Quantum error correction and mitigation (part 2)

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Path to full-scale QC through error mitigation and correction
Error mitigation is essential for obtaining accurate results on near term quantum computers

Probabilistic Error Cancellation

Average over many circuit instances with additional gates inserted to reconstruct the noise inverse

Zero noise extrapolation

Increase noise through stretching circuits and extrapolate back to the zero noise limit

\[ N^{-1}(\rho) = \gamma (p_1 \rho - p_2 X_2 \rho X_2 - p_3 Y_2 \rho Y_2 - p_4 Z_2 \rho Z_2) \]

Temme, Bravyi, Gambetta, Phys. Rev. Lett. 119, 180509, 2017
Zero-noise extrapolation for 127 qubit, depth 60 circuits

Learn device-wide noise
Instead of cancelling the noise, amplify it
Extrapolate to zero noise limit from measurements at amplified noise levels

manuscript in preparation
Mitigation beyond expectation values

Coherent Pauli checks

Single-shot error mitigation by coherent Pauli checks
van den Berg et al, arXiv:2212.03937 (2022)

CPC construction:
Roffe et al, Quant. Sci. Tech., 3(3):035010 2018
Debroy and Brown, PRA 102(5):052409 2020
Gonzales et al, arXiv:2206.00215 2022

Number of logical qubits:
- n = 10
- n = 8
- n = 6
- n = 4
- n = 2

Logical error probability

# of checks
Combining mitigation & correction: mitigated T-gates

How to combine error mitigation and correction to overcome near-term resource limitations?

Resource overhead limited by magic state preparation.


Piveteau et al, Error mitigation for universal gates on encoded qubits, PRL 127, 200505, 2021
Smooth path toward quantum advantage and full-scale QC?

- Error mitigation
  - Mitigated expectation value measurements
  - Pauli Checks
  - PEC
  - ZNE

- Error correction
  - Canonical quantum algorithms
  - Mitigated t-gate

What techniques can we introduce to incrementally increase the complexity of problems we can access?

How do we practically apply mitigation and error correction together in the near term?
Reducing the cost of full-scale fault-tolerant architectures
Planar code architecture is expensive

An $[n, k, d]$ stabilizer code in 2D satisfies $n \geq c \, k \, d^2$ for constant $c$. (⇒ high overhead)

New connectivity constraints?

Qubits have small numbers of connections

- Embeds into a small number of planes
- Hierarchical and modular structures
- Unrealistic & unnecessary

practical but constrained

nearest-neighbor

limited non-nearest-neighbor

connected all-to-all
Modular architecture at IBM

**Coupler types**

- **C-coupler / hyperedge**: (on-chip, w-local, constant diameter)
- **M-coupler**: (medium range, NN between chips)
- **L-coupler**: (long range, perimeter only)

Low-density parity check (LDPC) codes

LDPC code families have checks whose weights do not grow with the size of the system, and each qubit also participates in a constant number of checks.

LDPC code with **local** checks

- 225 code qubits / logical
- correct 7 errors
- 4 logical qubits
- [[225, 1, 15]]
- surface code

LDPC code with **non-local** checks

- 18 code qubits / logical
- correct 6 errors
- 50 logical qubits
- [[900, 50, 14]]

Cartoon: 8 non-adjacent qubits


general LDPC codes have high rate but require long-range checks

Progress in quantum LDPC code theory

Good quantum LDPC codes exist

Need small, high-rate LDPC codes with simple fault-tolerant gates and practical classical decoders

finite codes with good performance: Panteleev and Kalachev, Quantum, 5(585), 2021

planar codes: high thresholds and local stabilizers -- ideal for near term

Surface codes are exemplars for all codes constrained to 2D (Bravyi, Poulin, Terhal, 2009)

expander codes/HGP: practical thresholds and non-local stabilizers (Tillich, Zemor, 2009; Fawzi, Grospellier, Leverrier, 2018)

State of the art until recently; vanishing relative distance

PK codes: discovered in 2021; asymptotically good rate and distance

(Panteleev, Kalachev 2021; Breuckmann, Eberhardt 2020)
Fault-tolerant gates in quantum LDPC codes

Homomorphic Logical Measurements
Huang, Jochym-O’Connor, Yoder, arXiv:2211.03625, 2022

Quantum Computation on Fractal Geometries
Zhu, Jochym-O’Connor, Dua, PRX Quantum 3, 030338, 2022

Low-overhead FTQC using long-range connectivity
Cohen, Kim, Bartlett, Brown, Sci. Adv. 8, eabn1717 2022

Generalized code deformation
Krishna, Poulin, Phys. Rev. X 11, 011023, 2021

Gates on hypergraph product codes
Quintavalle, Webster, Vasmer, arXiv:2204.10812, 2022

Fold-transversal gates
Breuckmann, Burton, arXiv:2202.06647, 2022

Pieceable gates
Yoder, Takagi, Chuang, Phys. Rev. X 6, 031039 2016

Parallel universal gates on quantum LDPC codes with low qubit overhead?