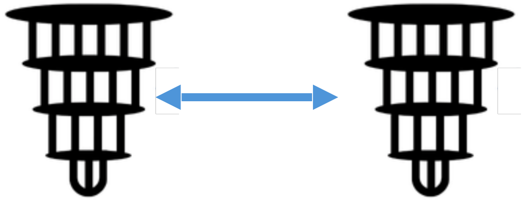
Scaling Quantum Error Mitigation in the Age of Distributed Quantum Computation

by María Gragera Garcés



Quantum Software Lab

THE UNIVERSITY OF EDINBURGH

Talk structure

- DQC the Background
- DQC errors: What breaks down
- Our current research in DQEM
- Conclusions

DQC the Background

“if you are building things for tomorrow’s quantum computers you are building things for distributed quantum computers”

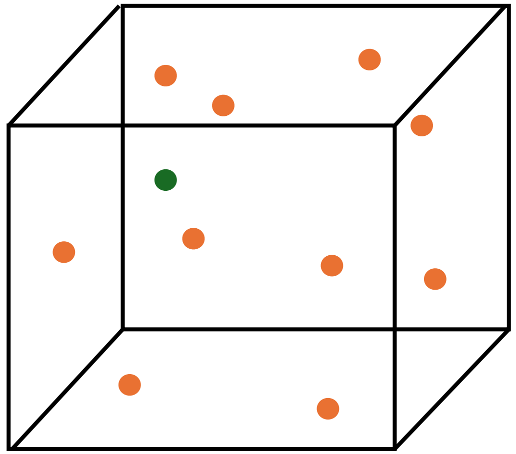
What is DQC?

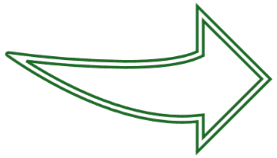
Scalability

- ➢ Qubit Capacity Expansion
- ➢ (Heterogeneous) Hardware Integration

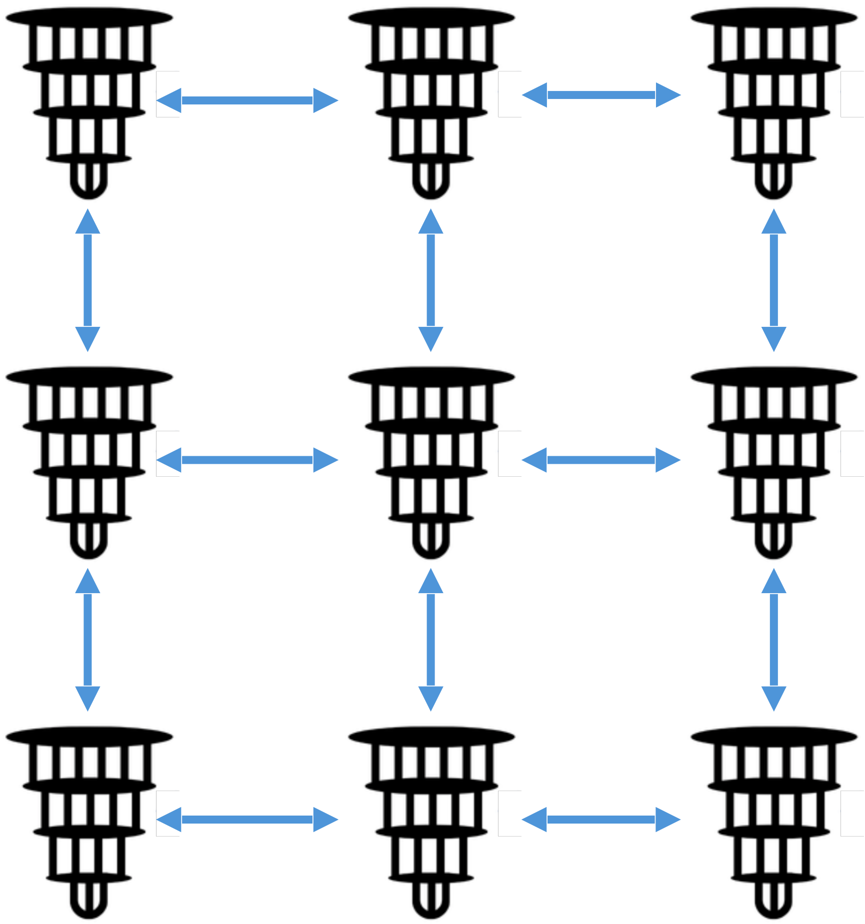
Computation + Communication

Problem





Network

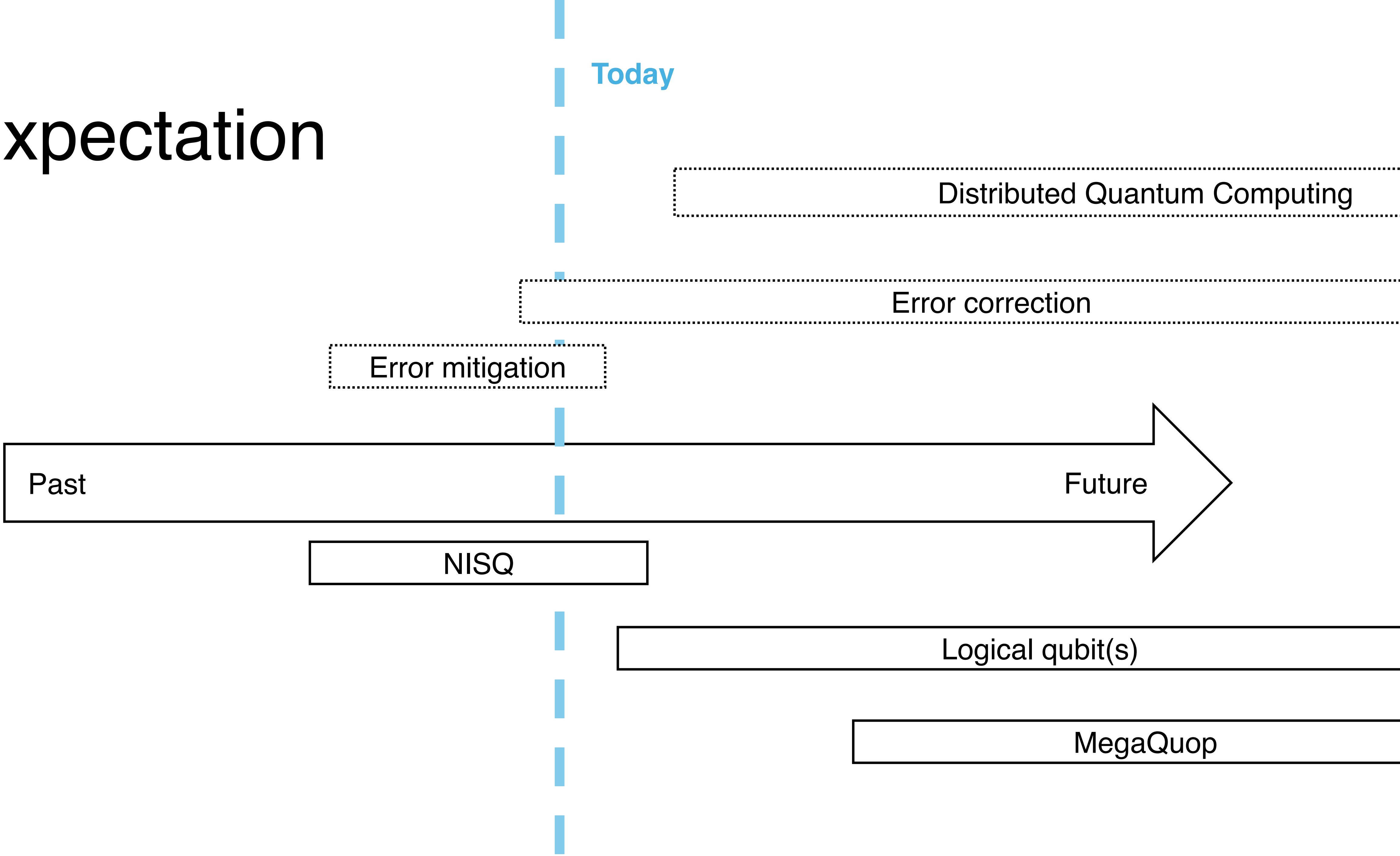


What counts as “DQC”

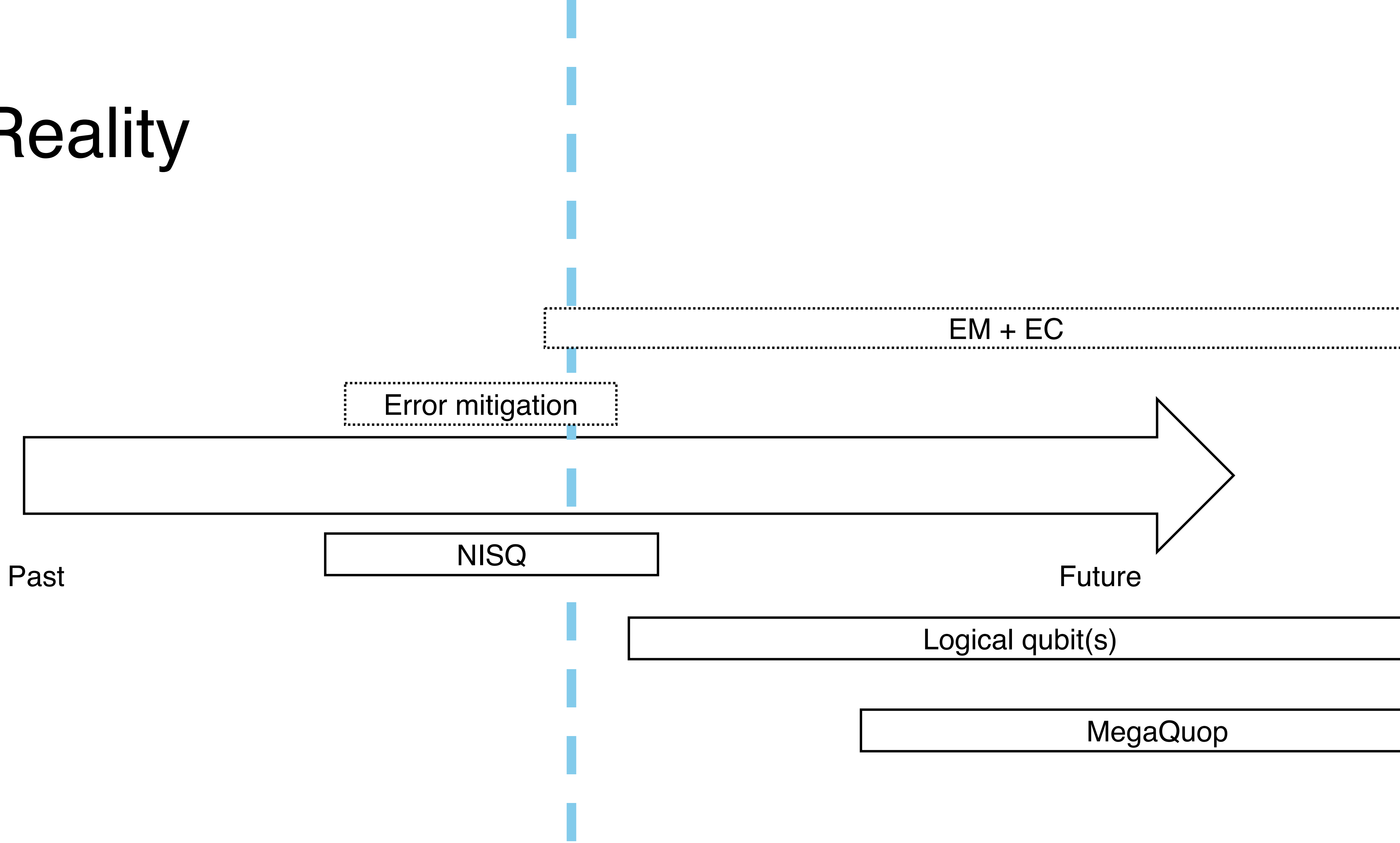
Quantum devices that can individually perform quantum computations that cannot be classically simulable, are separated spatially, and are interconnected with each other via quantum channels

- Multiple quantum chips within a single device, performing a joint quantum computation and communicating via quantum channels under a shared classical control system (aka I’ll permit shared memory access *for now*).
- Separate quantum computers interconnected via a local quantum network, enabling quantum state transfer and entanglement distribution to perform distributed algorithms (HPC like cluster applications).
- Long-range quantum communication (quantum internet like stuff) coordinating remote quantum nodes with the purpose of quantum computation.

Expectation



Reality


EM + EC
Error mitigation
NISQ
Past
Future
Logical qubit(s)
MegaQuop

Rigetti Demonstrates Industry's Largest Multi-Chip Quantum Computer; Halves Two-Qubit Gate Error Rate

Distributed Quantum Computing

EM + EC

Error mitigation

NISQ

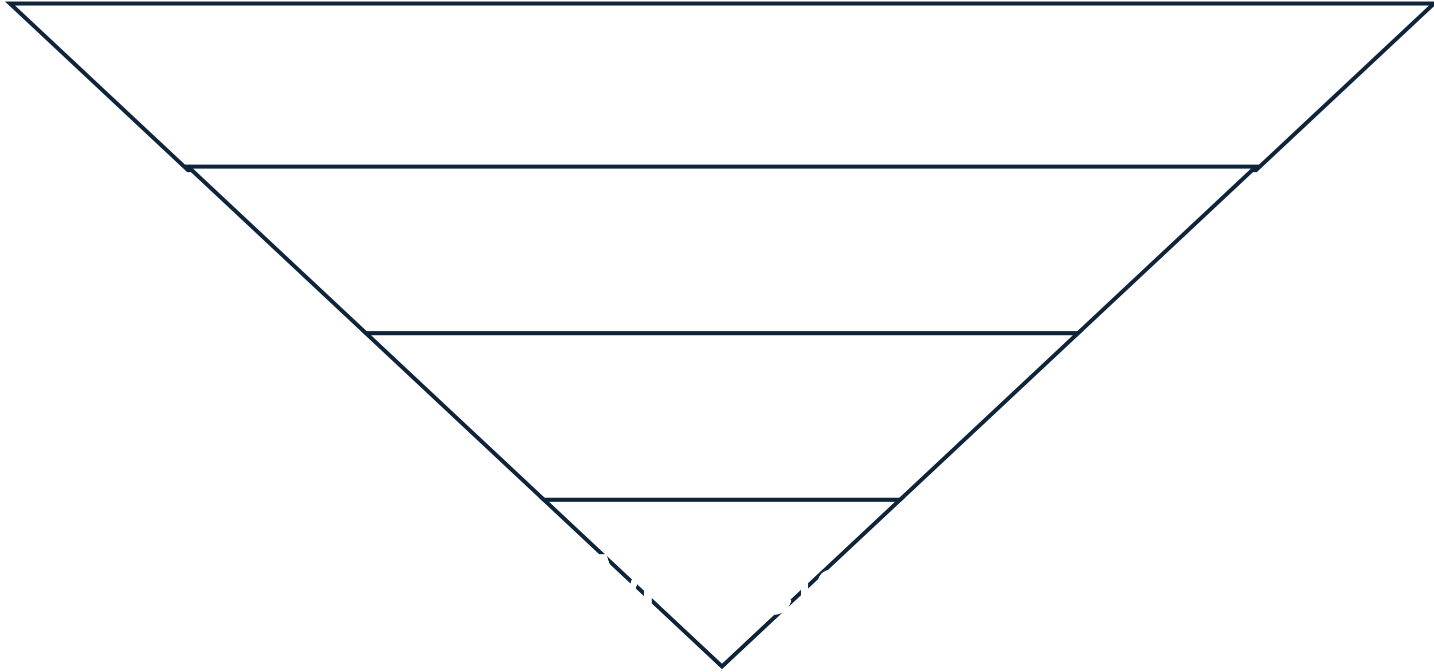
Past

Future

Logical qubit(s)

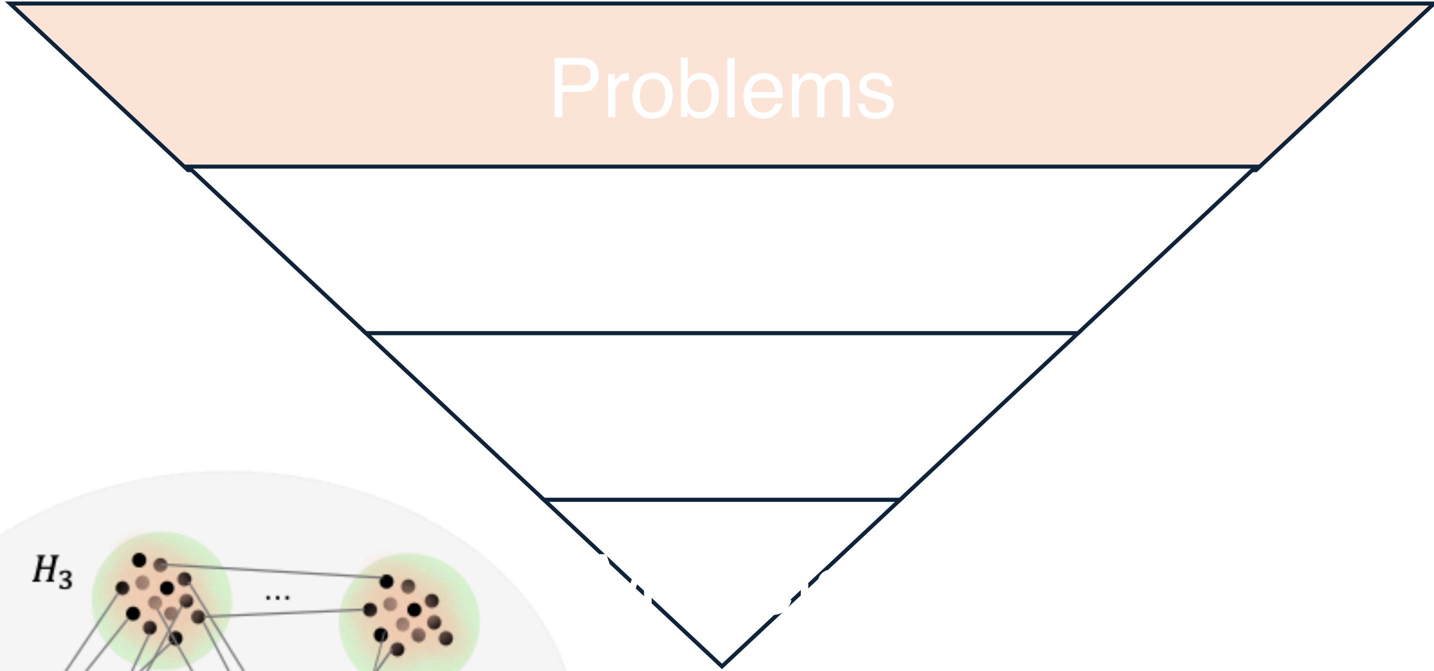
MegaQuop

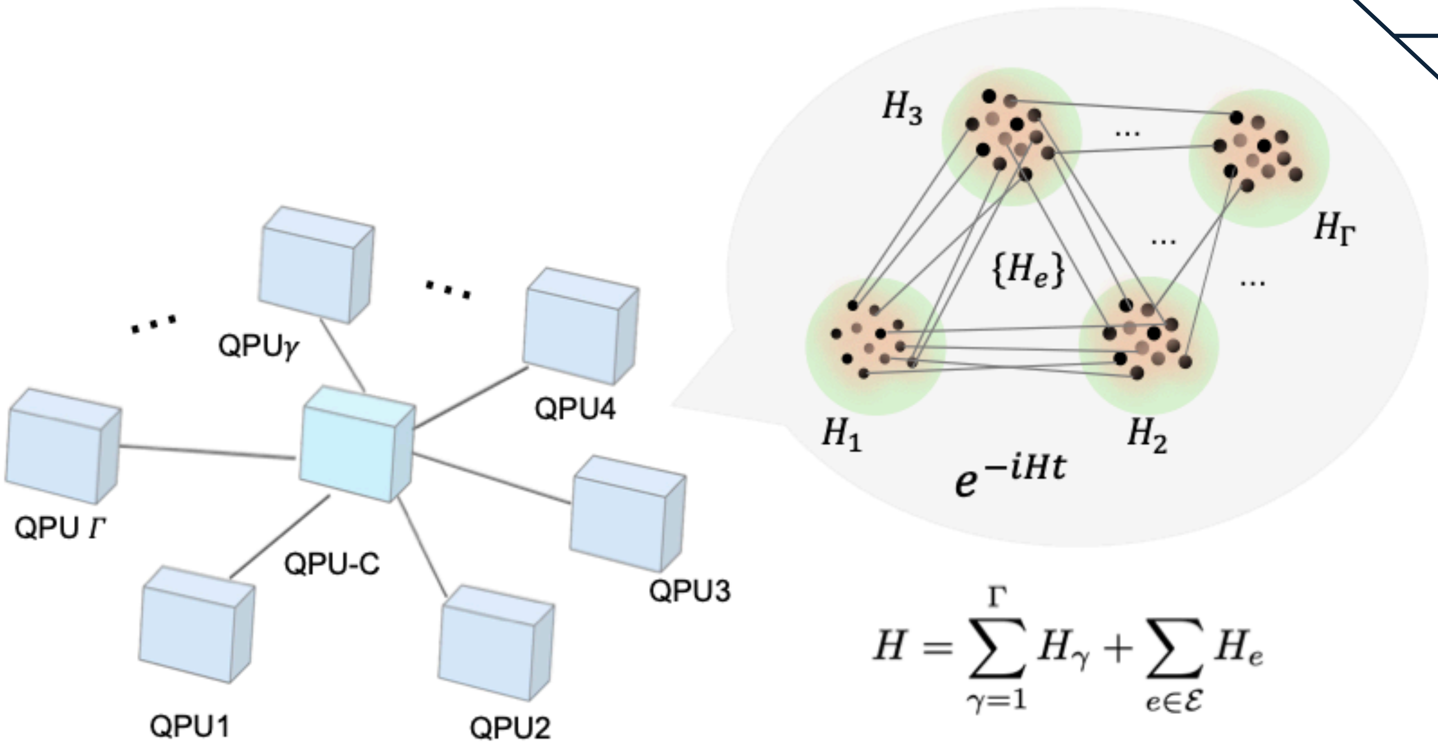
How do we DQC?



Computations

How do we DQC?

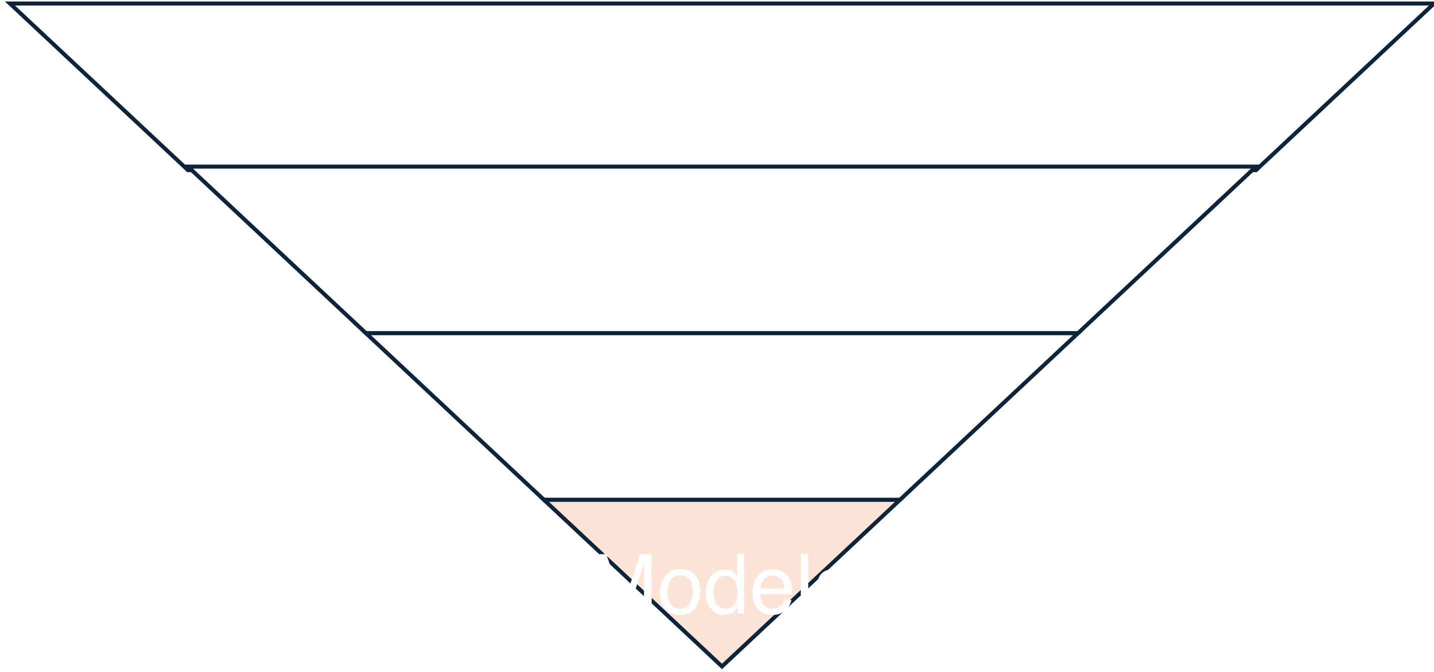


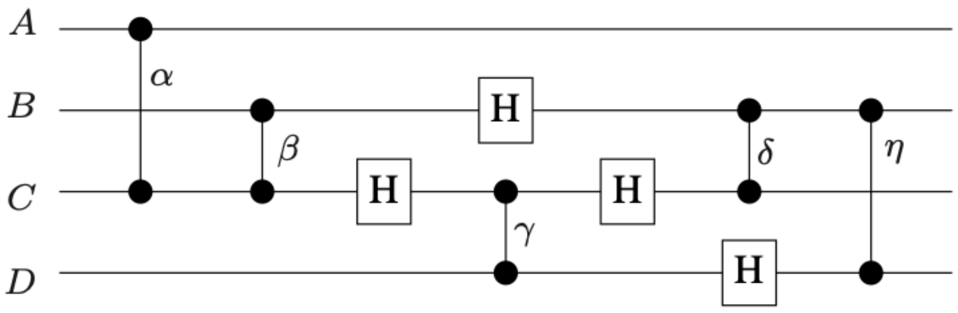


$$H = \sum_{\gamma=1}^{\Gamma} H_\gamma + \sum_{e \in \mathcal{E}} H_e$$

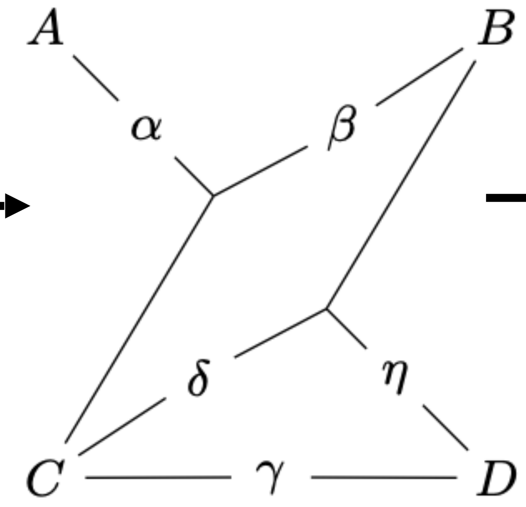
Feng, Tianfeng, et al. "Distributed Quantum Simulation." *arXiv preprint arXiv:2411.02881* (2024).

How do we DQC?





Heunen, Christiaan, and Pablo Andres Martinez. "Automated distribution of quantum circuits." *Physical Review A* 100 (2019): 032308.



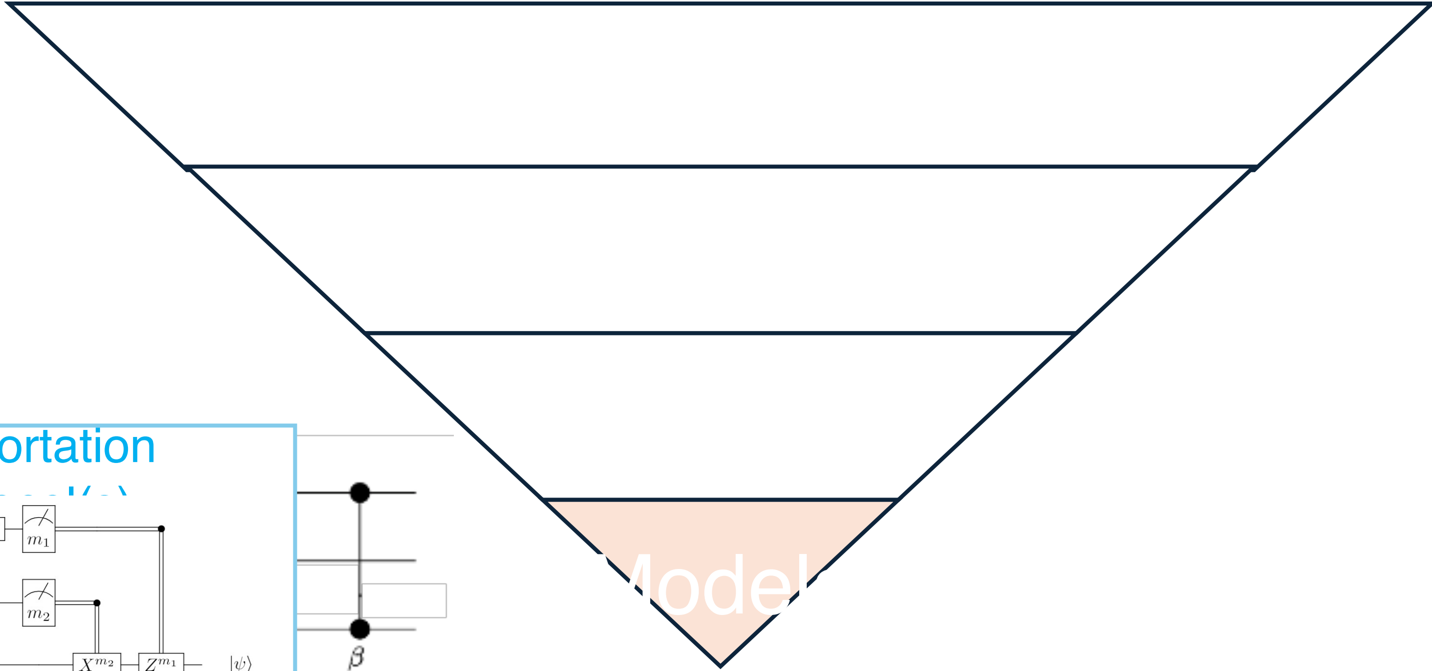
Hypergraph partitioning heuristics

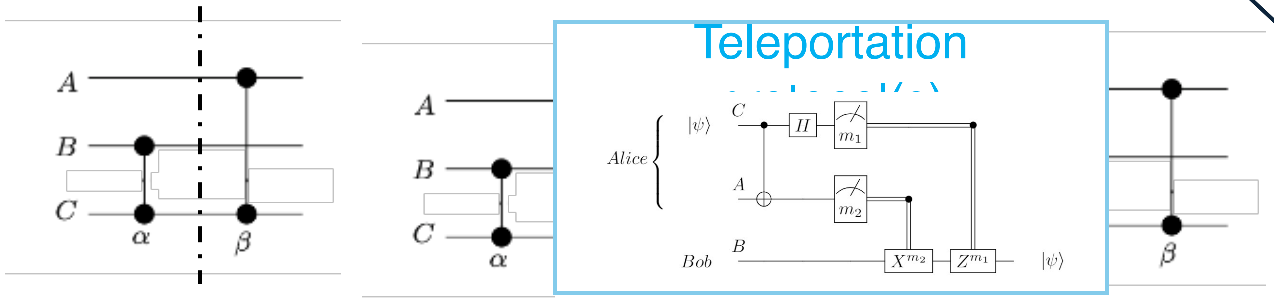
KaHyPar

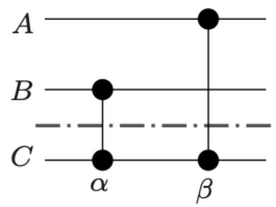
KARLSRUHE HYPERGRAPH PARTITIONING

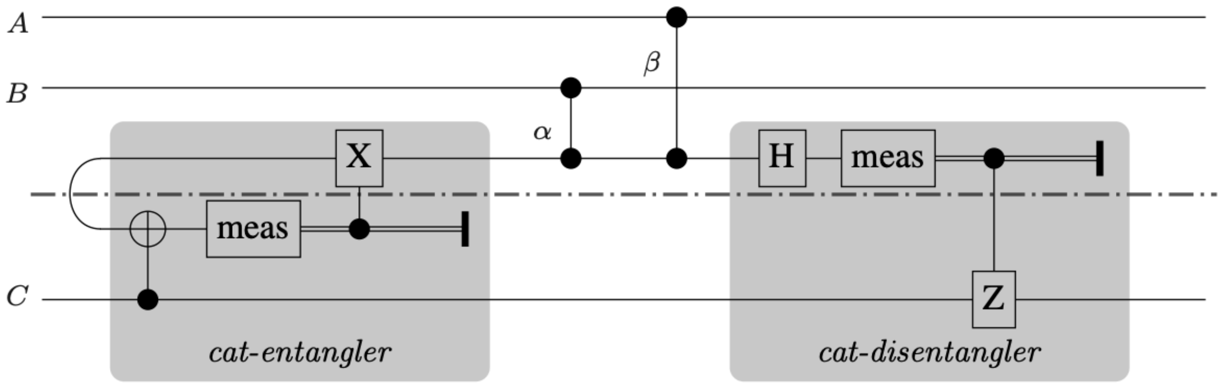
FIDUCCIA MATTHEYSES

How do we DQC?









Non local gates

Primitives

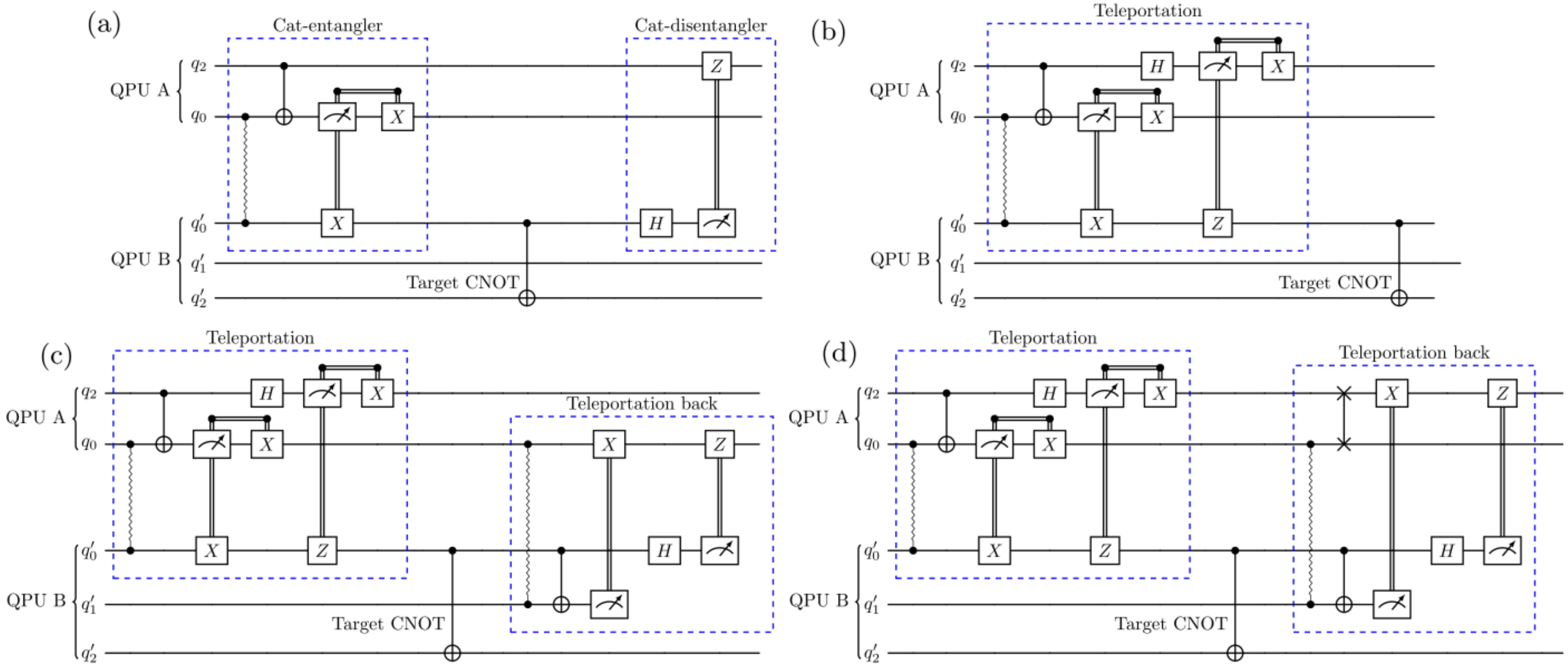


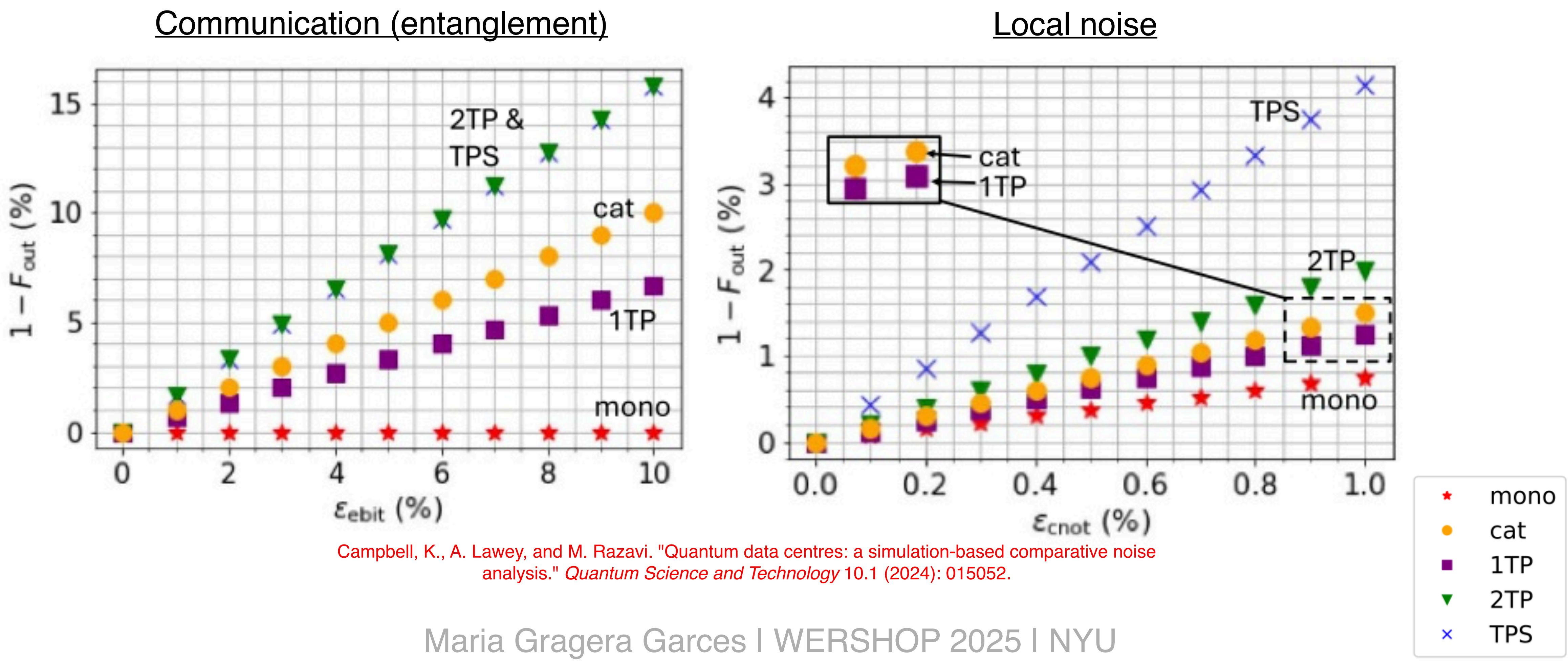
Figure 2. A remote CNOT gate implemented using: (a) cat-comm [19, 20]; (b) 1TP; (c) 2TP; and (d) TP-safe. Zigzags represent ebits, which here, in the ideal case, are Bell pairs in the state $|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$. Double lines represent classical communication. Gates classically connected to a measurement device activate on a measurement result of '1' only.

Campbell, K., A. Lawey, and M. Razavi. "Quantum data centres: a simulation-based comparative noise analysis." *Quantum Science and Technology* 10.1 (2024): 015052.

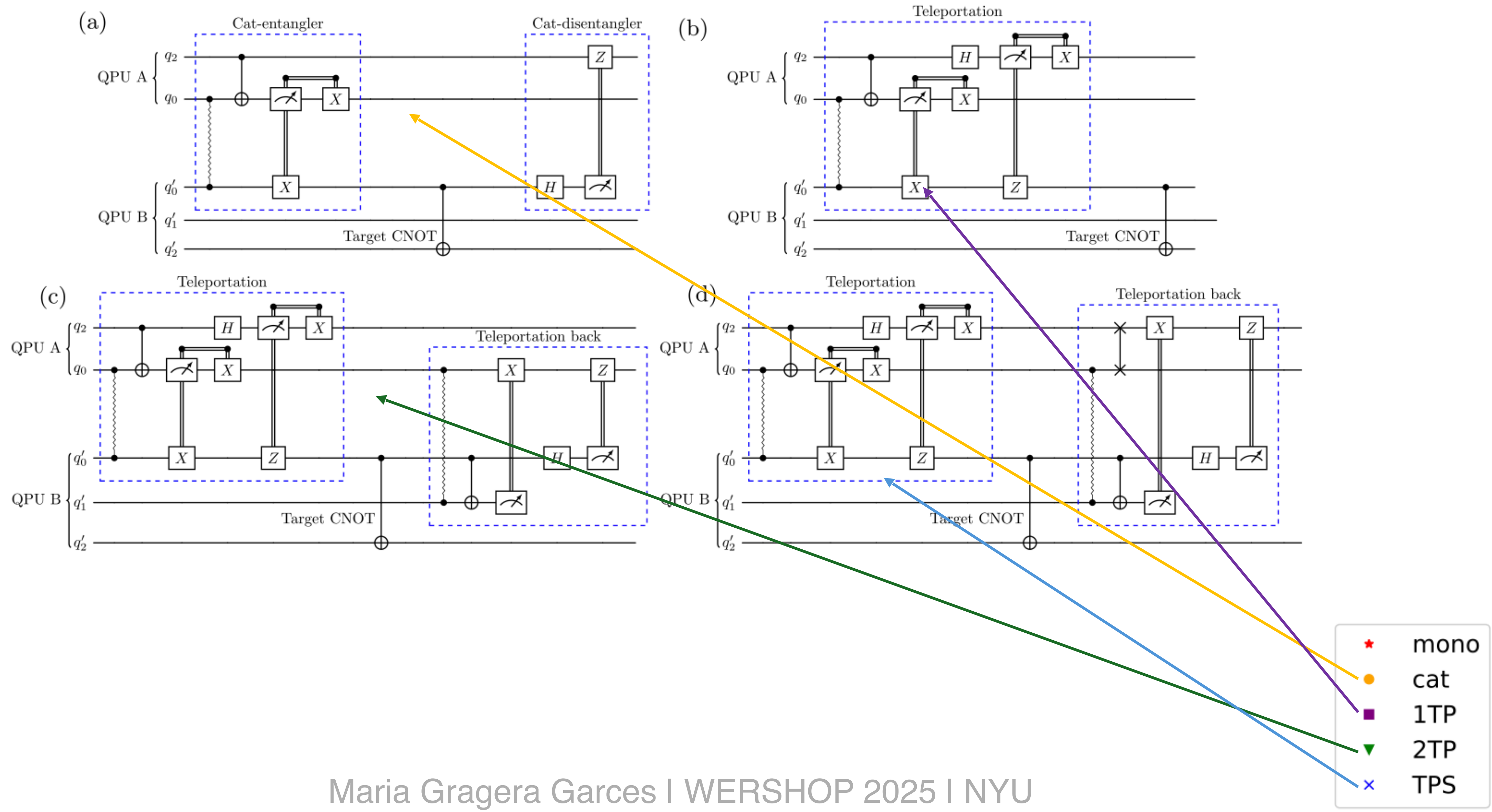
DQC errors: What breaks down

The weight of errors

What is the bigger problem? Local errors or communication errors?



Campbell, K., A. Lawey, and M. Razavi. "Quantum data centres: a simulation-based comparative noise analysis." *Quantum Science and Technology* 10.1 (2024): 015052.

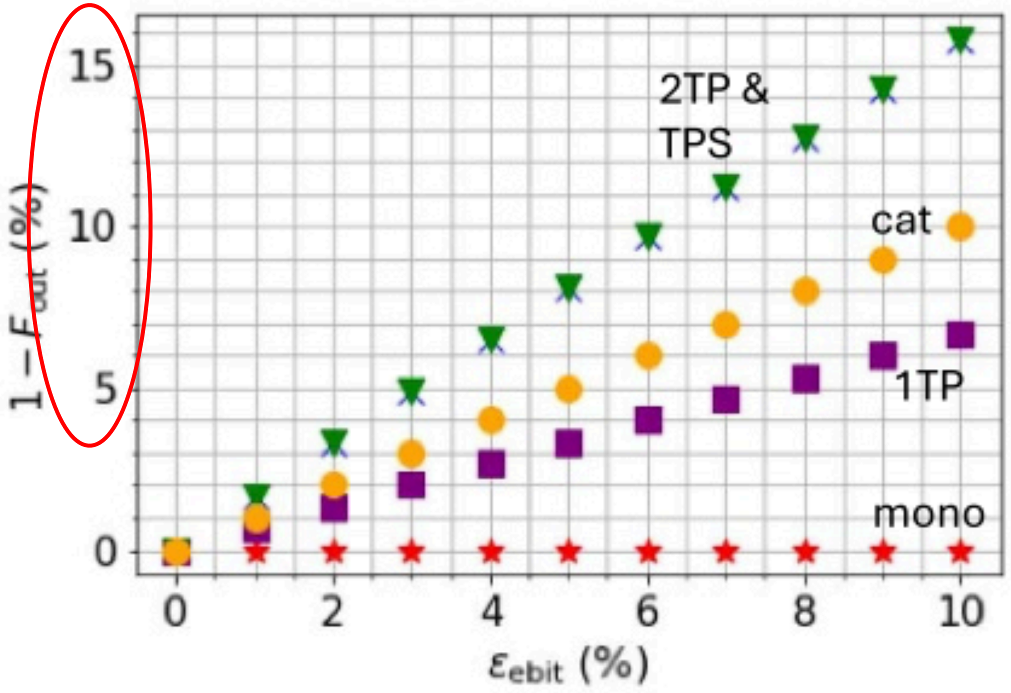


(a)
Cat-entangler
Cat-disentangler
QPU A
QPU B
Target CNOT
(b)
Teleportation
Target CNOT
(c)
Teleportation
Teleportation back
Target CNOT
(d)
Teleportation
Teleportation back
Target CNOT
mono
cat
1TP
2TP
TPS

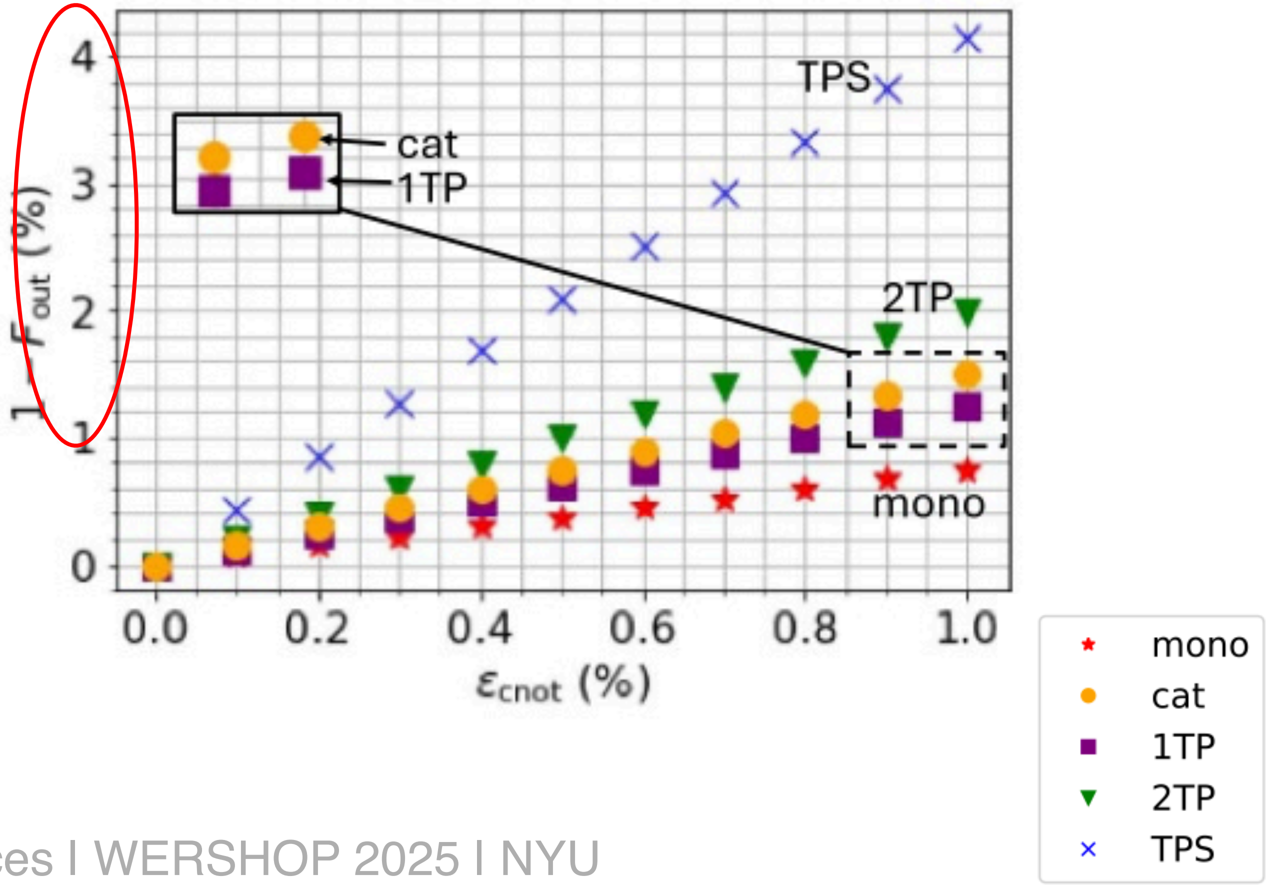
The weight of errors

What is the bigger problem? Local errors or communication errors?

Communication (entanglement)

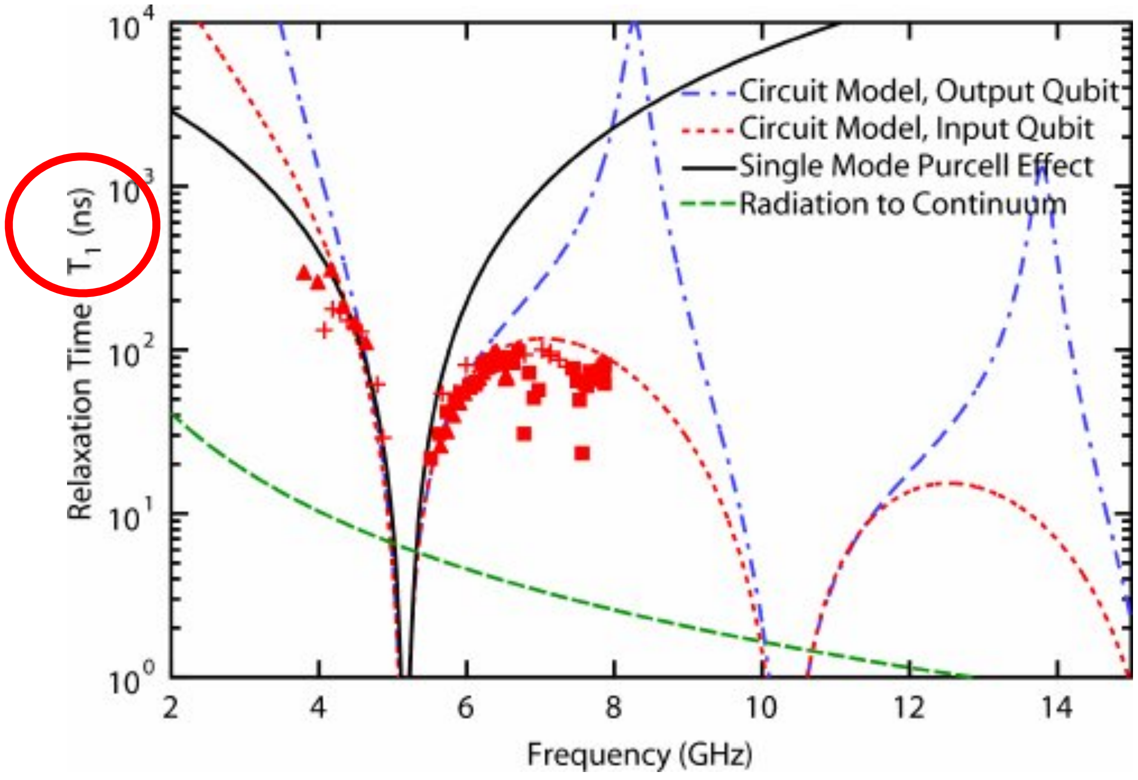


Local noise

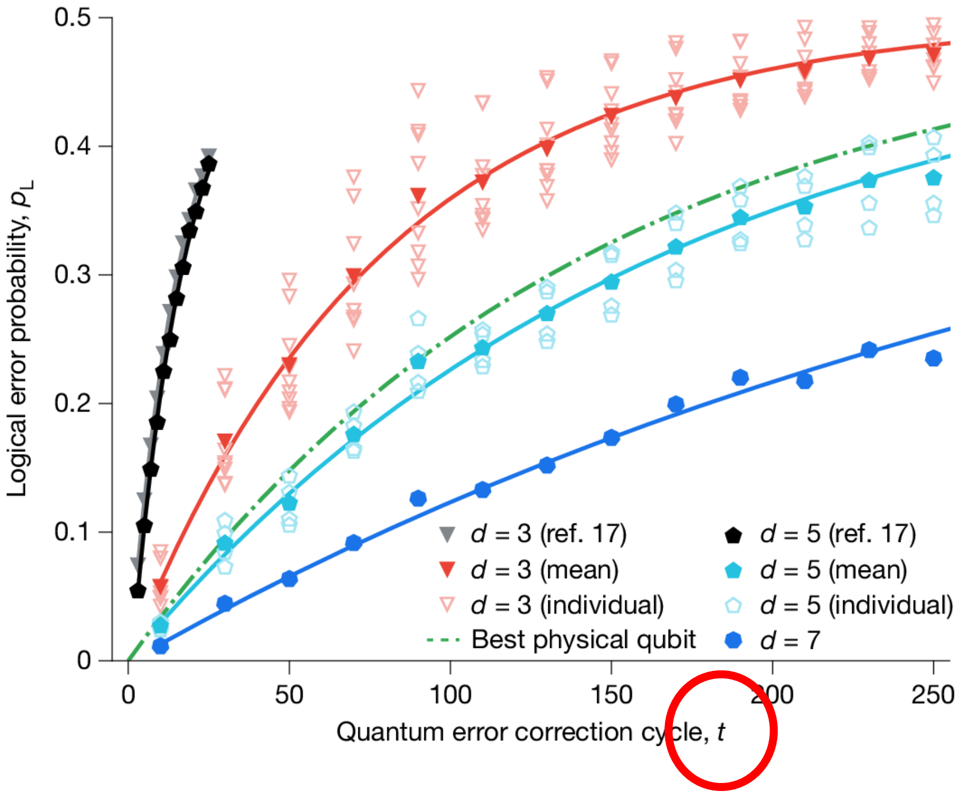


Synchronization lag

Temporal drift can break assumptions which rely on tightly controlled models.



Houck, Andrew Addison, et al. "Controlling the spontaneous emission of a **superconducting transmon** qubit." *Physical review letters* 101.8 (2008): 080502.



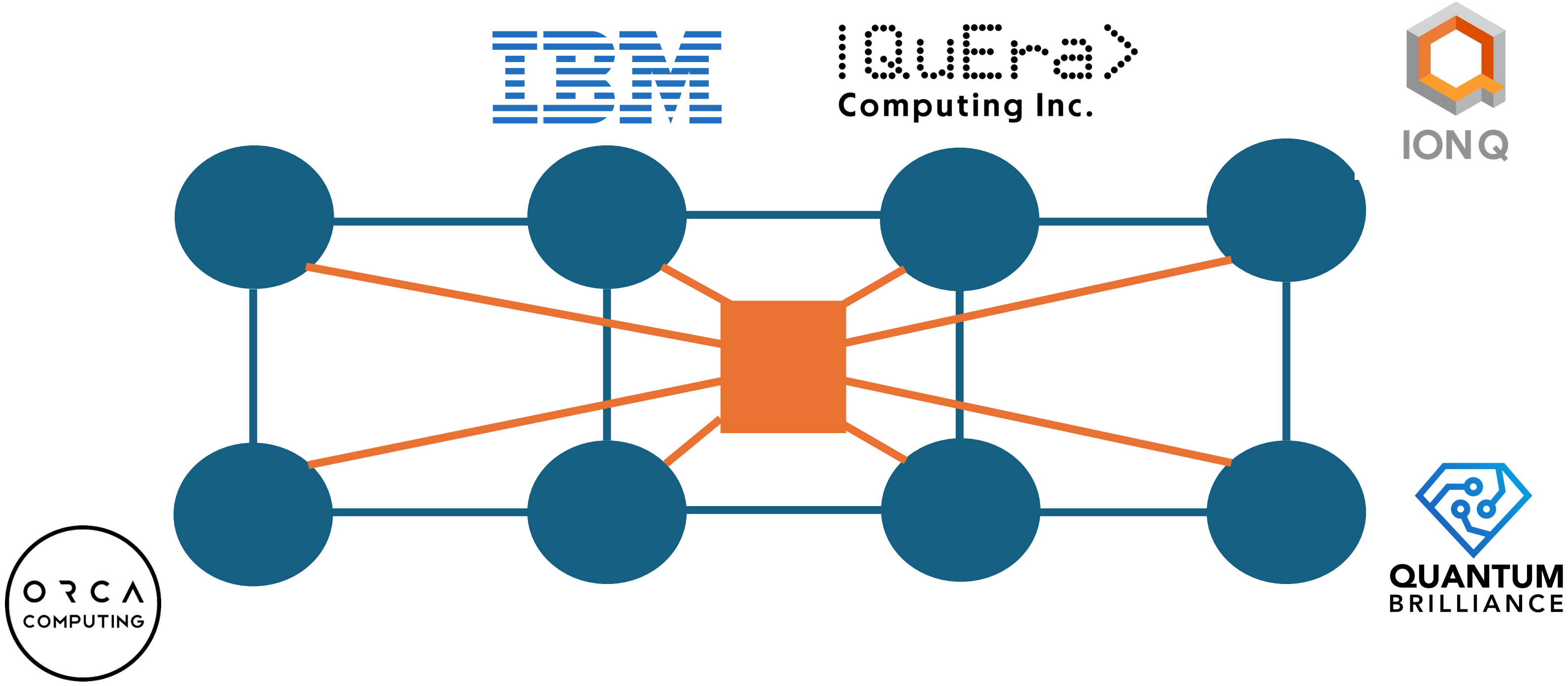
Acharya, Rajeev, et al. "Quantum error correction below the surface code threshold." Nature (2024).

Heterogeneous landscape

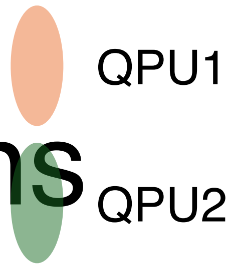
Classical computer

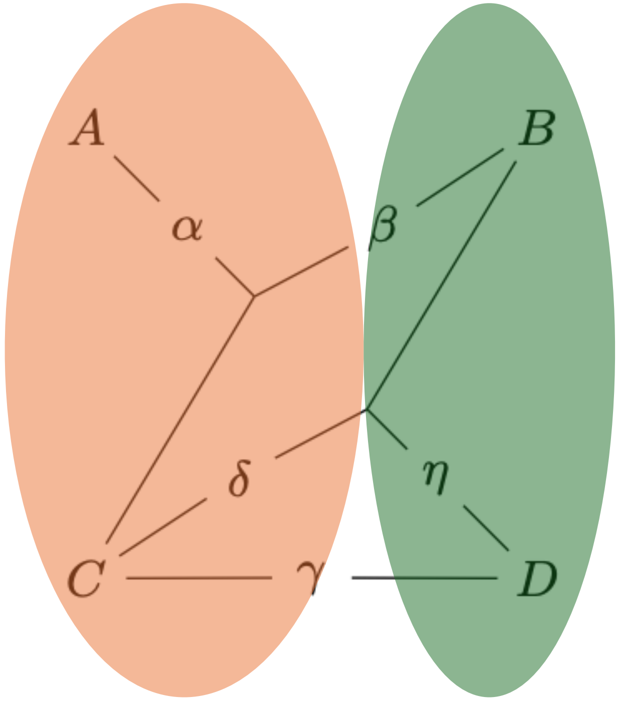
Quantum computer

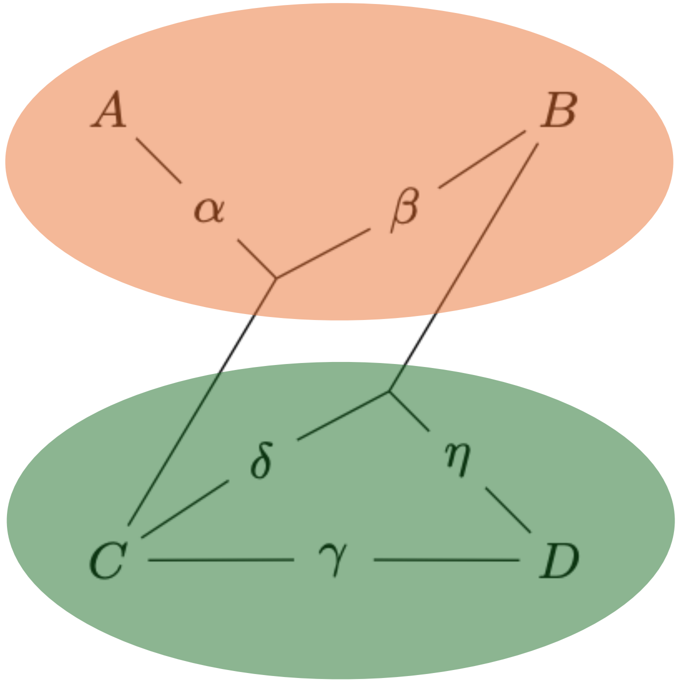
- Redundant mitigation
- Heterogeneous noise profiles
- Overhead from classical coordination



Compilation Choices: open questions

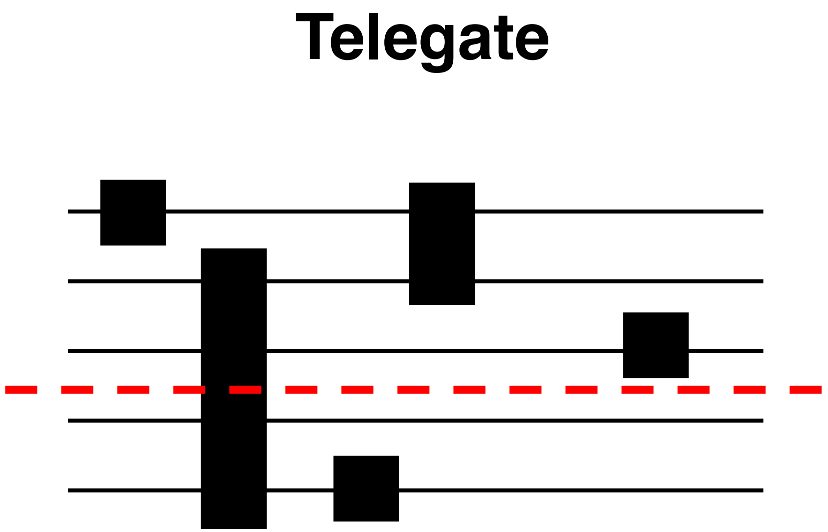


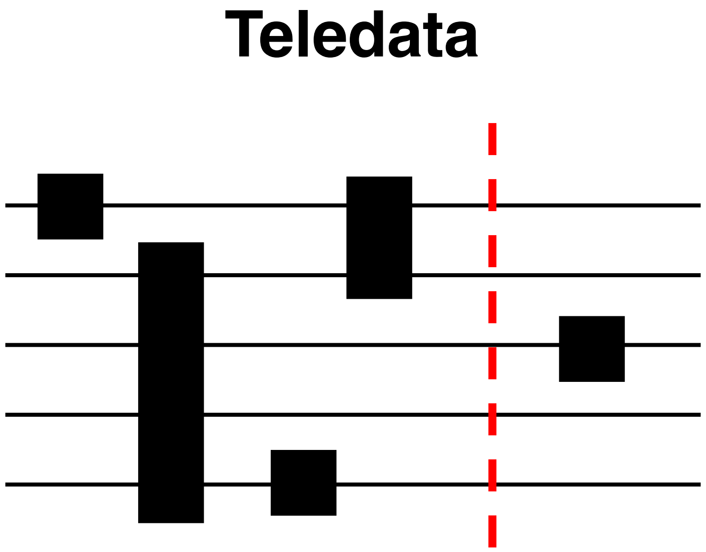




How do we know which partitioning strategy is optimal in advance?

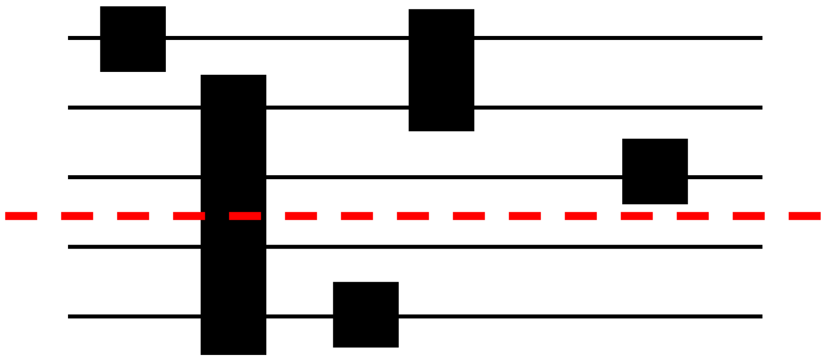
Vertical vs Horizontal cuts: a quick vocab sidetrack



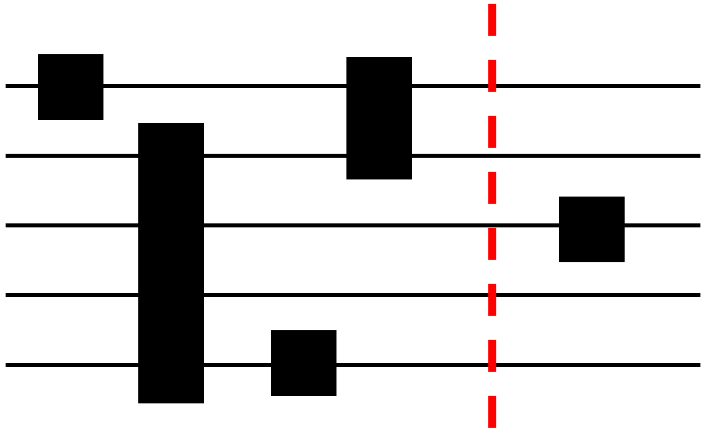


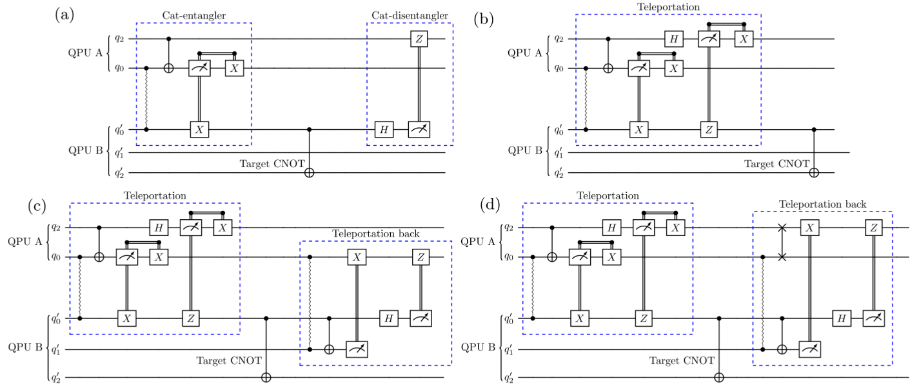
Vertical vs Horizontal cuts: a quick vocab sidetrack

Telegate



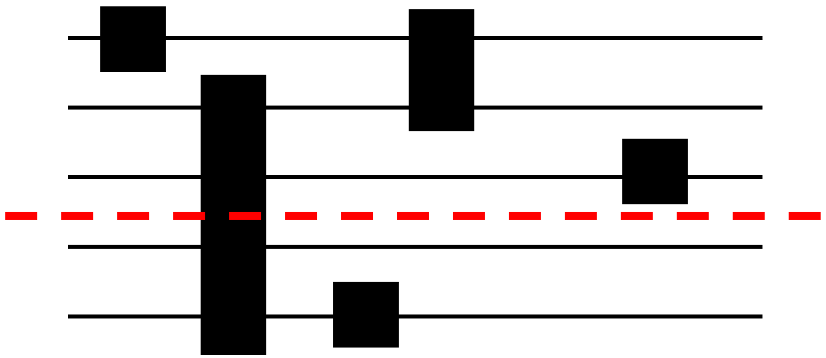
Teledata





Vertical vs Horizontal cuts

Telegate



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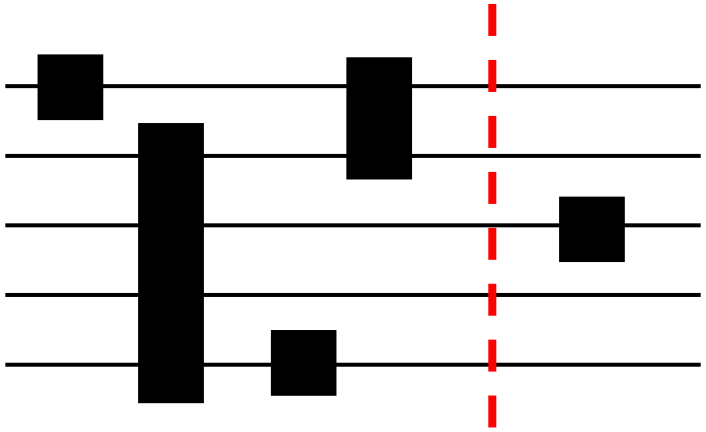
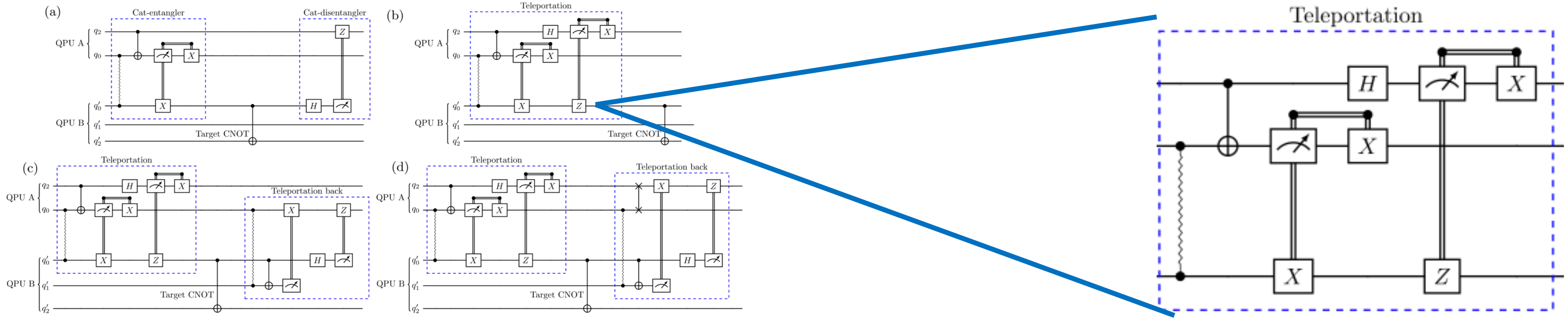
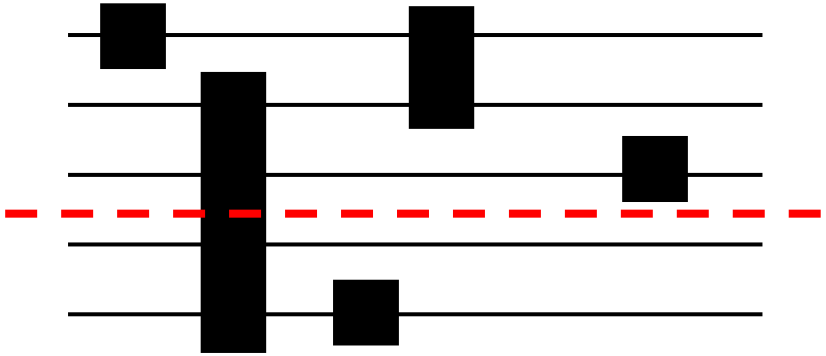




Vertical vs Horizontal cuts

Telegate



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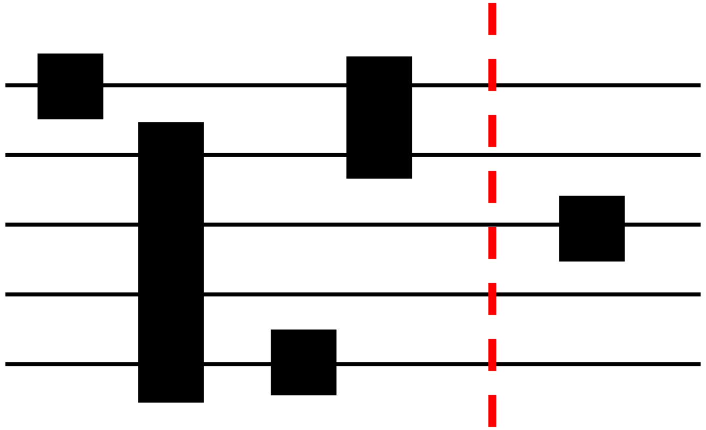
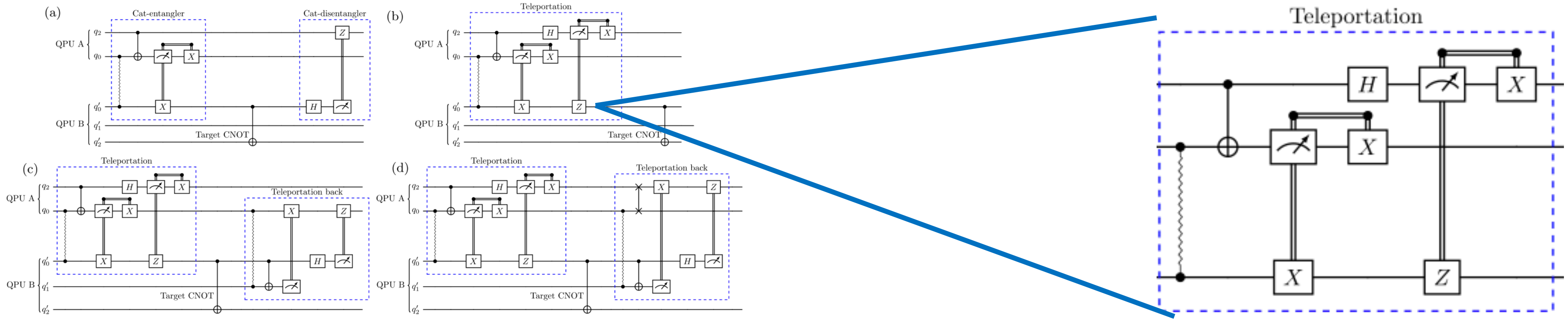
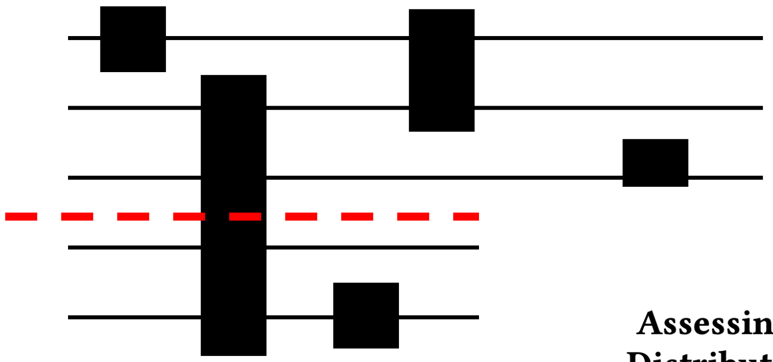




“quantum compilers should be noise aware”

Vertical vs Horizontal cuts

Telegate



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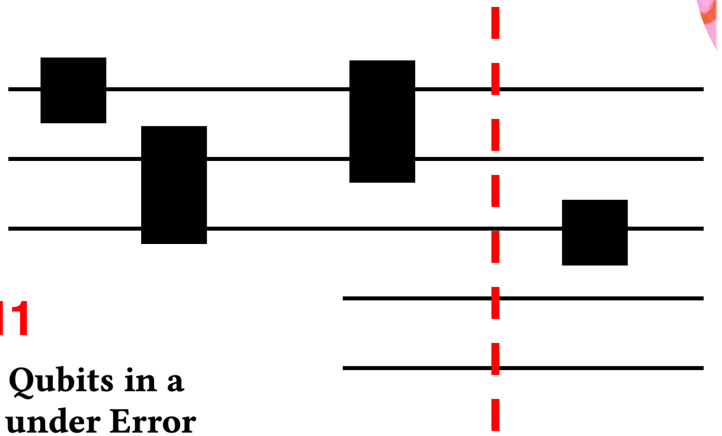

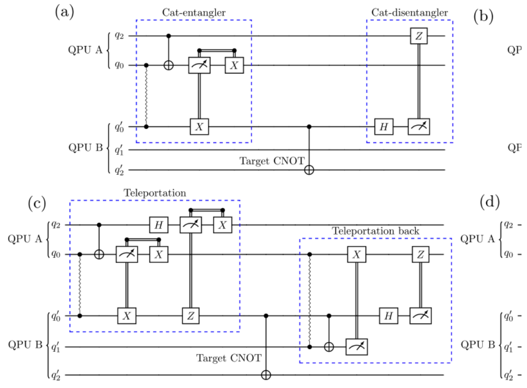

arXiv: 2504.05611

Assessing Teleportation of Logical Qubits in a Distributed Quantum Architecture under Error Correction

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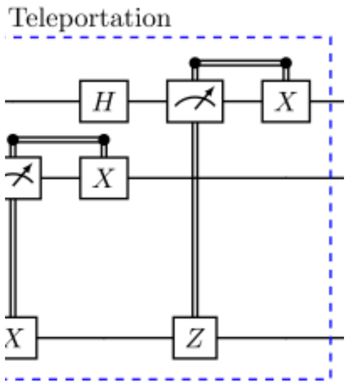
[quant-ph] 8 Apr 2025

Abstract

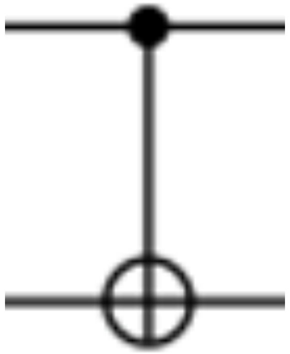
Quantum computing is facing challenges in terms of scaling to thousands of qubits and implementing quantum error correction (QEC). Scaling efforts focus on connecting multiple smaller quantum devices in a distributed manner while error correction, as a means to overcome noisy physical qubits, is being addressed by developing denser codes with protocols for logical qubits and logical quantum gates. Teleportation of quantum states becomes an important operation as it transfers states from one node to another node within a distributed device. For physical qubits, today's high quantum network noise rates prevent the teleportation of states with useful accuracy. By employing QEC, we show that logical qubits can be teleported between nodes under Surface Code and qLDPC encodings with very low logical error rates, even with network noise in near-term regimes. We

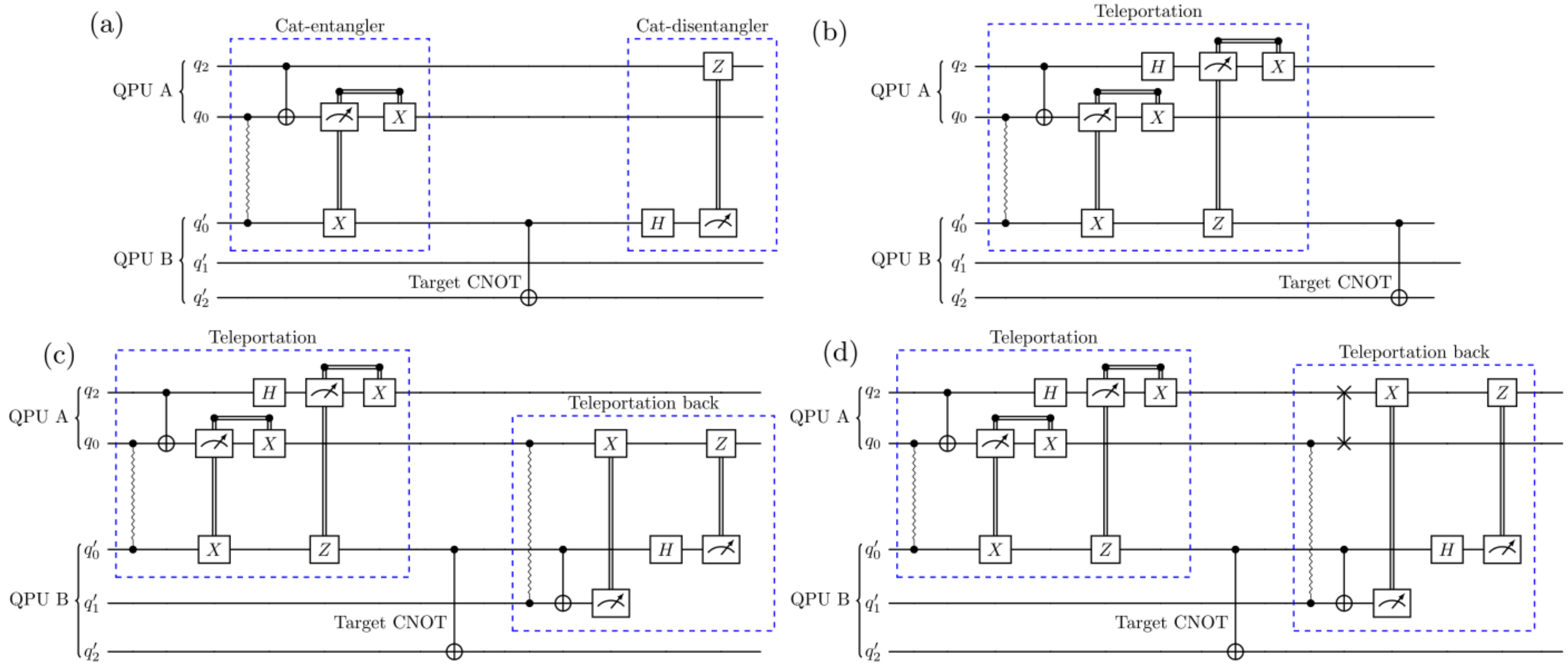
computers together to form a distributed quantum computer (DQC) has been proposed.

What constitutes a DQC is ambiguous, such a device can be realized in many different ways. A DQC may be implemented using classical post-processing and several QCs that are purely classically connected [8]. This is known as circuit knitting. Essentially, a circuit is sliced space-wise either around gates, which is called wire cutting and corresponds to non-local gates, or through gates, which is called gate cutting and corresponds to teleportation. The two (or more) circuits produced by the slicing are executed separately and their results are then combined to infer the results of the original circuit. Unfortunately, the sampling overheads to perform circuit knitting at scale increase exponentially in the number of gates or wires cut [8]. Therefore, this approach is infeasible for circuits with more than a low degree of entanglement

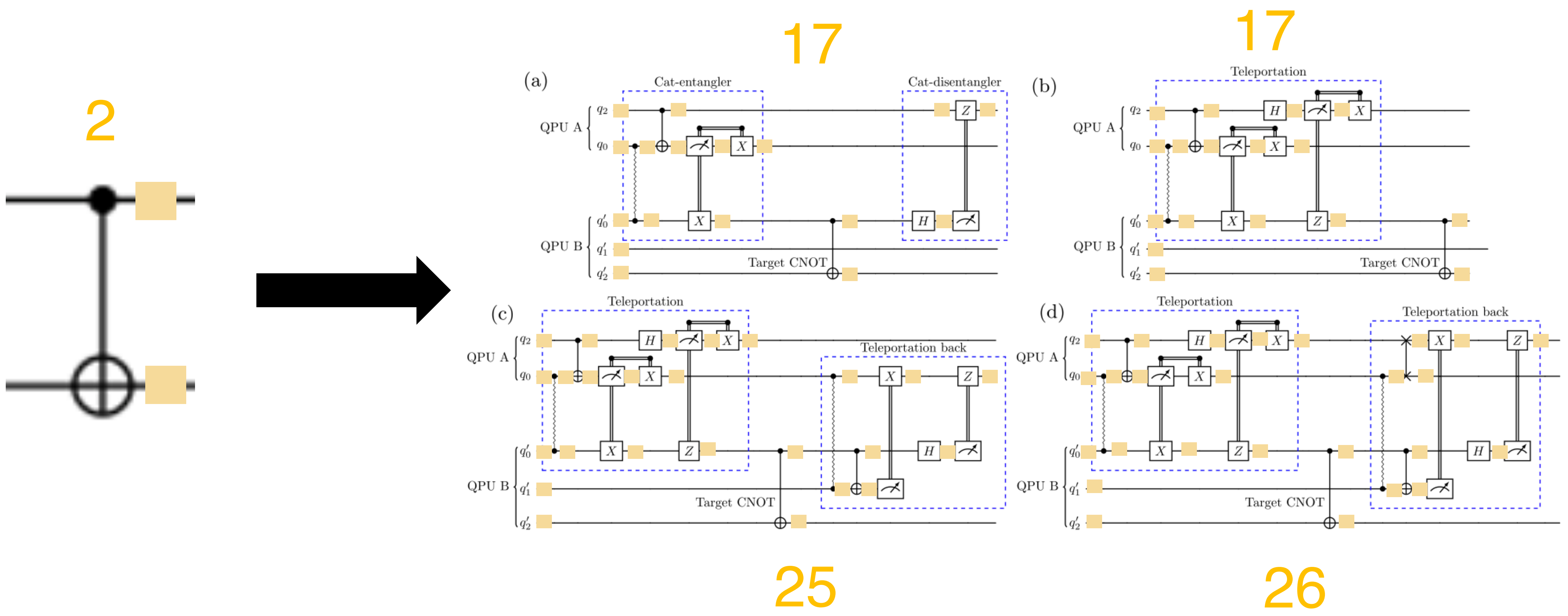


Primitive priorities

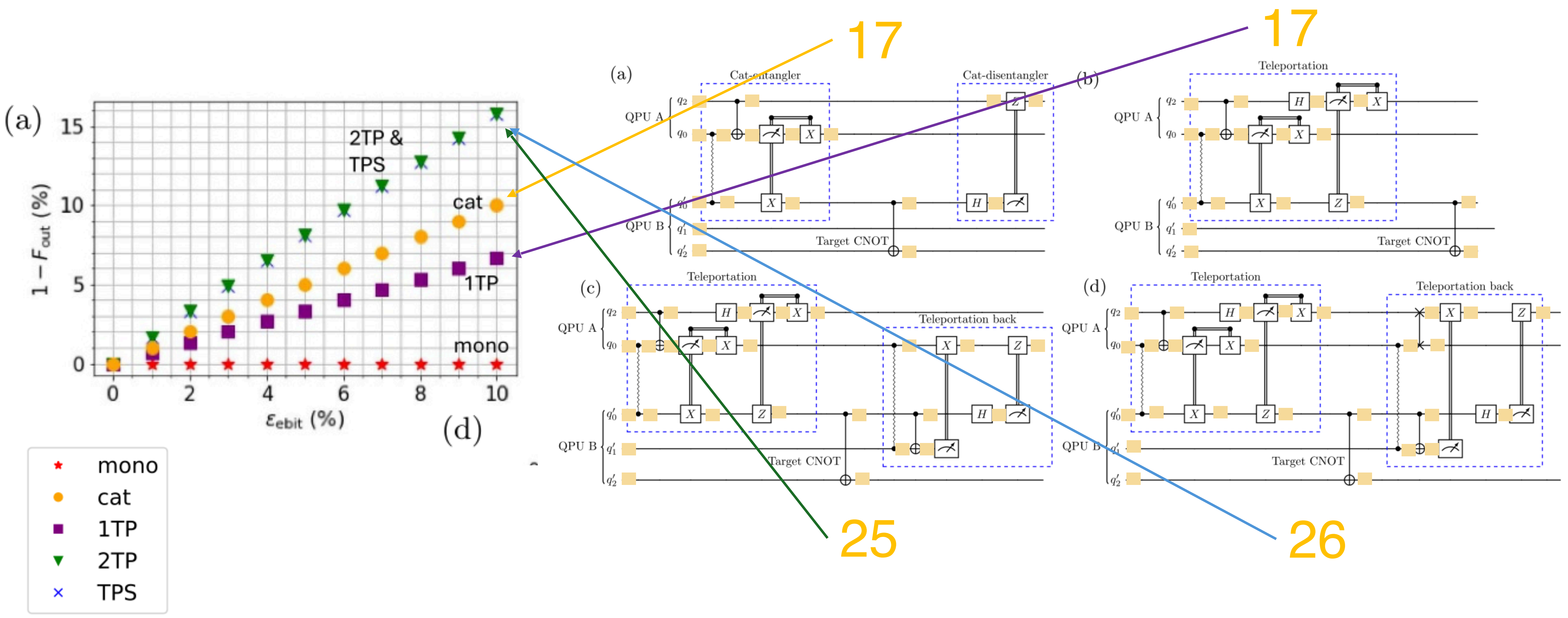




Primitive priorities



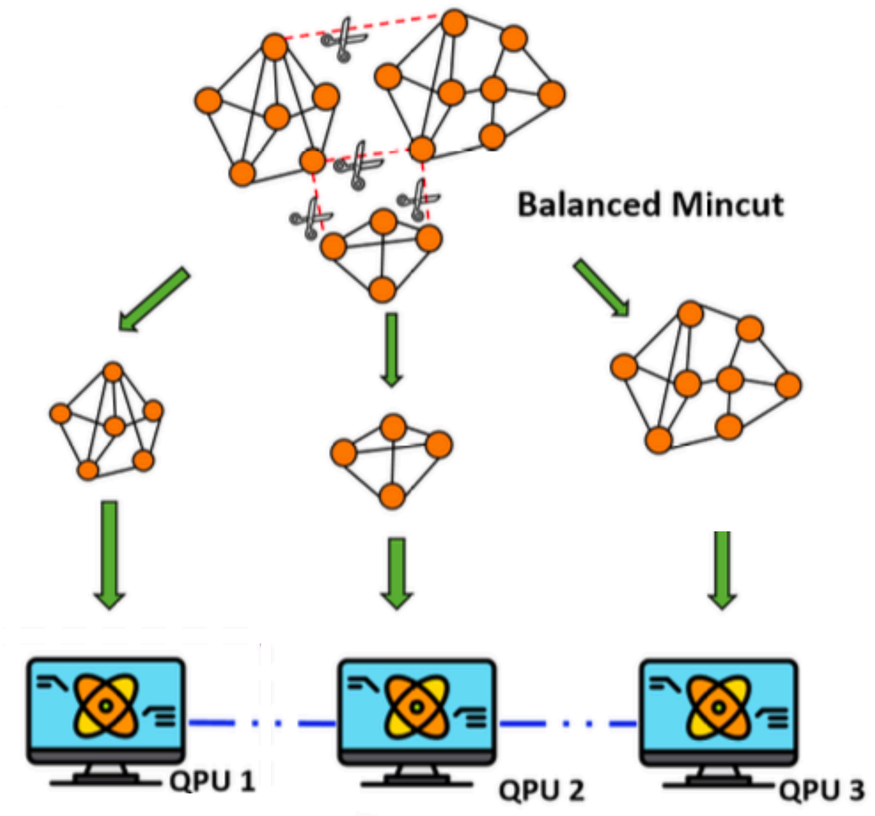
Primitive priorities



QEM Techniques in a Distributed World

Noise-aware sampling in distribution today

Error mitigation: noise-aware compilation points the circuit to the best qubits (low error from calibration data), skip the bad ones, and run the same QAOA subcircuit across multiple clean qubit blocks (multi-sampling).



Chen, Kuan-Cheng, et al. "Noise-aware distributed quantum approximate optimization algorithm on near-term quantum hardware." 2024 IEEE International Conference on Quantum Computing and Engineering (QCE). Vol. 2. IEEE, 2024.

What happens to error mitigation techniques when you distribute?

Let's look at some simulation results!

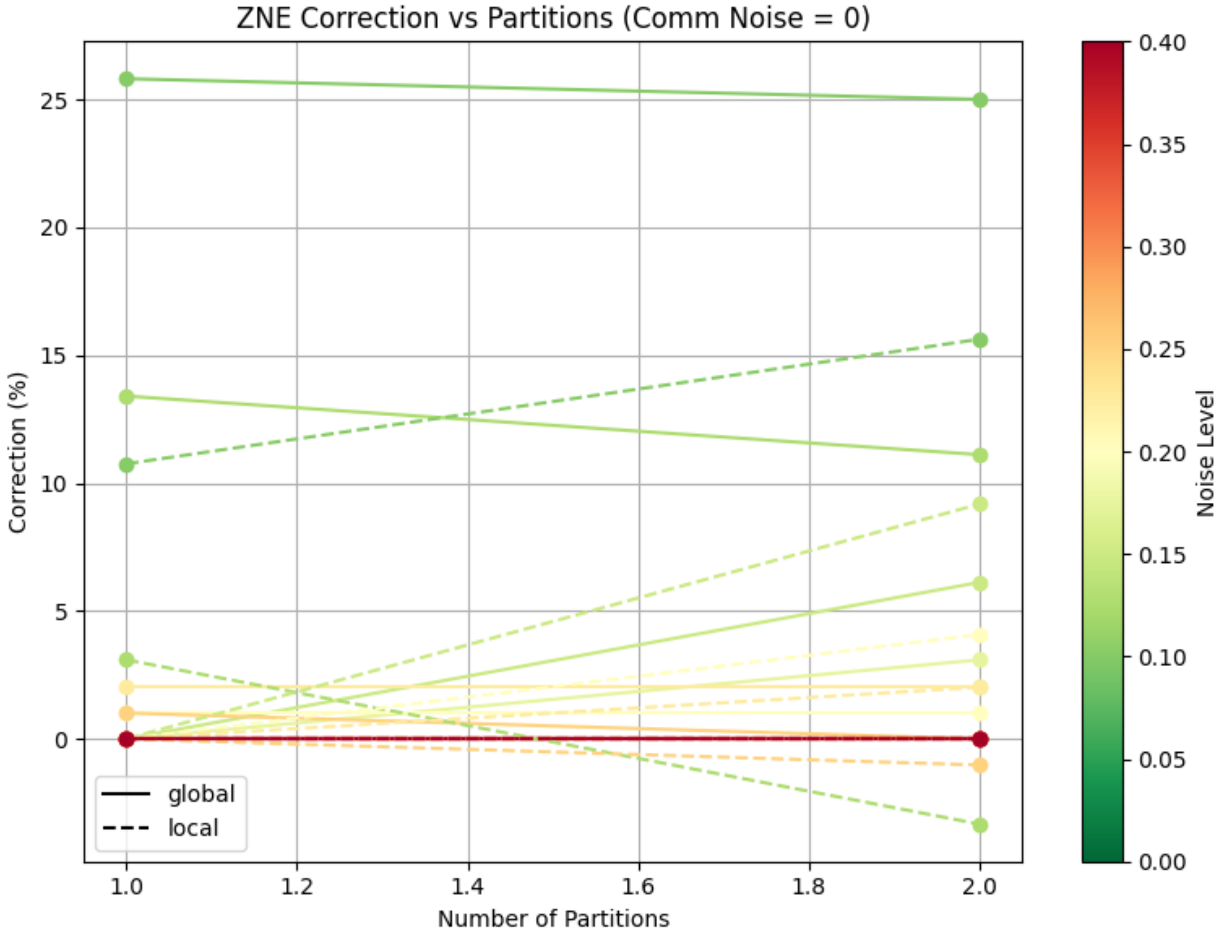
Local noise: 0 - 0.4 (probability that the output is replaced by a random Pauli error)

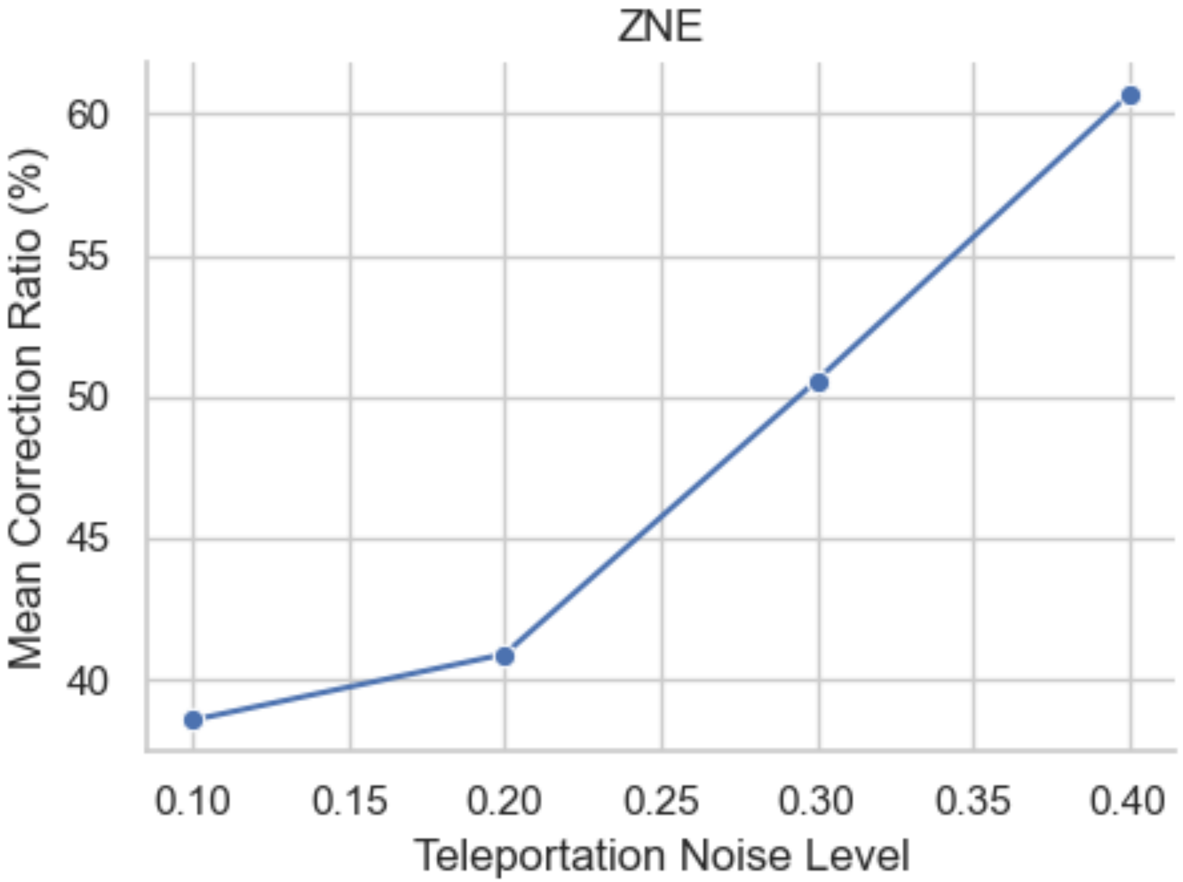
Telecom noise: 100 to 120% of local noise

Partitions: 2,4

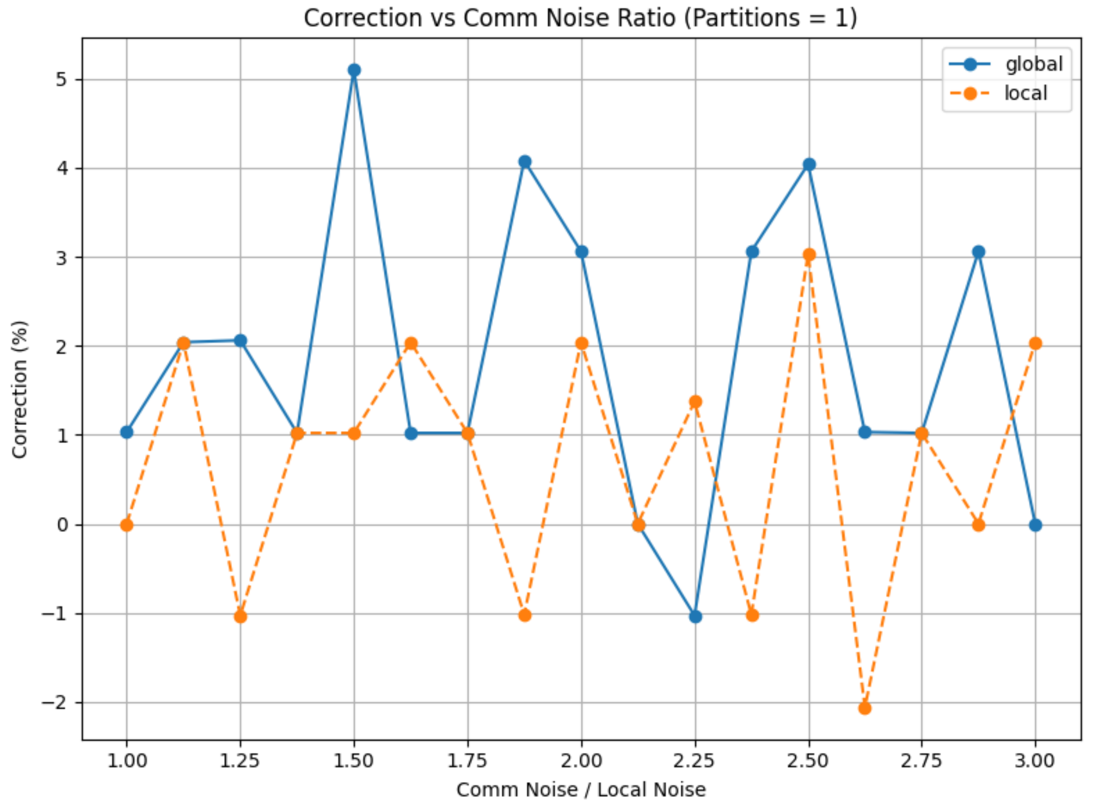
Circuits: 20 logical qubits

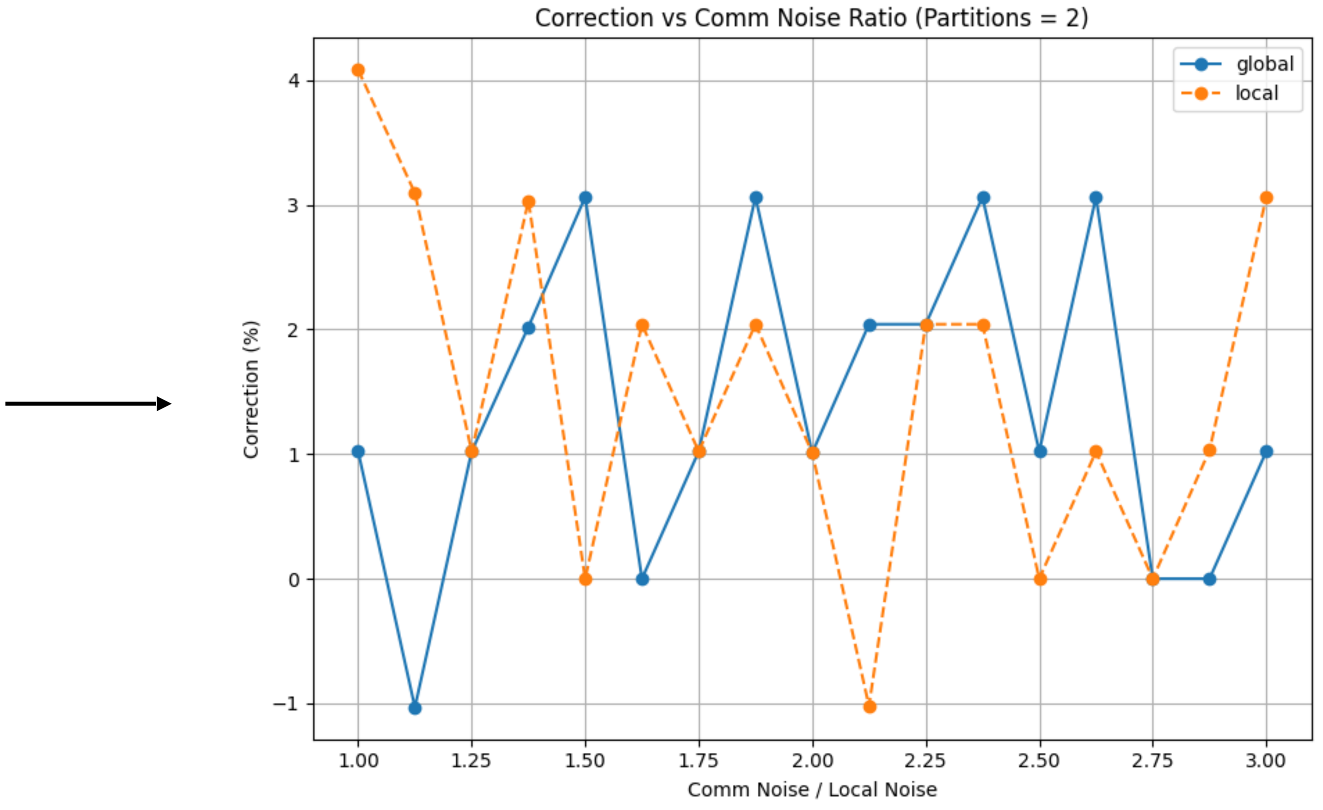
ZNE in a Distributed World: Teleportation noise





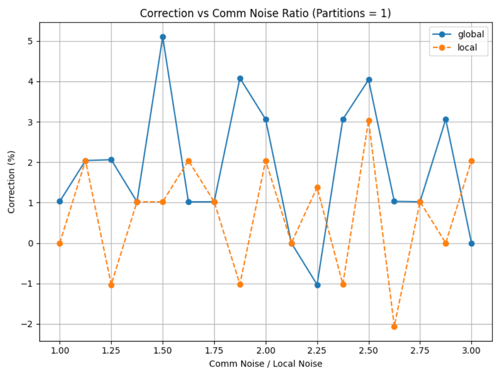
Local vs Global folding corrections under partitioning





Bottlenecks

- Simple simulators cannot uphold realistic distributed circuits (realistic benchmarks are too large)
- There are no accessible distributed quantum systems where we can direct workloads straightforwardly for testing



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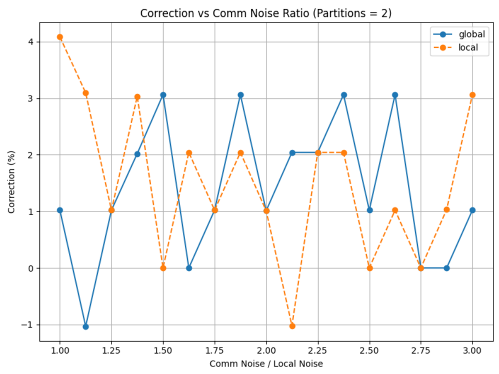

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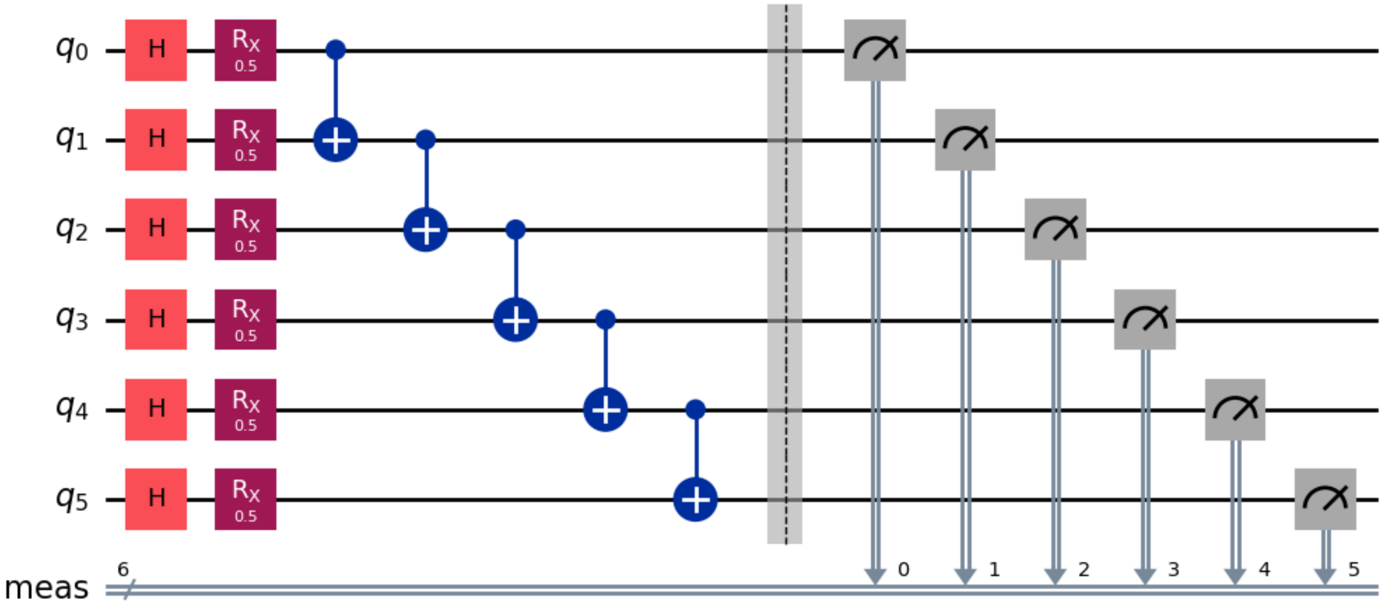
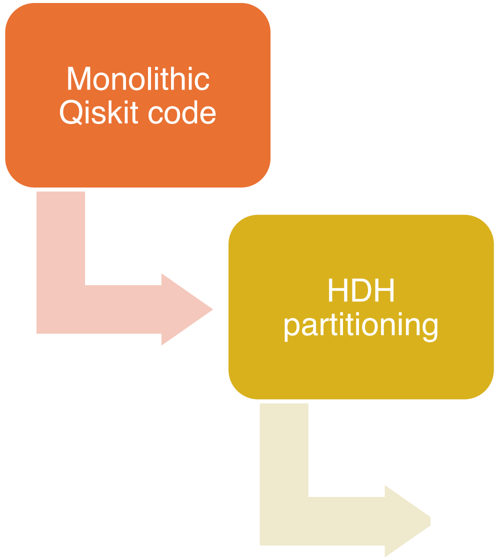
QEM Techniques in a Distributed World

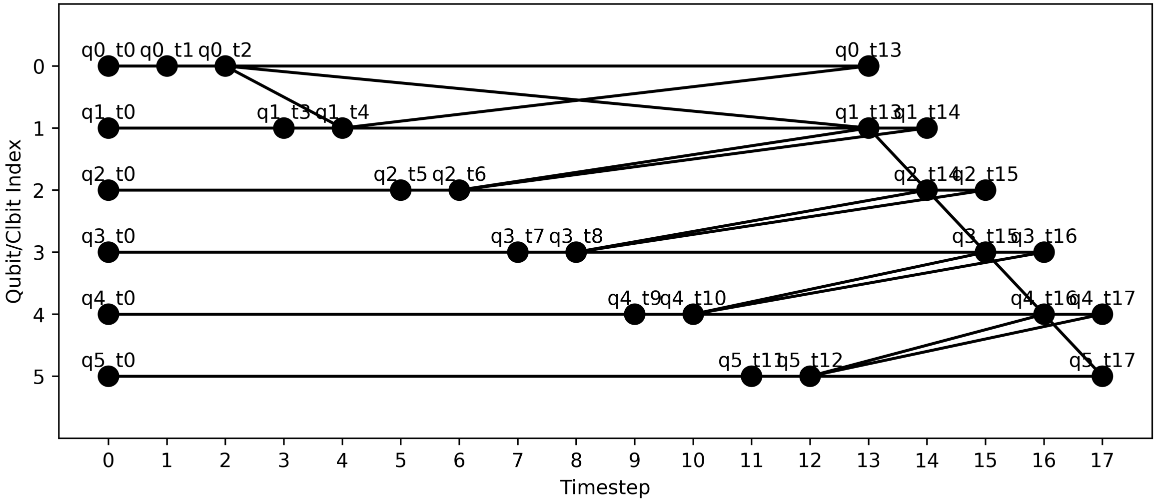
How we are doing it:

Ongoing work



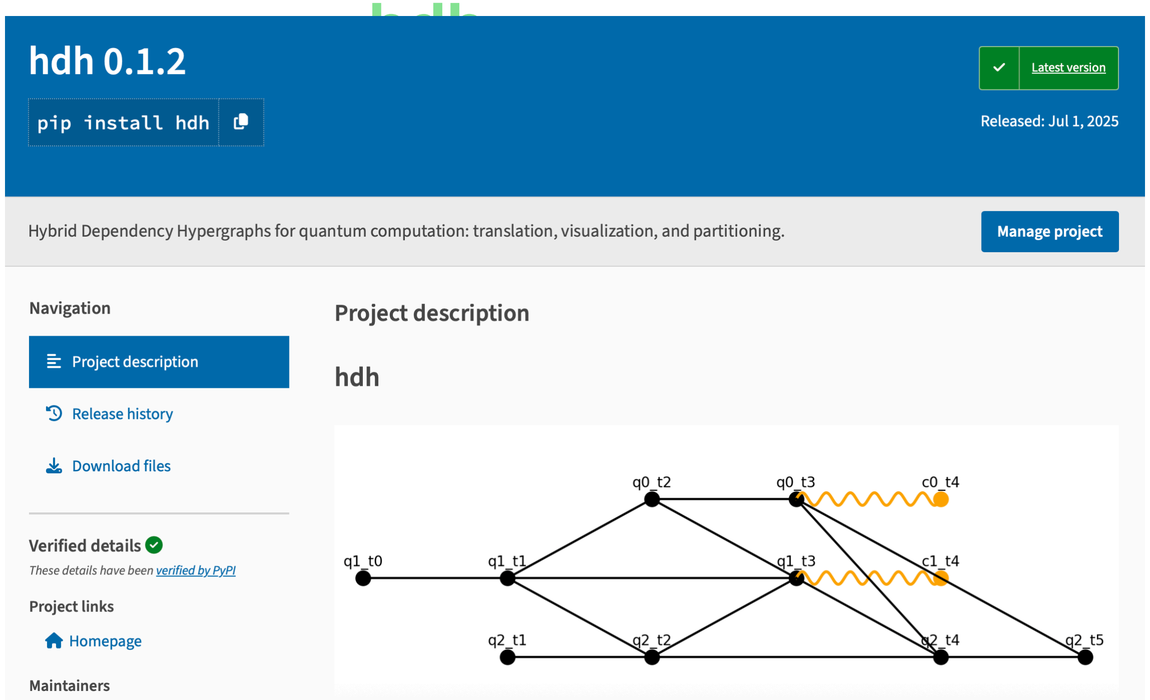
hdh = from_qiskit(qc)
hdh_cut = compute_cut(hdh, num_parts = 2)



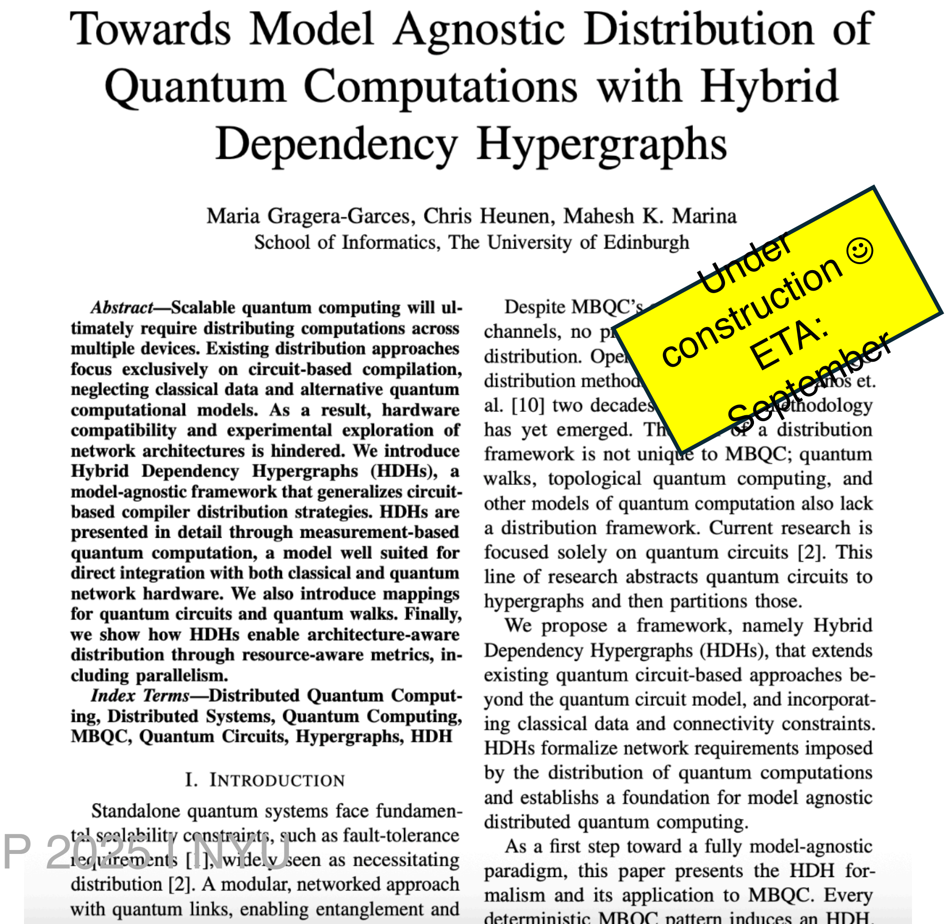


The shameless plug: HDH package

pip install hdh



- Model agnostic
- Consider telegate and teledata simulateneously
- Backwards compatible with QASM and Qiskit monolithic codes



Towards Model Agnostic Distribution of Quantum Computations with Hybrid Dependency Hypergraphs

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Abstract—Scalable quantum computing will ultimately require distributing computations across multiple devices. Existing distribution approaches focus exclusively on circuit-based compilation, neglecting classical data and alternative quantum computational models. As a result, hardware compatibility and experimental exploration of network architectures is hindered. We introduce Hybrid Dependency Hypergraphs (HDHs), a model-agnostic framework that generalizes circuit-based compiler distribution strategies. HDHs are presented in detail through measurement-based quantum computation, a model well suited for direct integration with both classical and quantum network hardware. We also introduce mappings for quantum circuits and quantum walks. Finally, we show how HDHs enable architecture-aware distribution through resource-aware metrics, including parallelism.

Index Terms—Distributed Quantum Computing, Distributed Systems, Quantum Computing, MBQC, Quantum Circuits, Hypergraphs, HDH

I. Introduction

Standalone quantum systems face fundamental scalability constraints, such as fault-tolerance requirements [1], widely seen as necessitating distribution [2]. A modular, networked approach with quantum links, enabling entanglement and

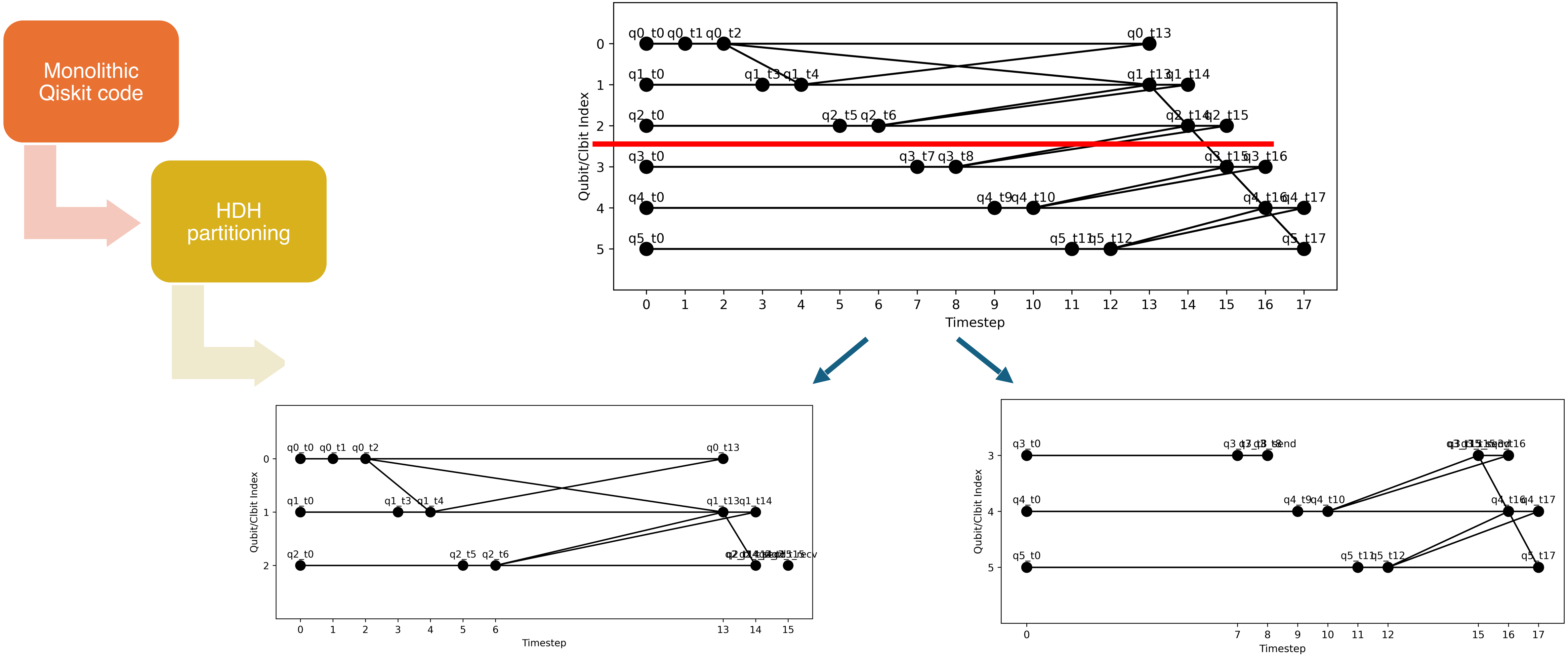
Despite MBQC's ... channels, no p... distribution. Ope... distribution method... al. [10] two decades ... methodology has yet emerged. Th... of a distribution framework is not unique to MBQC; quantum walks, topological quantum computing, and other models of quantum computation also lack a distribution framework. Current research is focused solely on quantum circuits [2]. This line of research abstracts quantum circuits to hypergraphs and then partitions those.

We propose a framework, namely Hybrid Dependency Hypergraphs (HDHs), that extends existing quantum circuit-based approaches beyond the quantum circuit model, and incorporating classical data and connectivity constraints. HDHs formalize network requirements imposed by the distribution of quantum computations and establishes a foundation for model agnostic distributed quantum computing.

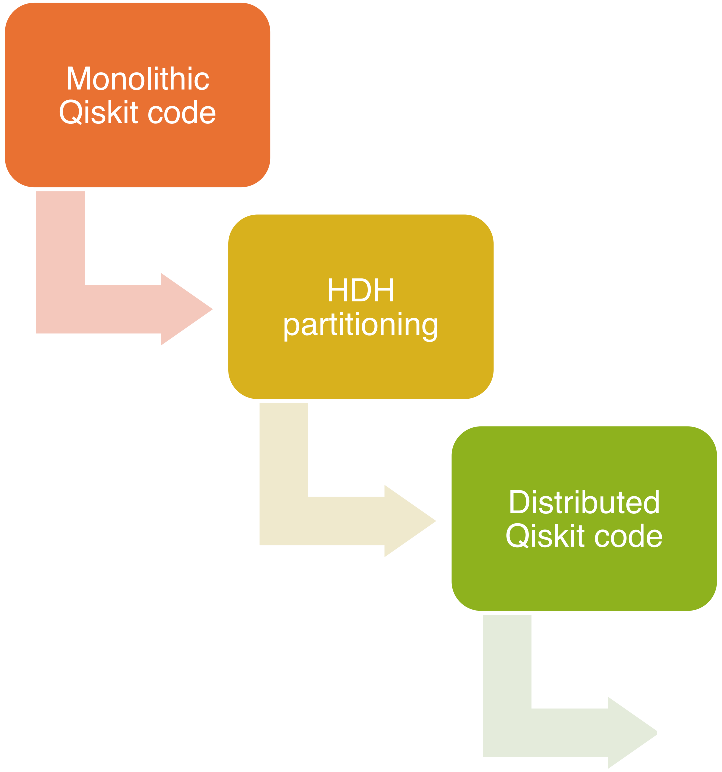
As a first step toward a fully model-agnostic paradigm, this paper presents the HDH formalism and its application to MBQC. Every deterministic MBQC pattern induces an HDH

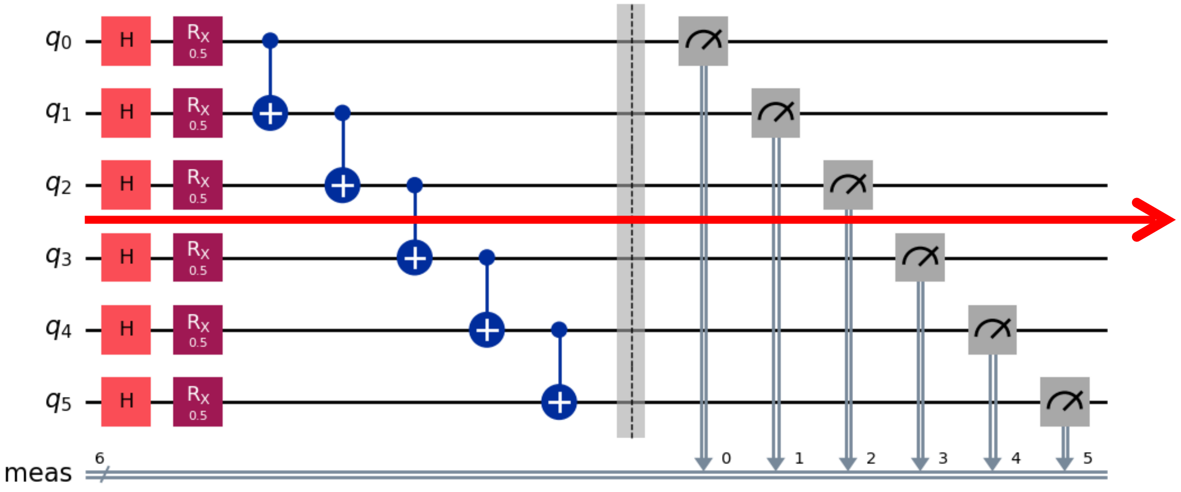
Under construction ☺ ETA: September

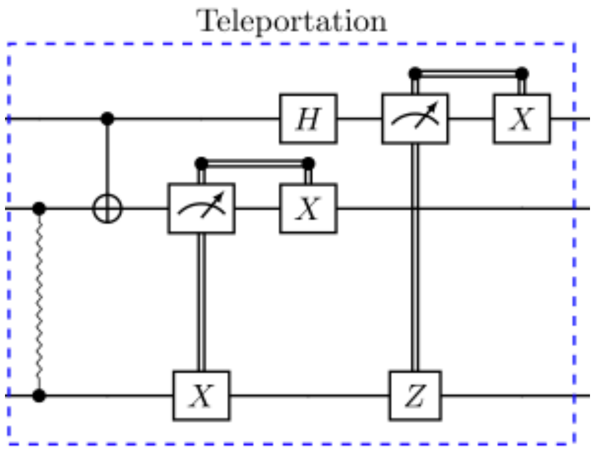
```
hdh = from_qiskit(qc)
hdh_cut = compute_cut(hdh, num_parts = 2)
```



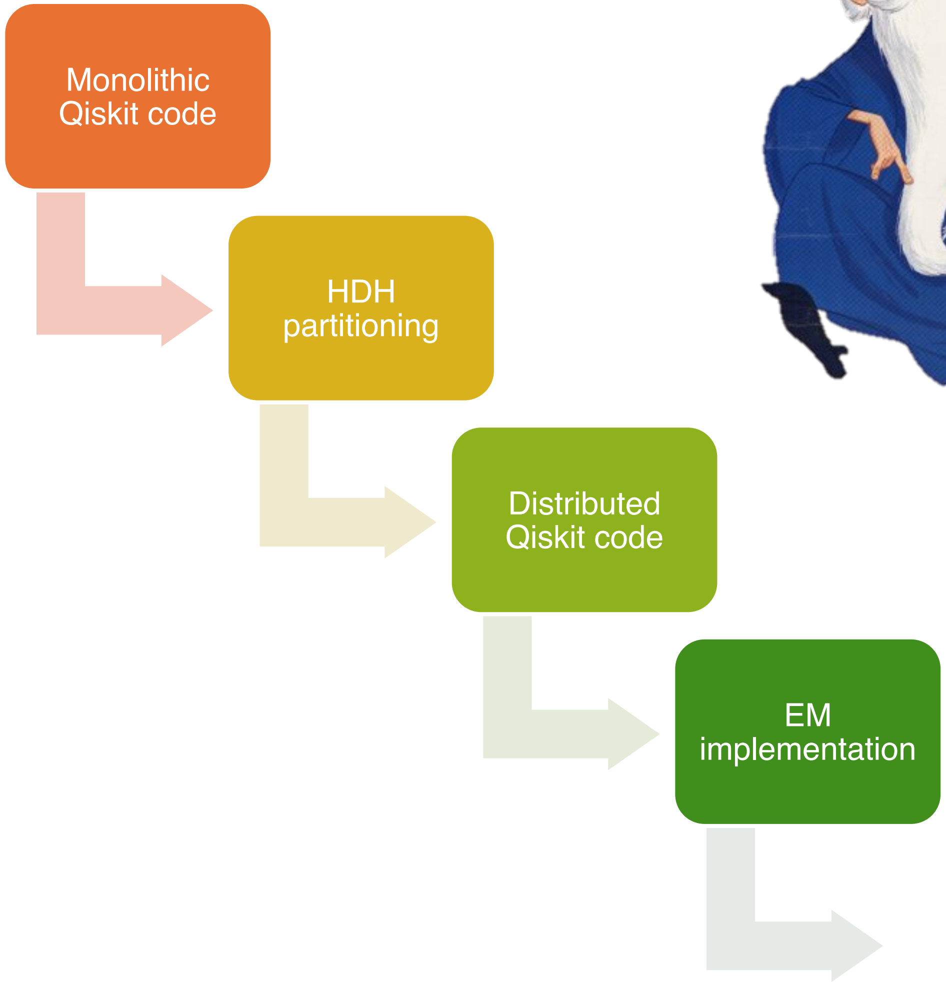
```
hdh = from_qiskit(qc)
cut_qc = cut_and_rewrite_hdh(hdh, num_parts = 2)
```





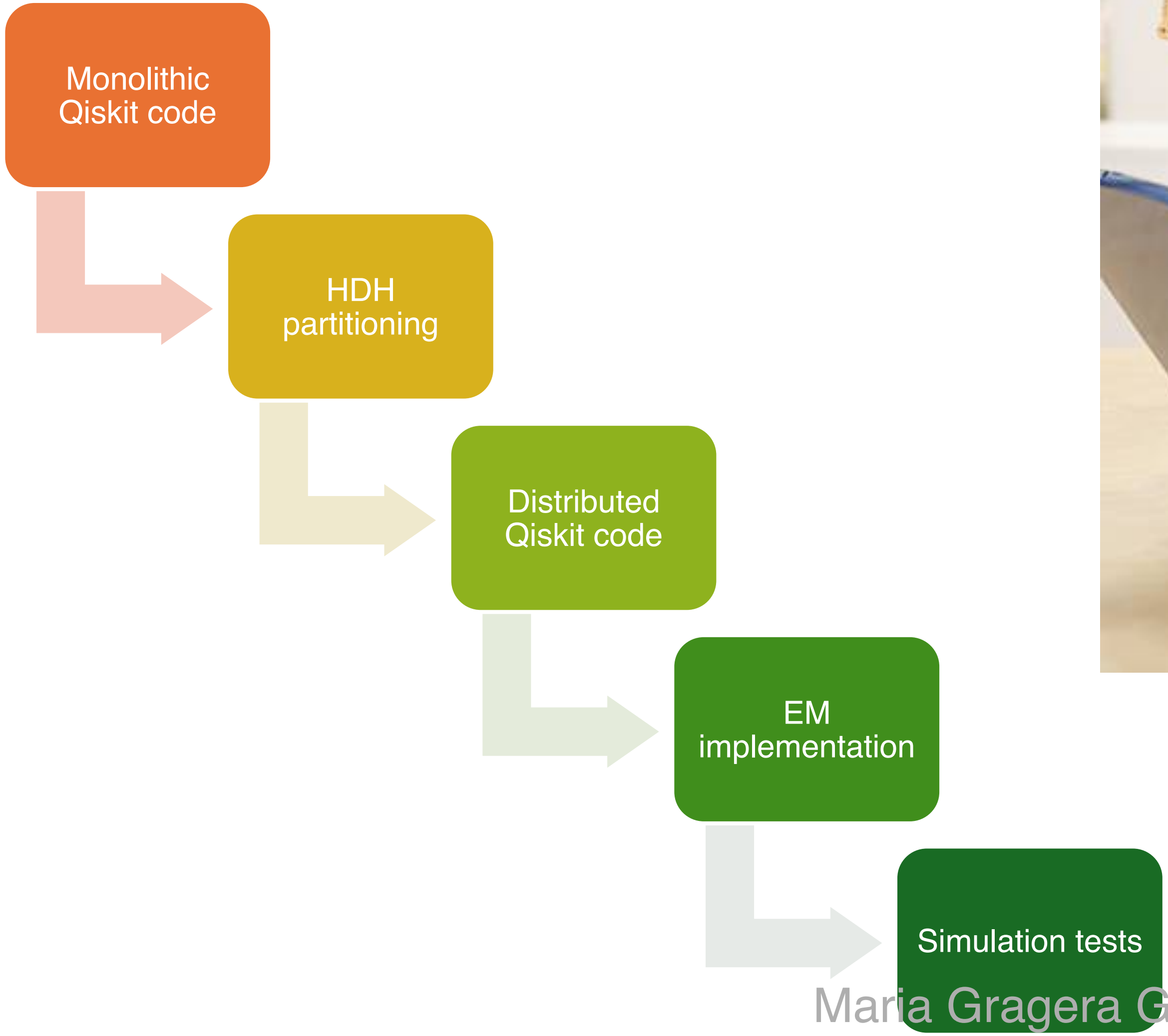


+ Additional teleportation channel error injections



Error mitigation software!

mitiq


Monolithic Qiskit code
HDH partitioning
Distributed Qiskit code
EM implementation
Simulation tests

Distribution-Aware QEM

How should the field move forward?

- More work on distributed error profiling both on **simulated** (large memory requirements for large systems) and real **devices** (few/none usable distributed quantum computers today)
- Testing error mitigation and correction techniques in distributed setups (suffers from the same issues as above)
- Development of error mitigation and error correction **software** that is distribution aware

“if you are building things for tomorrow’s quantum computers you are building things for distributed quantum computers”

Thanks!