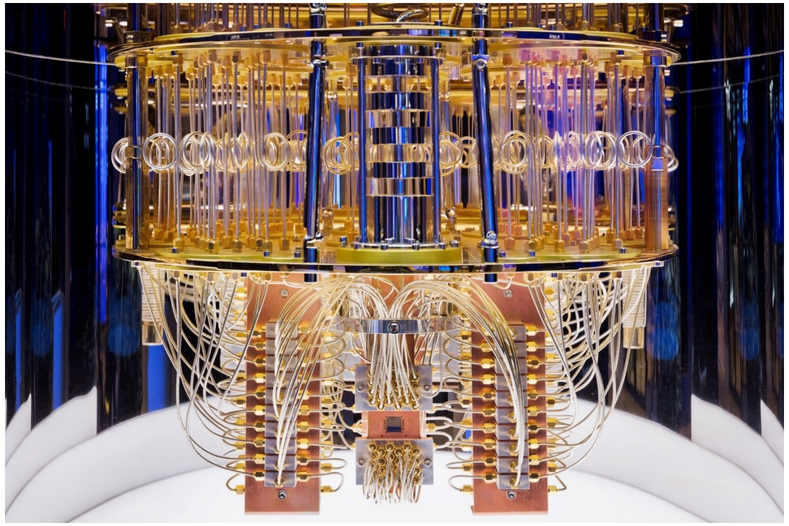
Benchmarking Quantum Computers by Error Correction Syndrome Measurements



State-of-the-art IBM Quantum computing system

A/Prof Muhammad Usman

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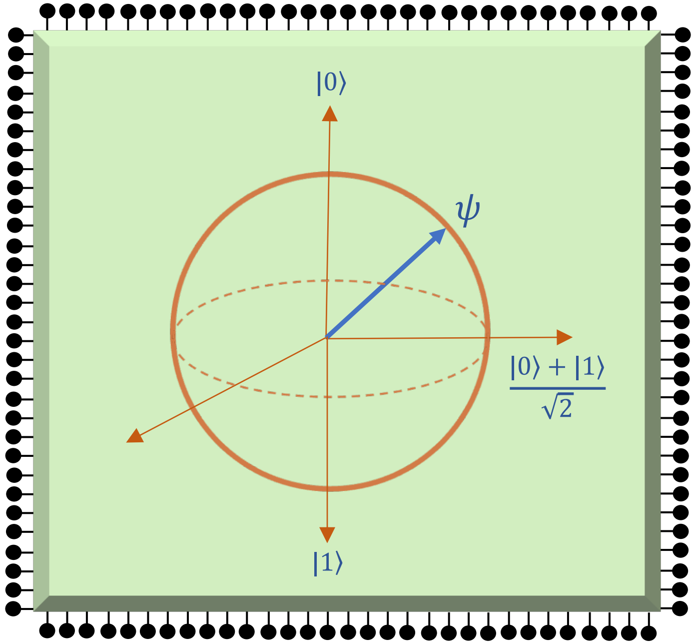
CSIRO's Data61
Australia
Contact: muhammad.usman@csiro.au



Collaborators: Spiro Gicev, Prof Lloyd Hollenberg (UniMelb)

2nd TQCI International Seminar on Benchmarks for Quantum Computers

Quantum @ CSIRO

CSIRO: Who we are

Australia's national science agency

One of the world's largest multidisciplinary science and technology organisations

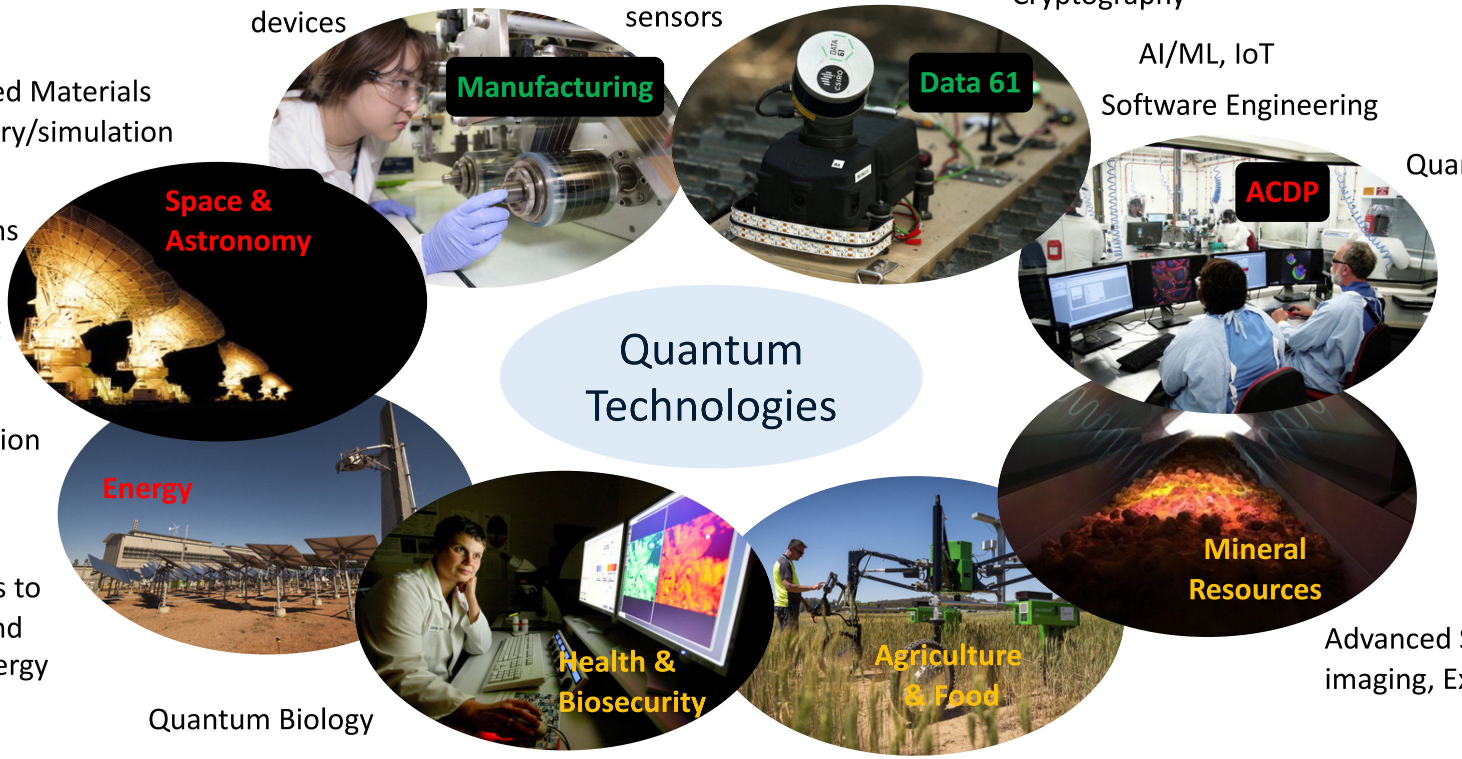
5,600+ dedicated people working across ~50 sites globally

State-of-the-art national research infrastructure

We delivered $10.2 billion of annual benefit to the nation

Quantum @ CSIRO

CSIRO's internal cross-disciplinary Business Units and where "quantum tech" could be developed



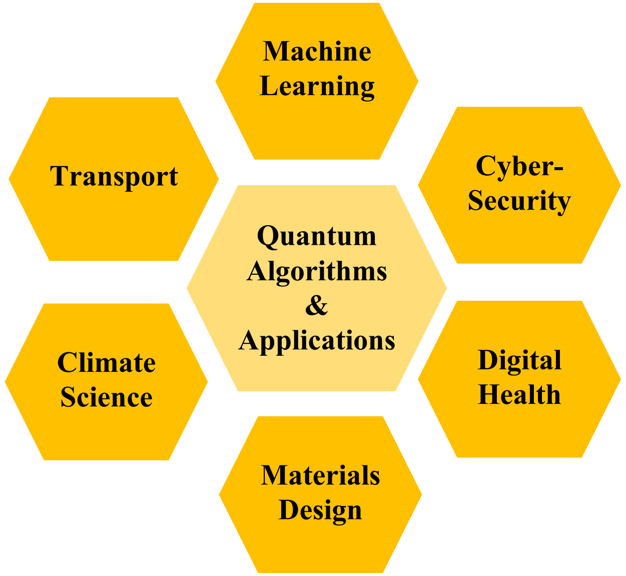
Quantum @ Data61

Quantum Software Stack

- Applications
- Algorithms
- Benchmarking/Performance
- Quantum Programming
- Logical Qubit Compiler
- Quantum Error Correction
- Quantum Control
- Hardware Mapping
- Quantum Processor

Lower the barrier for quantum application developers

Quantum Algorithms & Applications



Advance the usability of quantum technologies

Quantum Security and Responsible Use

Adaptation of quantum technologies with trust and responsible Use

Applications:

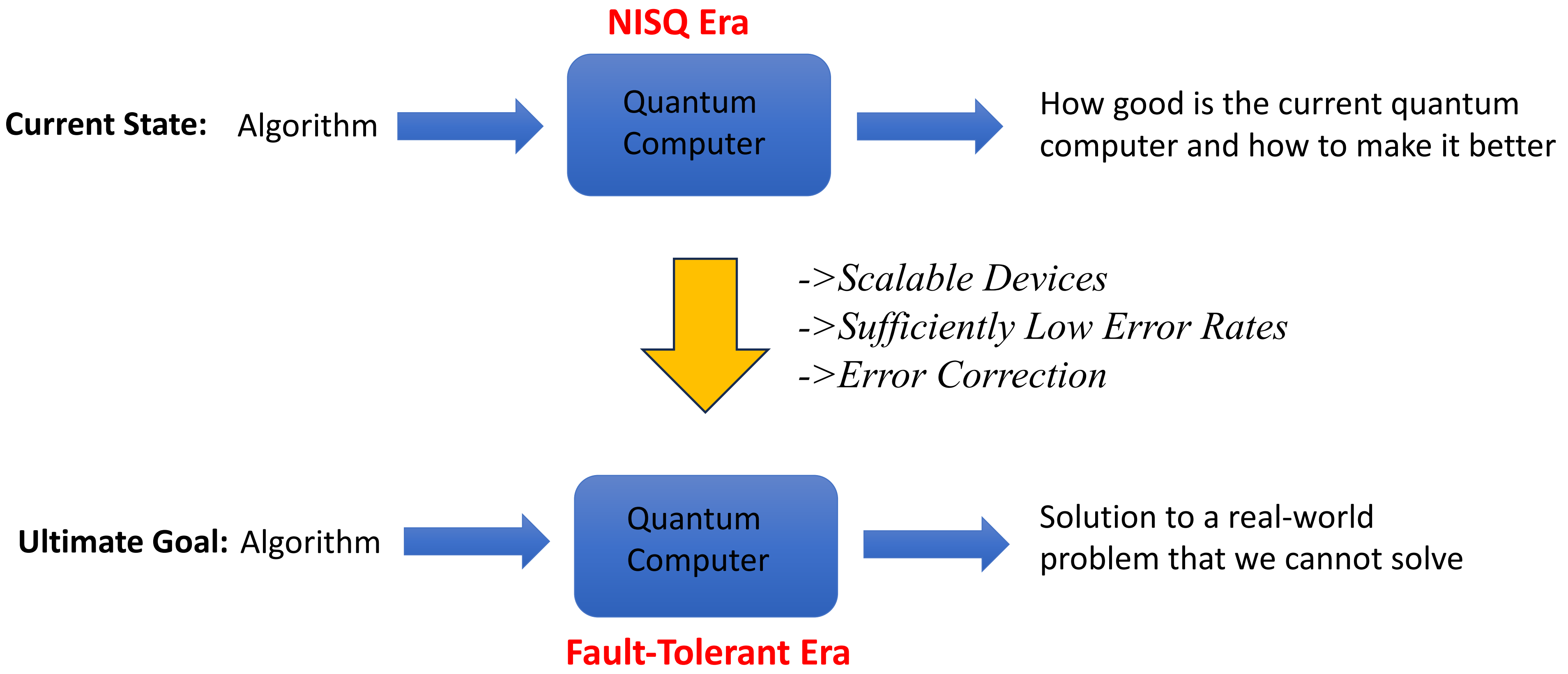
Computational capability of quantum computing offers the potential to revolutionize many areas of research and technologies:

- ✓ Physical Sciences (Materials Design, Physics, Chemistry …)
- ✓ Data Science (Machine Learning, Data Analysis, Factoring)
- ✓ Optimization (Traffic Routing, Finance, Logistics, Scheduling)

Benchmarking Quantum Computers in NISQ Era and beyond

The current generation of quantum processors are often referred to as "Near-term Intermediate Scale Quantum" devices.

NISQ devices will range from a few hundred to a few thousand qubits.



Benchmarking Quantum Computers in NISQ Era and beyond

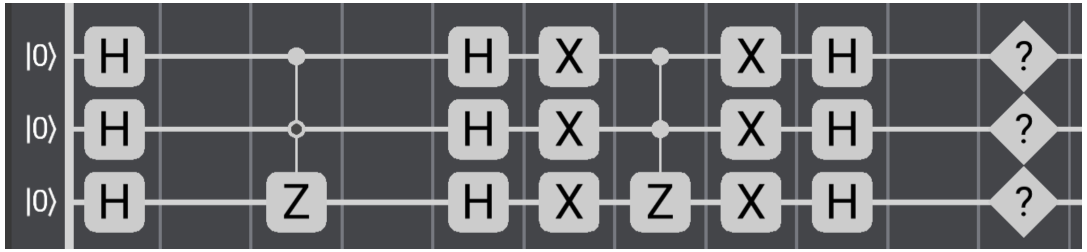
- Development of benchmarks for quantum processors will allow universal performance measures, leading to a coordinated approach towards practicality.
- With increasing number of qubits and their improved quality to run deeper circuits, benchmarks applicable at individual qubit level or gate level may not scale well and provide useful comparison metrics.
- Likewise, benchmarking quantum processors by running quantum algorithms may provide a holistic insight but would be very specific to the implemented circuits.
- Standardisation of Quantum Technologies should establish global benchmarks, e.g., JTC-3

Can quantum processors be benchmarked based on error syndrome measurements?

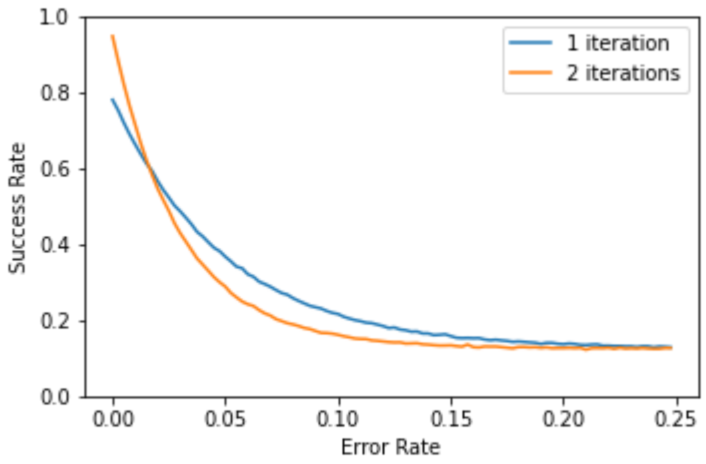
What can we learn about noise in a quantum processor by error syndrome measurements?

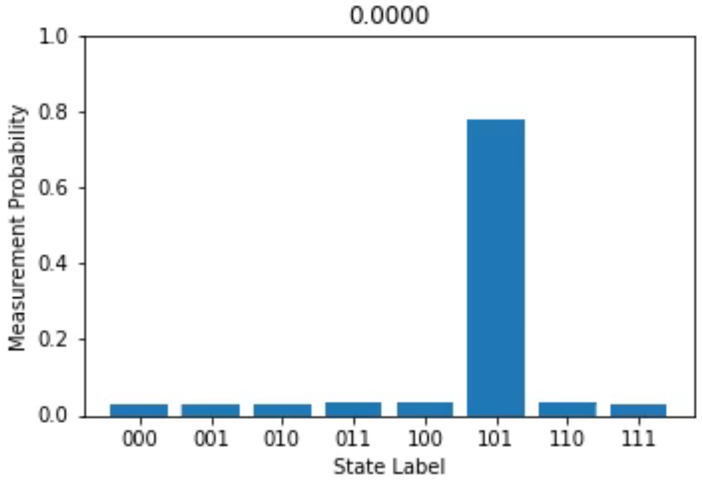
Errors in Quantum Computers

- Noise degrades quantum device performance.
  - Control Errors
  - State Preparation and Measurement Errors
  - Decoherence
- Individual circuits become exponentially unlikely to give correct outcomes.
- Expectation values require exponentially many shots for sufficient mitigation.



3 qubit Grover's algorithm circuit. (Visualized with the QUI simulator at https://qui.research.unimelb.edu.au/)



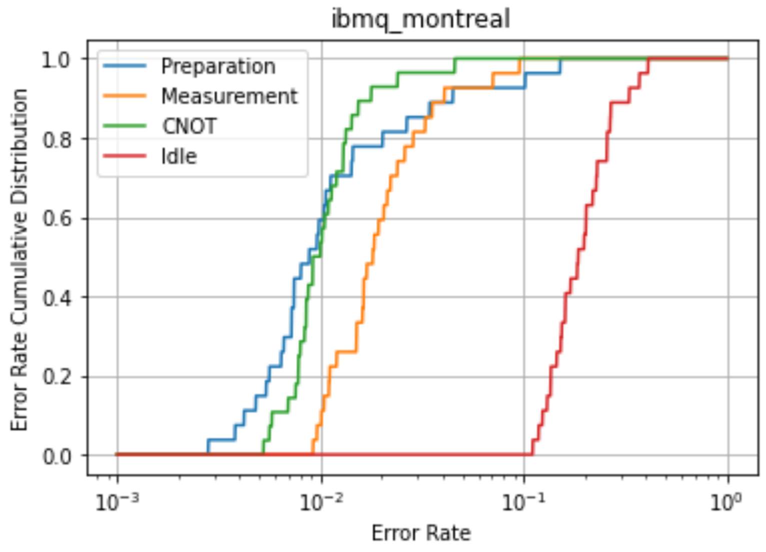


3 qubit Grover's algorithm performance with errors. (Simulated with qiskit https://qiskit.org/)

S. Brandhofer, S. Devitt, and I. Polian. "Arsonisq: Analyzing quantum algorithms on near-term architectures". In 2021 IEEE European Test Symposium (ETS). IEEE (2021).

Error Models

- Error rates are one of the primary measures of progress in quantum computing.
- Threshold theorems exist which allow arbitrary suppression of errors only if error rates can be reduced beneath a particular value.
- Knowledge of error model details allows improved choice of code, decoding and circuit compilation.
- Noise characteristics of quantum devices feature non-markovian elements and drift continuously (rarely modelled in QEC literature).



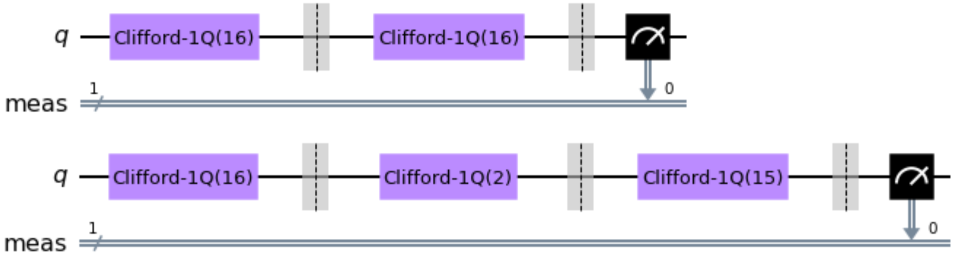
"ibm_montreal" error rates for gates relevant to QEC.

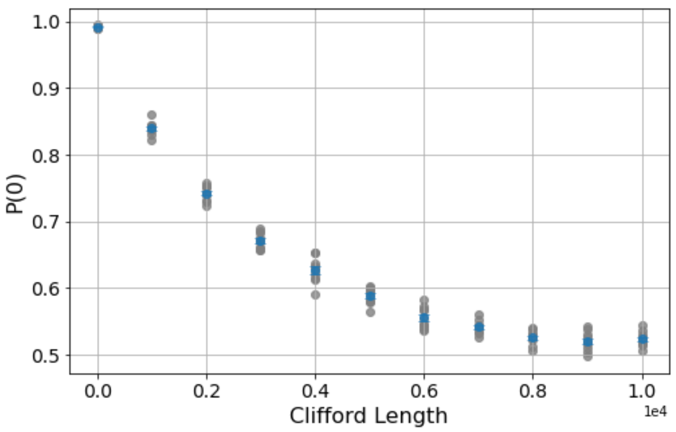
Can anything be said about the noise present in a quantum device without repeatedly performing dedicated benchmarking circuits?

J. R. Wootton. "Measurements of floquet code plaquette stabilizers" (2022). arXiv:2210.13154.

Characterizing Errors: Randomized Benchmarking

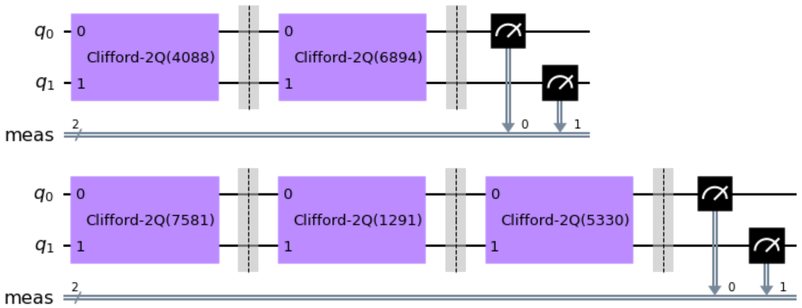
- Single-qubit randomized benchmarking.

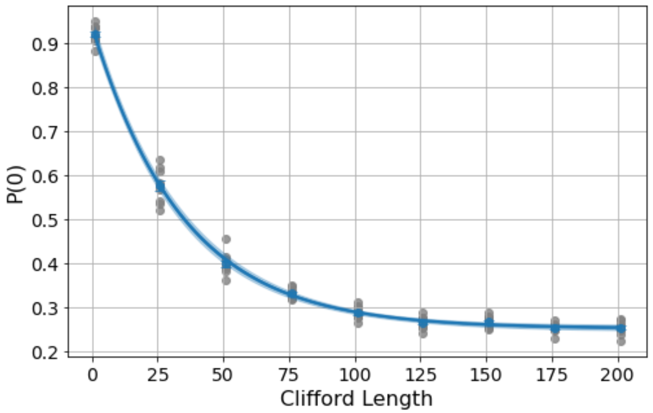




Calculate average error rates by fitting to $\mathrm{P} = A\alpha^l + B$, for l Cliffords.

- Two-qubit randomized benchmarking.





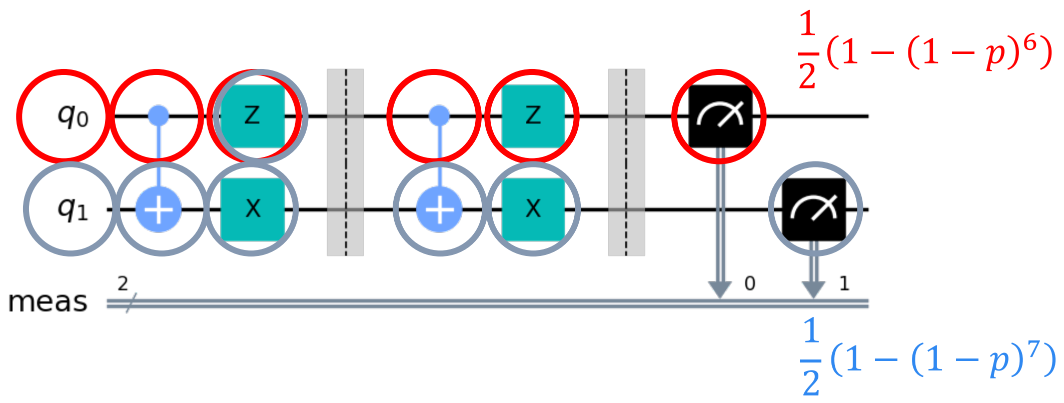
Calculate individual error rates with interleaved randomized benchmarking.

E. Knill, D. Leibfried, R. Reichle, J. Britton, R. B. Blakestad, J. D. Jost, C. Langer, R. Ozeri, S. Seidelin, and D. J. Wineland. "Randomized benchmarking of quantum gates". Phys. Rev. A 77, 012307 (2008).

E. Magesan, J. M. Gambetta, and J. Emerson. "Characterizing quantum gates via randomized benchmarking". Phys. Rev. A 85, 042311 (2012).

Analytic Change Rate Expressions

- Consider an individual randomized benchmarking circuit.



- With no noise, the second set of gates applies an inverse and ‘00’ is always measured.

- With depolarizing noise, what is the relationship between the underlying noise model and the change rate of each individual measurement?

- After each operation, an error can occur. Suppose these all have uniform strength, p.

- We can count the number of circuit elements or sites that can cause errors to propagate and change a given measurement outcome, n_s.
- The measurement change rate is then,

$$R = \frac{1}{2}(1-(1-p)^{n_s}),$$

which corresponds to half the probability that no error occurs after any of the relevant circuit elements.

Is depolarizing noise realistic? Are these systems of equations over-determined or under-determined in QEC?

Heavy Hexagon Code

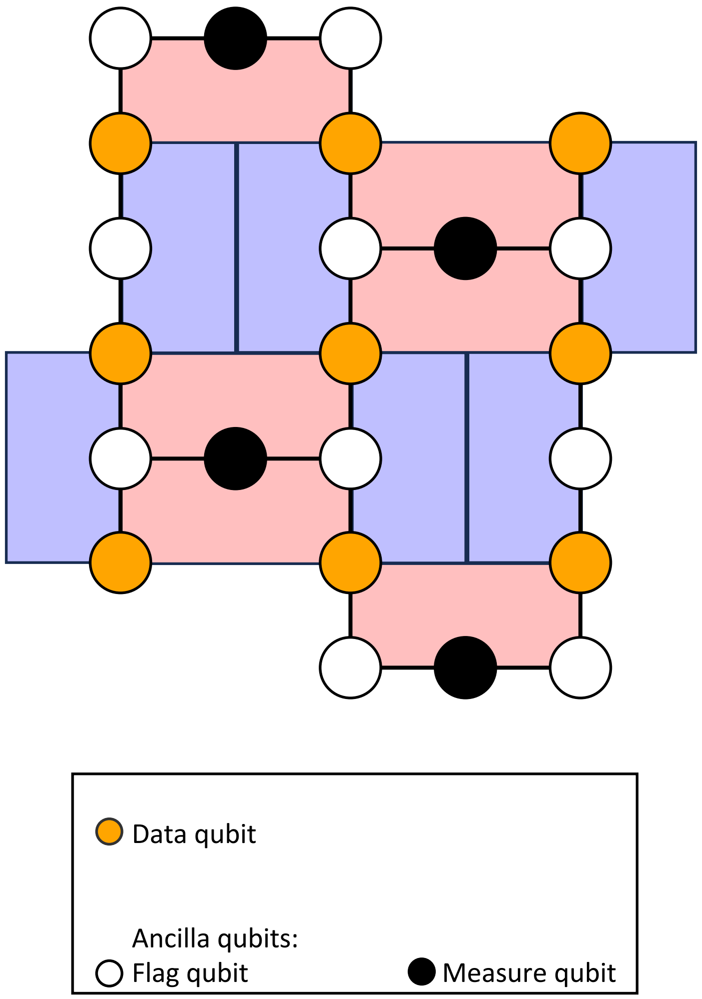
- Subsystem code with qubits on a heavy-hexagon lattice.
- Z stabilizers: surface-code type:

$$Z_S = Z \otimes Z \otimes Z \otimes Z$$

- X stabilizers: Bacon-Shor type:

$$X_S = X \otimes X \otimes X \otimes X \otimes X \otimes X$$

- The weight of the X stabilizers increases with code distance.
- Gauge operators are measured rather than stabilizer operators.
- Gauge operators do not commute with one another. However, they each commute with the logical operators of the code, which is sufficient to not change logical information.

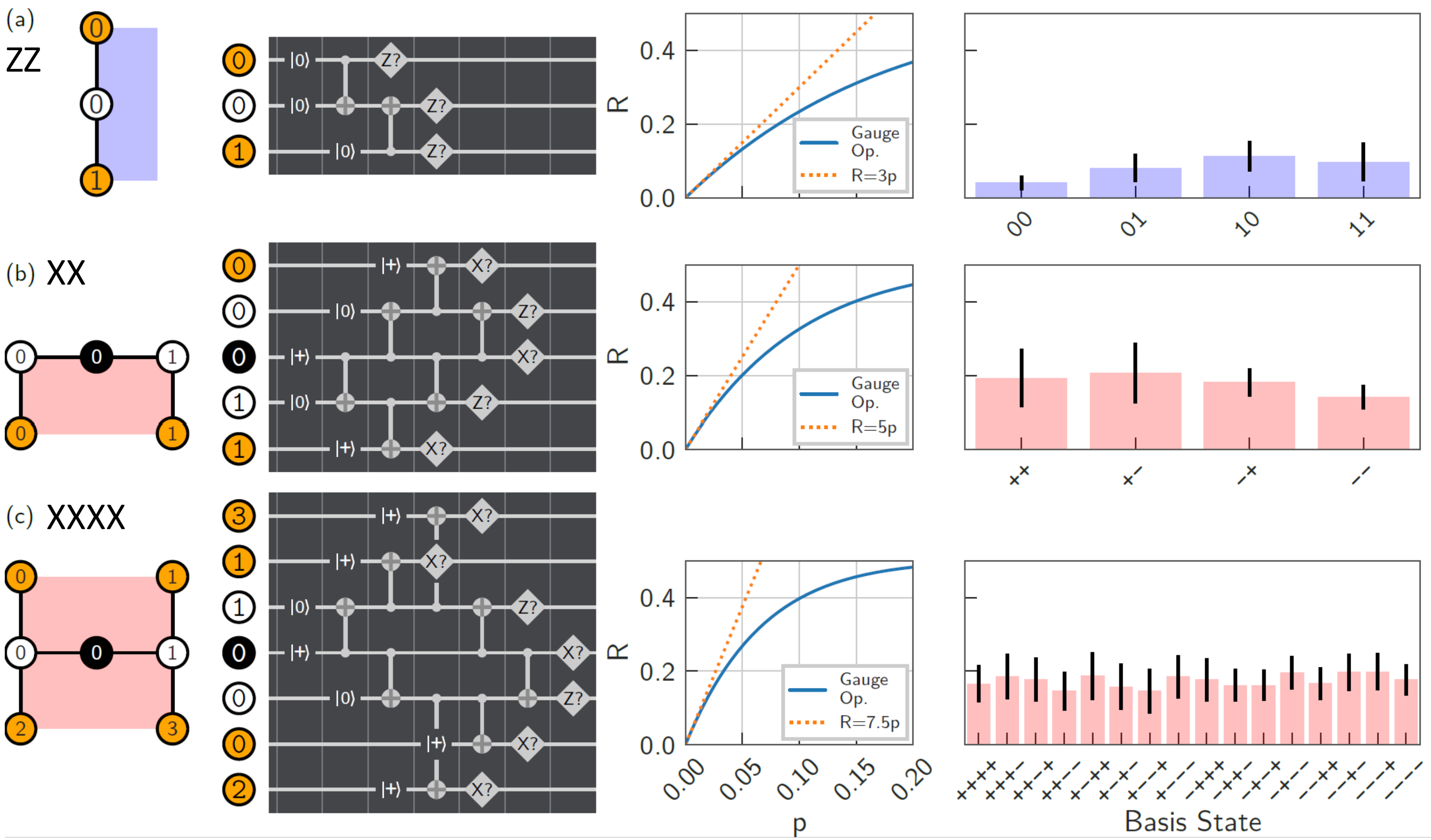


Distance 3 heavy-hexagon code.

C. Chamberland, G. Zhu, T. J. Yoder, J. B. Hertzberg, and A. W. Cross. “Topological and subsystem codes on low-degree graphs with flag qubits”. Phys. Rev. X 10, 011022 (2020)

Individual Operators

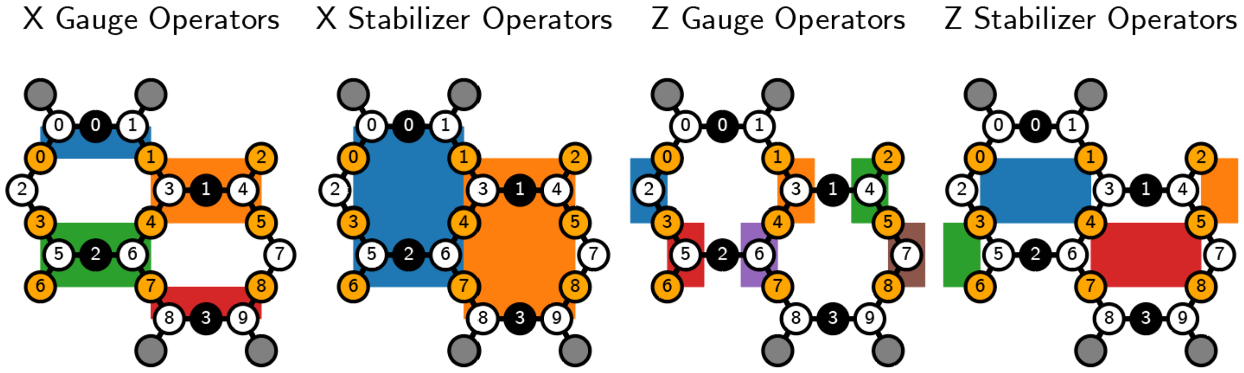
- Different initial product states.
- Dependence on initial state.
- Fluctuations with device calibration.
- Average depolarizing parameter of around 3.3%, corresponding to error rate of 2.5% for single qubit gates.

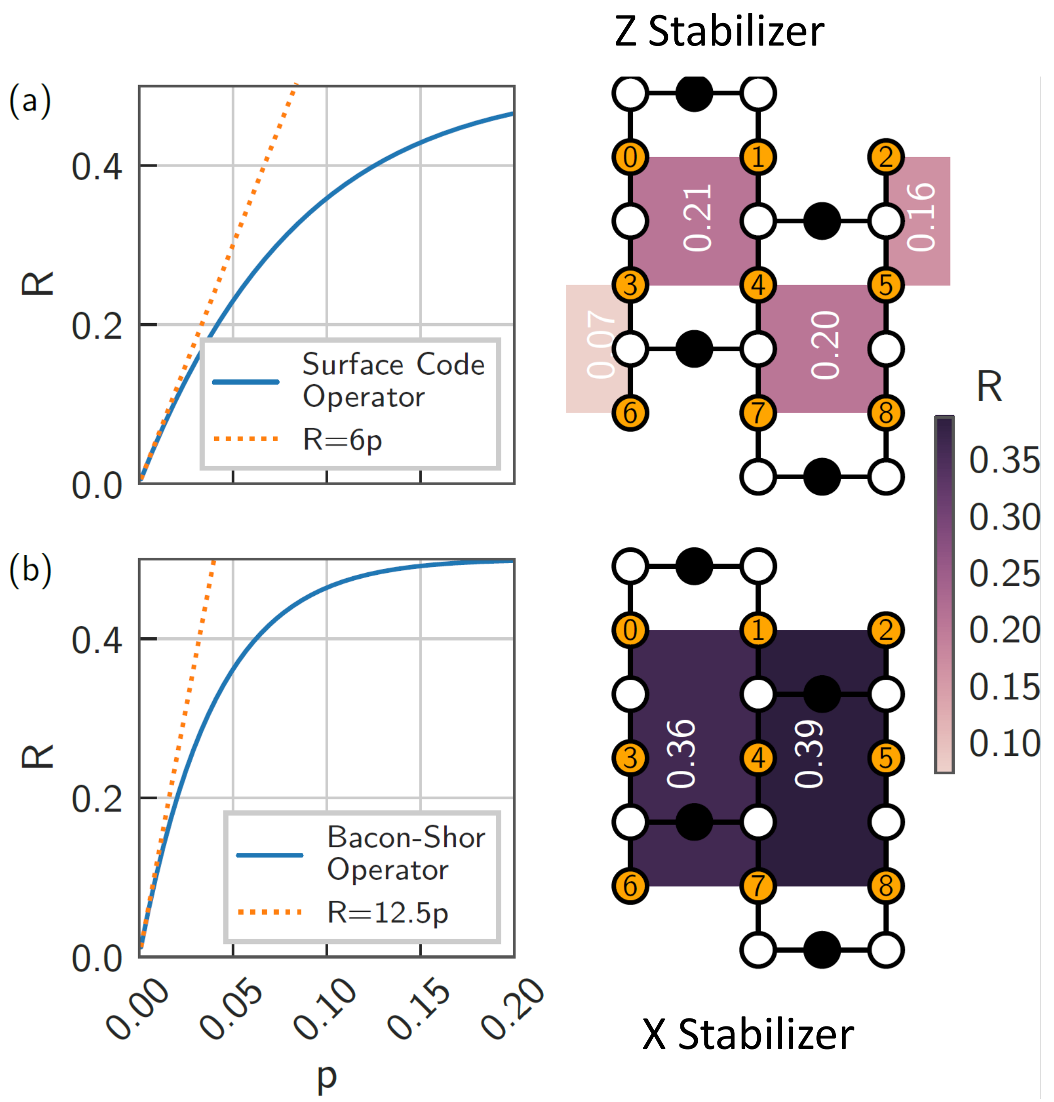


S. Gicev, L. C. L. Hollenberg, and M. Usman. "Quantum computer error structure probed by quantum error correction syndrome measurements" (2023). arXiv:2310.12448.

Simultaneous Measurements

- The eigenvalues of larger operators are inferred from the measurement results of smaller operators.
- Generally higher change rates due to dependence on additional gates.
- Results consistent with average depolarizing noise parameter of 4.8% corresponding to single qubit error rates of 3.6%





Repeated Measurements

arXiv > quant-ph > arXiv:2310.12448

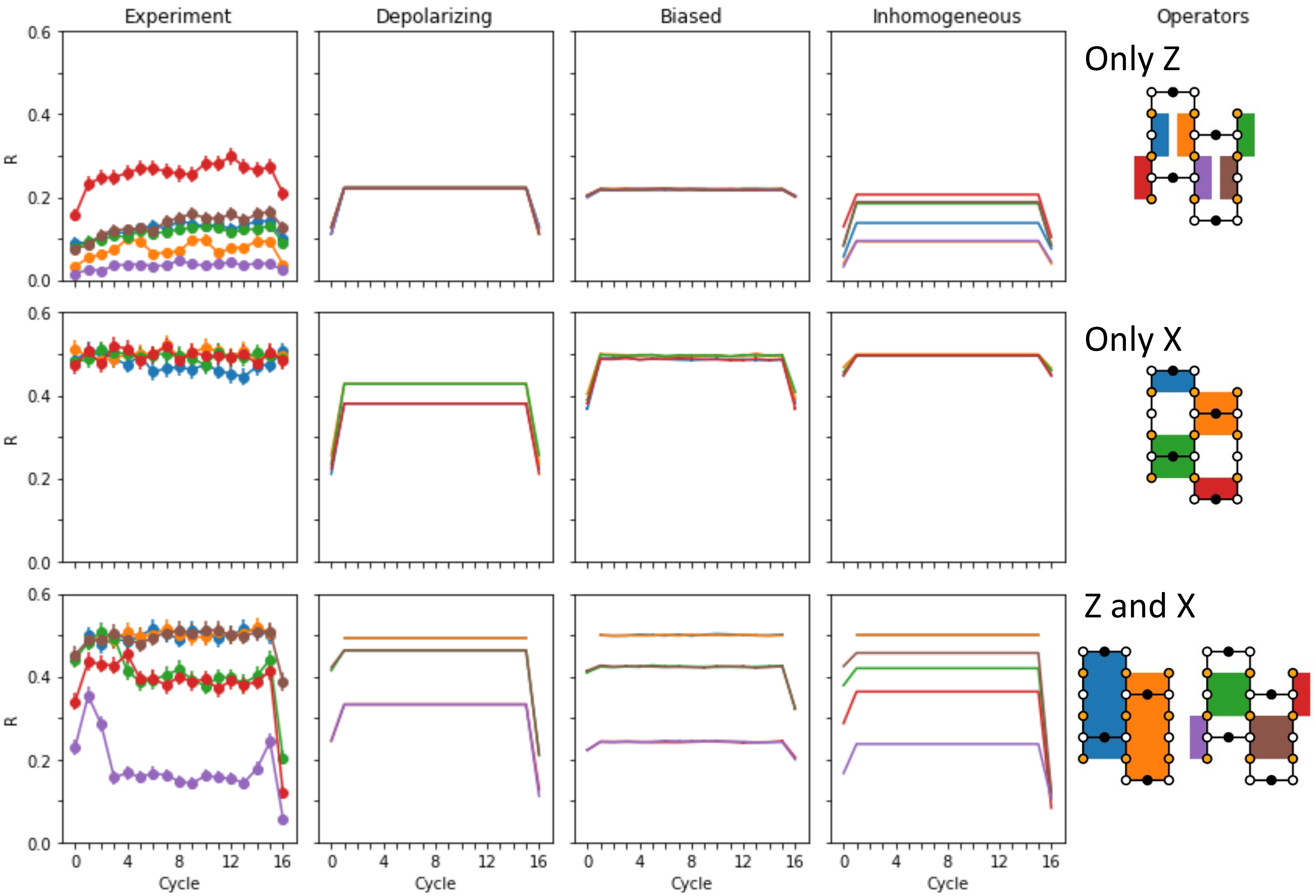
Quantum Physics

[Submitted on 19 Oct 2023 (v1), last revised 25 Mar 2024 (this version, v2)]

Quantum computer error structure probed by quantum error correction syndrome measurements

Spiro Gicev, Lloyd C. L. Hollenberg, Muhammad Usman

- Repeated Z, X and both operator measurements.
- Instances of steadily rising R in experiment which cannot occur under fixed Pauli-based noise.
- Uniform error rate simulations overlap by operator type.
- Simultaneously fitting using inhomogeneous noise captures some of the different orderings.



Z. Chen et al. “Exponential suppression of bit or phase errors with cyclic error correction”. Nature 595, 383–387 (2021).

Correlations in Repeated Measurements

- Additional Information can be found in correlated change rates. Results are shown for repeated Z gauge operator measurements.

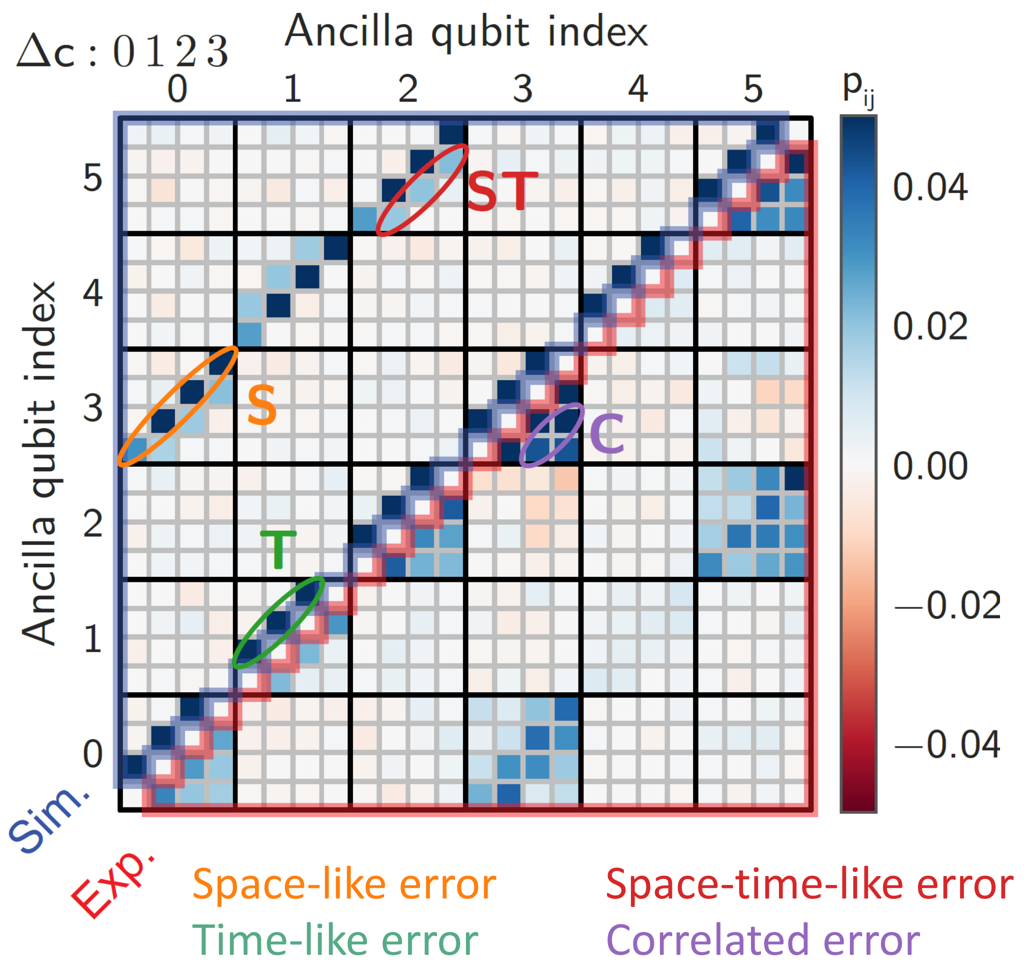
- Correlation matrix elements,

$$p_{ij} = \frac{\langle x_i x_j \rangle - \langle x_i \rangle \langle x_j \rangle}{(1 - 2\langle x_i \rangle)(1 - 2\langle x_j \rangle)},$$

where x_i is 0 if a particular operator didn't change since the last cycle and 1 otherwise.

- Minor gridlines correspond to different measurement cycles.

- There is significantly more correlations among different cycles than expected under depolarizing noise.



Z. Chen et al. "Exponential suppression of bit or phase errors with cyclic error correction". Nature 595, 383–387 (2021).

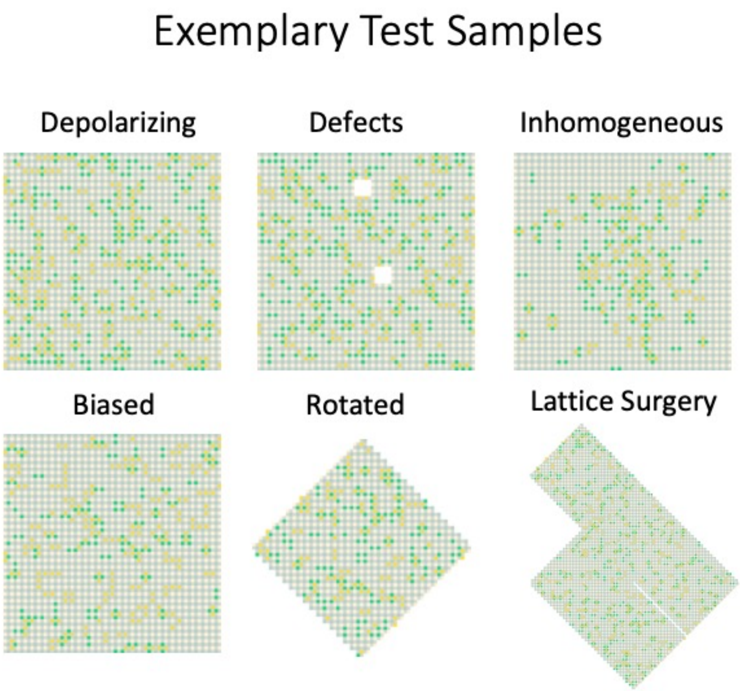
Quantum Error Correction by Artificial Intelligence

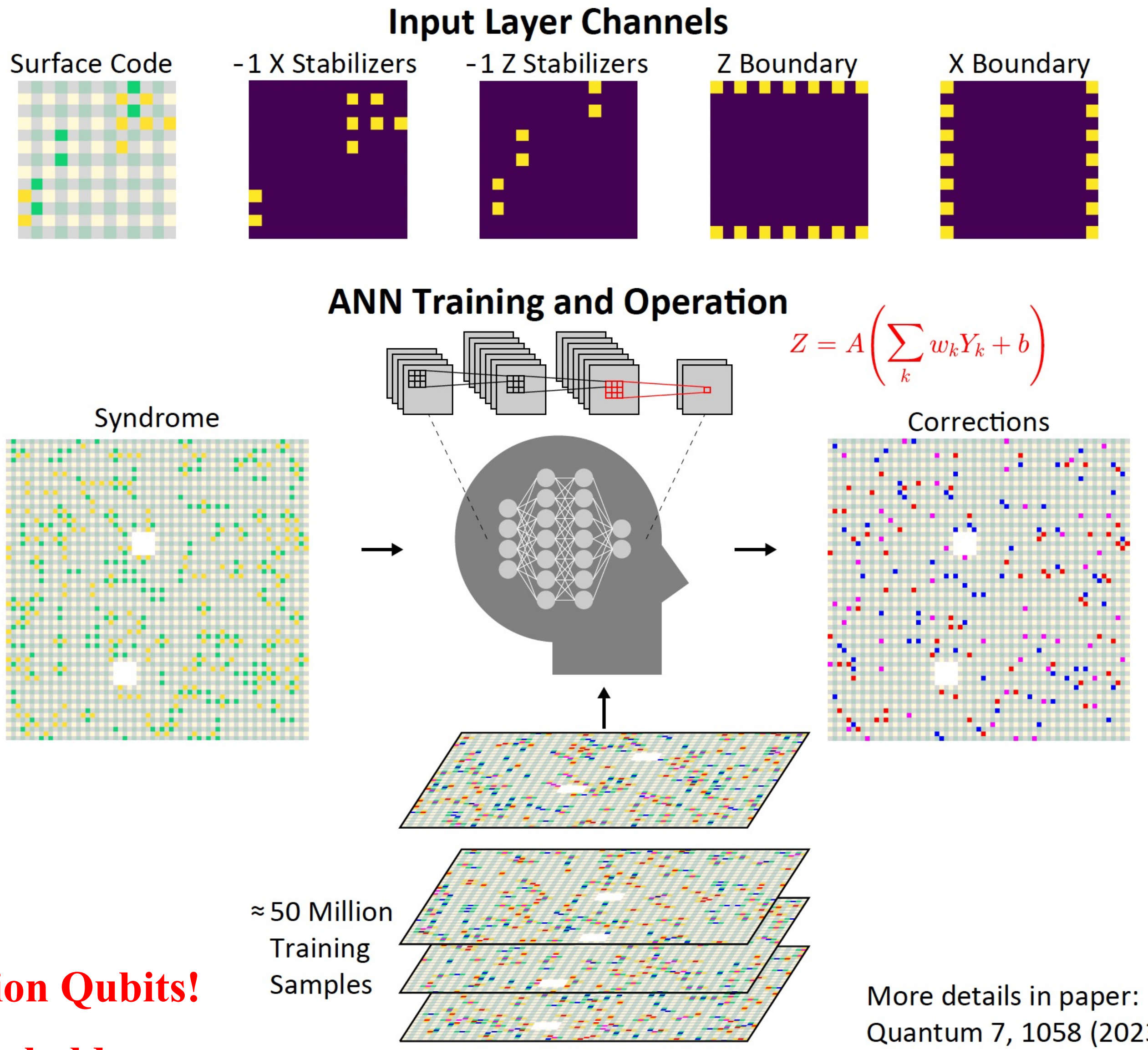
Quantum
the open journal for quantum science

PAPERS PERSPECTIVES

A scalable and fast artificial neural network syndrome decoder for surface codes

Spiro Gicev[1], Lloyd C. L. Hollenberg[1], and Muhammad Usman[1,2,3]





Error Correction Over > 4 Million Qubits!

μsec Latency, Comparable Threshold

More details in paper:
Quantum 7, 1058 (2023)

Quantum Error Correction on IBM Quantum Processor

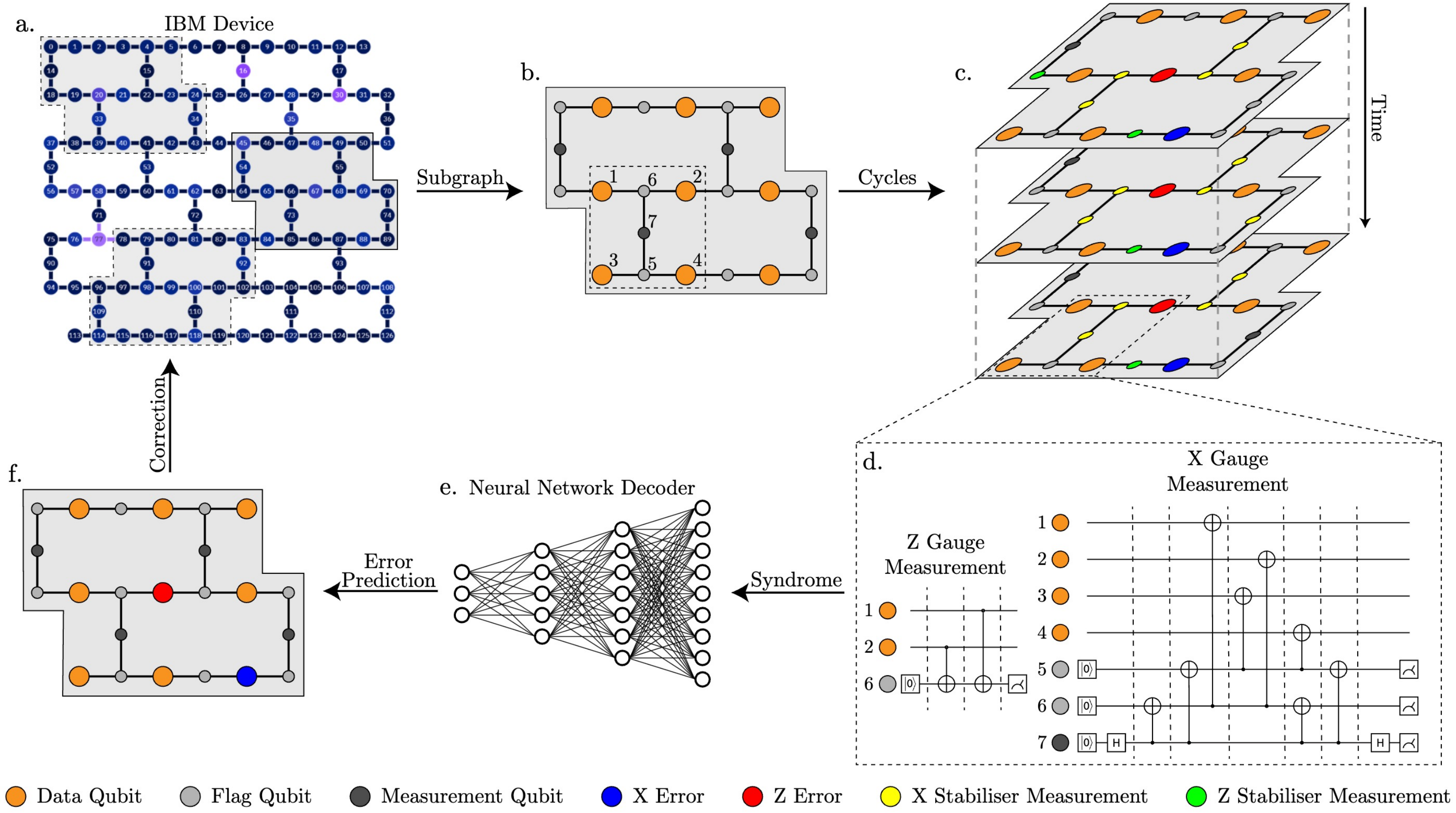
arXiv > quant-ph > arXiv:2311.15146

Quantum Physics

[Submitted on 26 Nov 2023]

Artificial Neural Network Syndrome Decoding on IBM Quantum Processors

Brhyeton Hall, Spiro Gicev, Muhammad Usman



Quantum Error Correction on IBM Quantum Processor

arXiv > quant-ph > arXiv:2311.15146

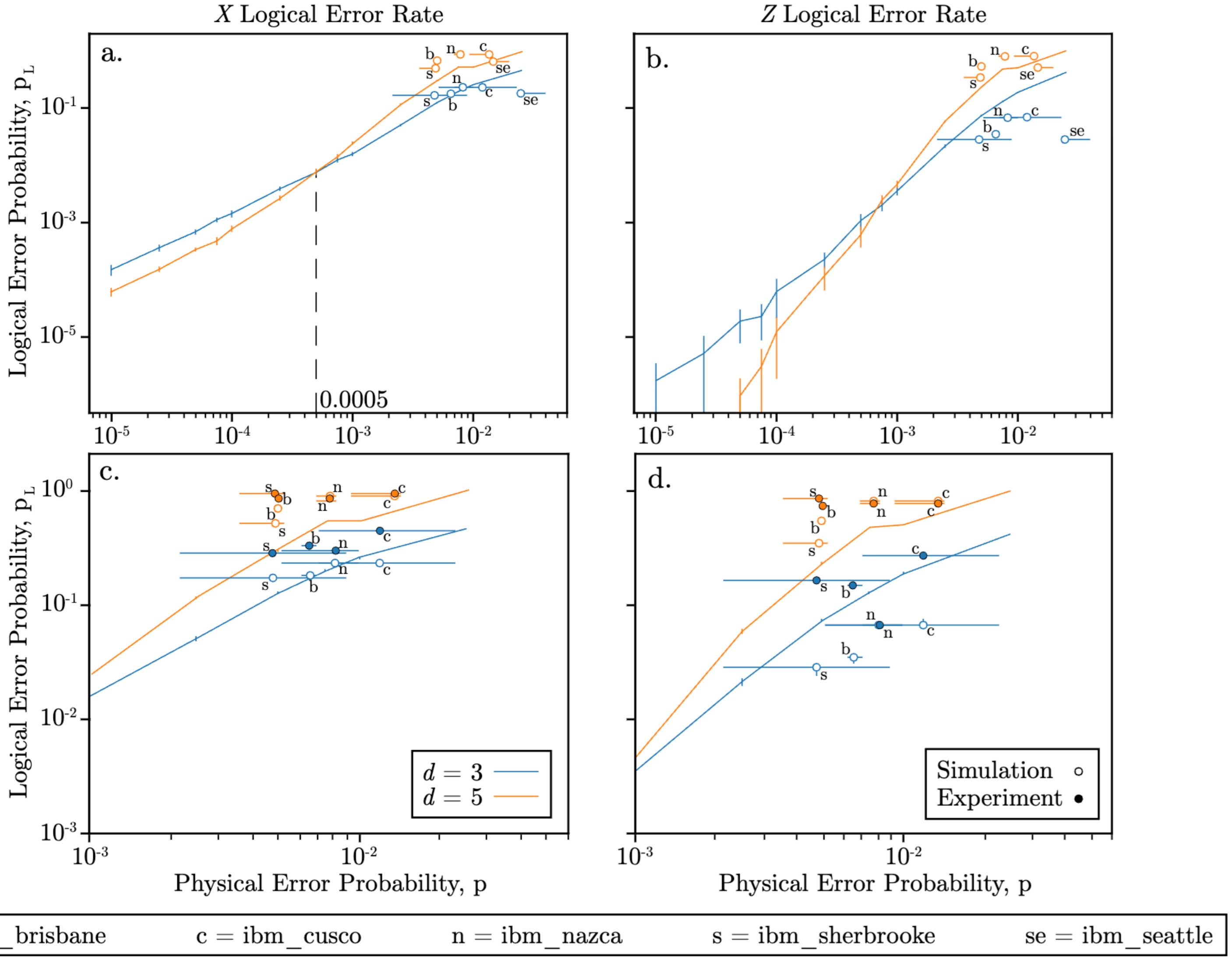
Quantum Physics

[Submitted on 26 Nov 2023]

Artificial Neural Network Syndrome Decoding on

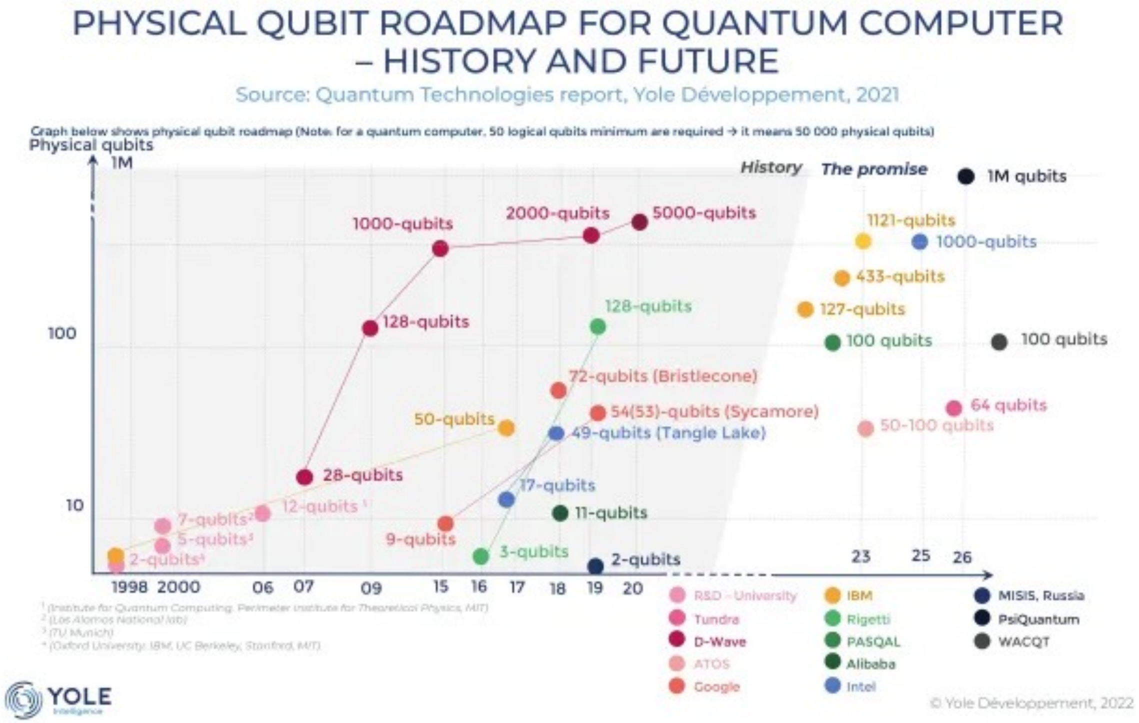
Brhyeton Hall, Spiro Gicev, Muhammad Usman

- ANN decoder was implemented on error measurements from IBM Quantum Devices
- Direct comparison was made with MWPM algorithm
- ANN decoder accurately decode complex noise from IBM devices.



Summary

- Quantum computers are scaling up faster than ever before
- Benchmarks designed at qubit and gate levels may not provide useful insights at scale
- New benchmarking methods are needed to measure the performance of quantum processors which are:
  - Reliability or Quality
  - Scalability
  - Universality
  - Relevance for Applications, e.g., resource estimation

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A Linear System Appears

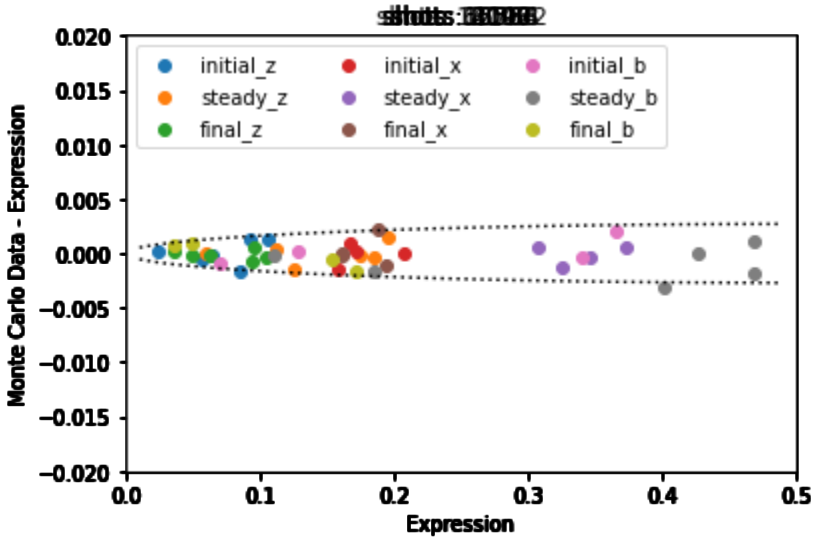
- Suppose instead that each gate had a unique error rate, p_i. The change rate R generalizes to,

$$R = \frac{1}{2}\left(1 - \prod_i (1 - p_i)^{n_i}\right),$$

where the i-th gate propagates errors n_i times.

- For simplicity define $F = 1 - 2R$ and $f_i = 1 - p_i$.
- If we take logarithms and consider different circuits or measurements over index j we can write a linear relationship involving the variables of the system,

$$\log(F_j) = \sum_i n_{ij} \log(f_i) \, .$$



Agreement (up to shot noise) among change rate polynomials and Monte Carlo simulations of Clifford circuits to be discussed later.

Is depolarizing noise realistic? Are these systems of equations over-determined or under-determined in QEC?