Figure 3: Initial modified circuit representation for Question 2

The process for all initial circuits is viewable following the rules given above

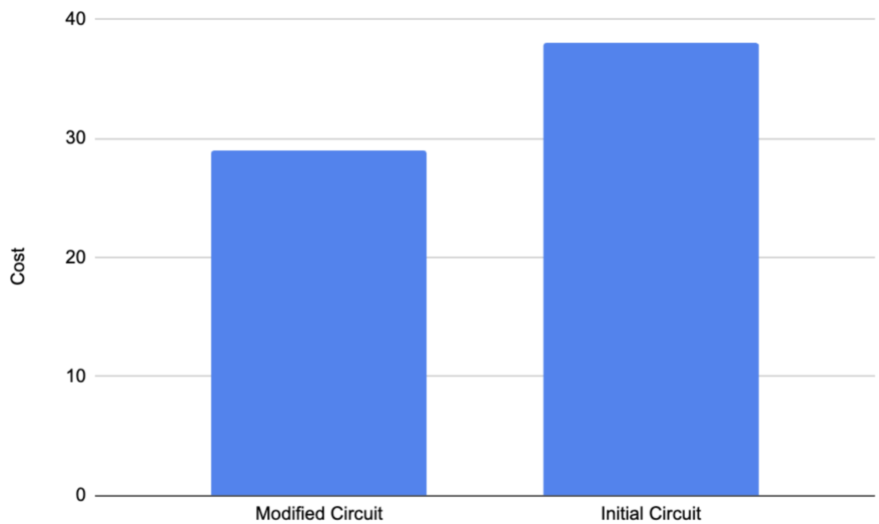


Figure 4: Problem 3 Estimated Cost for Modified Circuit

on how to apply these transformations. For question 3, this provided an overall decrease in the approximate cost by 28

## Restructured Approach

It was discovered to our team that the set of operations that could be implemented wasn't a universal set and just a Native Gate Set. Therefore, for complex circuits 'magic states' were implemented in this case using 2D color codes which helps with reconfiguring and creating parallel control utilizing atom shuttling. These color codes as seen in Fig 4 are done by measuring stabilizers or qubits that flag inconsistencies. However, there is a considerable qubit overhead for a single logical qubit and allows for transversal gates. For question 5, this provides an alternate form of encoding which is easy to parallelize.

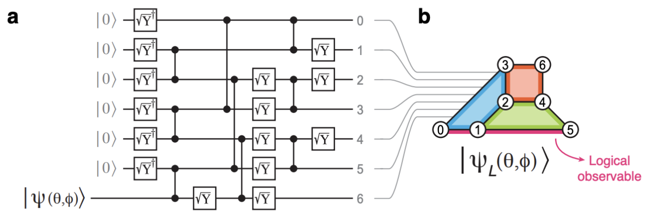


Figure 5: Representation of color code stabilizers and logical operators

To actually find an injection circuit for 2D color code, we have provided an algorithm although this is unlikely to be optimal. This effectively looks at the matrix representation with rows as a data qubit and column as a check operator. A row operation relates to the application of CNOT while column operations are for stabilizers and logical operators.

## Application to Steane 7-qubit

Applying this algorithm to the 2D color code presented in Figure -, includes corresponding colored regions for both X and Z checks and logic operators which is observable to produce a final matrix which can be row reduced to the final matrix below:

$$M^{final} = \begin{array}{c|cccc} & S_0 & S_1 & S_2 & L_0 \\ q_0 & 1 & - & - & - \\ q_1 & - & - & - & - \\ q_2 & - & 1 & - & - \\ q_3 & - & - & - & - \\ q_4 & - & - & 1 & - \\ q_5 & - & - & - & - \\ q_6 & - & - & - & 1 \end{array}$$

Figure 6: Matrix defining all qubits for the Steane circuit

## Bibliography

[1] W. Schober, "Extended quantum circuit diagrams." [Online]. Available: https://arxiv.org/ abs/2410.02946

[2] P. S. Rodriguez et al., "Experimental Demonstration of Logical Magic State Distillation." [Online]. Available: https://arxiv.org/abs/2412.15165