CPS Quantum Computing

Talk Excerpts

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Outline

Outline

Resource Estimation [1]

- Fault-tolerance requires too much resource

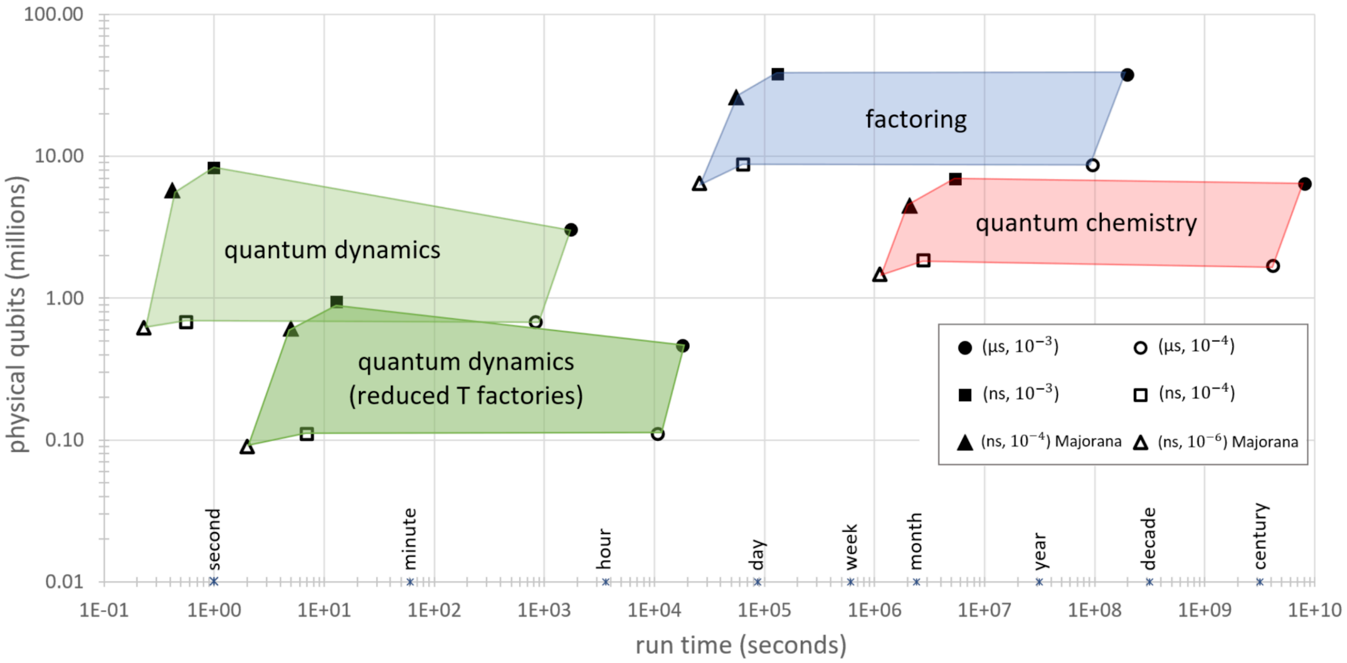


Figure 1: Resource Estimation for Various Application and Hardware Quality.

Correlated Decoding [2]

- For transversal entangling gates “errors detected on one logical qubit can contain information about which errors occurred on other logical qubits”

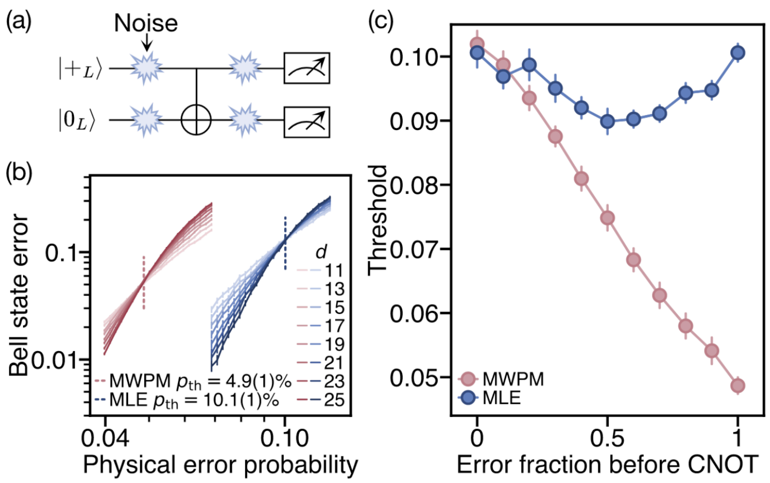


Figure 2: In Simulation with Correlated Error, threshold is improved from 5.1% to 10.3%

Correlated Decoding [2]

- "if we can perform fewer than d rounds between transversal CNOTs, by leveraging the deterministic propagation of stabilizer measurement errors through CNOTs to verify stabilizer measurements using surrounding rounds of syndrome extraction"
- "stabilizer measurement errors near transversal CNOTs generate hyperedges that make conventional decoding approaches challenging"

Correlated Decoding [2]

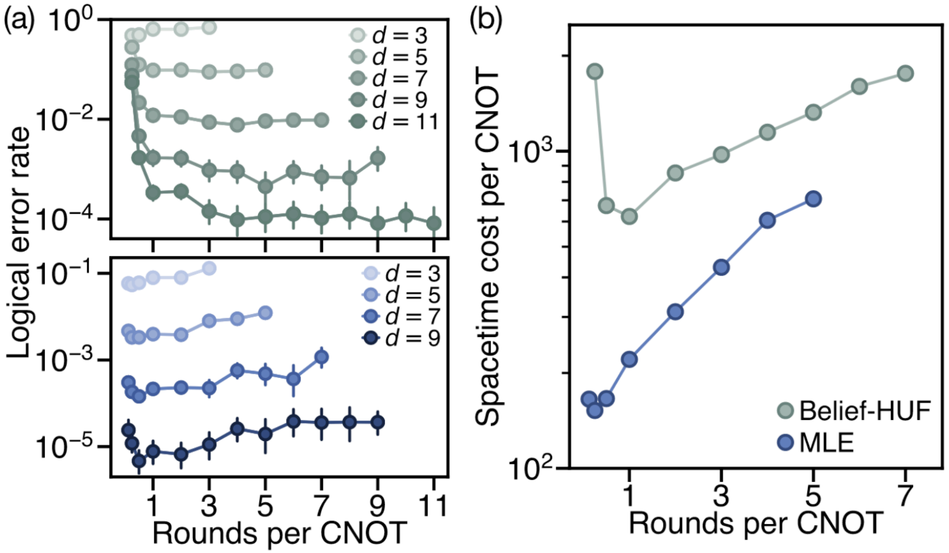


FIG. 4. Reducing the space-time cost of deep logical circuits. (a) The rounds of syndrome extraction per CNOT can be reduced to $n_r \simeq \frac{1}{2}$ for MLE (bottom) and $n_r \simeq 3$ for belief-HUF (top), without increasing P_L. (b) The extrapolated space-time cost to reach $P_L = 10^{-6}$ is minimized at $n_r = 1$ for belief-HUF and $n_r = \frac{1}{4}$ for MLE.

Algorithmic Fault-Tolerance [3]

- “a key component of many schemes for achieving universality is magic state teleportation, which crucially relies on the ability to realize feed-forward operations.”
- “such feed-forward operations require on-the-fly interpretation of logical measurements, followed by a subsequent conditional gate, when only a subset of the logical qubits have been measured”
- “Surprisingly, we find that these inconsistencies can be accounted for in classical processing, with a reinterpretation of subsequent measurement results”

Algorithmic Fault-Tolerance [3]

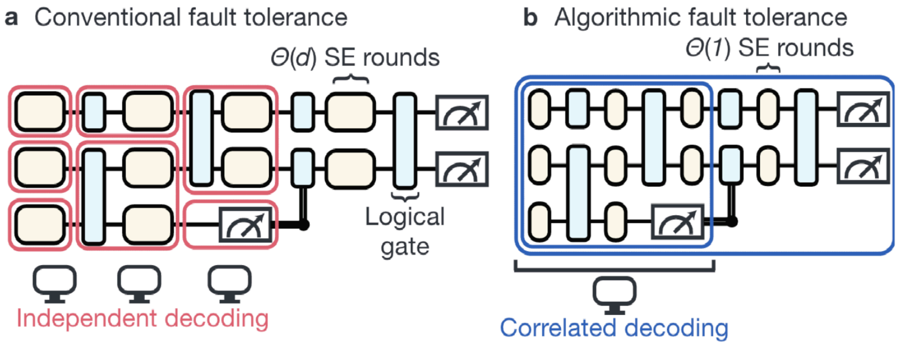
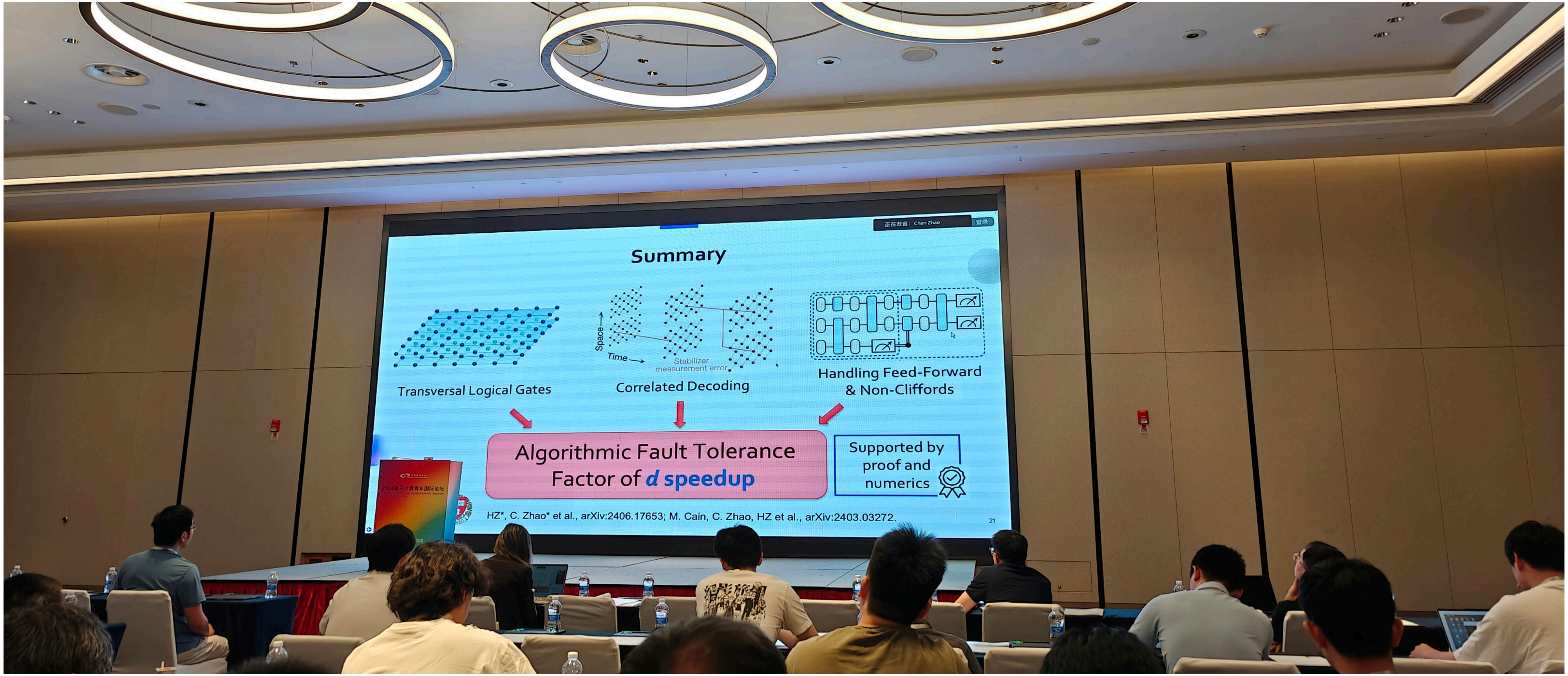


FIG. 1. **Algorithmic fault tolerance.** (a) Conventional FT analysis separately examines each gadget (red boxes) in the circuit and ensures they are individually FT [4, 7, 31]. This requires $\Theta(d)$ syndrome extraction (SE) rounds to achieve FT. (b) Algorithmic FT directly uses all accessible syndrome information up to a logical measurement (blue box), and guarantees FT of the measurement result, even if the gadgets are not individually FT and if future syndrome information is not yet accessible (partial decoding). We realize algorithmic FT through transversal operations, and only require a single SE round per logical operation, thus allowing constant time implementations of logical operations.

Summary


Summary
Transversal Logical Gates
Space
Time
Stabilizer measurement error
Correlated Decoding
Handling Feed-Forward & Non-Cliffords
Algorithmic Fault Tolerance
Factor of d speedup
Supported by proof and numerics
HZ*, C. Zhao* et al., arXiv:2406.17653; M. Cain, C. Zhao, HZ et al., arXiv:2403.03272.

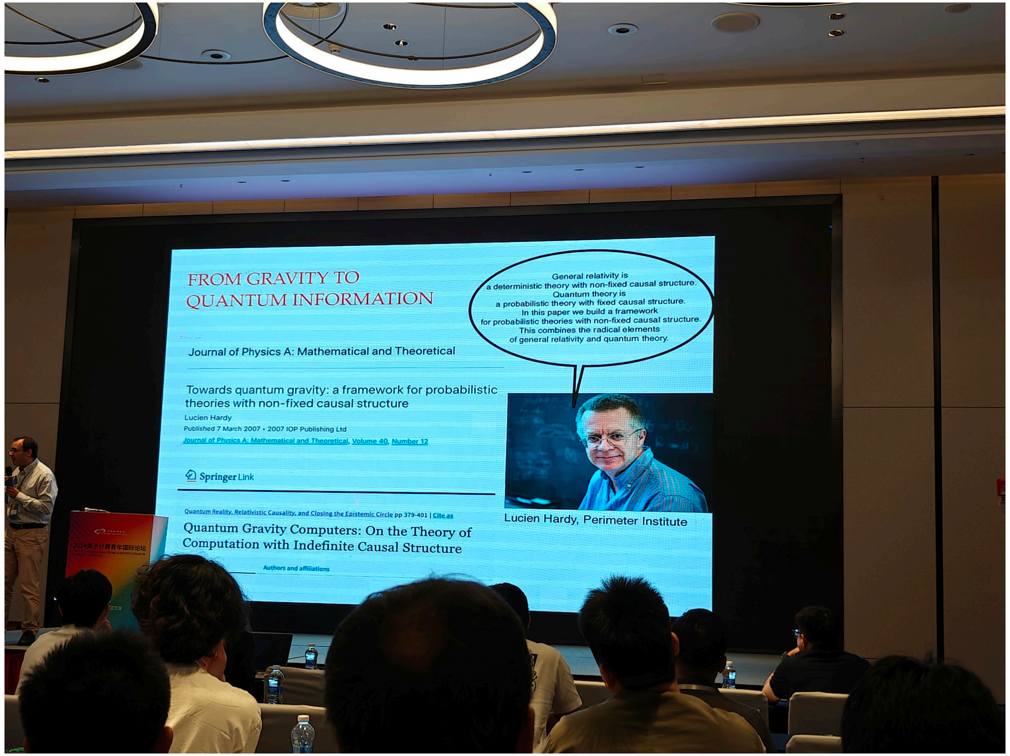
Outline

Summary [4]

- “a quantum processor with such an instruction set, designing an instruction by replacing iSWAP with its matrix square root SQiSW can both reduce the gate error and improve compilation capabilities substantially”
- “taking only roughly half of the time of iSWAP, the SQiSW gate is expected to be implemented with much higher fidelity. Moreover, it has superior compilation capabilities than iSWAP in the task of compiling arbitrary two-qubit gates. An iFRB experiment, which can benchmark non-Clifford gates, on our capacitively coupled fluxonium quantum processor shows the gate error is reduced by 41% and the Haar random two-qubit gate error is reduced by 50% compared to iSWAP on the same chip”
- Online Recoding of Talk

Outline

Picture

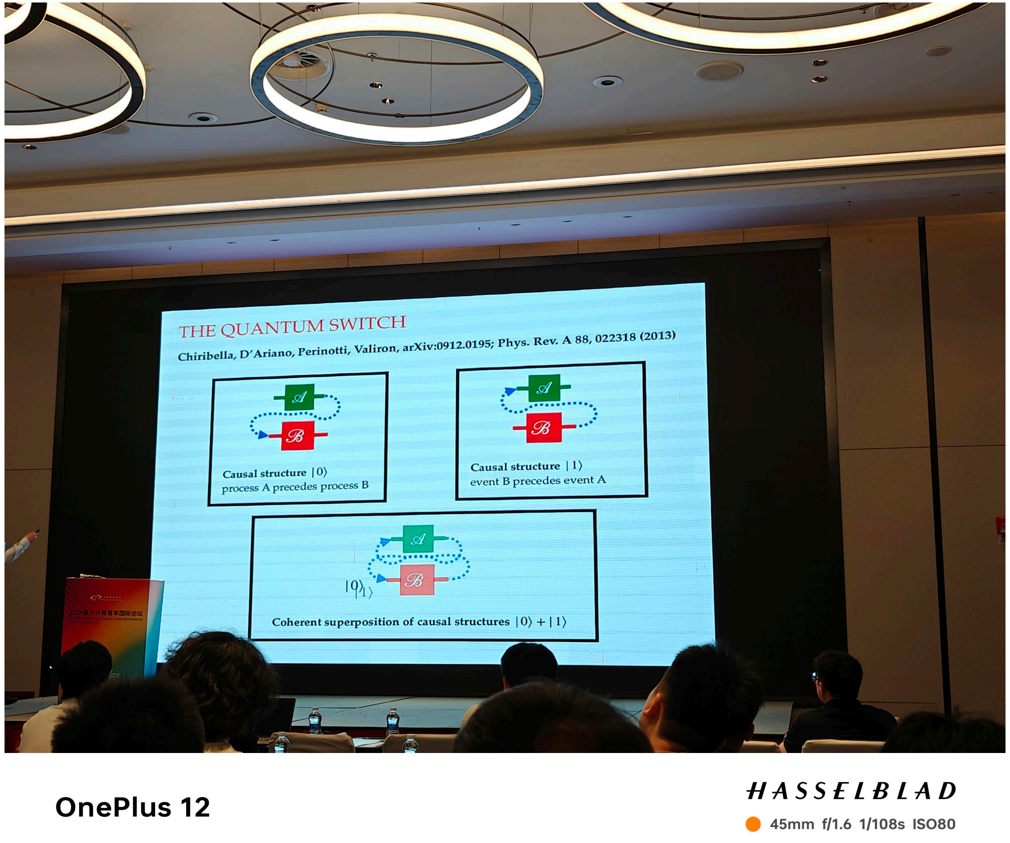


OnePlus 12

HASSELBLAD

45mm f/1.6 1/108s ISO80

Picture


THE QUANTUM SWITCH
Chiribella, D'Ariano, Perinotti, Valiron, arXiv:0912.0195; Phys. Rev. A 88, 022318 (2013)
Causal structure |0⟩
process A precedes process B
Causal structure |1⟩
event B precedes event A
Coherent superposition of causal structures |0⟩ + |1⟩
OnePlus 12
HASSELBLAD
45mm f/1.6 1/108s ISO80

Picture

OnePlus 12

HASSELBLAD
45mm f/1.6 1/106s ISO100

Picture

OnePlus 12

HASSELBLAD

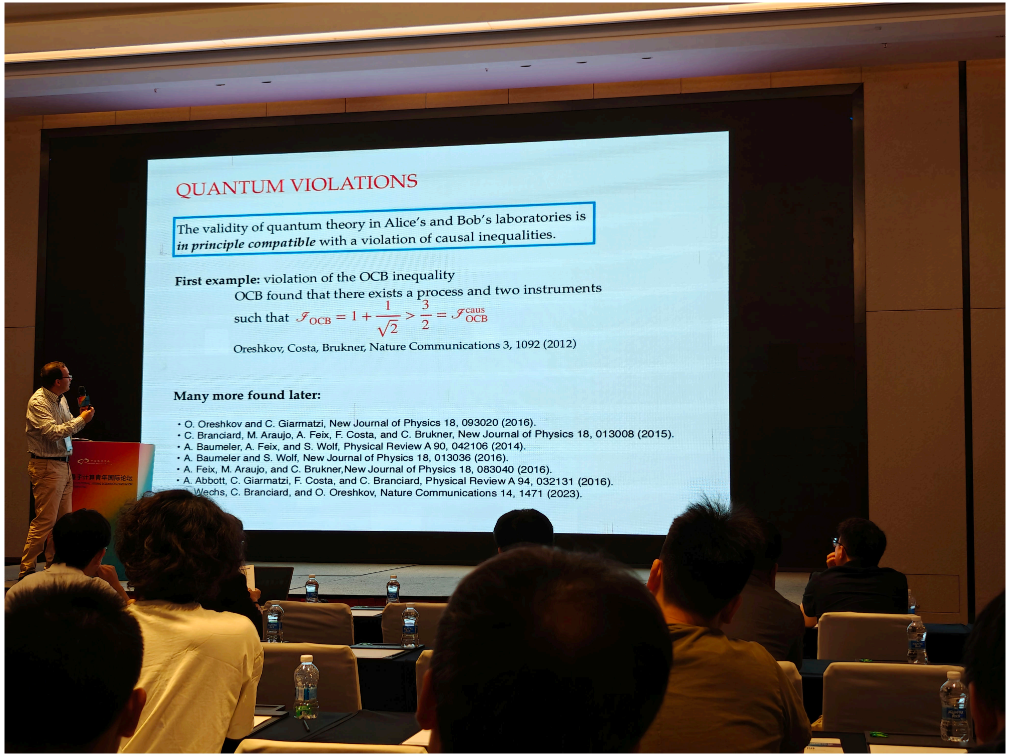
45mm f/1.6 1/106s ISO80

Picture

OnePlus 12

HASSELBLAD
23mm f/1.6 1/106s ISO160

Picture



OnePlus 12

HASSELBLAD

47mm f/1.6 1/212s ISO100

Picture


THE QUANTUM BOUNDARY
FOR
CAUSAL INEQUALITIES
Liu and Chiribella, arXiv:2403.02749
OnePlus 12
HASSELBLAD
23mm f/1.6 1/106s ISO200

Notes

- Indefinite Causal order used to improve metrology with continuous variable system https://www.nature.com/articles/s41567-023-02046-y
- Indefinite causal order: wasn't it just a relaxation of the quantum channel between two parties, of-course it could violated some CHSH like inequality (ref Porf Xin Wang's course)
- Def Indefinite Causal Order: If you cannot represent the process of two parties as a probabilitistic combination of two processes in one where A happens before B and the other otherwise.
- What is the boundary of violation of all possible experiment and all possible order....
- Quantum mechanics + causal order violates some inequality but not maximal (algebraically)

Outline

Summary

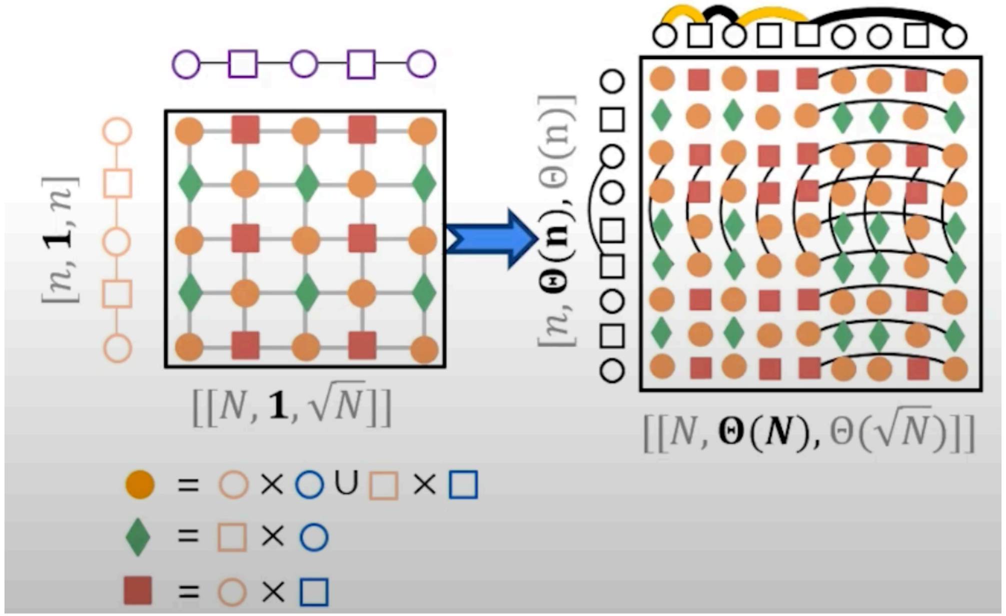
- “Practical implementation of product qLDPC code by (globally) rearranging atoms”
- “High-threshold, constant-space-overhead memory under circuit-level fault-tolerant design”
- “Fault-tolerant commputation via teleportation to topological codes”
- “qLDPC-based FT quantum computer”

qLDPC is necessary

- For surface code $[[n, k, d]]$, "$\frac{n}{k} = d^2$"
- "Connectivity constrains quantum code" [5]
- "High-rate qLDPC code: constant space overhead" $\left[\left[n, \Theta(n), \Theta\left(n^{\alpha \geq \frac{1}{2}}\right)\right]\right]$ [6–8]
- Con of qLDPC
  - "requires non-local and complicated connection"
  - "Large code size & low threshold"
  - QIP2024 Talk

Example of qLDPC code: Hypergraph product Code [9]

- “The HGP code is constructed from two classical LDPC codes”



Example of qLDPC code: Hypergraph product Code [9]

Table 1 | Total number of data and ancilla qubits required to reach target numbers of logical qubits and LFRs using HGP codes and LP codes, compared to using surface codes

Logical qubits	25	80	180	400
Logical failure rate	10^{-3}	10^{-4}	2×10^{-5}	6×10^{-6}
HGP code physical qubits (improvement over surface code)	1,235 (×1)	4,606 (×2.8)	10,760 (×4.0)	19,600 (×6.9)
LP code physical qubits (improvement over surface code)	851 (×1.4)	1,367 (×9.4)	2,670 (×16.2)	

We use (×β) to indicate a β times qubit saving compared to the surface codes by using the corresponding qLDPC codes. The physical error rate is set to 10^{-3}. The estimates for the HGP and LP codes are based on the numerical data in Fig. 3.

Logical Operation with qLDPC code [9]

- “performingfault-tolerant logical operations and perform the first numerical simulation of logical gate performance on qLDPC codes”
- “We teleport the logical information between the qLDPC memory and ancillary topological codes using a measurement-based circuit”
- “prescribed logical measurements are implemented using lattice surgery”
- “Universal logical operations can then be performed in the topological codes using standard techniques”
- “To use these LDPC codes for quantum computation, one must be able to fault-tolerantly implement a universal set of protected logic gates. While Ref. [32] establishes a method to perform quantum computation using faulttolerant gate teleportation [39], the cost associated with the distillation of the requisite resource state [40] is not understood well in the practical regime of interest” [10]

Recording of Talk

- QIP2024 Talk
- QEC2023 Talk

Outline

Summary

- Question: Can tensor network formalism represent physically interesting materials: eg. free-fermion Chern Insulator ?
- Chirality and gappedness cannot co-exist in tensor network representation of Chern insulator
- Zipper: separate long-range entangled state from the short range entanglement by some BASIS CHANGE [11]
- Catch: bond dimensino of PEPS grows polynomially as the size of the system.

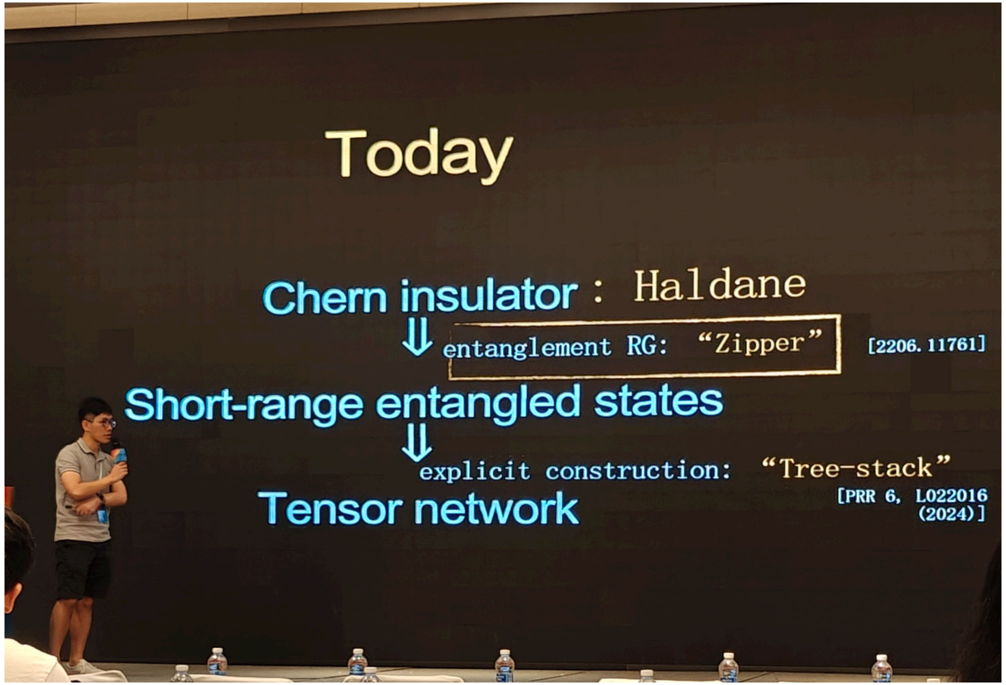
Chern Insulator: the “trouble maker”

- locally describable
  - dressed product states
  - Atomic Insulator
  - Quasi-1D Description (e.g. quantum Hall)
  - ??? non-chiral topological order ... toric code)
- Physically Interesting
  - Chiral states
  - Semi-metals
  - Critical states
  - Metals
  - ...

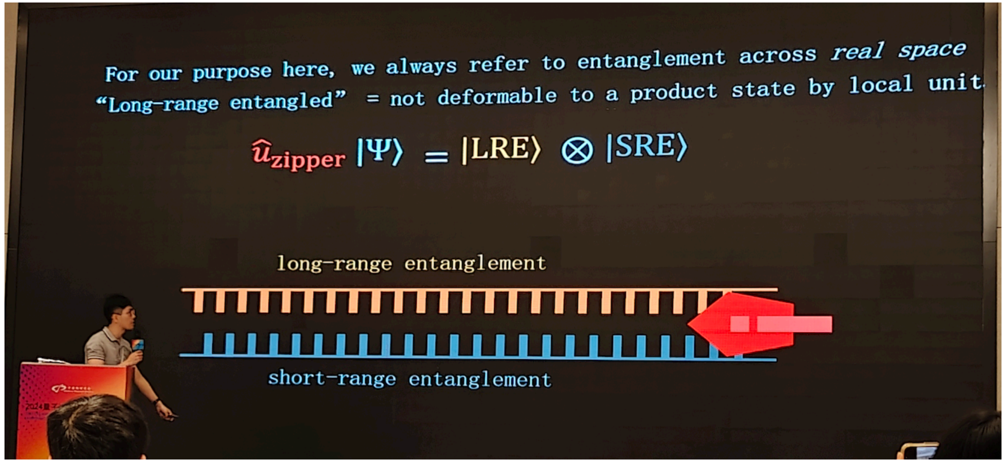
Difficulties with Chiral Tensor Networks

- General picture: PEPS with finite bond dimensions can be chiral but [12,13]
  - No gapped, local parent Hamiltonian
  - Algebraically decaying correlation (which might approximate the short-range part well)
- No-go proven for free fermions w/ translation invariance [13]
- Interaction not as rigorously studied but the overall picture still holds [14–16]

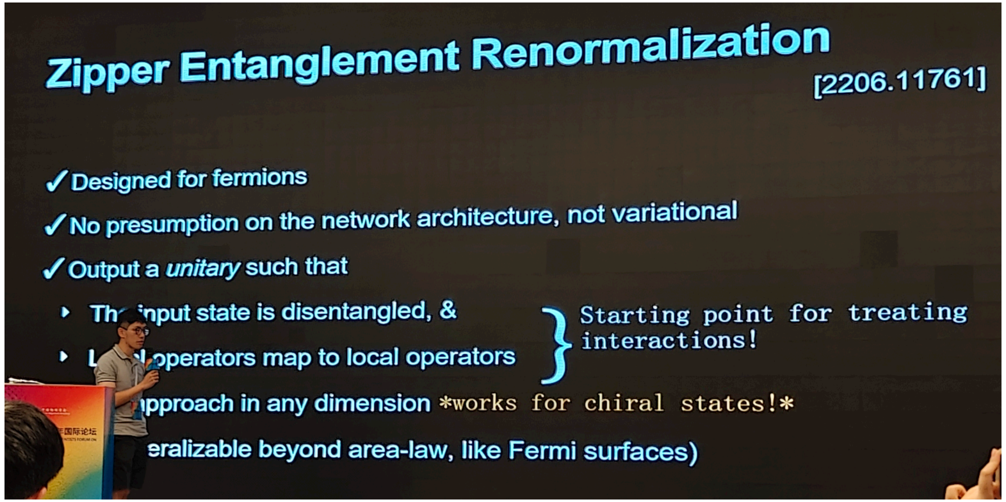
Photos


Today
Chern insulator : Haldane
entanglement RG: "Zipper"
[2206.11761]
Short-range entangled states
explicit construction: "Tree-stack"
Tensor network
[PRR 6, L022016 (2024)]

Photos


For our purpose here, we always refer to entanglement across *real space*
"Long-range entangled" = not deformable to a product state by local unit
$\hat{u}_{zipper} |\Psi\rangle = |LRE\rangle \otimes |SRE\rangle$
long-range entanglement
short-range entanglement

Photos


Zipper Entanglement Renormalization
[2206.11761]
✓Designed for fermions
✓No presumption on the network architecture, not variational
✓Output a *unitary* such that
input state is disentangled, &
operators map to local operators
Starting point for treating interactions!
pproach in any dimension *works for chiral states!*
eralizable beyond area-law, like Fermi surfaces)

Outline

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