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A magic-state-free architecture for early fault-tolerant quantum computers

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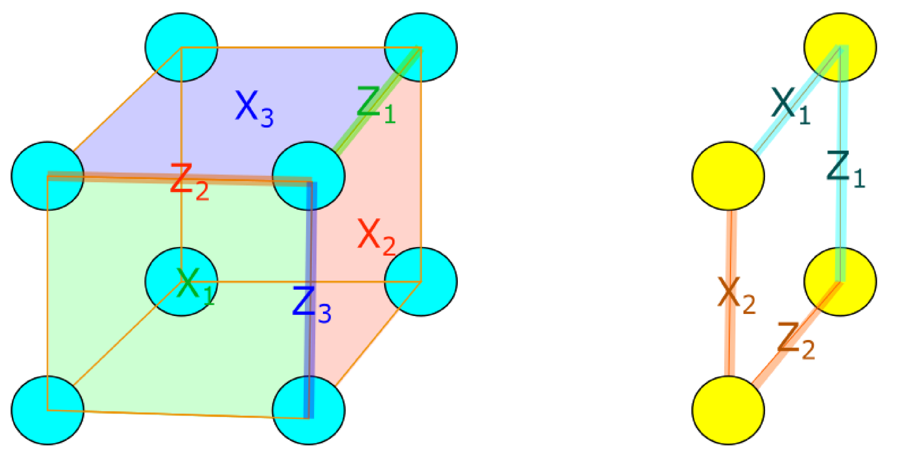
Abstract

The costs of quantum simulation tasks tend to be dominated by non-Clifford gates. On a surface code architecture these gates must be performed via magic-state distillation and gate teleportation, requiring additional space on a quantum device dedicated to distillation. This additional space may be prohibitive to near-term devices where physical qubits are limited. We present an architecture for early fault-tolerant quantum computers that avoids the need for qubit-costly magic-state distillation during runtime. It uses only transversal gates, boot-time preparations of the +1 eigenstate of the single-qubit Hadamard operator, and state teleportation between ⟦4,2,2⟧ (2D) and ⟦8,3,2⟧ (3D) error-detecting color codes. Our architecture realizes the universal logical gate basis consisting of measurement and preparation of qubits in the Z-basis, single-qubit Hadamard gates, and controlled-controlled-Z gates. We provide explicit transpilations from the widely used Clifford + T gate basis to this one, allowing for optimal gate synthesis up to a constant prefactor. We characterize our architecture with two performance metrics and propose empirical tests based off mirror circuit fidelity estimation to estimate these performance metrics at various computational volumes

The ⟦8, 3, 2⟧ and ⟦4, 2, 2⟧ Codes

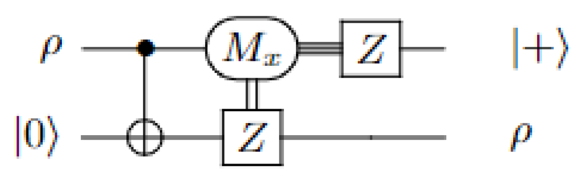
- The ⟦8,3,2⟧ and ⟦4,2,2⟧ error-detecting codes combined posses a transversal universal gateset
- Circles depict physical qubits, colored edges/faces depict logical operators

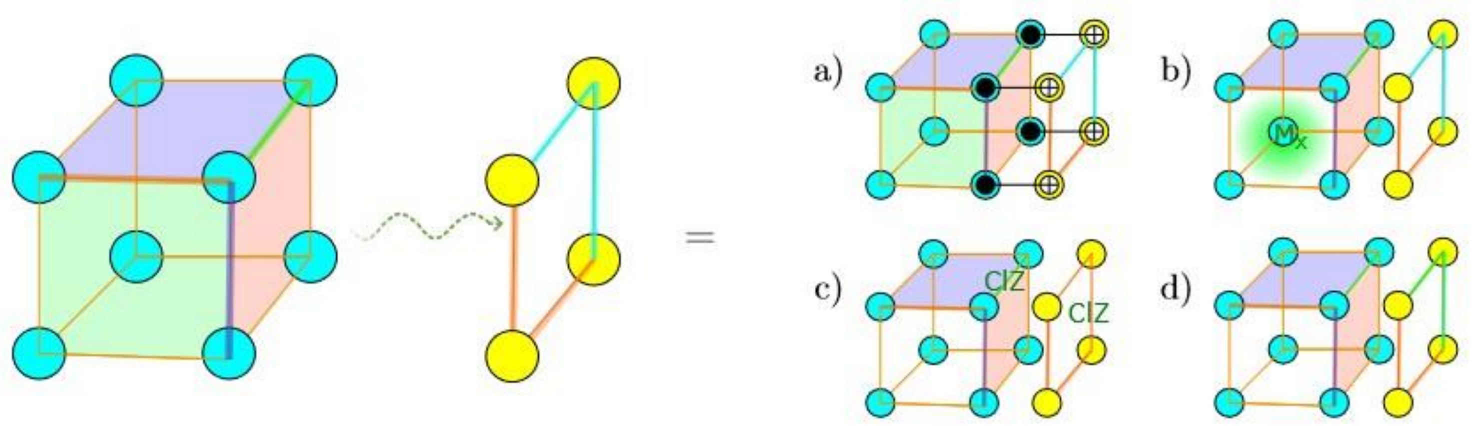


⟦8,3,2⟧
Transversal CCZ

⟦4,2,2⟧
Transversal H

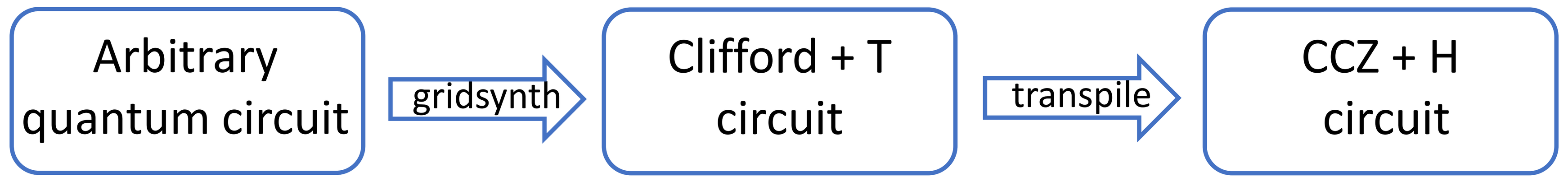
- A transversal CNOT between the two codes allows state teleportation between codes [1].



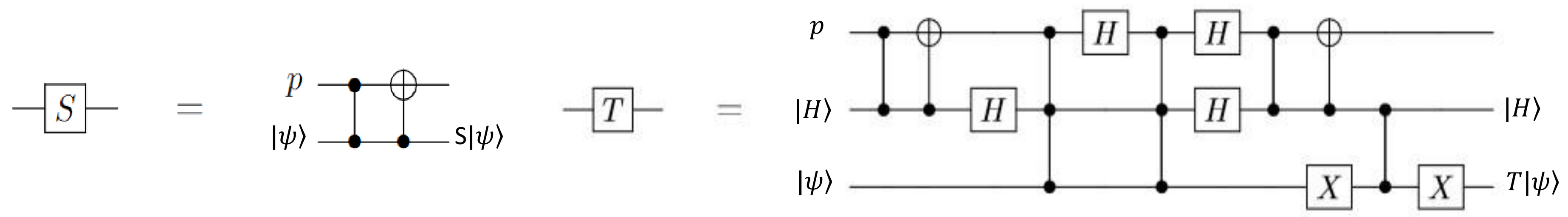


State teleportation between ⟦8,3,2⟧ and ⟦4,2,2⟧ codes, consisting of a) transversal CNOT between codes, b) logical X measurement, c) classically controlled Z gates, and d) the state is now teleported from the ⟦8,3,2⟧ to the ⟦4,2,2⟧ code

Transpilation



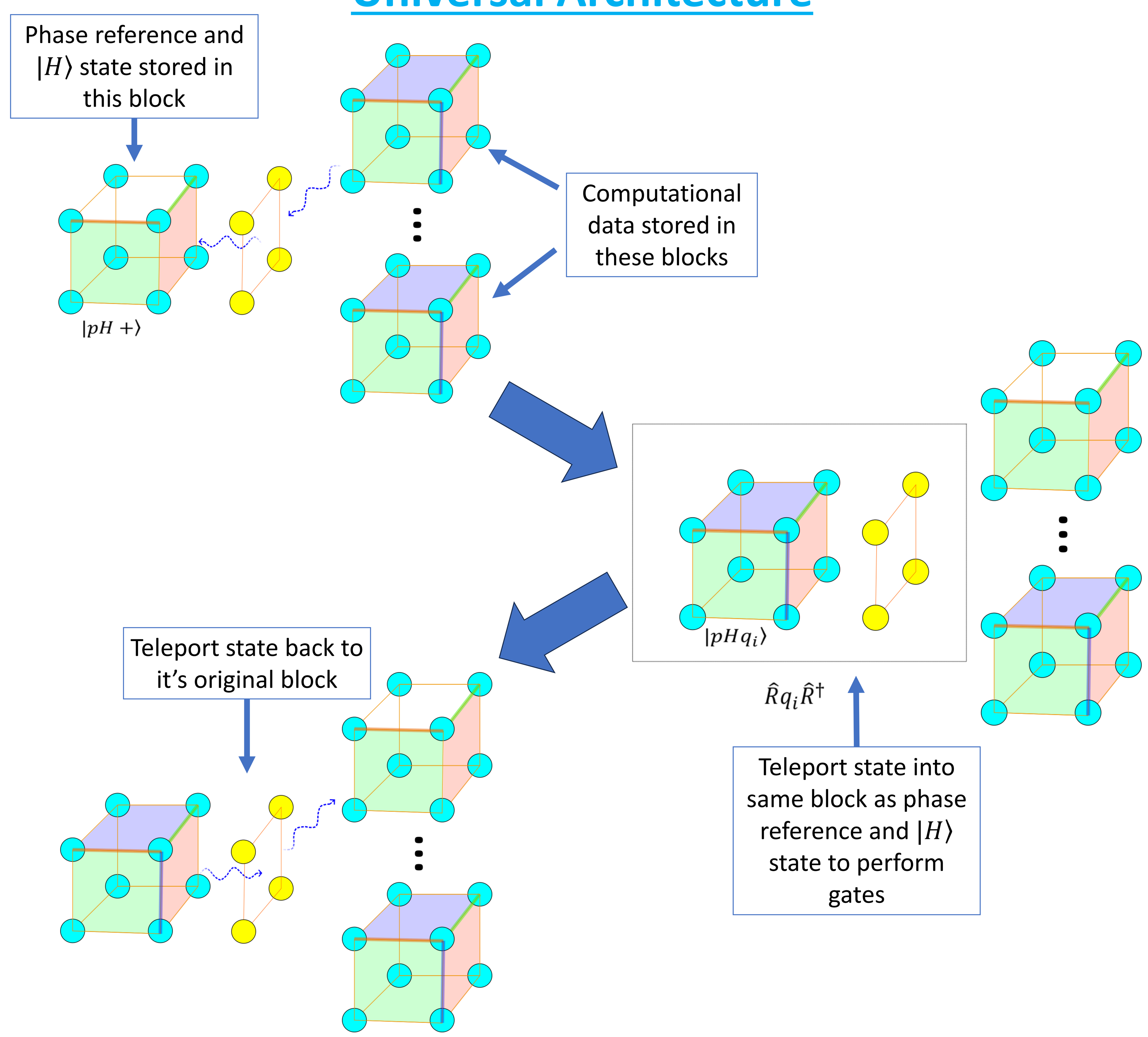
- CCZ+H is universal, given access to a "phase reference" qubit [2] pointing to the real and imaginary subspaces of the Hilbert space
- First synthesize a circuit into a Clifford+T circuit using gridsynth [3], then exactly transpile all gates from Clifford+T to CCZ+H
- ⟦8,3,2⟧ also has transversal CZ, CX, and Paulis, only need to transpile S and T.



Circuit transpilations for S and T, the phase reference qubit is denoted p. For the transpiled T gate the +1 eigenstate of the Hadamard gate (denoted $|H\rangle$) is used catalytically, meaning it can be reused for all transpiled T gates

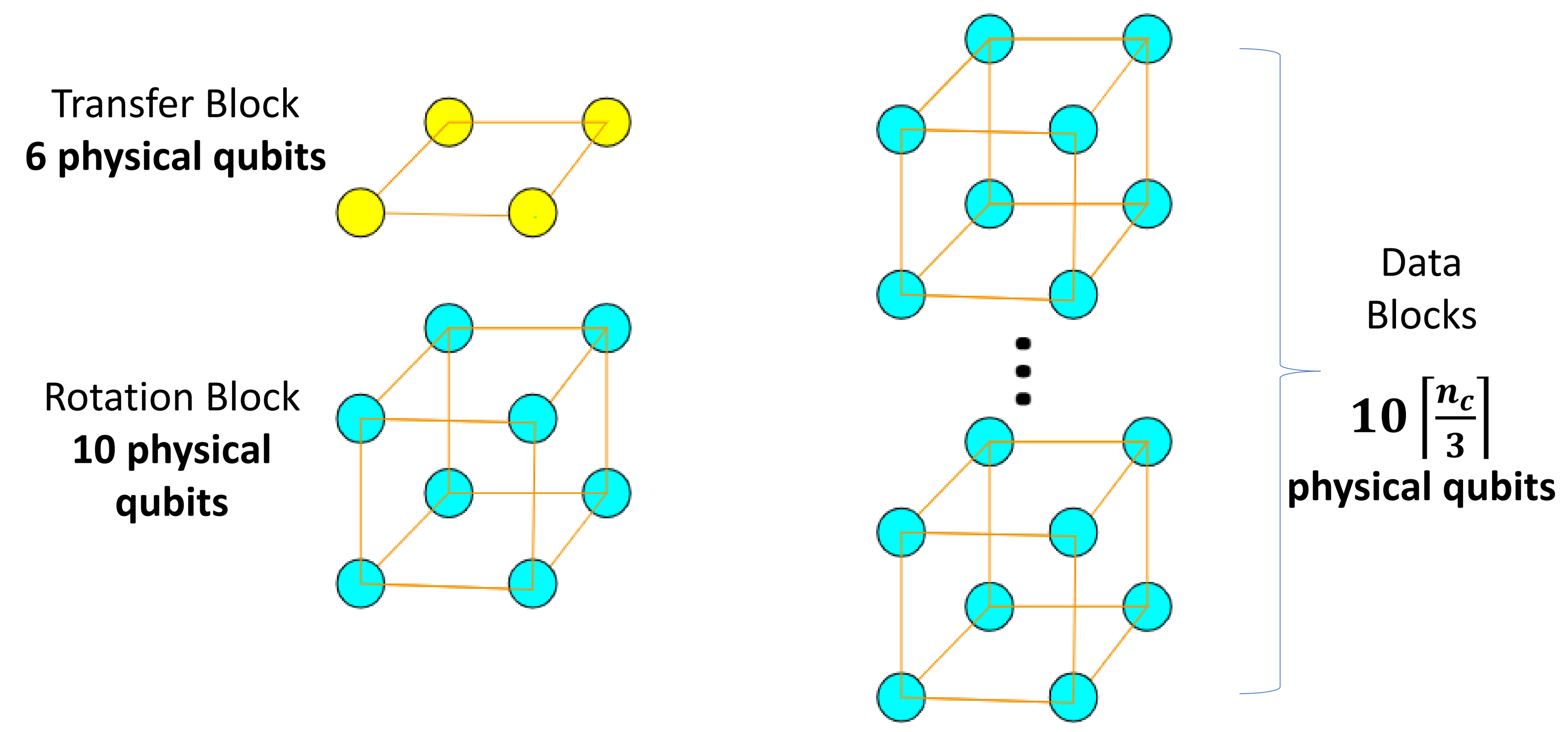
- $|H\rangle$ can be distilled on the ⟦4,2,2⟧ code [4]. As $|H\rangle$ is catalytic, this is only done once at boot-up.

Universal Architecture



Spatial Requirements

Physical qubits: $10\left\lceil\frac{n_c}{3}\right\rceil + 16$ Distance 2 surface code: $8\lceil 1.5n_c\rceil + 112$ [5]



- Each block requires at least 2 additional physical qubits for stabilizer measurements

Performance

Performance is characterized by two metrics:

- Confidence – probability that data is error-free after error-detection and post-selection
- Yield – fraction of runs kept by post-selection

Confidence and yield can be estimated at various computational volumes using mirror circuit fidelity estimation techniques

Conclusions and Ongoing Work

- We present a fault-tolerant error-detecting architecture that avoids magic-state distillation, achieving significantly fewer required physical qubits than the surface code at distance 2
- We present a compilation strategy to compile any circuit into a CCZ+H that first synthesizes the circuit into a Clifford+T circuit using gridsynth, then exactly transpiles all gates to CCZ+H
- Ongoing work is aimed at development of empirical methods to estimate the performance of a device utilizing this architecture.

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