Introduction to Helmi

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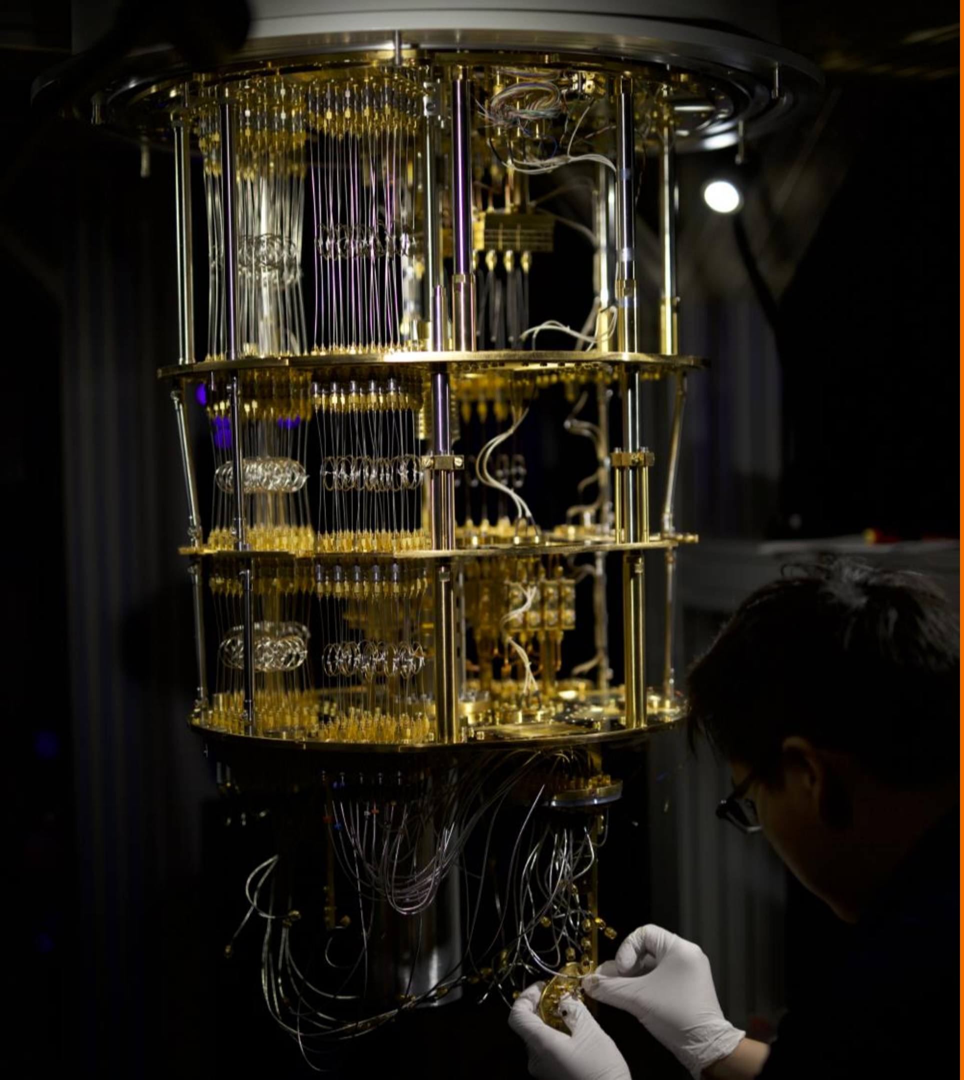
Quantum Algorithm and Software

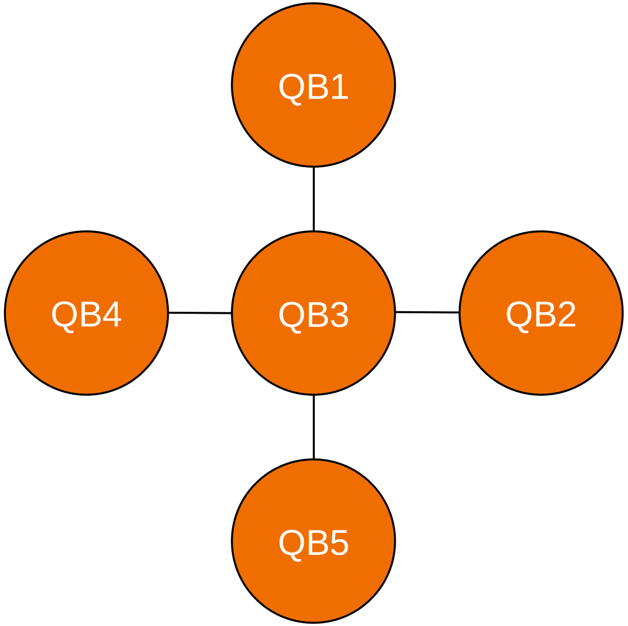
02/12/2024 **VTT – beyond the obvious**



Physical Characteristics of Helmi

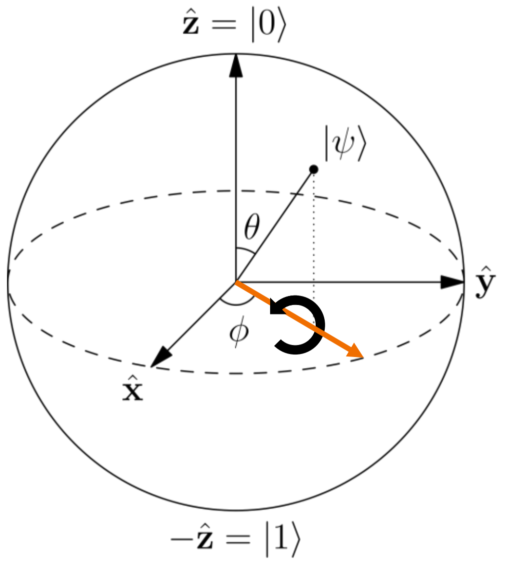
Actual Hardware

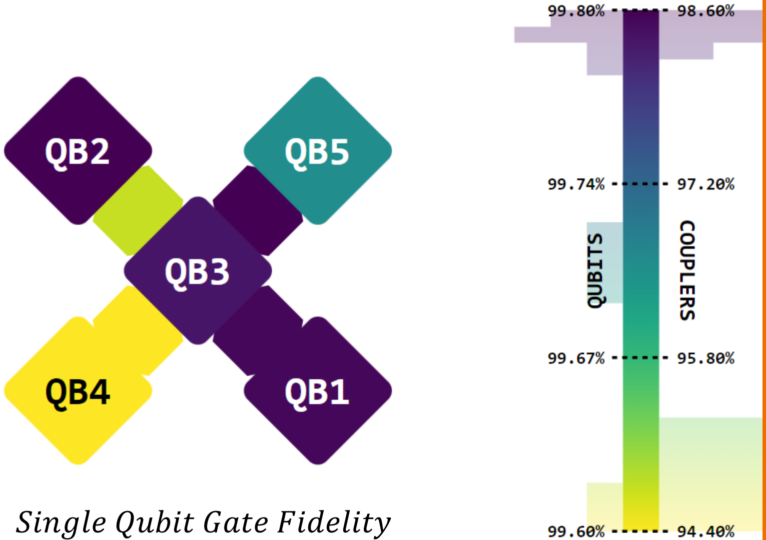
- Helmi is a 5-qubit superconducting quantum computer arranged in a star-shaped topology (VTT, 2024).
- Jointly developed by IQM and VTT, it consists of 5 flux-tuneable transmons connected by tuneable couplers.
- Helmi can be accessed through CSC via LUMI, Europe’s fastest supercomputer.



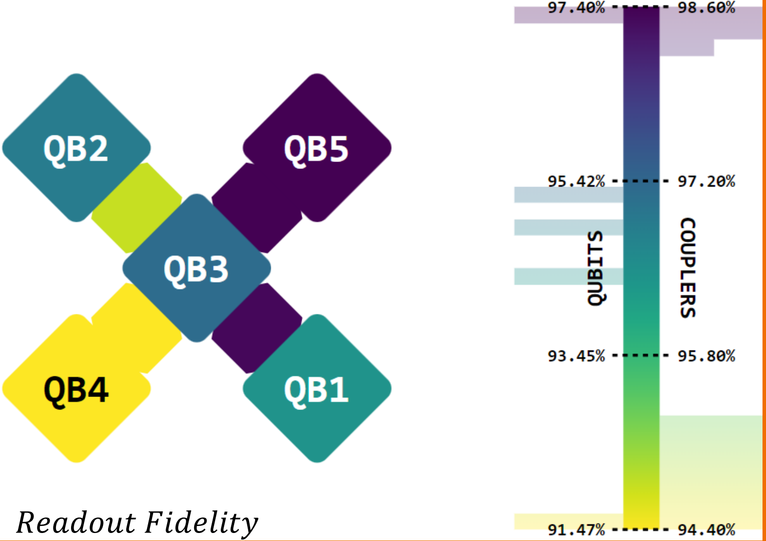
Gates and Measurements

- We can natively do Phased-*RX* and Controlled-*Z* gates.
- We do measurements in the *Z*-basis.
- We can do Virtual *RZ* gates using the control stack (McKay et al., 2017).
- Helmi is a Noisy Intermediate Scale Quantum computer (NISQ), which means that circuits cannot be run without errors.
  - However, this does not mean that NISQ devices are not useful.
  - There are some techniques we can use to get better results on NISQ devices – and we'll cover the most useful ones for Helmi.





Single Qubit Gate Fidelity

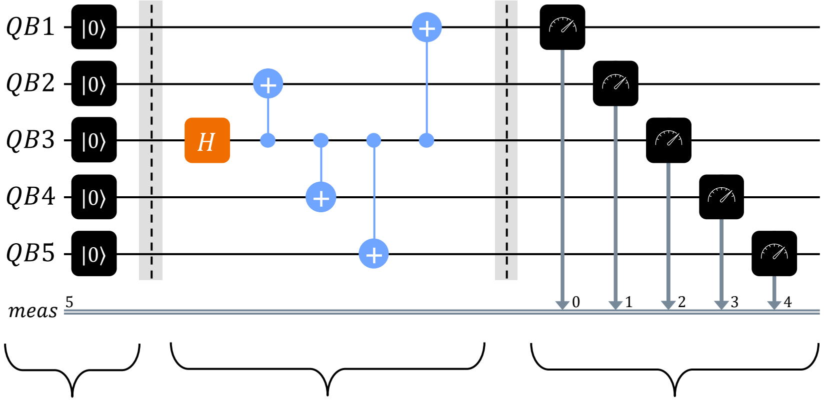


Readout Fidelity

Errors in NISQ Devices

GHZ States

- The n qubit Greenberger–Horne–Zeilinger state (GHZ) can be described as $\frac{|0\rangle^{n}+|1\rangle^{n}}{2}$.
- The largest GHZ state that can be created on a quantum computer is a good indicator of its general utility.
  - Fidelity $> 50\%$ is the cutoff
- Let’s prepare a 5 qubit GHZ state on Helmi!



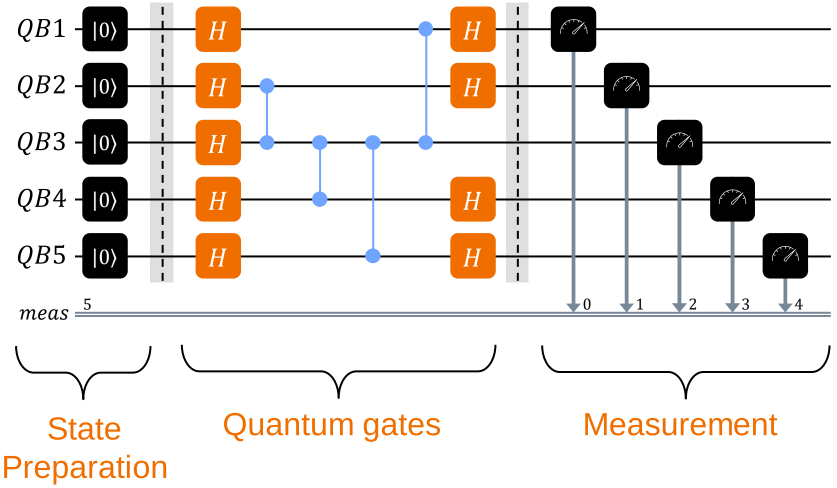
State Preparation

Quantum gates

Measurement

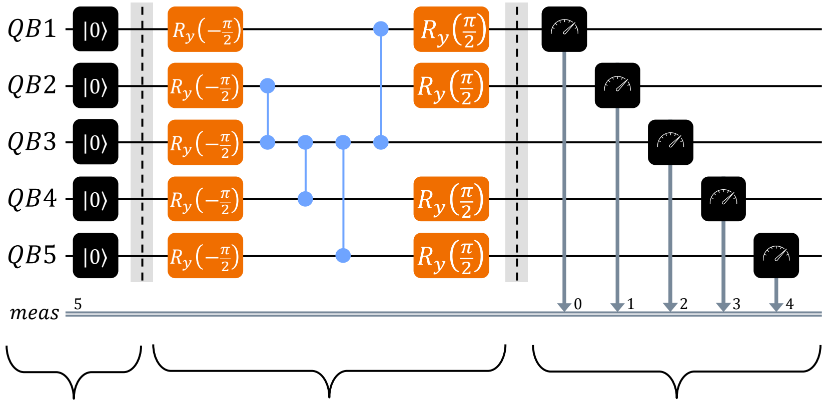
GHZ States

- Let’s convert *CNOT*s to *CZ*s.



GHZ States

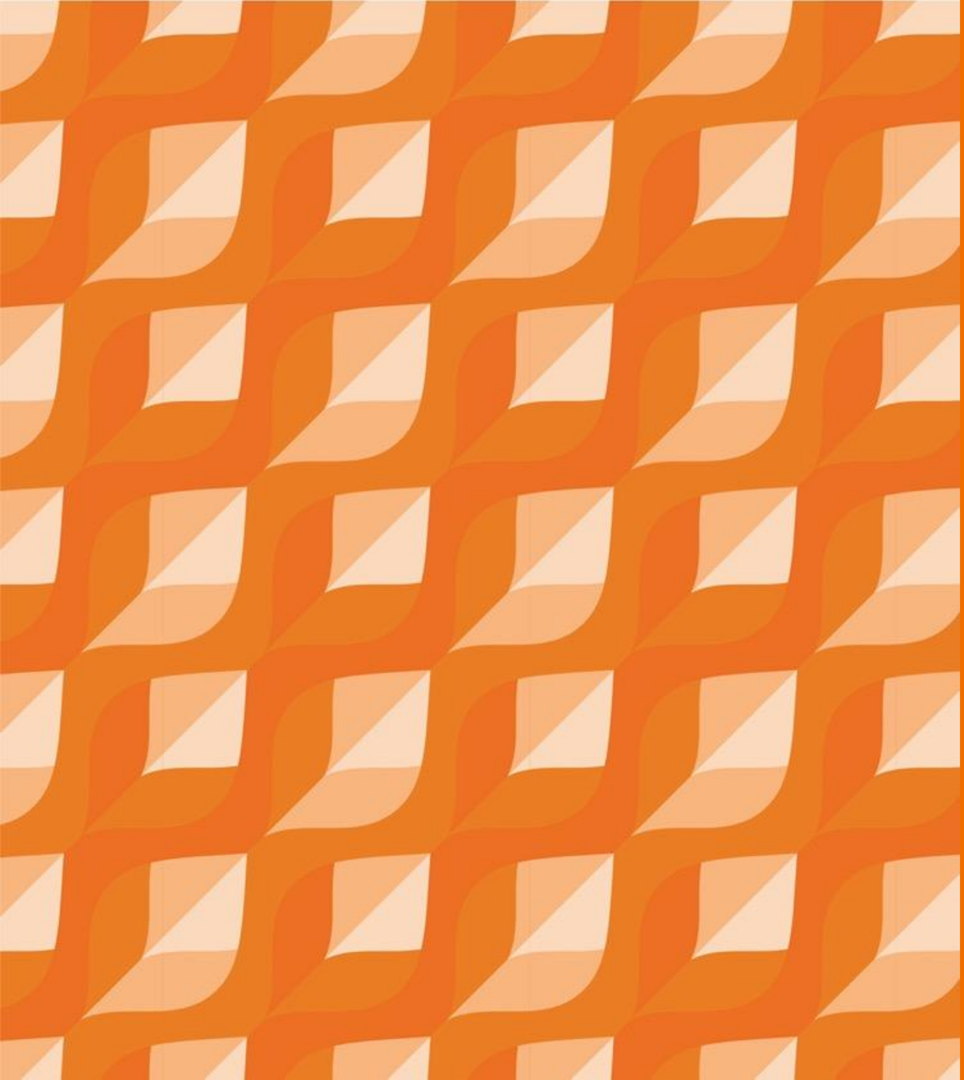
- We can decompose the *H* gate down to our native gate set (Phased-*RX* and Controlled-*Z* gates).
- Since we measure in the *Z* basis, we can optimise away some of the virtual *RZ* gates.
- This is the actual circuit that we end up running on Helmi.



State Preparation

Quantum gates

Measurement



Optimisations

Reducing Errors

Error Suppression

- Closest to hardware – may involve changing the pulses
- Examples include DRAG pulses, which reduce leakage errors.

Error Mitigation

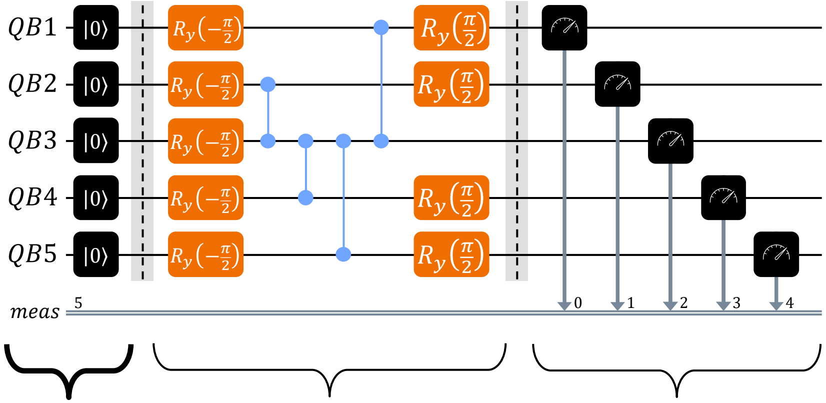
- Most relevant for NISQ devices.
- Involves changing the circuit and running multiple circuits to mitigate errors.

Error Correction

- Combine many noisy, physical qubits for fault-tolerant, logical qubits.
- Examples include Stabiliser codes and Topological codes.

State Preparation

- Assume that our state is correctly initialised to $|0\rangle$.
- We can use heralding (postprocessing) or active reset to increase the odds of the qubit being correctly initialised to the $|0\rangle$ state.
- Heralding only works for small NISQ devices, whereas active reset requires specific hardware.



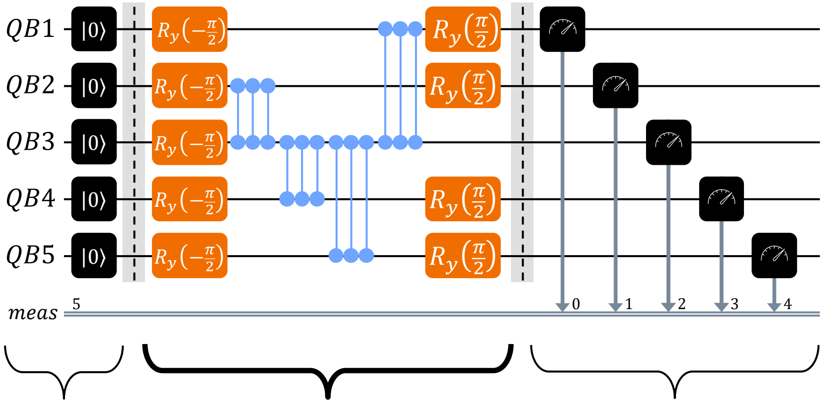
State Preparation

Quantum gates

Measurement

Quantum Gates

- Every gate that we run could have an error attached to it.
- We can mitigate this error using Pauli twirling (randomly replacing a gate with a different representation of that gate), ZNE (repeating a gate multiple times to see how the expectation value scales), etc.



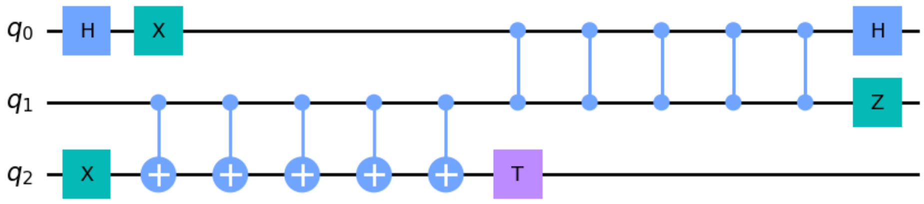
State Preparation

Quantum gates

Measurement

What is ZNE?

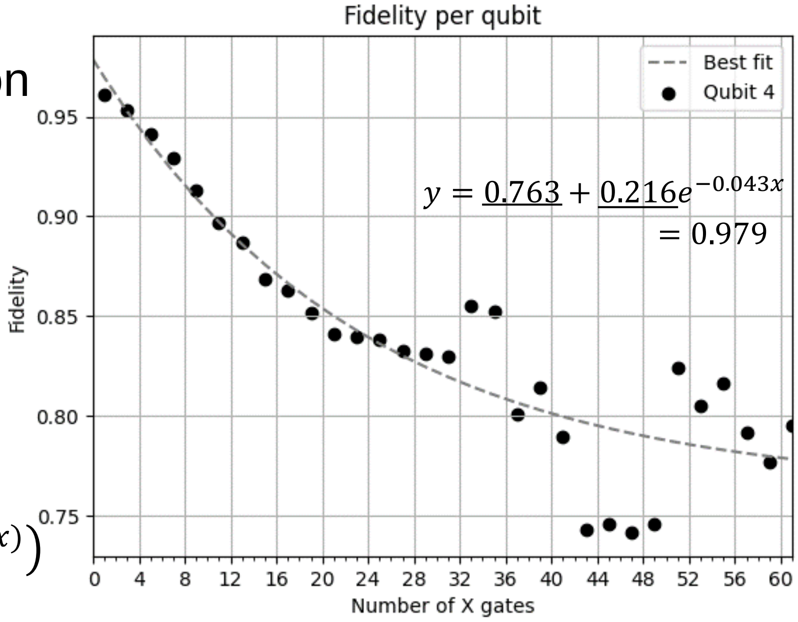
- Zero Noise Extrapolation (ZNE) is a noise-mitigation technique where we vary the noise in a circuit to extrapolate it away.
- Instead of physically worsening the qubits, we can do this digitally by repeating gates.



How to perform ZNE?

We can define an observable (such as $P(0)$), and fit a function to the data:

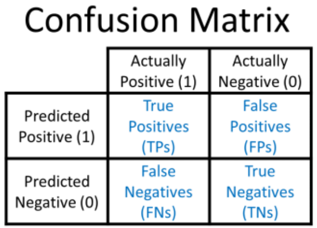
- Linear fit – $O(x)$
- Polynomial fit
  - Quadratic fit – $O(x^2)$
  - Richardson fit – $O(x^{n-1})$
- Exponential fit - $O(e^x)$
- Poly-exponential fit - $O\left(e^{\text{poly}(x)}\right)$



$$y = \underline{0.763} + \underline{0.216e}^{-0.043x} = 0.979$$

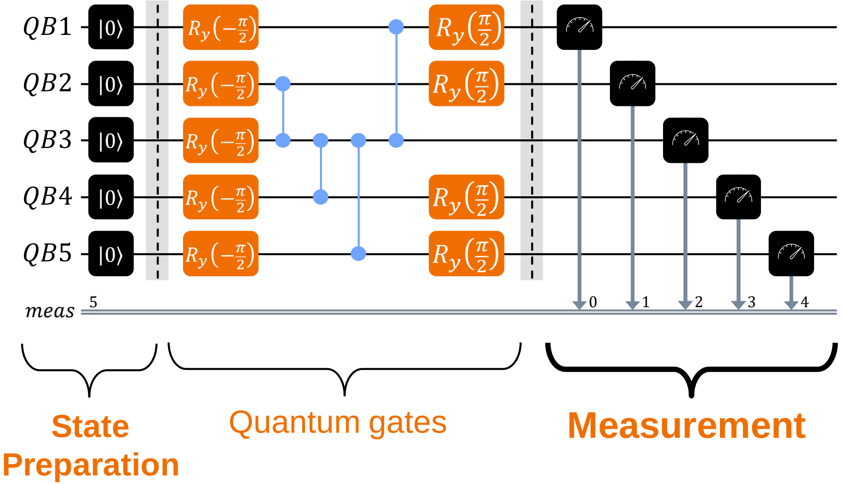
Measurement

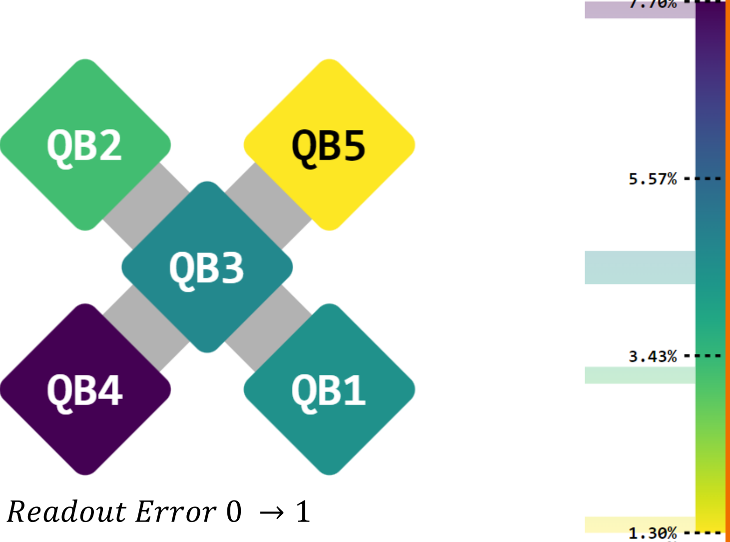
- For NISQ devices, readout mitigation is one of the easiest ways to improve the results.
- The simplest readout mitigation technique requires us to prepare a confusion matrix and invert it to get a better estimate of the actual measurement values (Mitiq, 2024).



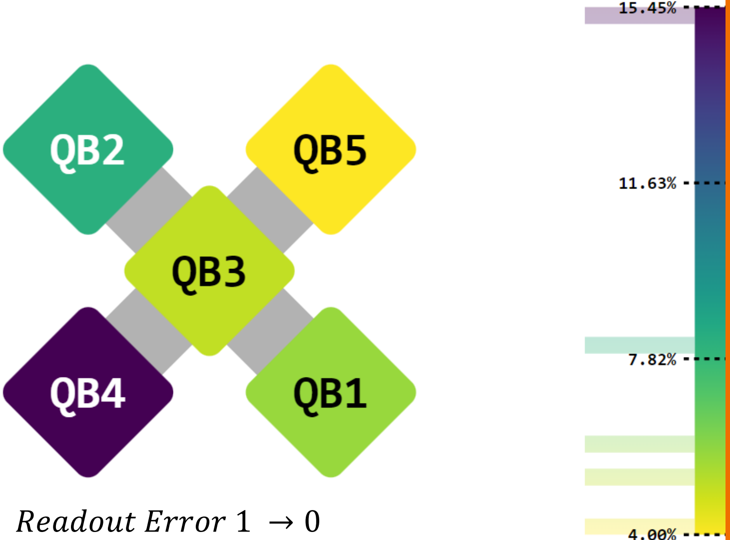
Confusion Matrix

	Actually Positive (1)	Actually Negative (0)
Predicted Positive (1)	True Positives (TPs)	False Positives (FPs)
Predicted Negative (0)	False Negatives (FNs)	True Negatives (TNs)





Readout Error 0 → 1

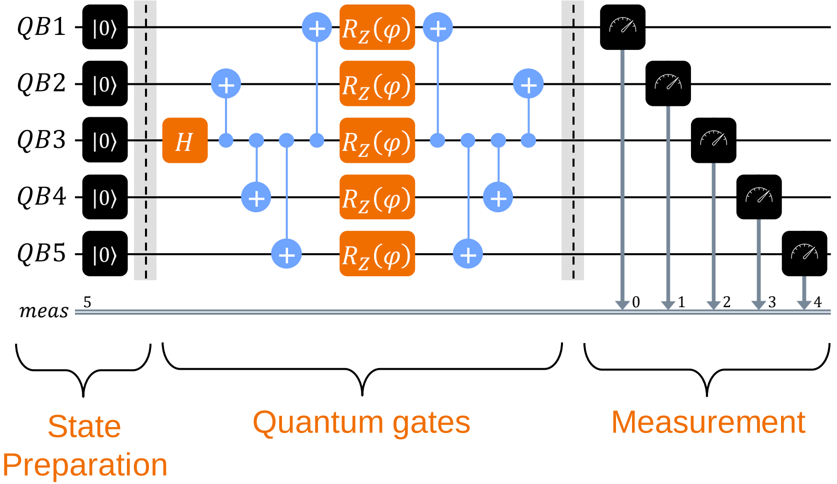


Readout Error 1 → 0

Smarter Algorithms

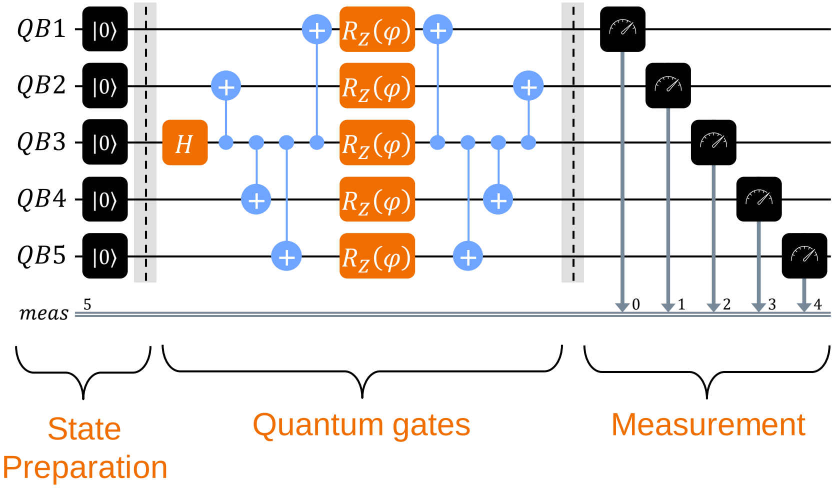
Multiple Quantum Coherences

- We can calculate the GHZ fidelity using Multiple Quantum Coherences (MQC) (Wei et al., 2020).
- We apply rotation gates with phase θ to the qubits, and de-entangle to apply a phase shift to the first qubit.



Multiple Quantum Coherences

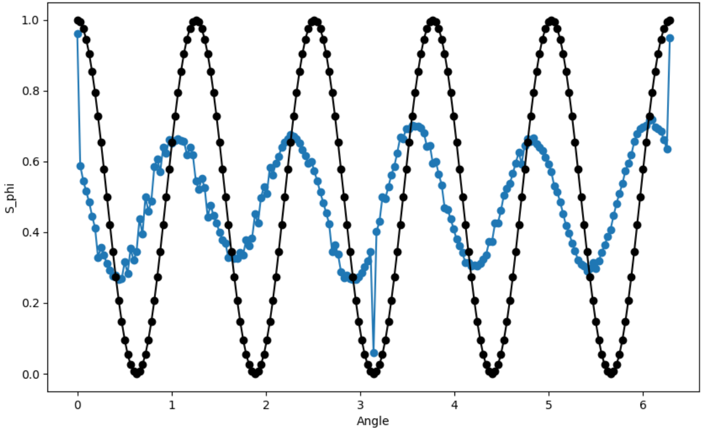
- For a N qubit GHZ circuit, we need to run this circuit at least $2N+2$ times, with $\varphi = \frac{\pi j}{N+1}\ \forall\, j \in \{0, \dots, 2N+1\}$.
- Ideally, we get only $|00000\rangle$ and $|00100\rangle$, and the probability of the former should be $\frac{1+\cos(N\varphi)}{2}$.
- We can use this to estimate the MQC fidelity.

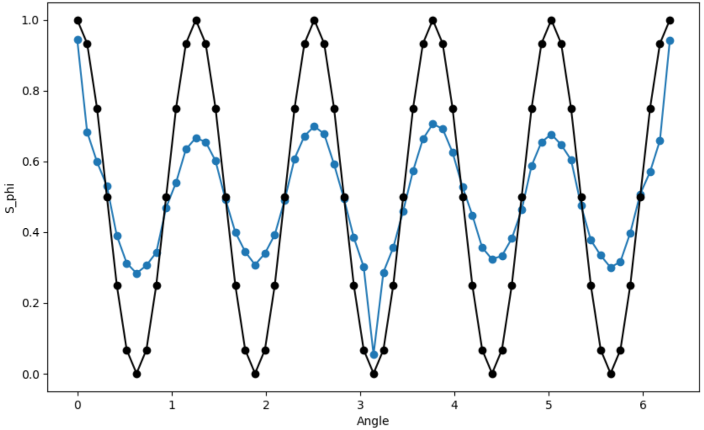


$$I_q = \mathcal{N}^{-1}\left|\sum_{\phi} e^{iq\phi} S_\phi\right|$$

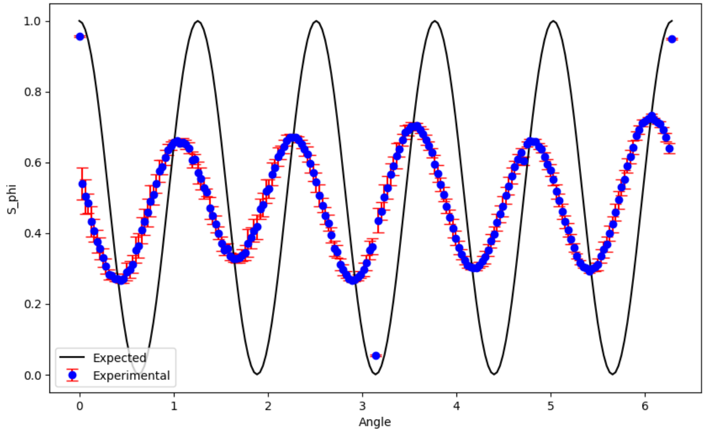
$$2\sqrt{I_N} \leq F \leq \sqrt{I_0/2} + \sqrt{I_N}$$

MQC – With vs. Without X

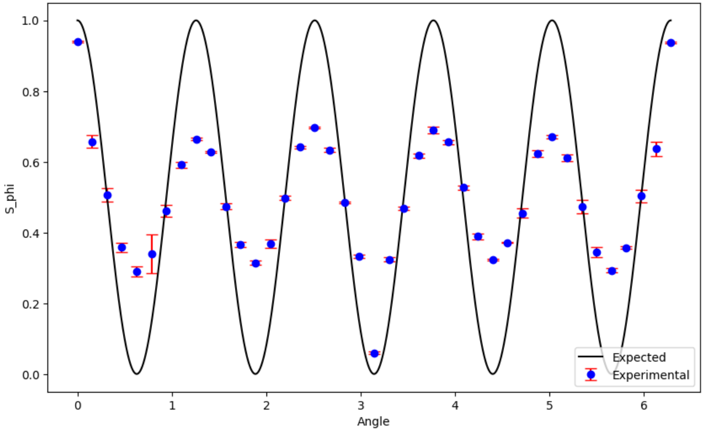




MQC Stability – With vs. Without X



$0.637 \leq F \leq 0.813$



$0.716 \leq F \leq 0.859$

Other Optimisations

- We could reorder the *CX* gates such that the qubits with shorter decoherence times take less time to perform the phase kickback.
- We could replace any idling time with pairs of *X* gates.
- We could perform readout mitigation and zero noise extrapolation, or other such error mitigation techniques to improve the results.
- We could increase the number of experiments we perform to achieve a higher fidelity.
- We could increase the number of shots, as well as average over multiple jobs to make our results less random.

Caveats

- Every mitigation technique we apply requires extra jobs, and as such it comes with a monetary and time cost.
  - However, we can often get greatly improved results for very little – readout mitigation is a great example.
- The more hardware-aware we make our algorithm, the less general it becomes. This is usually very difficult to automate.
- Optimising NISQ algorithms is still being actively studies, especially in the hopes that many of these techniques can scale to larger NISQ devices.

References

- VTT. (2024). *VTT Quantum Computer Documentation*. https://vttresearch.github.io/quantum-computer-documentation/
- McKay, D. C., Wood, C. J., Sheldon, S., Chow, J. M., & Gambetta, J. M. (2017). Efficient *Z* gates for quantum computing. *Physical Review A*, *96*(2), 022330. https://doi.org/10.1103/PhysRevA.96.022330
- Mitiq. (2024). *What is the theory behind REM?* https://mitiq.readthedocs.io/en/stable/guide/rem-5-theory.html
- Wei, K. X., Lauer, I., Srinivasan, S., Sundaresan, N., McClure, D. T., Toyli, D., McKay, D. C., Gambetta, J. M., & Sheldon, S. (2020). Verifying Multipartite Entangled GHZ States via Multiple Quantum Coherences. *Physical Review A*, *101*(3), 032343. https://doi.org/10.1103/PhysRevA.101.032343