Experimenting with quantum error correction on near-term quantum computers

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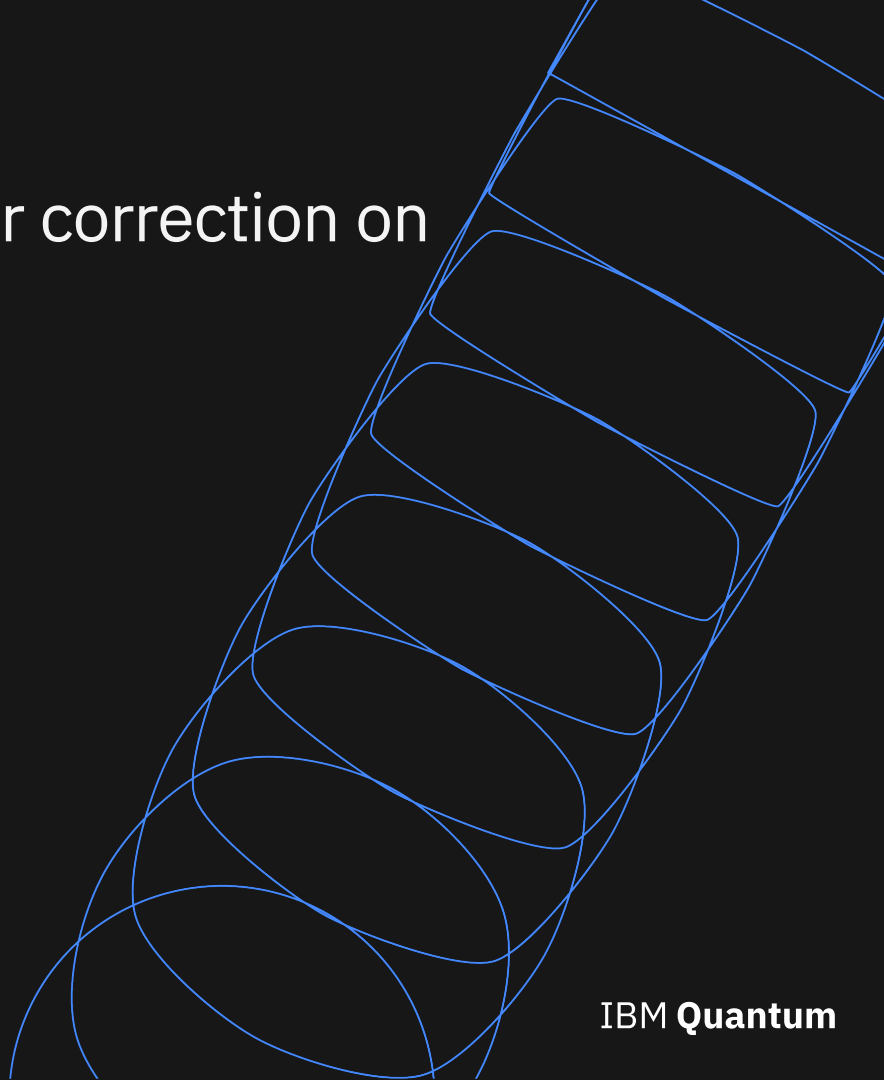

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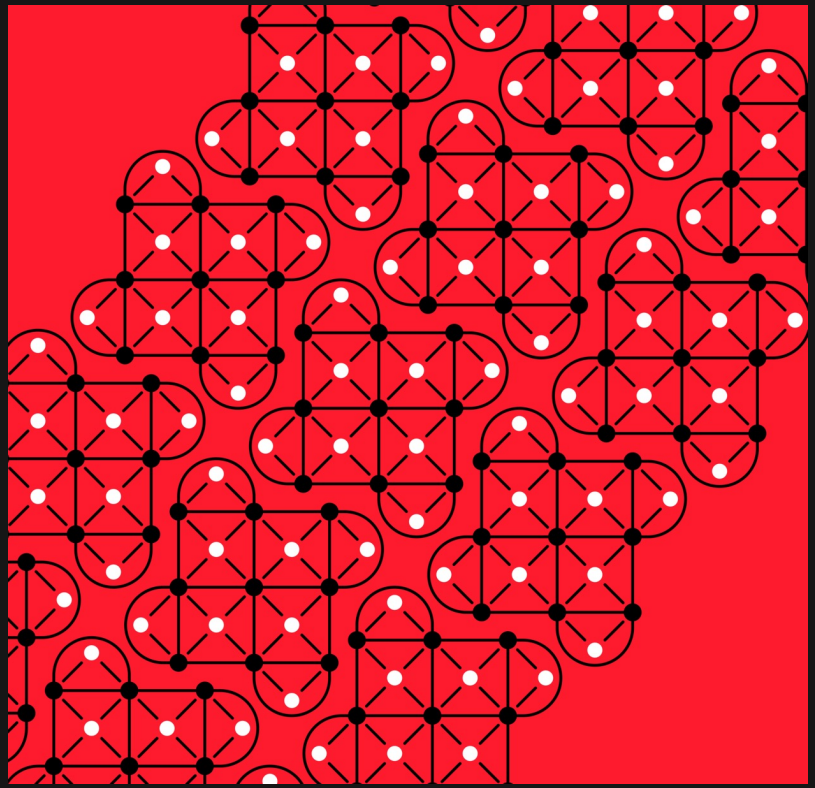
Intro to Fault-tolerance

- Qubits are full of imperfections
- Textbook quantum algorithms are designed for perfect qubits
- So we need to:
  - Design and run algorithms to avoid the imperfections
  - Fault-tolerance: Pump out all the errors
- QEC is how we do the latter
- Constantly measure to find traces of errors



NCCR SPIN

Comparing progress towards fault-tolerance

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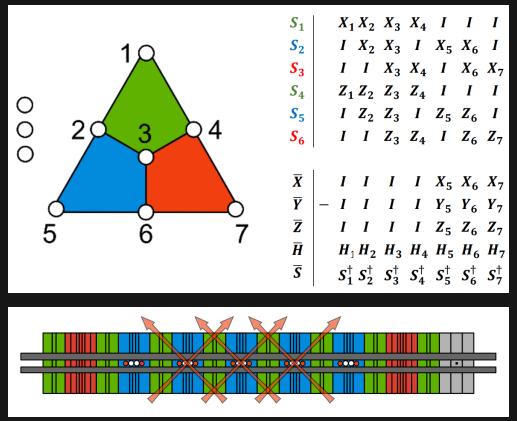
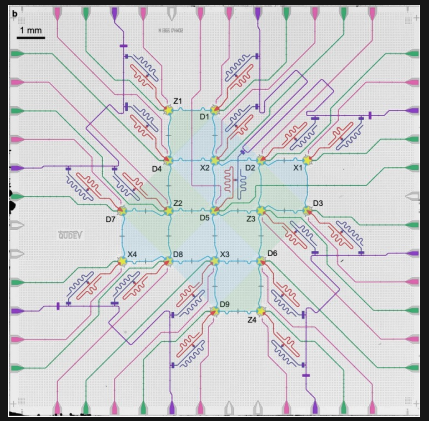
- Many groups are demonstrating progress towards fault-tolerance
- Different routes taken make it hard to compare and contrast
- How can we make a cross-platform diagnostic?



Quantinuum



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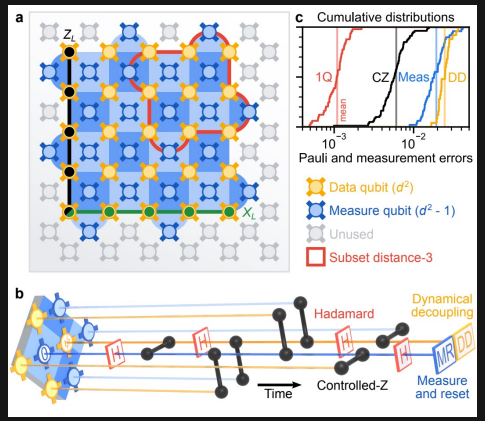
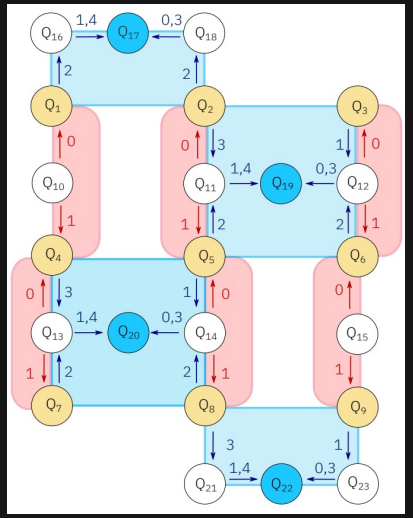


Google



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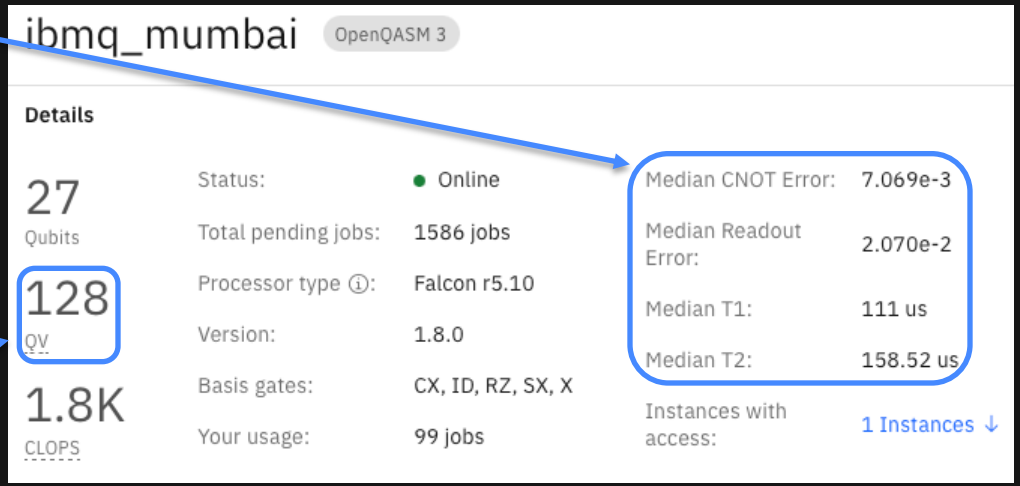
Current Benchmarks and Diagnostics

Microscopic benchmarking

- Reports on single components at the physical level (qubits, gates, etc)
- Prime examples: T1, T2, SPAM, RB

Macroscopic benchmarking

- Reports on collective performance of components for relevant tasks
  - Pre-QEC (and without MSM): QV, XEB
  - Towards QEC: ?
  - FTQC: Logical RB/QV/Running an algorithm?



What will fill the gap?

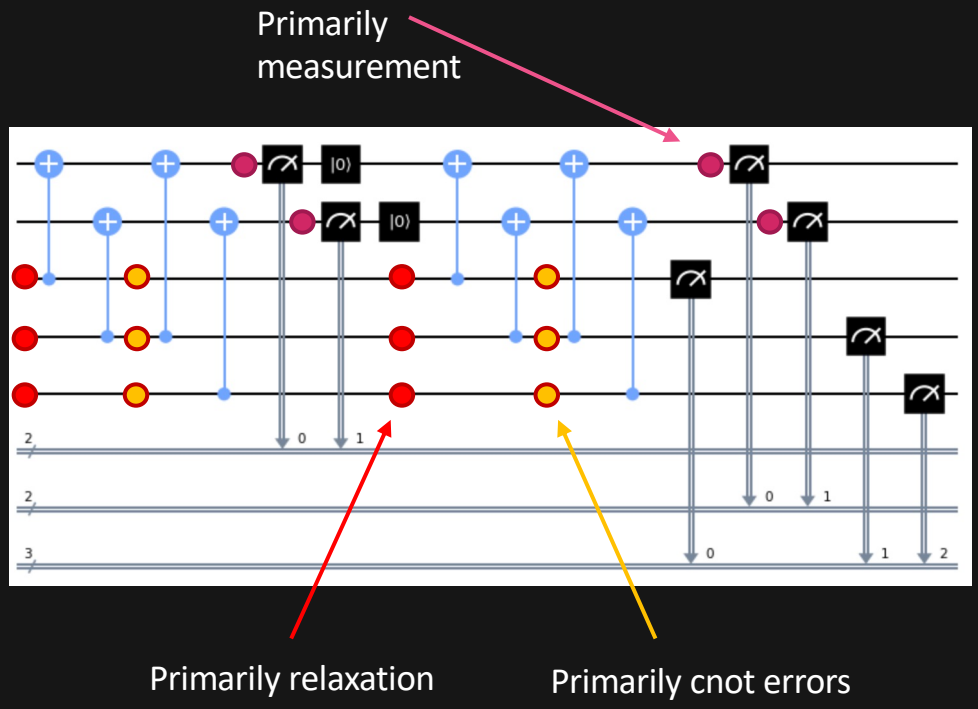
Diagnostics using QEC (advantages)

Microscopic

- Syndrome is designed to detect errors, and tell us when and where they happen
- Allows us to calculate probabilities of errors at every point in the circuit (as done by me and Google)

Macroscopic

- Requires constant, system-wide entangling gates and measurements
- All towards goal of protecting stored info
- Fidelity of that info measures how well everything works together



Diagnostics using QEC (disadvantages)

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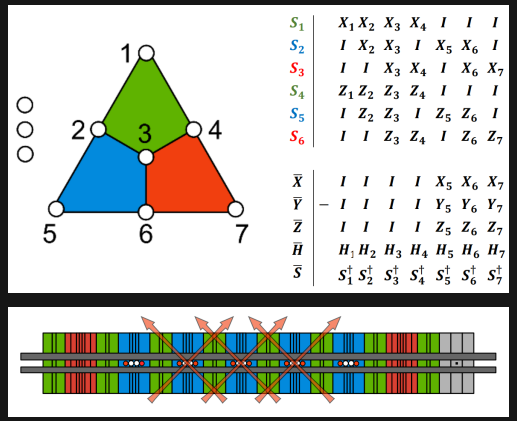
- Codes need to be co-designed with architecture
- Imposing the same design on everyone would unfairly bias results



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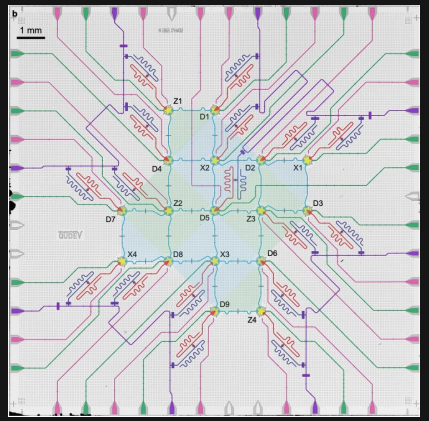

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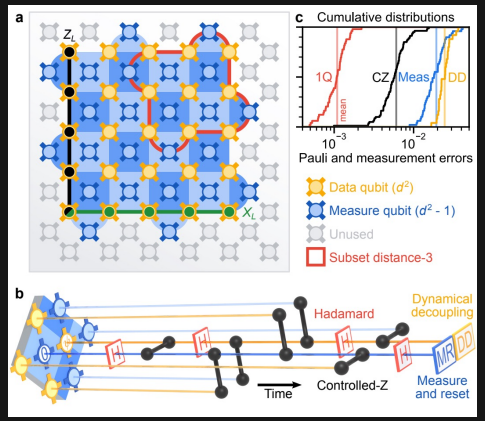
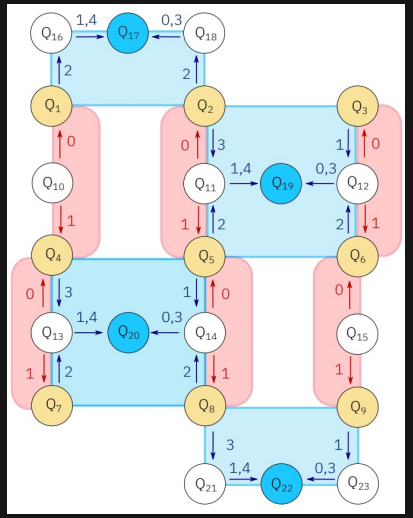


Google



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Design Brief

- Based on QEC
  - Success at the diagnostic directly implies QEC techniques can be implemented successfully
- Platform agnostic
  - Not biased towards particular connectivity, etc
- Fast and scalable to run and process
- Sensitive to all forms for error
- Stores logical information (not necessarily a qubit)
  - Allows use and testing of decoders
  - Including testing of real-time decoders

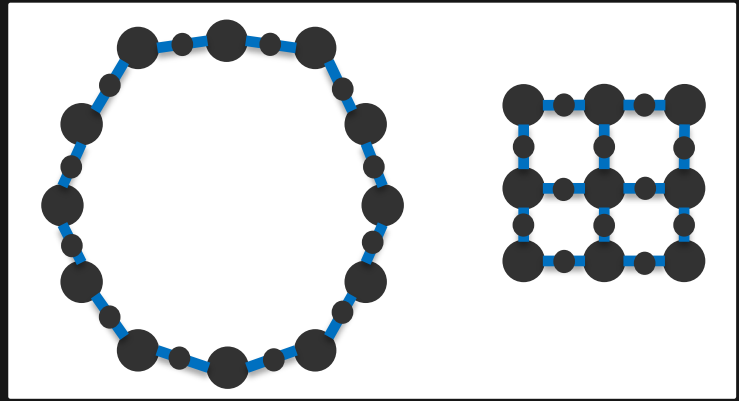
Repetition Code

The simplest example of QEC almost does everything

- Uses the techniques of QEC
- Can be adapted to any architecture
- Macroscopic diagnostic: lifetime of bit
- Microscopic diagnostic : Probabilities of single errors
- Straightforward to run and analyze

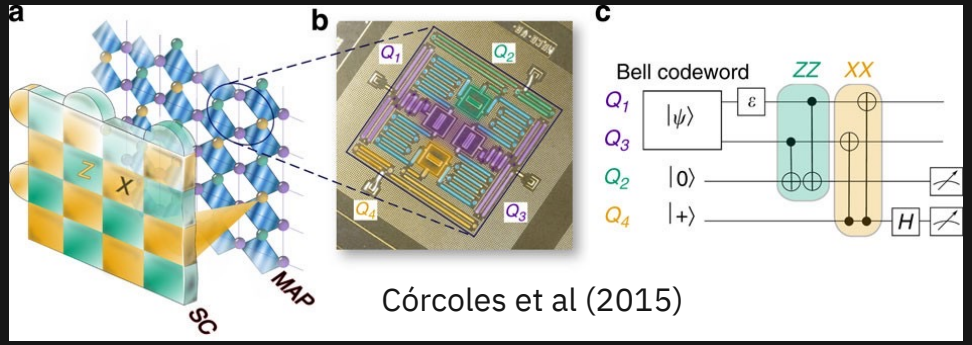
But it only works for one type of error

- Different stabilizers needed to detect bit or phase
- Can’t be done simultaneously



	Repetition code
QEC based	✓
Platform agnostic	✓
Bit and phase	✗
Macro+micro	✓
Scalable	✓

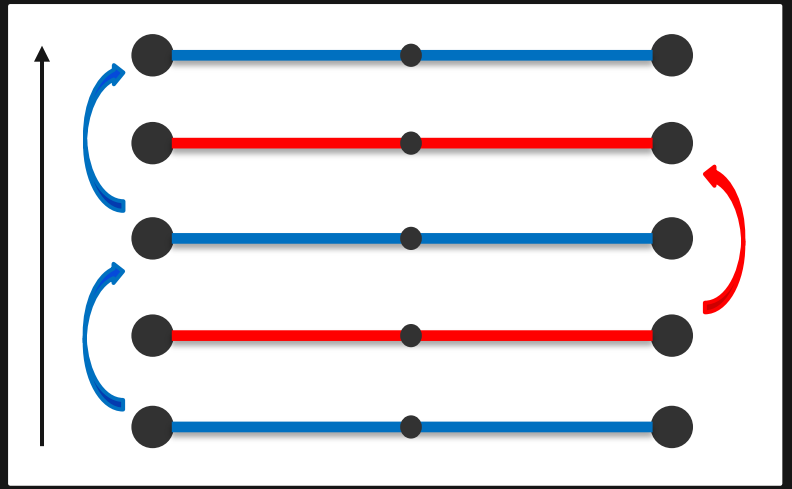
[[2,0,2]] Code



Córcoles et al (2015)

Simplest proof-of-principle experiment

- 2 code qubits
- 2 syndrome measurements
- Only requires the hardware for a single 2-qubit parity measurement
- Detects bit and phase flips



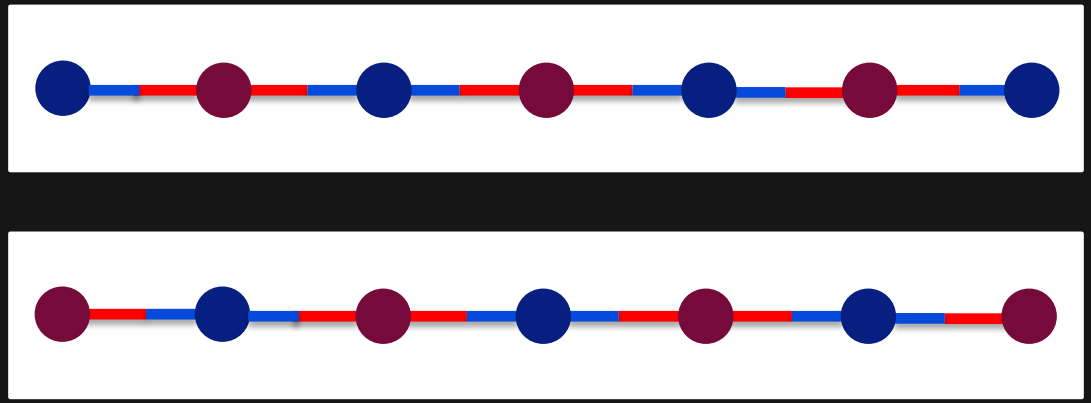
But it is inherently small

- Not scalable

Anisotropic Repetition Code

One possible workaround

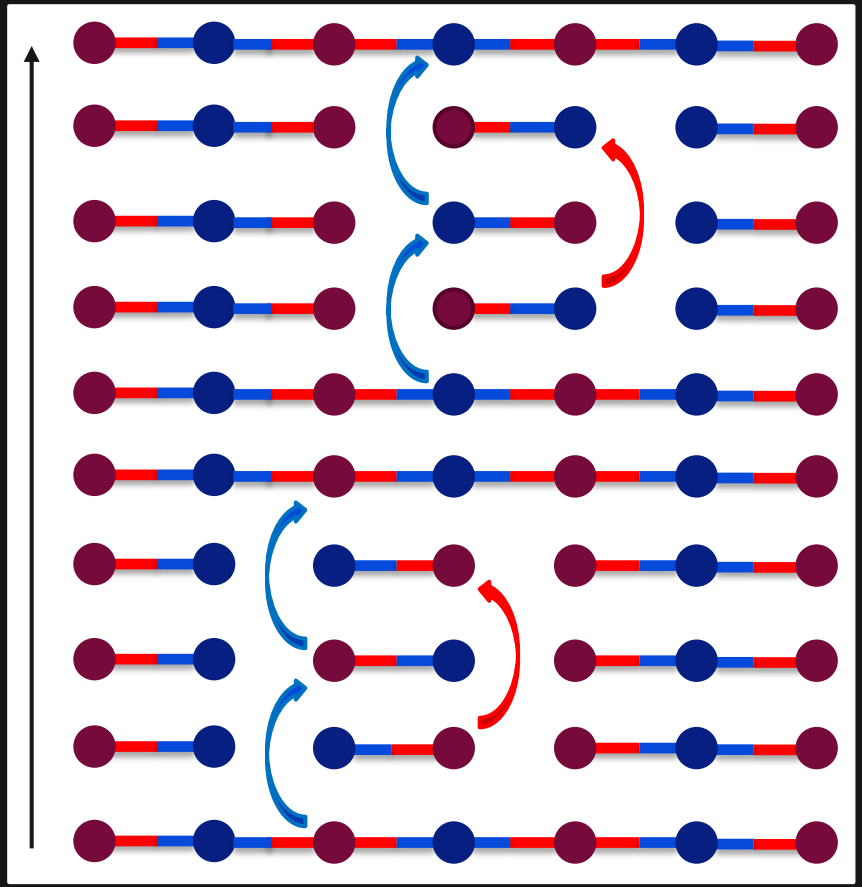
- Different qubits detect different errors
- Every area is sensitive to both
- Different experiments run to cover all errors on all qubits



Anisotropic Repetition Code

[[2,0,2]] codes can then be worked into this

- Alter syndrome measurements throughout
- Go through links one-by one



Microscopic diagnostics

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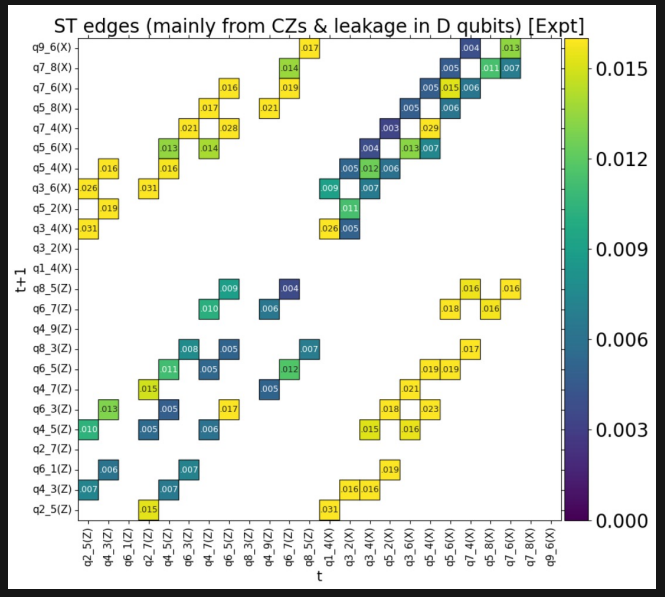
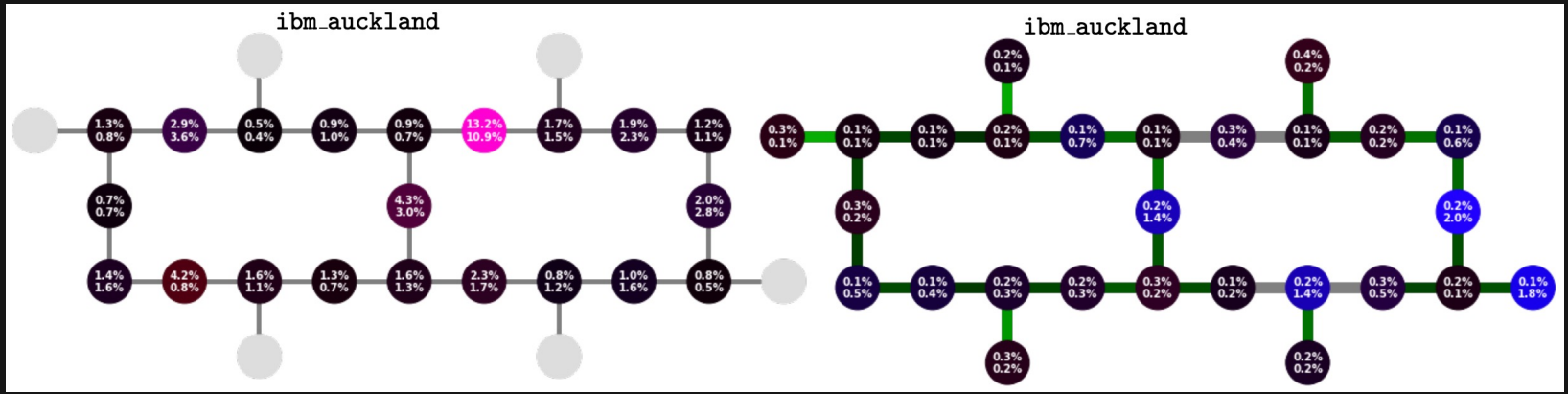
Syndrome derived error rates

- As in
  - Wootton, arXiv:2207.00553
  - Google, arXiv:2207.06431

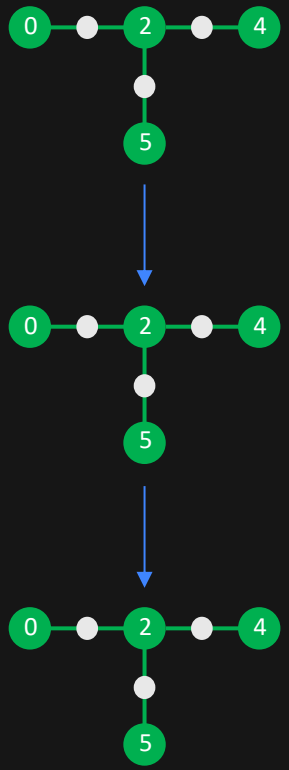
Link-by-link [[2,0,2]] results



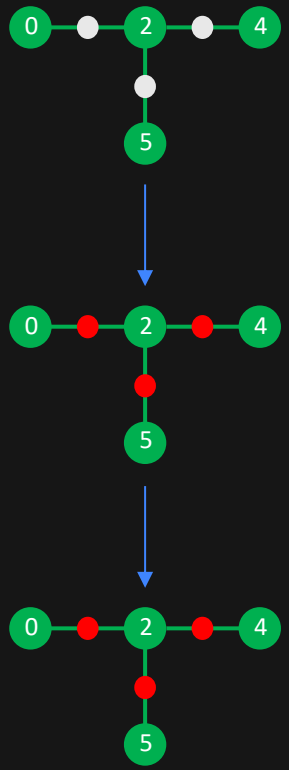


Calculating probabilities

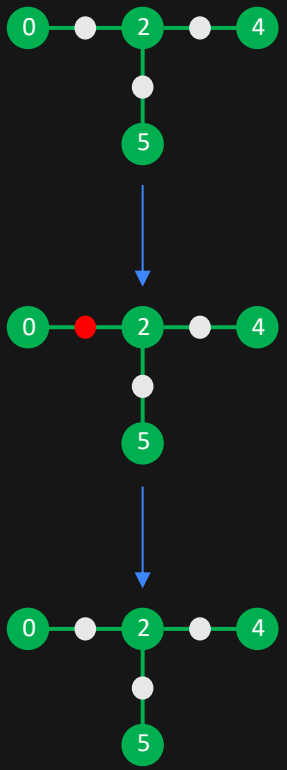
No error



Error on qubit 2



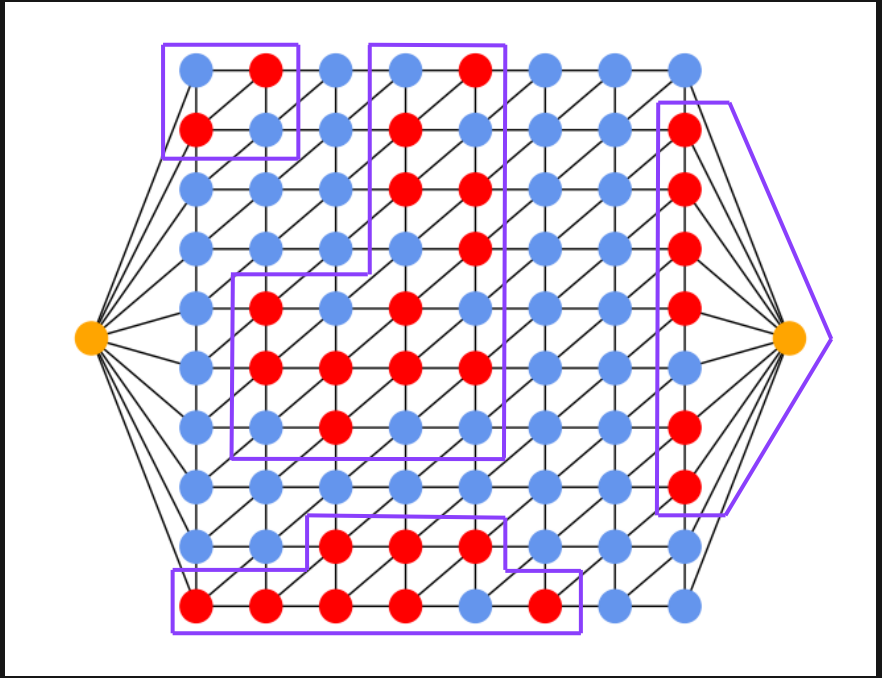
Measurement error on qubit 1



Macroscopic benchmarks

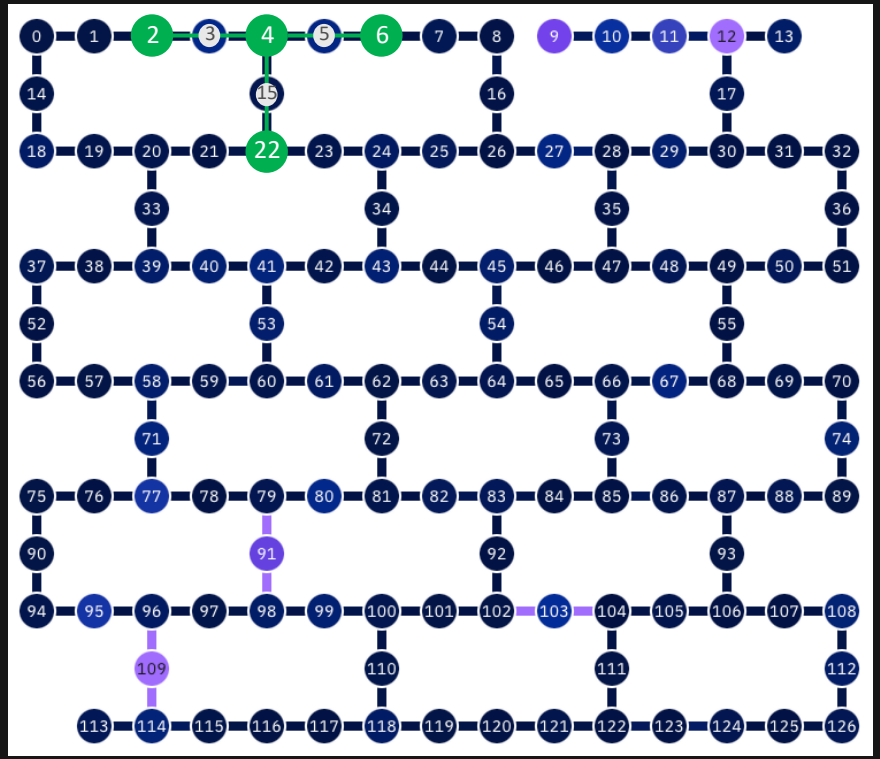
- Usual to use logical lifetime
- But these require many circuits to be run
  - Different code sizes
  - Different numbers of rounds before readout

- Phase transition in syndromes
  - Everything can be derived from a single long run
  - More efficient than logical lifetimes



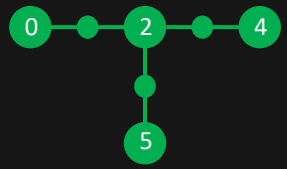
(Very) Preliminary Results

- Repetition code with
  - 52 code qubits
  - 68 ancilla qubits
  - 125 syndrome measurement rounds
- Here I'll show you the mysteries from the first run
- Diagnostic for
  - The hardware
  - My dynamical decoupling skills
- See later publication for the real results

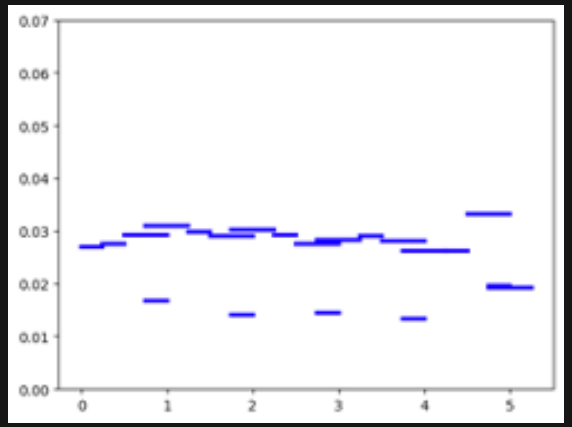


Simulated results

- First let's look at simulated results
- 7 qubits, standard error model

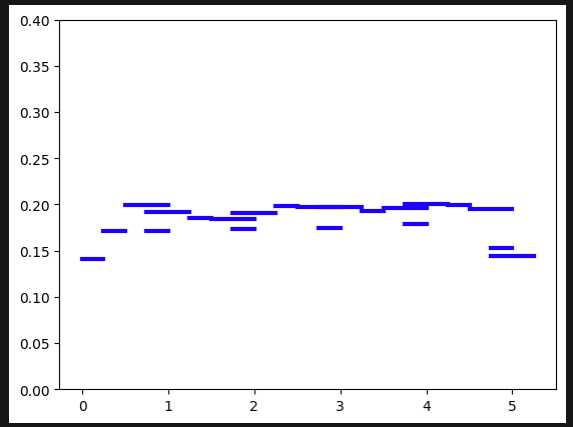


p=0.01, qubit 2



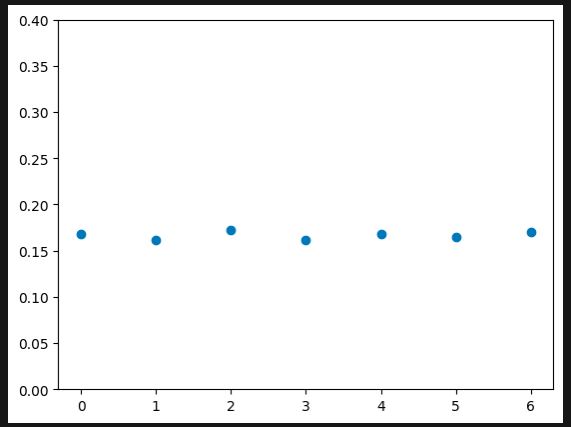
Measurement round

p=0.05, qubit 2



Measurement round

p=0.05, averages

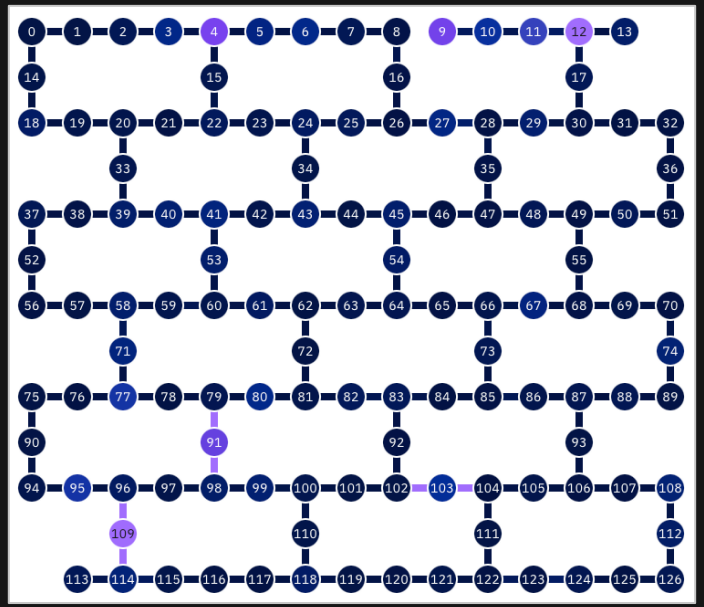


Qubit index

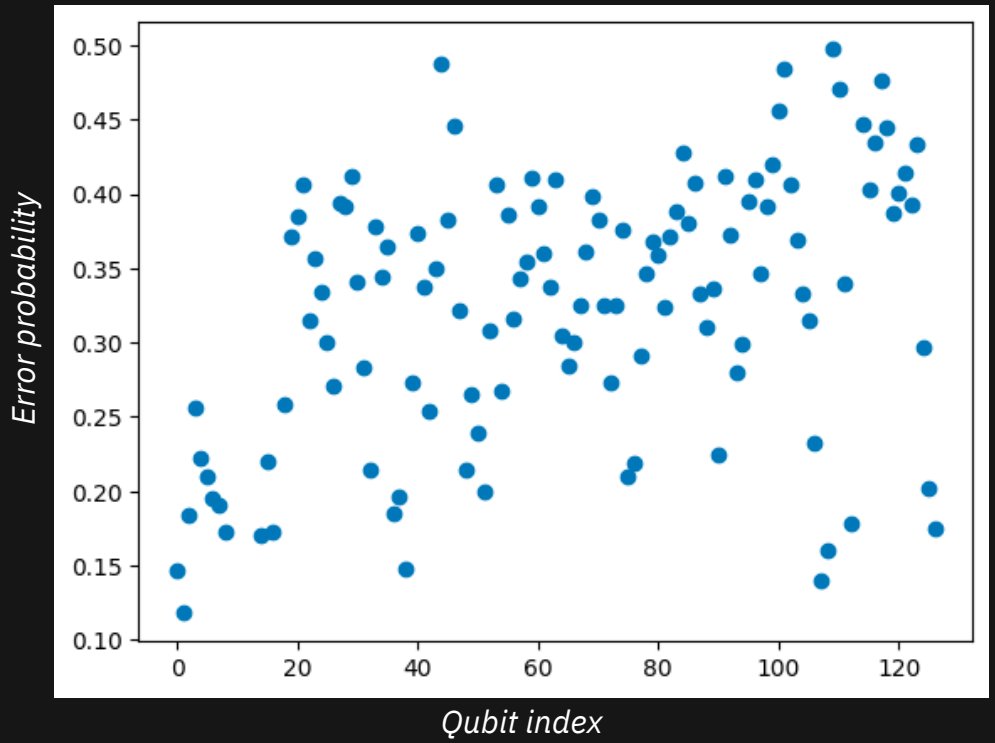
Error probability

- Observed error is ~3p (makes sense)

Results from ibm_washington



Mean error for each qubit



Results from ibm_washington

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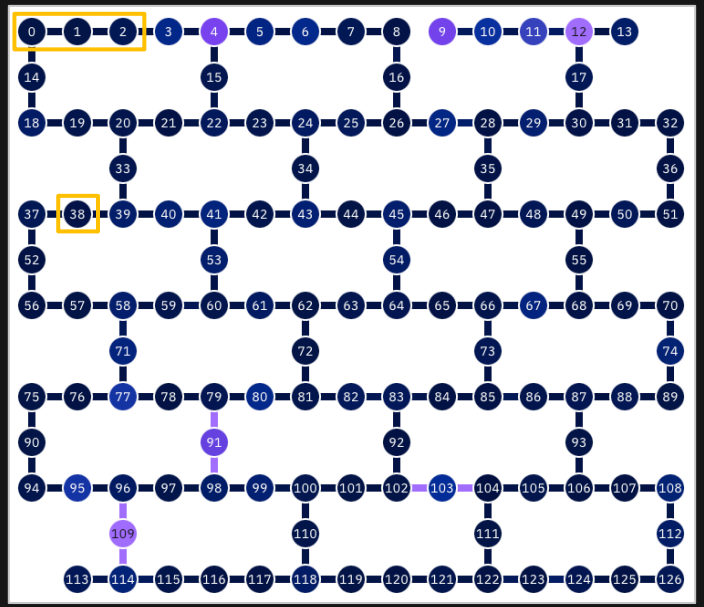
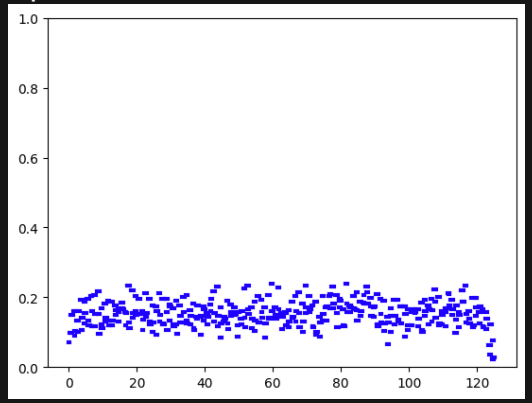
- A few of the best qubits

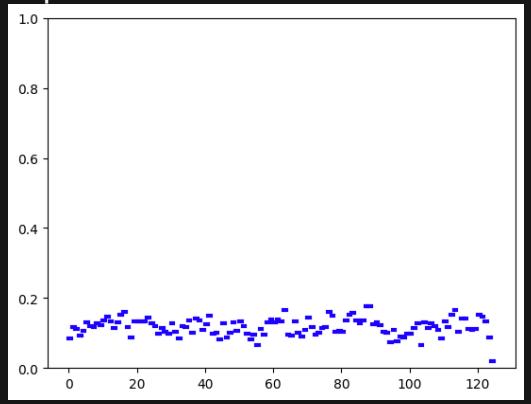


- Consistent with p=5% simulation

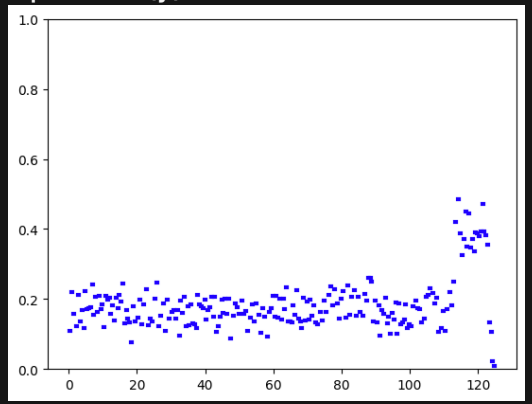
qubit 0 (x)



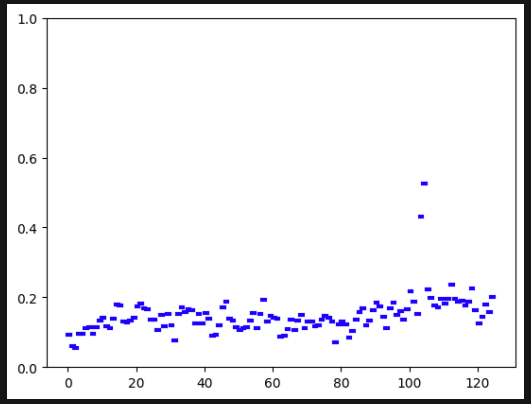
qubit 1



qubit 2 (y)



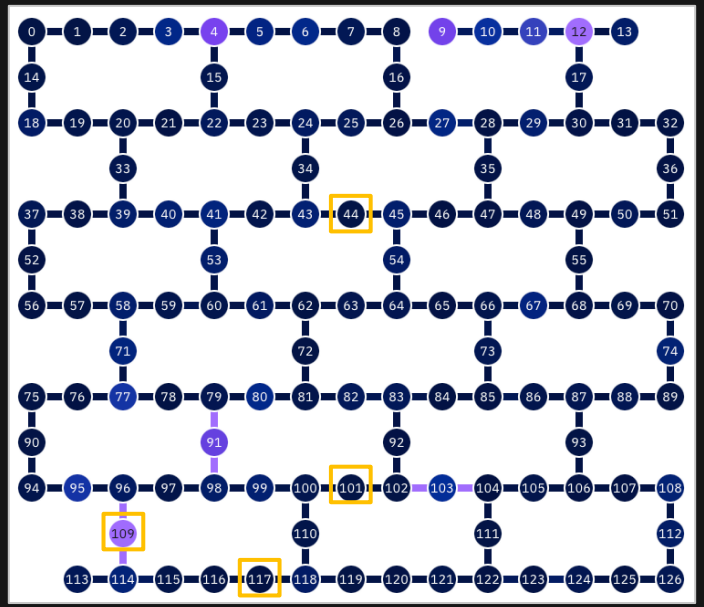
qubit 38



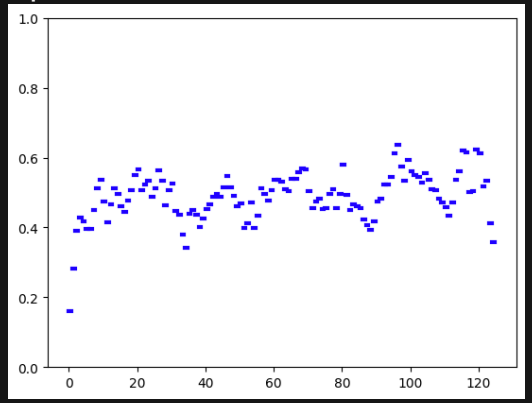
Results from ibm_washington

IBM **Quantum**

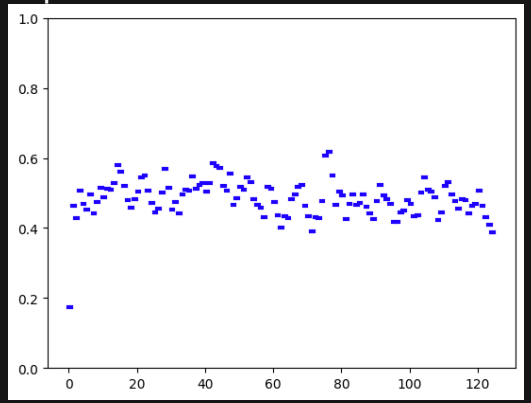
- A few of the worst qubits (all ancillas)



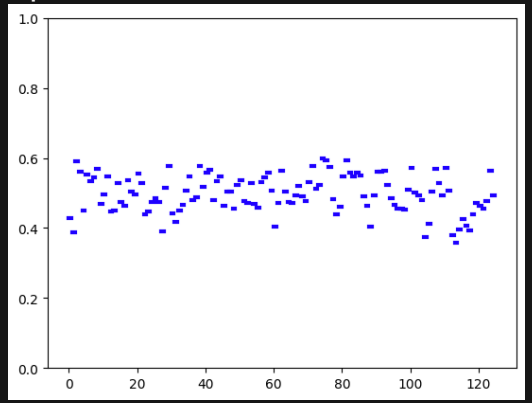
qubit 44



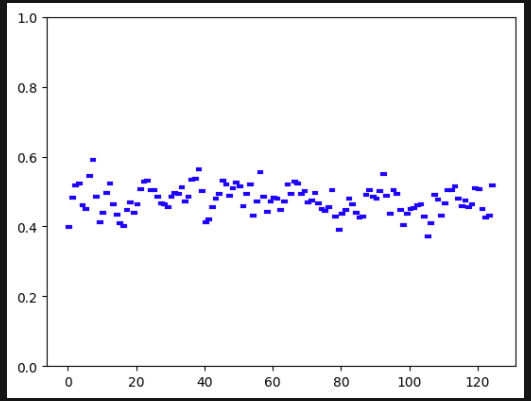
qubit 101



qubit 109



qubit 117



Results from ibm_washington

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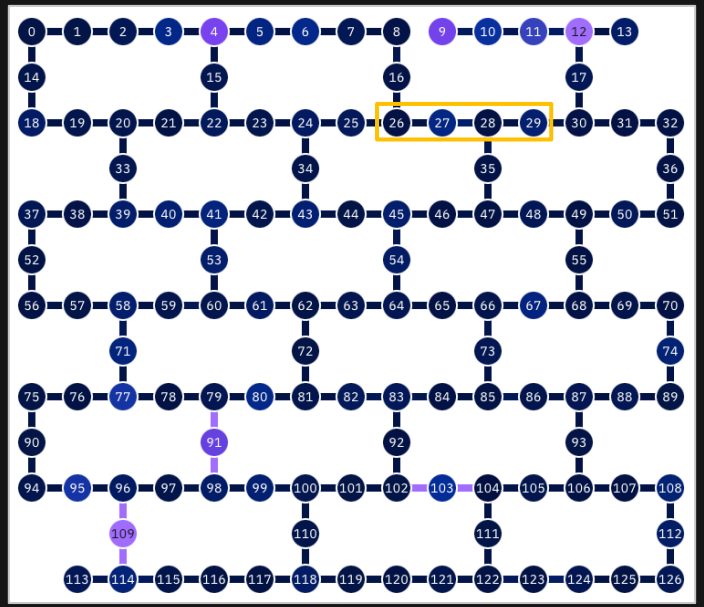
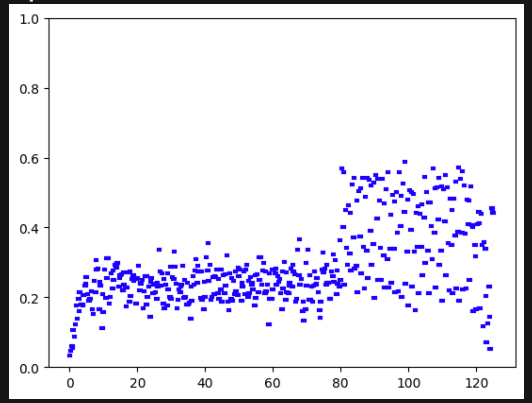
- A few of the weirdest qubits

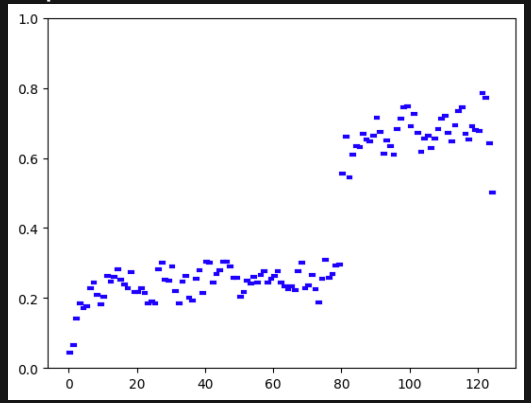


- What happens at 80 after rounds?

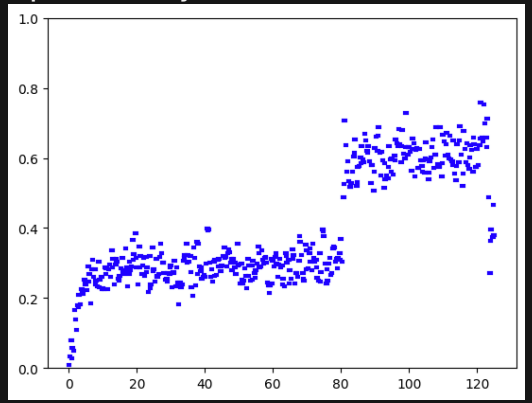
qubit 26 (x)



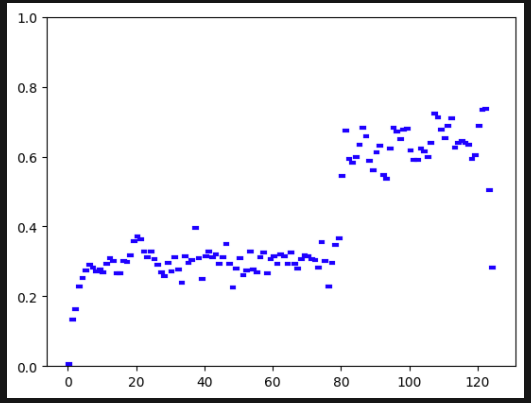
qubit 27



qubit 28 (y)



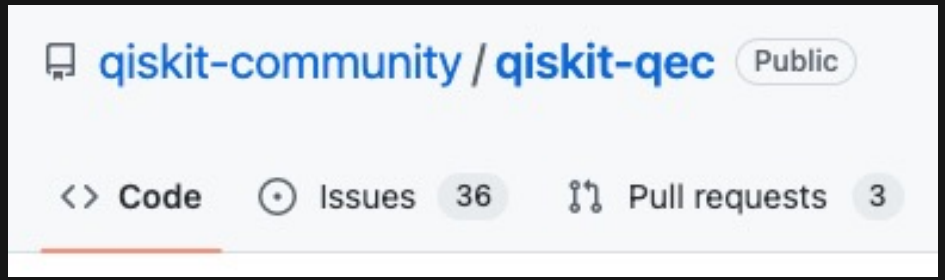
qubit 29



Conclusions

- We should find a way to compare progress towards fault-tolerance
- We need to run the same code and do the same analysis
- Let’s run Anisotropic Repetition Codes + [[2,0,2]]s!

- You’ve seen what 127 IBM Quantum qubits can do! How do yours compare?
- Everything is available in Qiskit-QEC, so you can find out (and collaborate!)



github.com/qiskit/qiskit-qec

Thanks for your attention!

Qiskit-QEC

github.com/qiskit/qiskit-qec