Surface Code Quantum Computation

Progress and Challenges

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1. Quantum Error Correction: Where We Are?

1.1 Why do we need QEC?

- Today's quantum computers are noisy: $\sim$ 1 error per 100 operations.
- Practical advantage of quantum computer needs *MegaQuOp* scale.
- Practical Application of quantum computer needs *GigaQuOp*/ *TeraQuop* scale.

Application (One shot of QPE)	Logical qubits N	Depth D	QuOps (lower bound) N.D
Hubbard model (8x8) Campbell Quantum Sci. Technol., 7 015007 (2021)	162	5.8 million	0.9 GigaQuOp
Jellium / Free electron gas (5x5x5) Kivlichan et. al. Quantum, 4, 296 (2020).	378	89 million	34 GigaQuOp
RSA with 2024 bits Ekera and Gidney Quantum, 5, 433 (2021).	6,115	2.1 billion	13 TeraQuOp
FeMoCo (Li orbitals / THC method) Lee et. al. PRX Quantum, 2, 030305 (2021).	2,196	130 billion	285 TeraQuop

Figure 1: *QuOp* Scale of Practical Quantum Application[1]

- We are at the point where the theory of QEC is beginning to be proven experimentally.
- We are still growing and improving single logical qubit.
- In 2024, Google demonstrated *sub-threshold* quantum error correction experimentally[2].

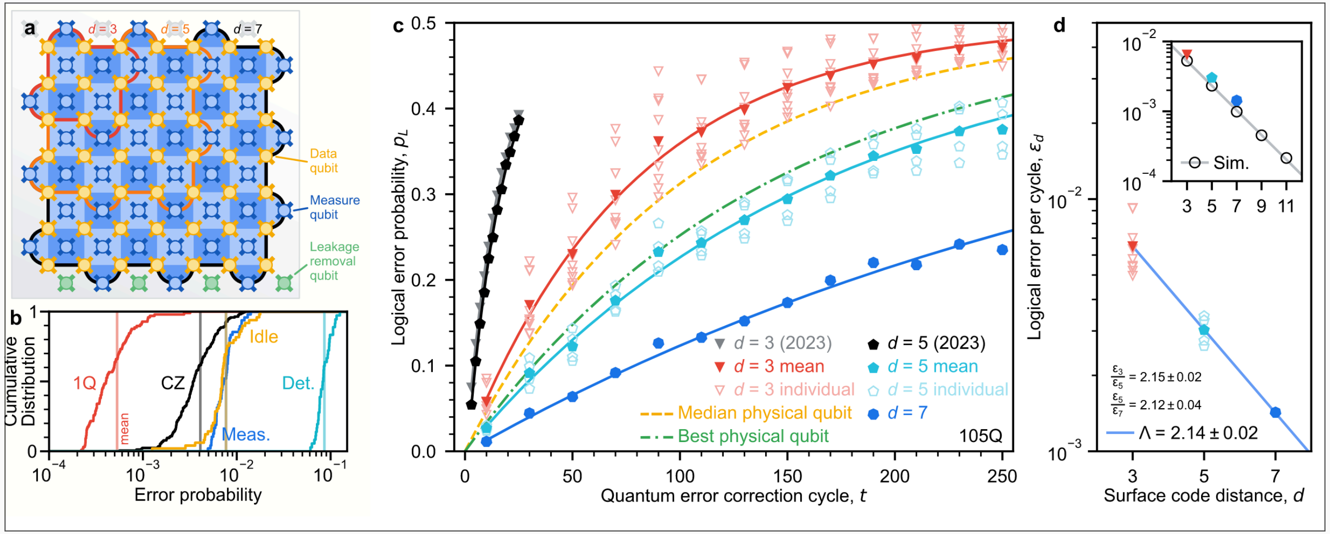


Figure 2: Google's Logical Memory Experiment(d=3,5,7)

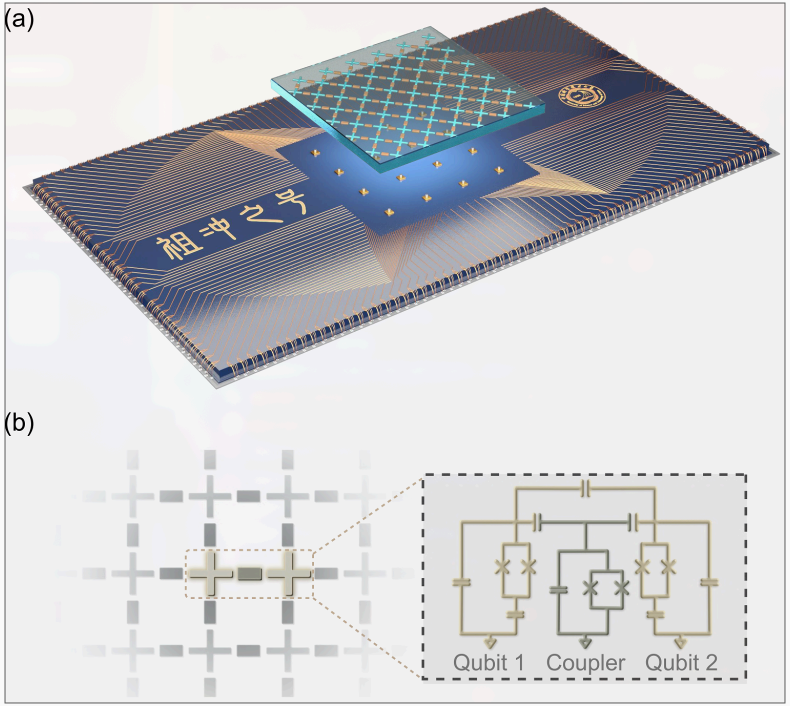


Figure 3: *Zuchongzhi2* Quantum Processor

We demonstrated $d = 3$ surface code on *Zuchongzhi2* processor in 2022[3]. The hardware has been improved since then:

- 100+ qubits with tunable couplers
- $T_1 \sim 50\mu s$
- Parallel 1Q gate $\sim 99.9\%$
- Parallel CZ gate fidelity $\sim 99.5\%$
- Parallel repeated measurement $\sim 98\%$
- Faster *repeated measurements*
- Support *reset* operation
- The design is optimized for targeted quantum error correction experiments

2. Surface Code: A Practical Way towards Fault-Tolerant Quantum Computation

2.1 Surface Code

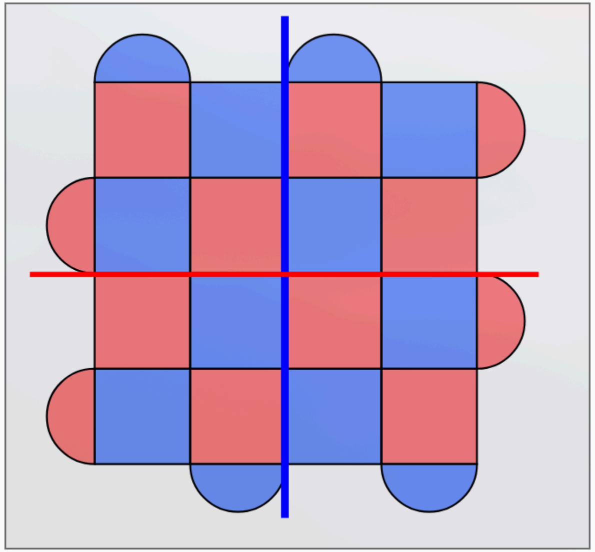


Figure 4: $d = 5$ Rotated Surface Code

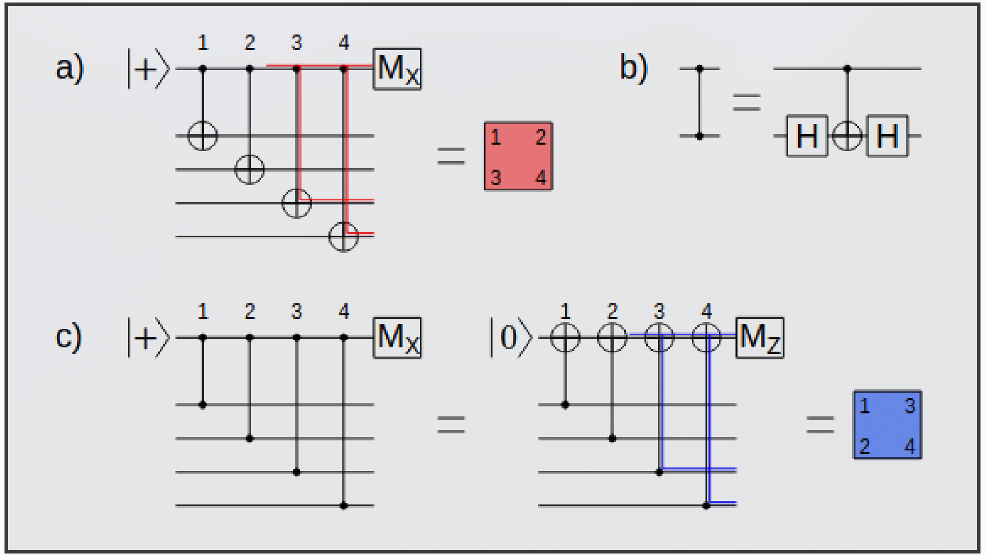


Figure 5: Syndrome Measurement Circuits

Pros

- A high error threshold: near 1%
- 2D Nearest-neighbor connectivity: suitable for superconducting qubits
- Good decoders available: MWPM, Union-Find, Tensor Network, Neural Network
- Mature protocols for logical operations: lattice surgery, transversal gates

Cons

- High resource overhead: vanishing encoding rate($\frac{1}{d^2}$)

- Logical init in X(Z) basis: reset all data qubits in $|+\rangle(|0\rangle)$ state, takes $O(1)$ time.
- Logical meas in X(Z) basis: measure all data qubits in X(Z) basis, takes $O(1)$ time.
- Logical init/meas in Y basis requires more complex circuits, which maps between the logical Y operator and the product of specific stabilizers, takes $\frac{d}{2}$ time.[4]

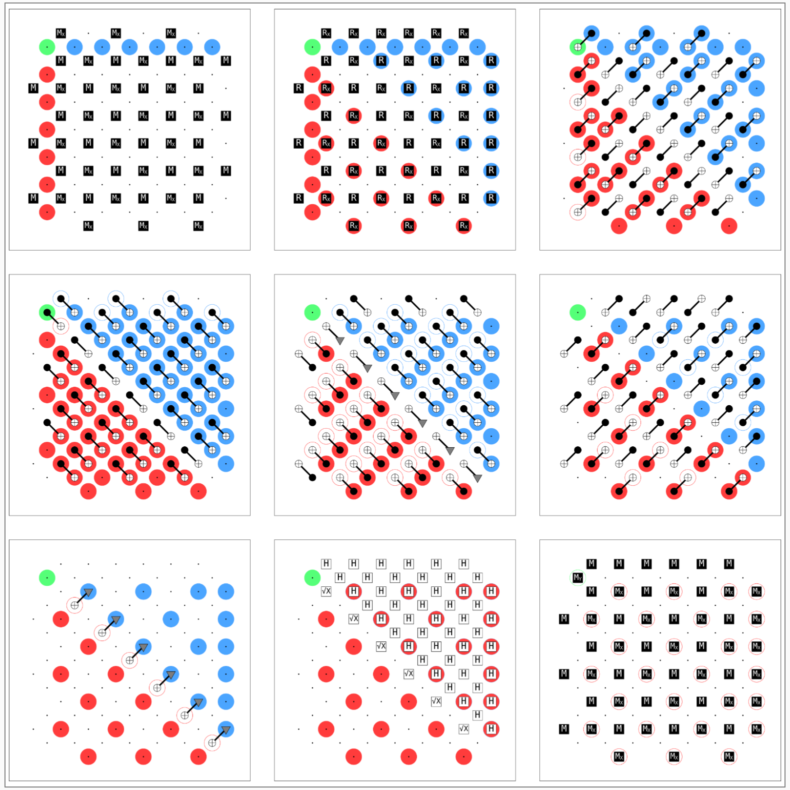


Figure 6: Y Basis Measurement

Logical Pauli gates(or corrections from decoding) can be tracked in software and do not require physical operations on hardware. Takes **zero** time.

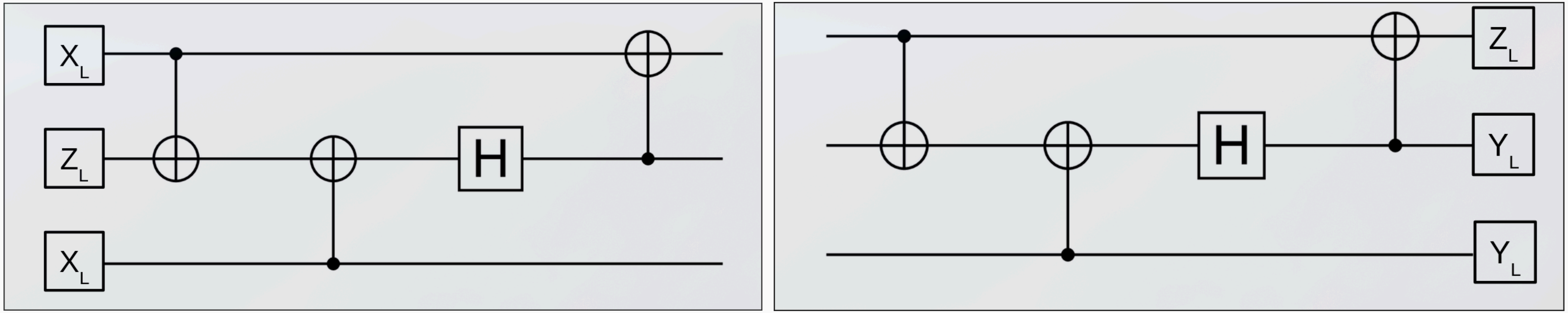


Figure 7: Pushing Pauli Gates Through the Circuit

Logical Hadamard Effect can be applied with a layer of transversal H gates on data qubits, while exchanging the boundary types. Takes $\boldsymbol{O(1)}$ time.

Rotating the boundary types back can be achieved in $\boldsymbol{4d^3}$ spacetime volume.

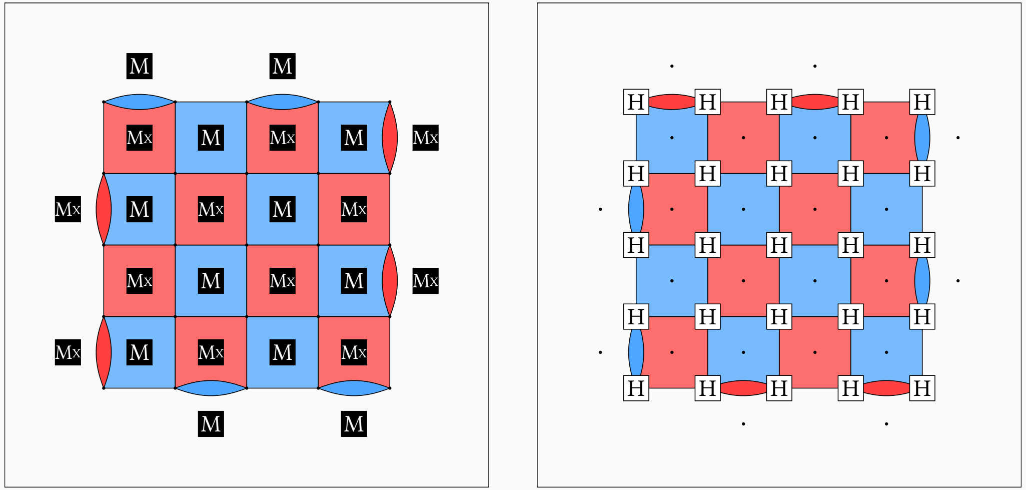


Figure 8: Logical H Effect

With space-time symmetry, the logical Hadamard effect can also be implemented in spatial direction.

Parity measurement is an elementary operation in lattice surgery based surface code quantum computation.

It can be achieved by merge and split operations between two logical qubits.

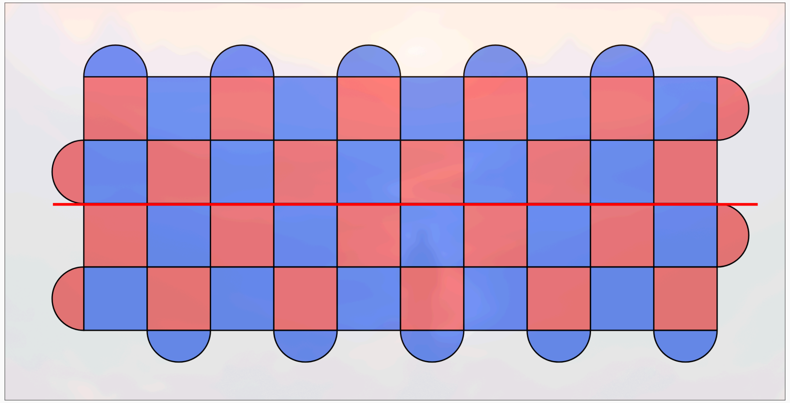


Figure 9: Product of physical qubit measurements realizes M_{XX}

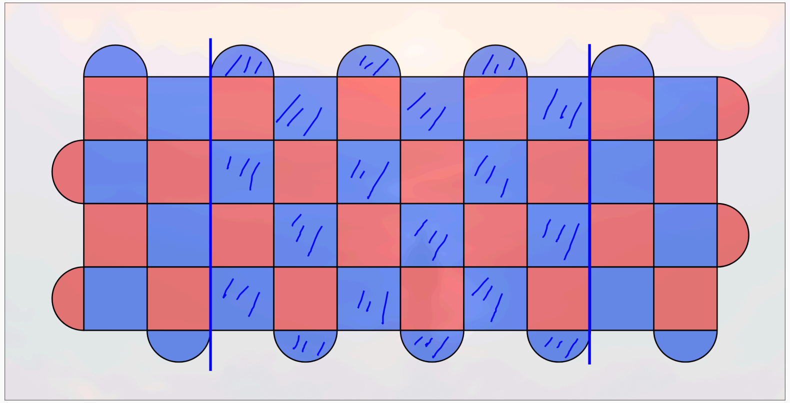


Figure 10: Product of stabilizer measurements realizes M_{ZZ}

2.6 Logical Operations: S

Logical S gate can be implemented via gate teleportation[4]. Takes $\mathbf{3d^3}$ spacetime volume.

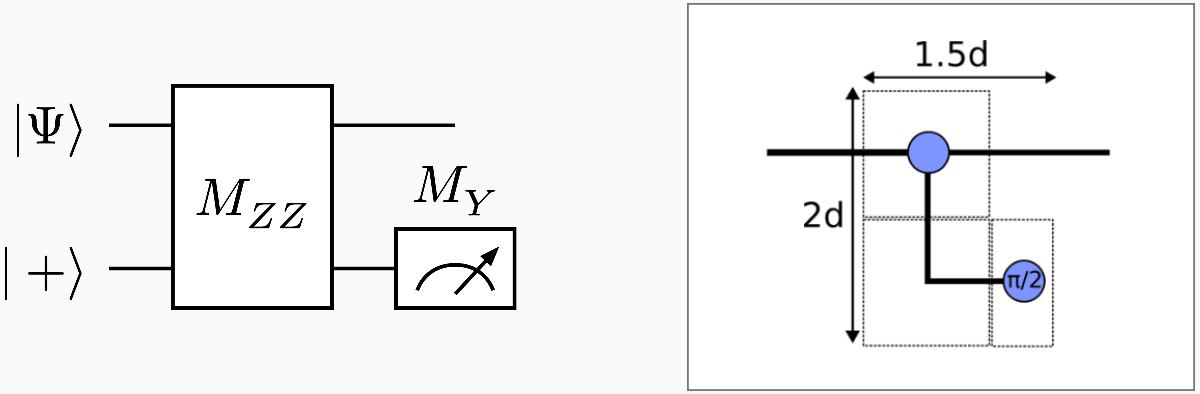


Figure 11: Logical S Gate[1]

[1] Pauli corrections conditioned on the measurement results are not plotted.

Logical CNOT gate can be implemented by two parity measurements. Takes $\mathbf{6d^3}$ spacetime volume.

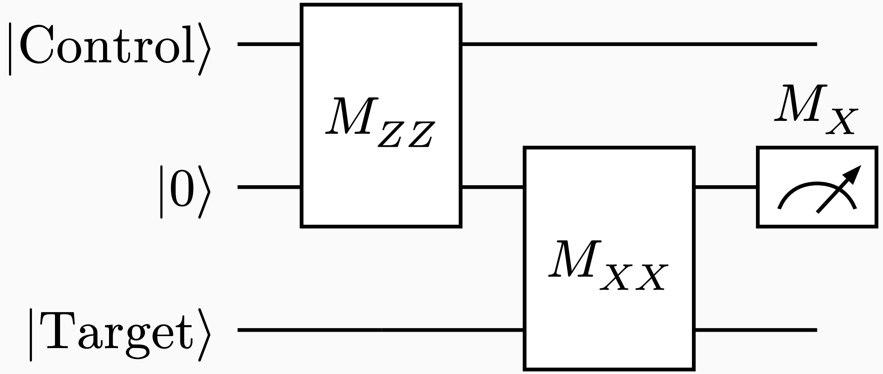


Figure 12: Logical CNOT Gate[1]

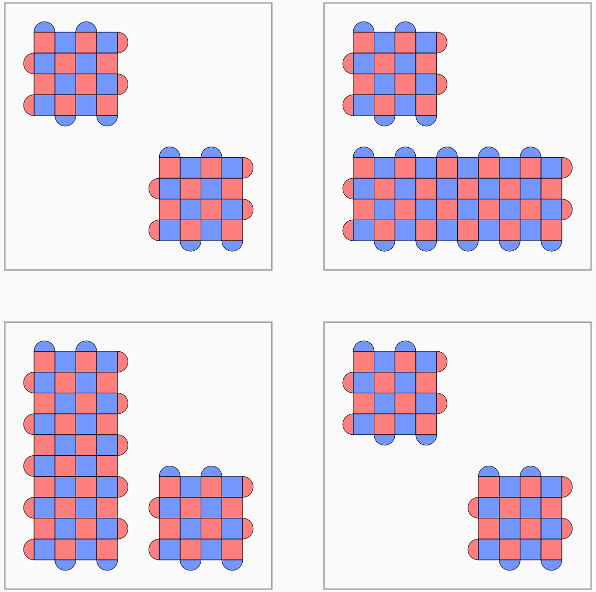


Figure 13: Logical CNOT Patches

[1]Pauli corrections conditioned on the measurement results are not plotted.

Historically, implmenting *T gates* requires expensive magic state distillation and is the main overhead of surface code quantum computation. Now preparing a high-fidelity magic state is as cheap as a logical CNOT gate[1] by cultivation[5].

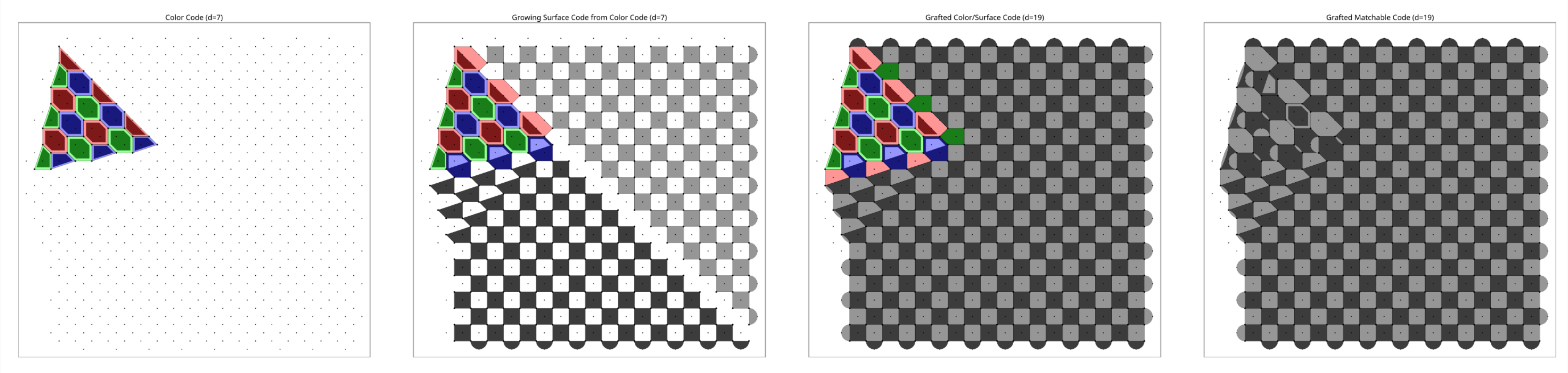


Figure 14: Magica State Cultivation

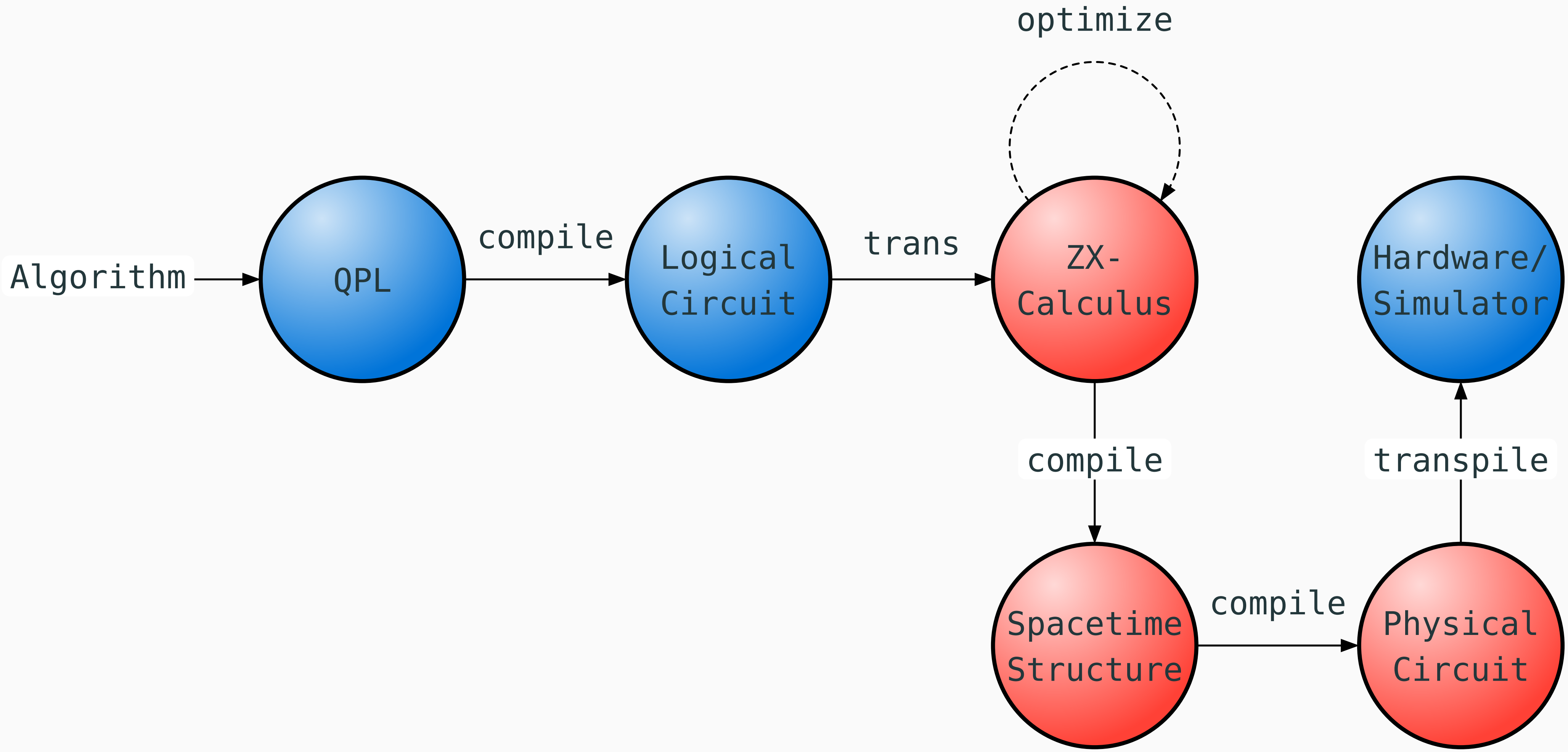
[1] for magic state fidelity achieving $1e^{-9}$

3. *TQEC*: Design Automation for Surface Code Quantum Computation

- *TQEC* is an open-source community for design automation of surface code quantum computation. It is organized by Austin G. Fowler from Google Quantum AI.
- We are building the tools to manage the complexity of scalable circuit compilation, arrangement optimization. It's not for good, but necessary…
- The code is open-source and available on GitHub: https://github.com/tqec/tqec.[1] It's still in the very early stage.

[1]Disclaimer: The author is one of the core maintainers of *TQEC*.

3.2 *TQEC* Workflow(Possibly)



3.3 ZXGraph and BlockGraph Representation

In TQEC, we represent a logical computation by either a ZXGraph or a BlockGraph.

There is strong correspondence between the two representations:

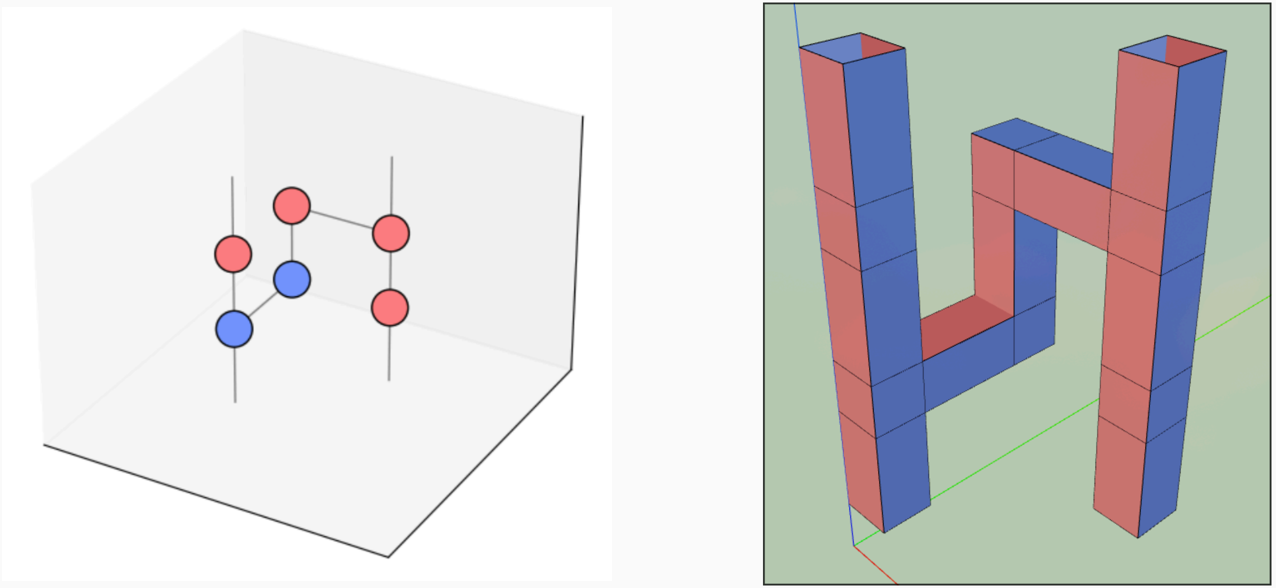


Figure 15: Logical CNOT Representation

3.3 `ZXGraph` and `BlockGraph` Representation

To build a logical computation, we can either:

- Build interactively with 3D model tool like SketchUp.
- Build programmatically with Python API.

Currently, only limited building blocks are implemented. And the compilation from a general `ZXGraph` to `BlockGraph` is not supported yet.

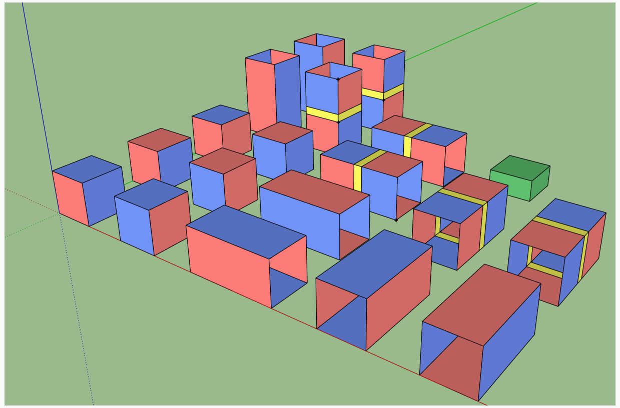


Figure 16: SketchUp Model of a Logical CNOT

Represent local circuits as `Plaquette` and compose the `Plaquettes` with the pattern specified by the `Template` to build scalable circuits.

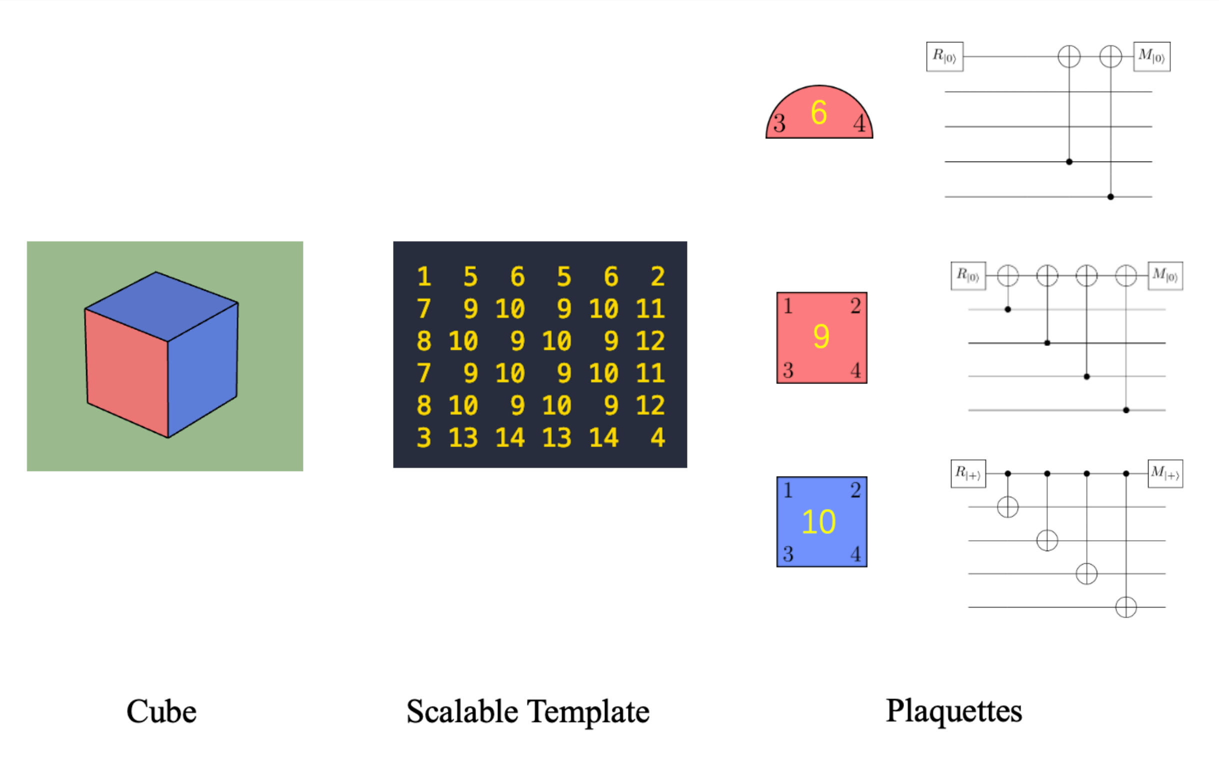


Figure 17: Build a `Cube` from `Template` and `Plaquettes`

3.5 Compose `Blocks`

- The complete set of *observables* supported by the logical computation can be found with the notion of `Correlation Surface`:

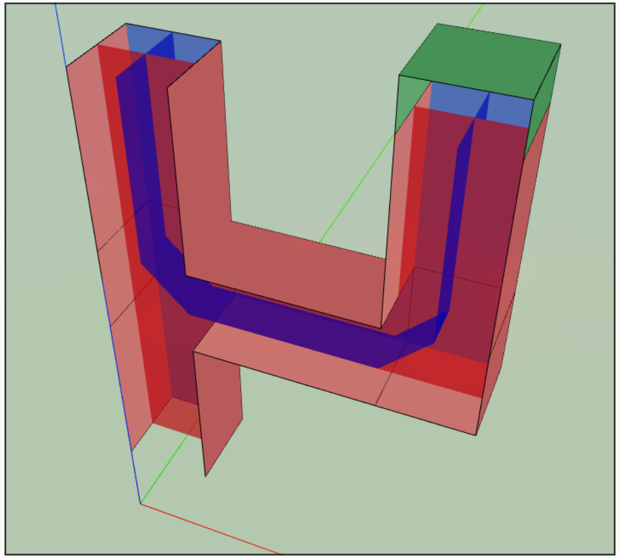


Figure 18: Correlation Surface

- The possible *detectors* in the circuit can be constructed automatically by matching the creation and destruction stabilizer flows.

3.7 Run the Circuit on Hardware/Simulator

The output circuit is of `.stim` format, and can be simulated with `stim` stabilizer simulator efficiently(when there is no non-Clifford gates). Here we show the simulation results of a single logical CNOT gate:

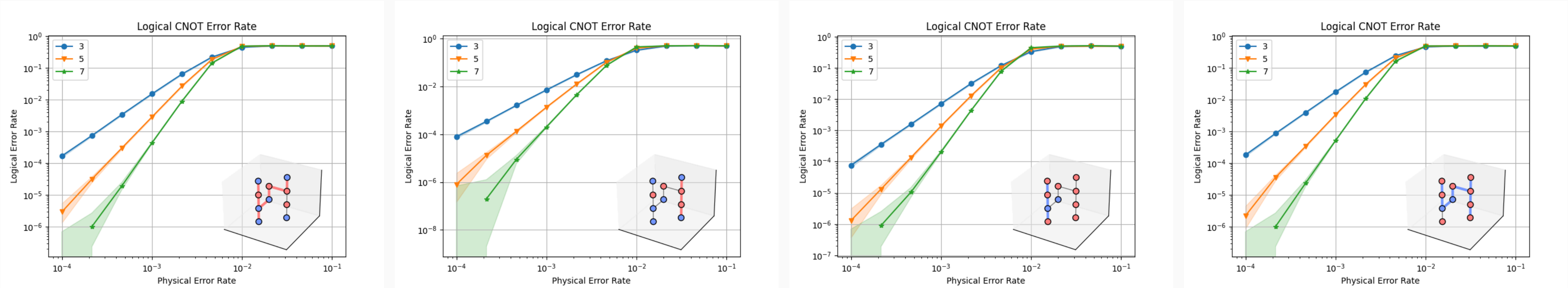


Figure 19: Logical CNOT Representation

Additionally, we have ran the circuits produced by `TQEC` on Google's 105-qubit Sycamore processor. The paper introducing the `TQEC` tool as well as the experimental results is in preparation.

4. Challenges and Future Directions

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- Real-time decoding: tradeoff between decoding speed and accuracy.
- Error sources that have effects under ultra-low error rate region, e.g. cosmic rays.
- Resource optimization for large-scale quantum computation: optimize for compact spacetime layout.
- The hardware/software architecture of large-scale FT quantum computer.
- ...

Thanks!

The slides are available at

https://github.com/inmzhang/surface_code_quantum_computation.

Bibliography

[1] Riverlane, "Quantum Error Correction Report 2024." [Online]. Available: https://www.riverlane.com/quantum-error-correction-report-2024

[2] R. Acharya *et al.*, "Quantum error correction below the surface code threshold," *arXiv preprint arXiv:2408.13687*, 2024.

[3] Y. Zhao *et al.*, "Realization of an error-correcting surface code with superconducting qubits," *Physical Review Letters*, vol. 129, no. 3, p. 30501, 2022.

[4] C. Gidney, "Inplace access to the surface code y basis," *Quantum*, vol. 8, p. 1310, 2024.

[5] C. Gidney, N. Shutty, and C. Jones, "Magic state cultivation: growing T states as cheap as CNOT gates," *arXiv preprint arXiv:2409.17595*, 2024.