Quantum error correction and mitigation (part 2)

Andrew Cross

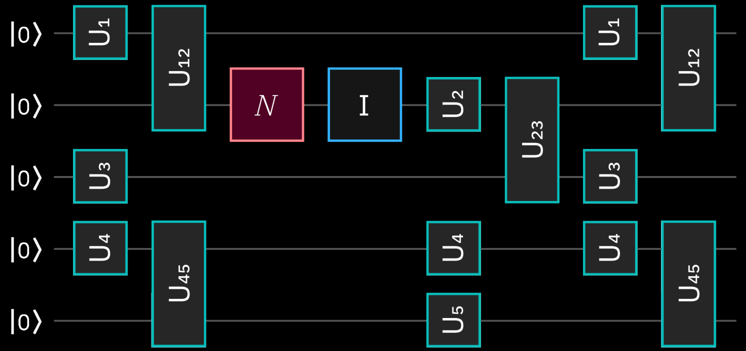
IBM **Quantum**

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

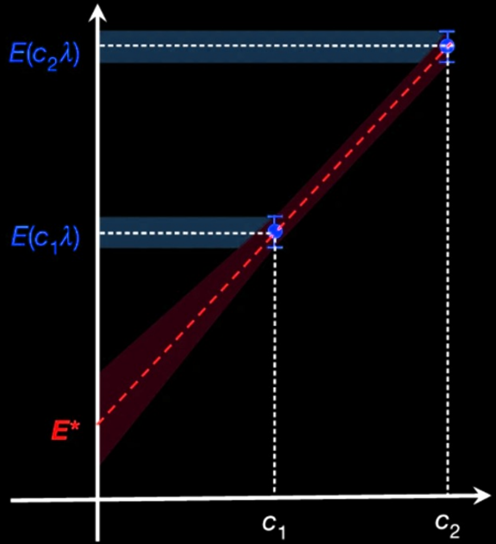


$$\mathcal{N}^{-1}(\rho) = \gamma\,(p_1\rho - p_2X_2\rho X_2 - p_3Y_2\rho Y_2 - p_4Z_2\rho Z_2)$$

Temme, Bravyi, Gambetta, Phys. Rev. Lett. 119, 180509, 2017

Zero noise extrapolation

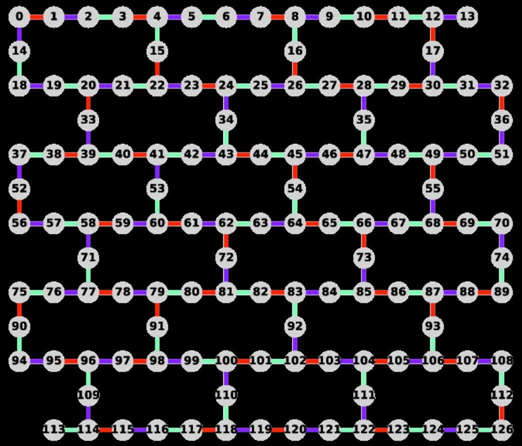
Increase noise through stretching circuits and extrapolate back to the zero noise limit



Noise amplification / stretch factor

Zero-noise extrapolation for 127 qubit, depth 60 circuits

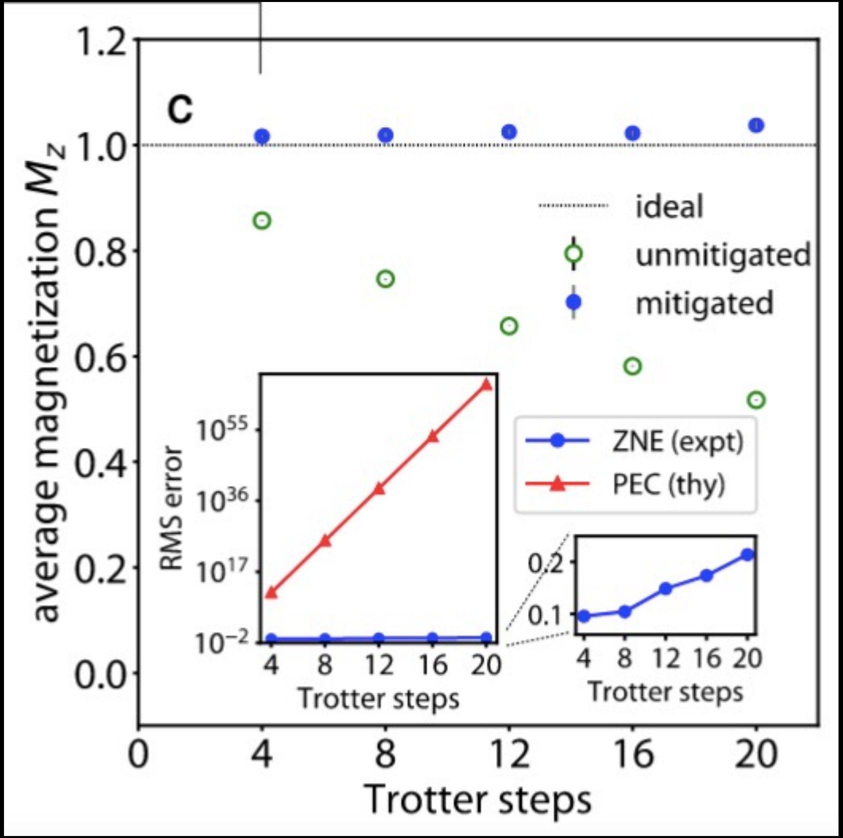
ibm_kyiv



Learn device-wide noise

Instead of cancelling the noise, amplify it

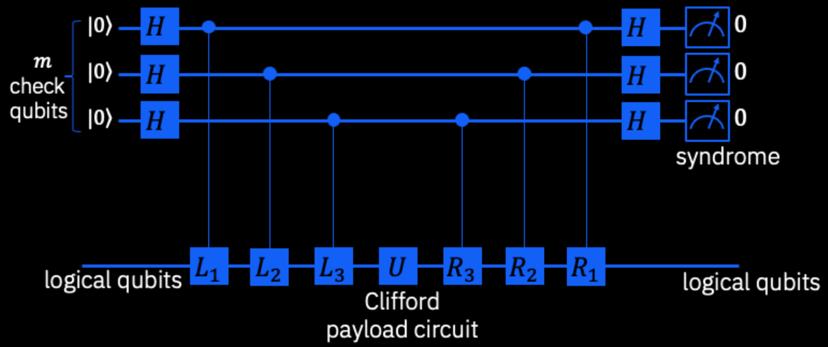
Extrapolate to zero noise limit from measurements at amplified noise levels



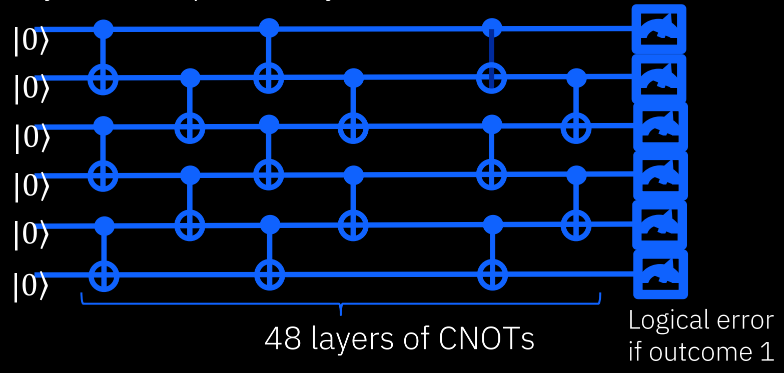
manuscript in preparation

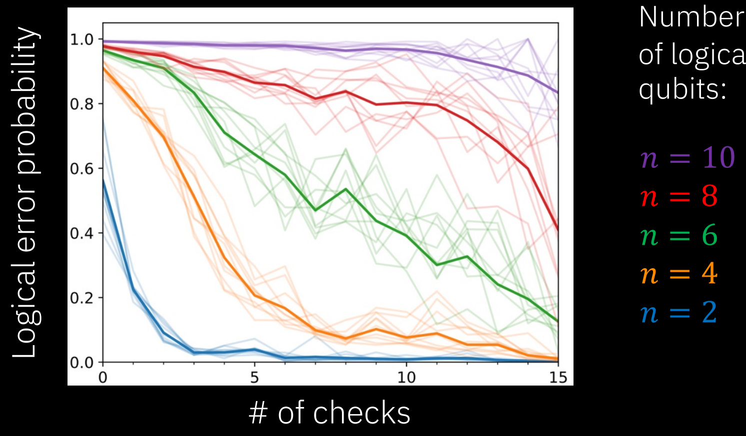
Mitigation beyond expectation values

Coherent Pauli checks



Payload 1: repeated layers CNOTs





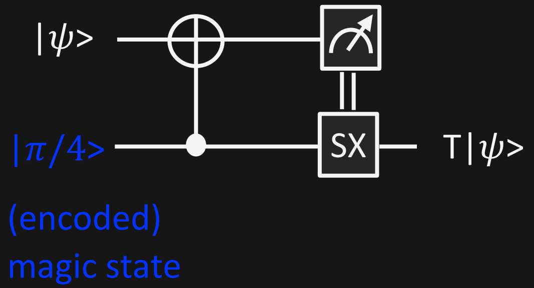
Single-shot error mitigation by coherent Pauli checks
van den Berg et al, arXiv:2212.03937 (2022)

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

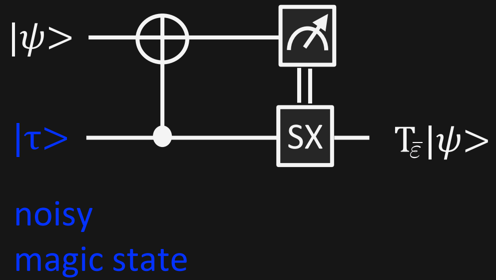
Combining mitigation & correction: mitigated T-gates

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

Resource overhead limited by magic state preparation.



Proposal: *correct resource-heavy noisy T-gates with error mitigation, reserving error correction for Clifford gates.*



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

Error correction

Mitigated expectation value measurements

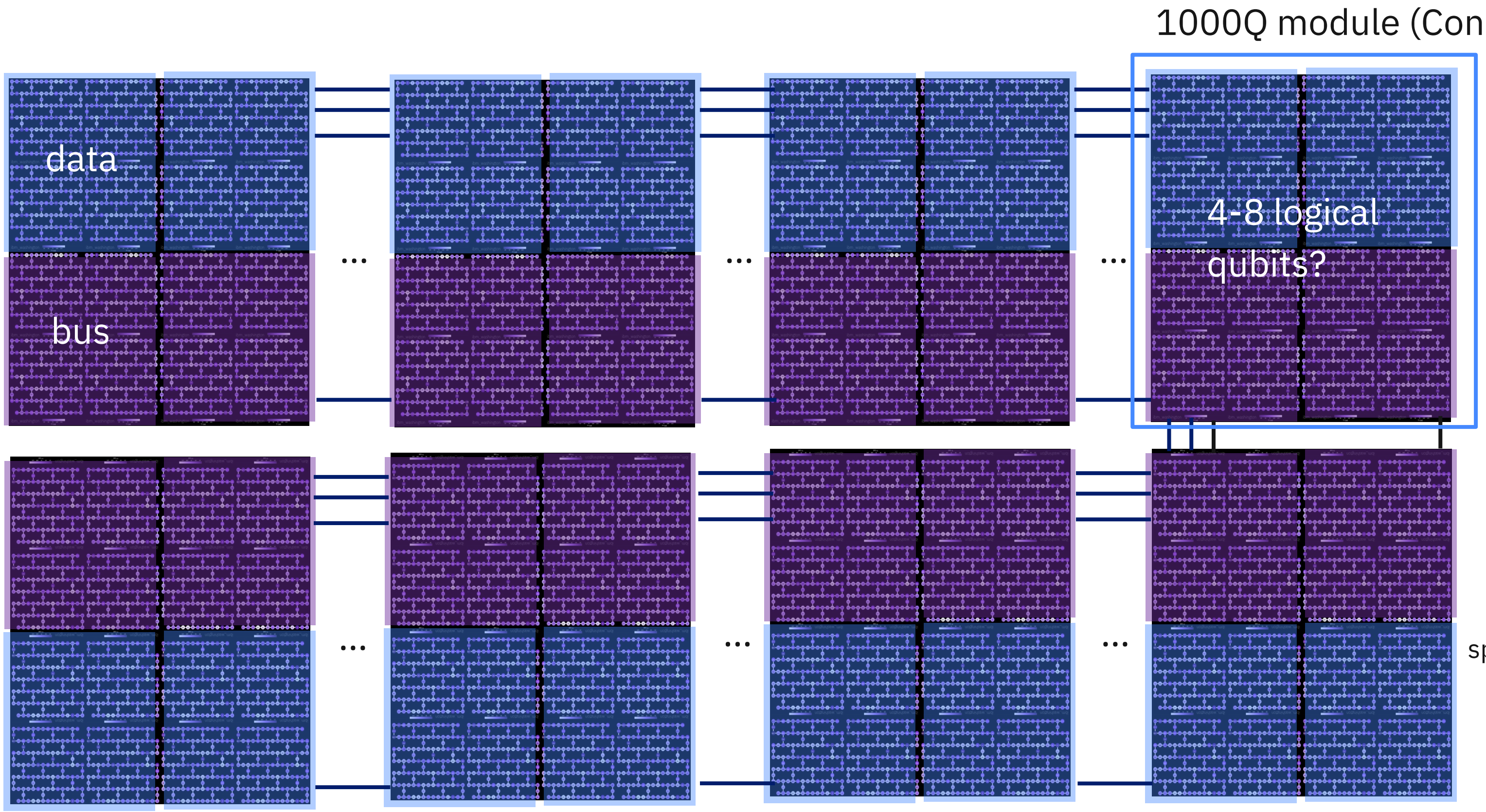
Canonical quantum algorithms

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



illustrates low encoding rate 1/O(d^2)

virtual linear array with space for planar code “bus”

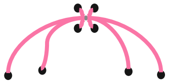
An $[\![n, k, d]\!]$ stabilizer code in 2D satisfies $n \geq c\ k\ d^2$ for constant c. **(⇒ high overhead)**

Bravyi, Poulin, Terhal, Phys. Rev. Lett. 104, 050503, (2010)

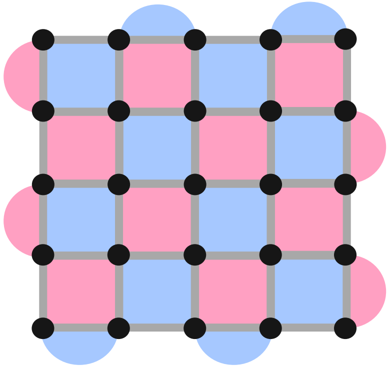
New connectivity constraints?

IBM **Quantum**

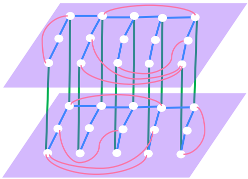
Qubits have small numbers of connections



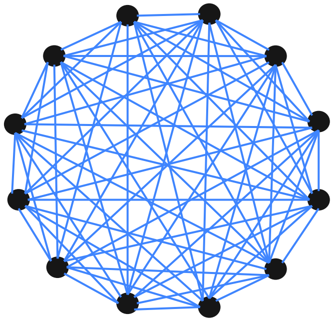
practical but constrained

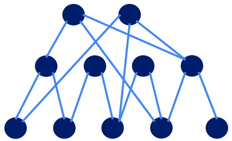


Embeds into a small number of planes



unrealistic & unnecessary





Hierarchical and modular structures

nearest-neighbor

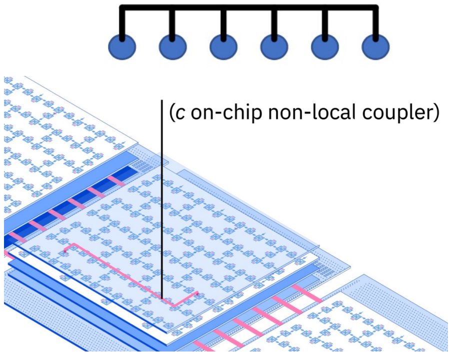
limited non-nearest-neighbor

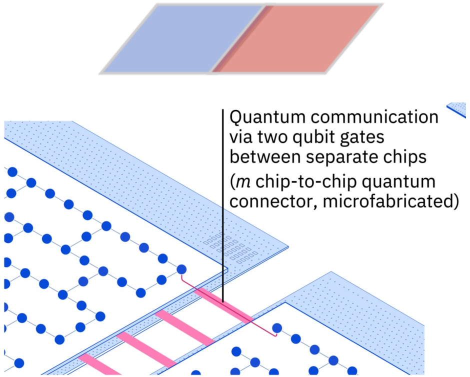
all-to-all

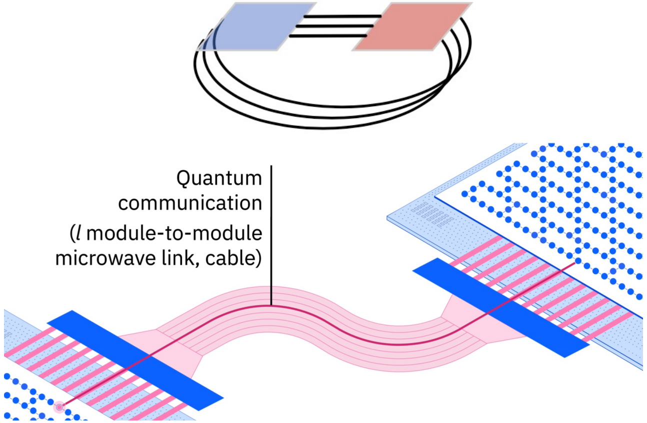
Modular architecture at IBM

Coupler types

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







Bravyi, Dial, Gambetta, Gil, Nazario, The Future of Quantum Computing with Superconducting Qubits, arXiv:2209.06841

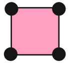
Low-density parity check (LDPC) codes

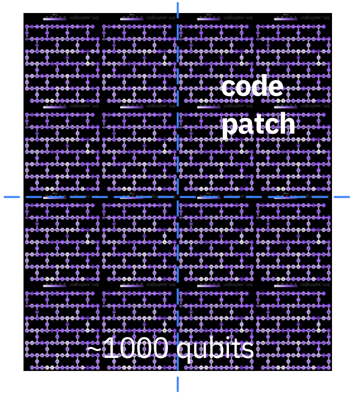
IBM **Quantum**

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.

Gottesman, *Fault-tolerant quantum computation with constant overhead*, QIC 14, 15-16, 2014

LDPC code with **local** checks





225 code qubits / logical

correct 7 errors

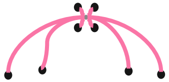
4 logical qubits

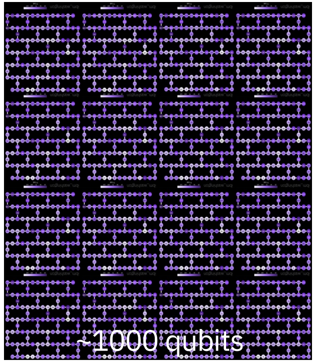
[[225, 1, 15]]

surface code

LDPC code with **non-local** checks

Cartoon: 8 non-adjacent qubits





18 code qubits / logical

correct 6 errors

50 logical qubits

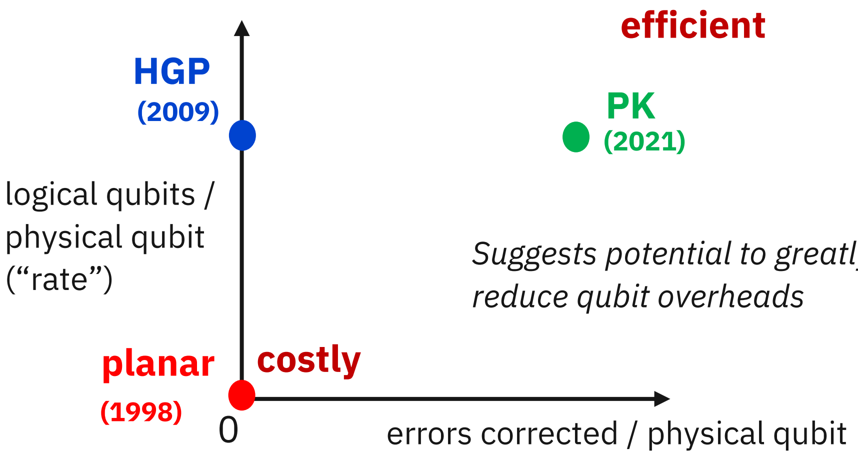
[[900, 50, 14]]

A. Kovalev and L. Pryadko, arXiv:1212.6703, ISIT 2012

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

Progress in quantum LDPC code theory

IBM **Quantum**



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

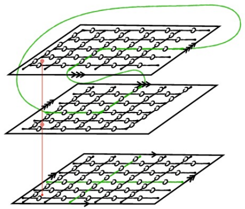
PK codes: discovered in 2021; asymptotically good rate and distance

(Panteleev, Kalachev 2021; Breuckmann, Eberhardt 2020)

Fault-tolerant gates in quantum LDPC codes

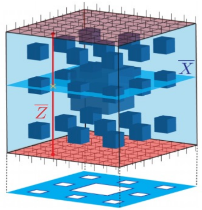
IBM **Quantum**

Homomorphic Logical Measurements



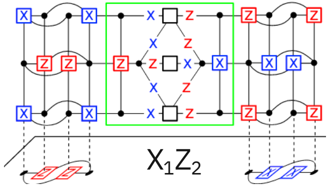
Huang, Jochym-O'Connor, Yoder, arXiv:2211.03625, 2022

Quantum Computation on Fractal Geometries



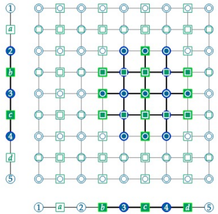
Zhu, Jochym-O'Connor, Dua, PRX Quantum 3, 030338, 2022

Low-overhead FTQC using long-range connectivity



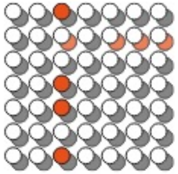
Cohen, Kim, Bartlett, Brown, Sci. Adv. 8, eabn1717 2022

Generalized code deformation



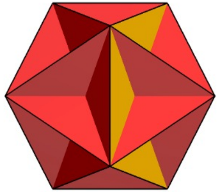
Krishna, Poulin, Phys. Rev. X 11, 011023, 2021

Gates on hypergraph product codes



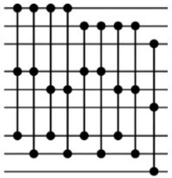
Quintavalle, Webster, Vasmer, arXiv:2204.10812, 2022

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?