Unifying flavors of fault tolerance with the ZX calculus

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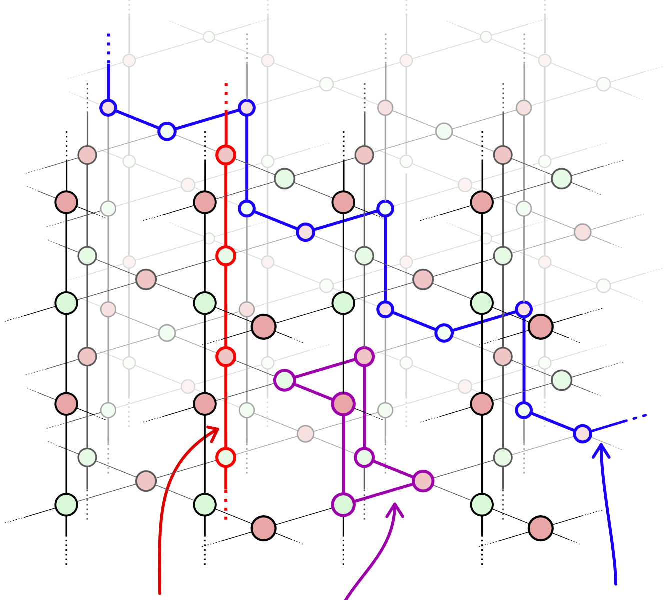
There are several models of quantum computation which exhibit shared fundamental fault-tolerance properties. Our work makes commonalities explicit by presenting different models in a unifying framework based on the ZX calculus. We focus on models of topological fault tolerance - specifically surface codes - including circuit-based [1], measurement-based [2] and fusion-based [3], as well as the recently introduced model of Floquet approach [4, 9]. We find that all of these models can be viewed as different flavors of the same underlying stabilizer fault-tolerance structure, and sustain this through a set of local equivalence transformations which allow mapping between flavors.

To do so, we represent the elementary quantum instruments of each model: qubit initialization, resource state preparation, unitary gates, single qubit, pair parity and fusion measurements using the ZX diagrammatic tensor network notation and some of its known identities. We show how the different models map onto each other via transformation and simplification rules which preserve the structure of parity checks and logical membranes.

Taking this perspective, the different models of fault-tolerant computation differ by which operations and error models are interpreted as native. Our approach brings us closer the notion of fault-tolerance phase identifying a shared underlying structure despite differing number of physical measurement outcomes. This unifying perspective is paving the way to transferring progress among the different views of stabilizer fault-tolerance and providing a Rosetta stone with which researchers familiar with one model can easily understand others [5]. For example, using this approach one can transfer known protocols for logical gates and decoding in circuit-based or measurement-based perspectives to the recently introduced Floquet approach [7]. One can also express explicit tensor factorization quantum encoding isometries [6] in a shared representation which can easily be refined to the desired model of computation.



(a) CBQC qubit worldline (c) FloBQC qubit worldline

(b) 6-ring resouce state

The figure depicts the common ZX tensor network diagram common to many known flavors of stabilizer fault tolerance. It corresponds to the bulk of the RBH MBQC protocol [8], which has the same representation as the circuit model of Ref [1], the fusion based computation example in [3] and the recently introduced floquet model of [9]. Together, this makes it the most studied model of stabilizer fault tolerance. Each flavor is expressed in terms of its own characteristic elements which are identified here in their shared representation.

[1] E. Dennis et al. JMP **43**, 4452 (2002)

[2] R. Raussendorf et al. Ann. Phys. **321**, 2242 (2006)

[3] S Bartolucci et al. Nat. Comm. **14**, 912 (2023)

[4] M. B. Hastings and J. HaahQuantum **5**, 564 (2021)

[5] N. de Beaudrap and D. HorsmanQuantum **4**, 218 (2020)

[6] A. B. Khesin et al. arXiv:2301.02356 (2023)

[7] T. D. Ellison et al. arXiv:2306.08027 (2023)

[8] R. Raussendorf et al Phys. Rev. A **71**, 062313 (2005)

[9] M. Davydova et al. arXiv:2210.02468 (2022)