EXTENDING QUANTUM STATE TOMOGRAPHY FOR SUPERCONDUCTING QUANTUM PROCESSORS

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ABSTRACT

Quantum State Tomography (QST):

- reconstruction of the density matrix of a quantum state via measurements
- critical to ensure the proper functionality of qubits and quantum operations in a quantum computer

QUBIT STATE $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

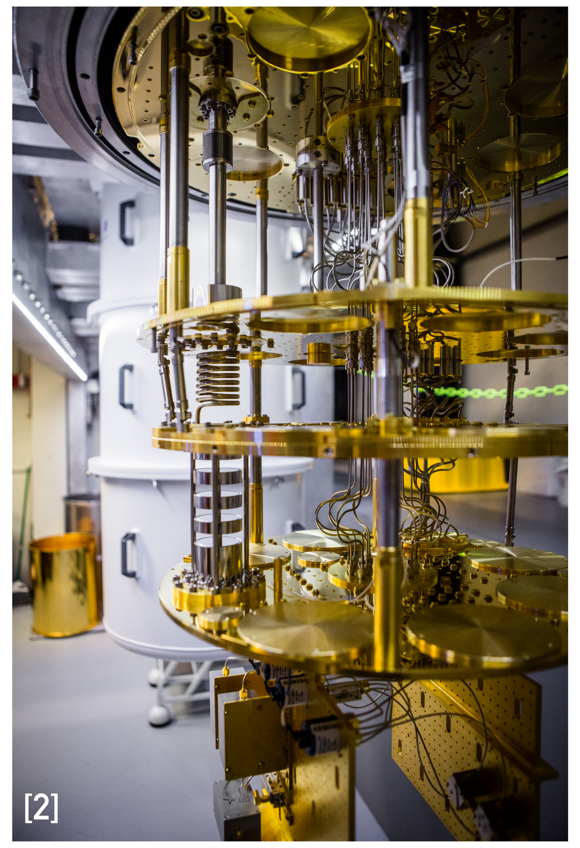
DENSITY MATRIX $\rho = |\psi\rangle\langle\psi|$

Prior:

- QST implementation for 1- and 2-qubit systems in our quantum processor [1]

In this work:

- Extend QST to **n-qubit** systems and test different implementations.
- Use Field Programmable Gate Arrays (**FPGAs**) to speed up measurement process



[2]

QUANTUM STATE TOMOGRAPHY BACKGROUND [3,4]

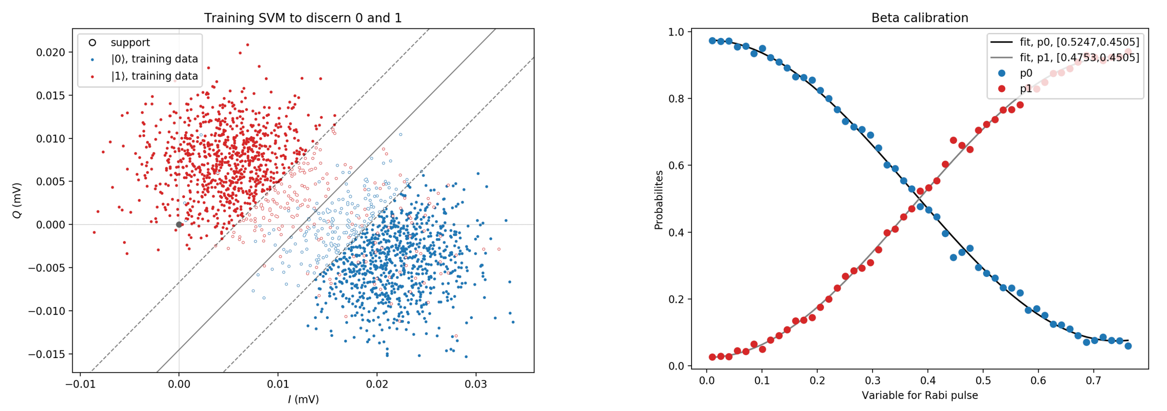
1 DECOMPOSE DENSITY MATRIX

$$\rho_{1QB} = \frac{1}{2}(\langle I\rangle I + \langle\sigma_x\rangle\sigma_x + \langle\sigma_y\rangle\sigma_y + \langle\sigma_z\rangle\sigma_z)$$

2 SOLVE FOR MEASUREMENT EXPECTATIONS

$$\begin{bmatrix} p_0 \\ p_1 \end{bmatrix} = \begin{bmatrix} \beta_I^{|0\rangle} & \beta_{\sigma_A}^{|0\rangle} \\ \beta_I^{|1\rangle} & \beta_{\sigma_A}^{|1\rangle} \end{bmatrix} \begin{bmatrix} \langle I\rangle \\ \langle\sigma_A\rangle \end{bmatrix}, A \in \{x, y, z\}$$

3 FIND PROBABILITIES AND 'BETA PARAMETERS'

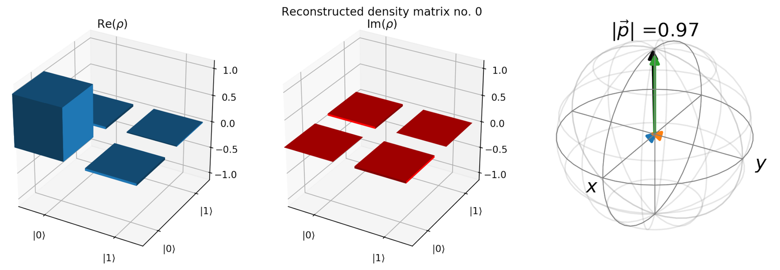


4 IMPOSE PHYSICALITY CONSTRAINTS

$$\rho_t = \frac{T^\dagger T}{Tr(T^\dagger T)}, \quad T = \begin{bmatrix} t_0 & 0 \\ t_2 + it_3 & t_1 \end{bmatrix} \quad t_0^2 + t_1^2 + t_2^2 + t_3^2 = 1$$

5 MAXIMUM LIKELIHOOD ESTIMATION

$$L = \sum_{P \in \{\sigma_x, \sigma_y, \sigma_z\}} (m_{\langle P\rangle} - Tr(P\rho_t))^2$$



EXTENDING QUANTUM STATE TOMOGRAPHY TO N-QUBITS

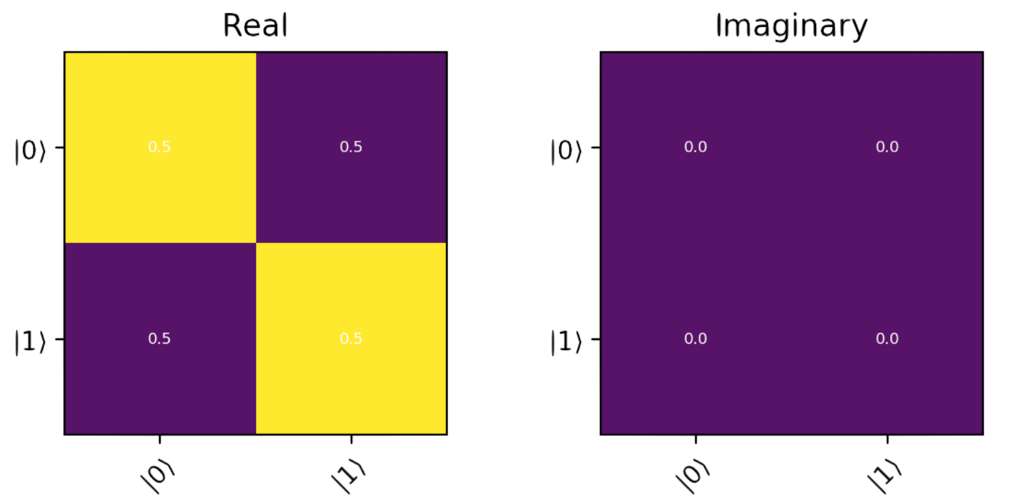
N-qubit simulated GHZ state density matrices: $|GHZ\rangle = \frac{|0\rangle^{\otimes N} + |1\rangle^{\otimes N}}{\sqrt{2}}$

Fidelity error metric: $F = \mathrm{Tr}\left(\rho_{\mathrm{ideal}}\rho_{\mathrm{at\ iteration}\ k}\right)$

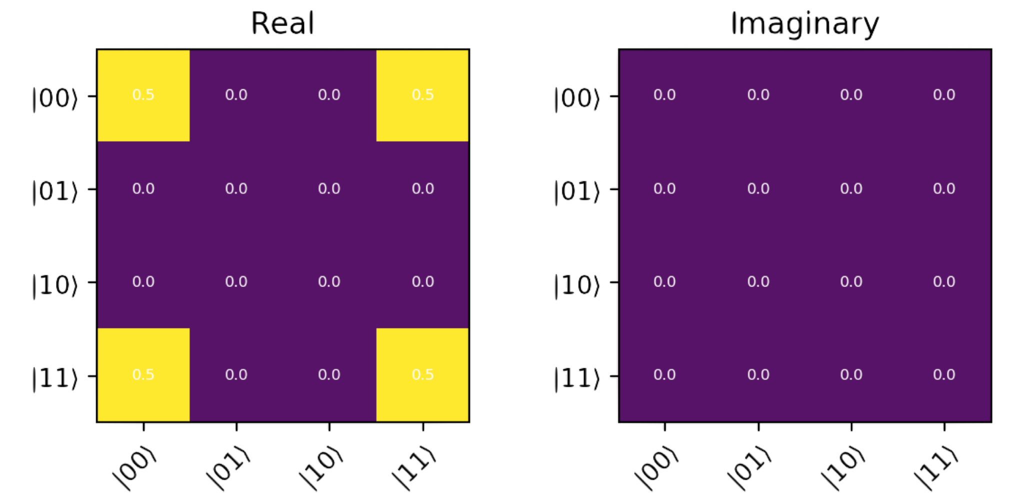
RECONSTRUCTED GHZ DENSITY MATRIX

FROM SIMULATED DATA

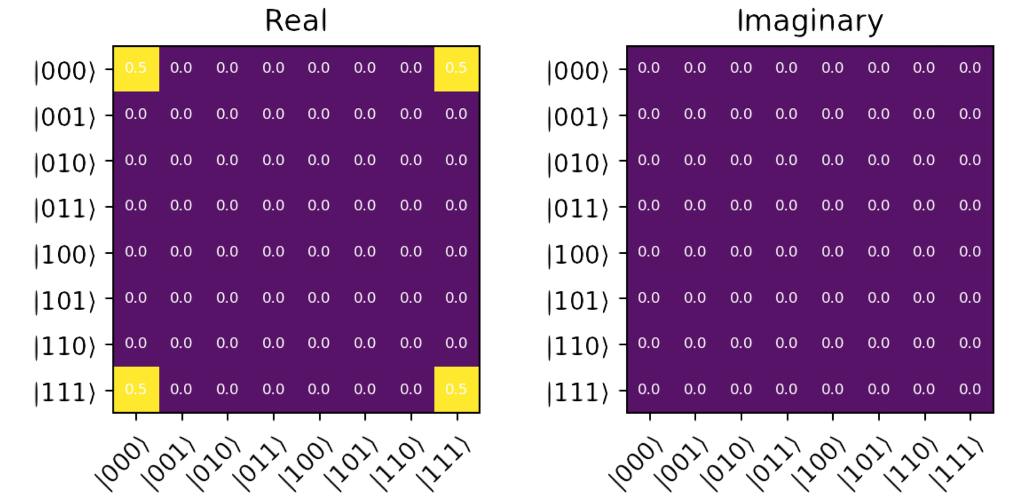
1-QUBIT



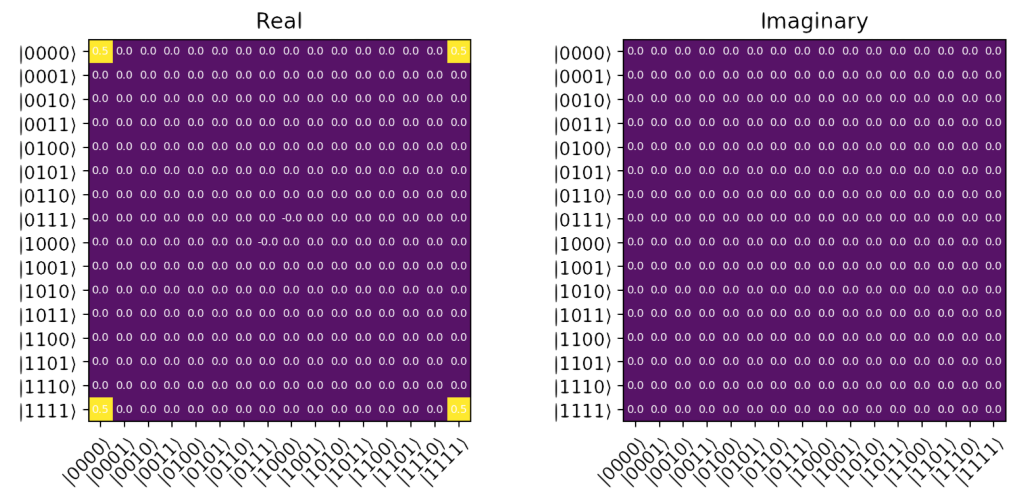
2-QUBITS



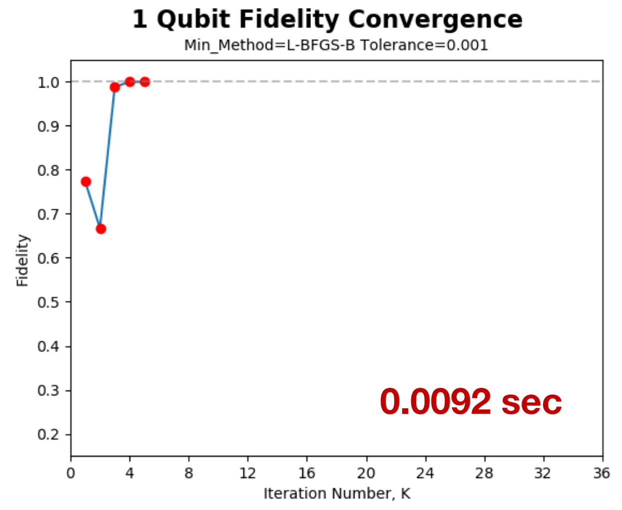
3-QUBITS

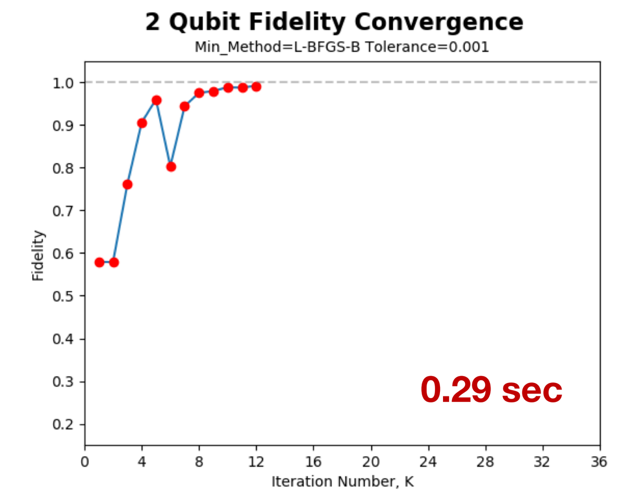


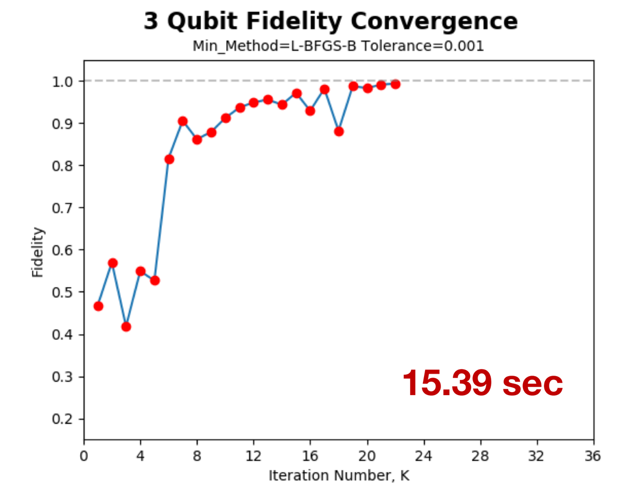
4-QUBITS

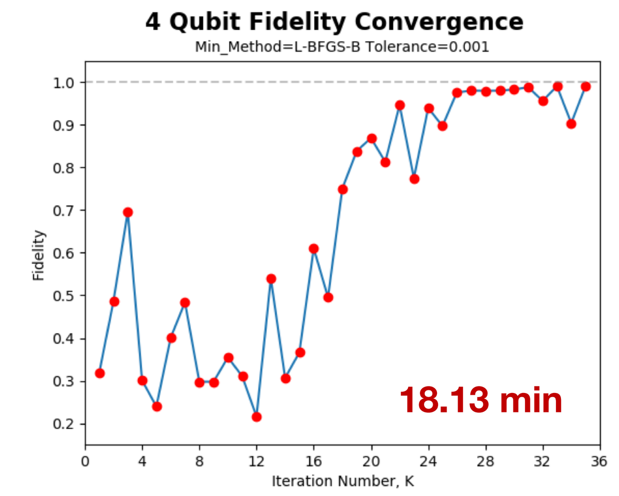


MLE RUNTIME



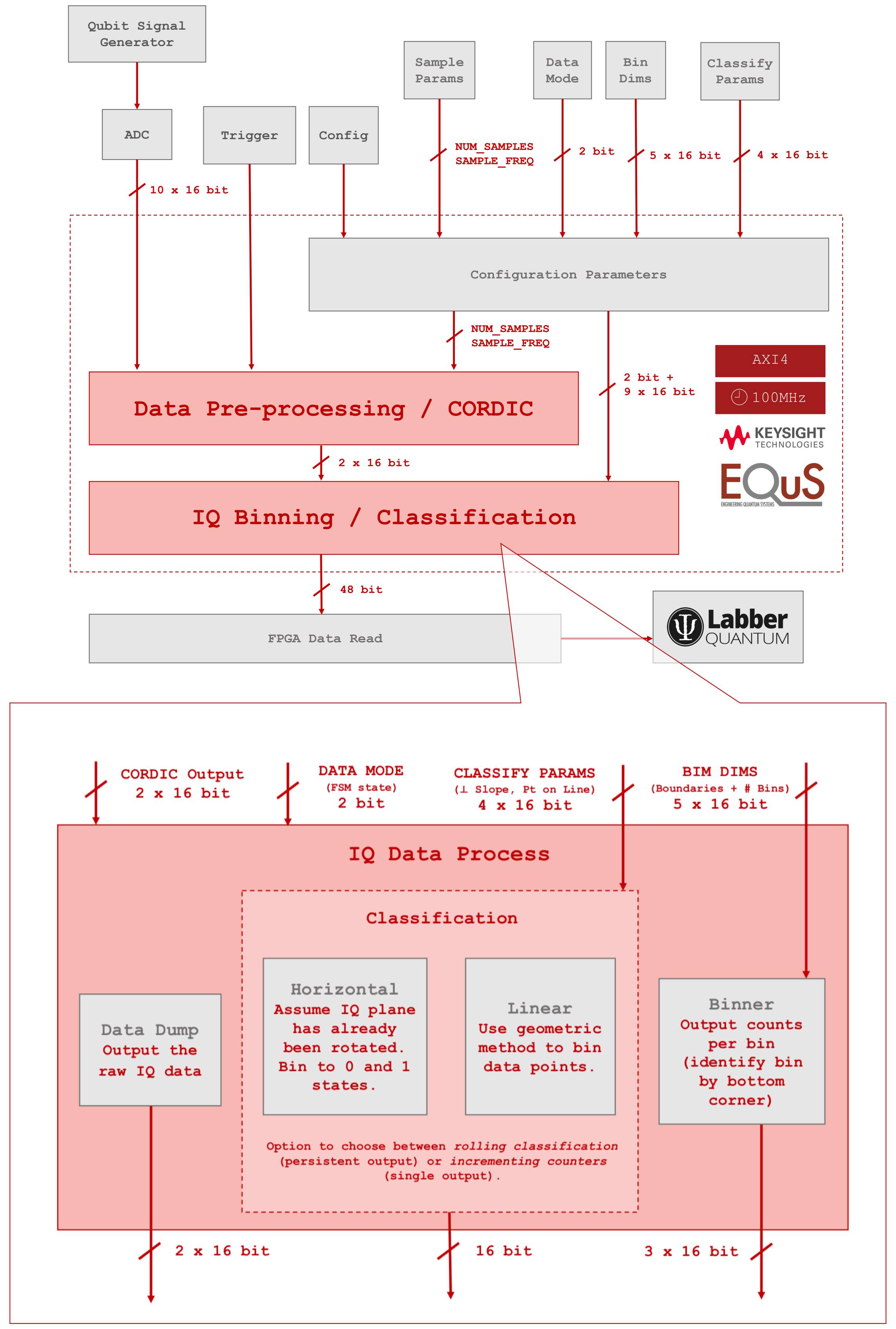






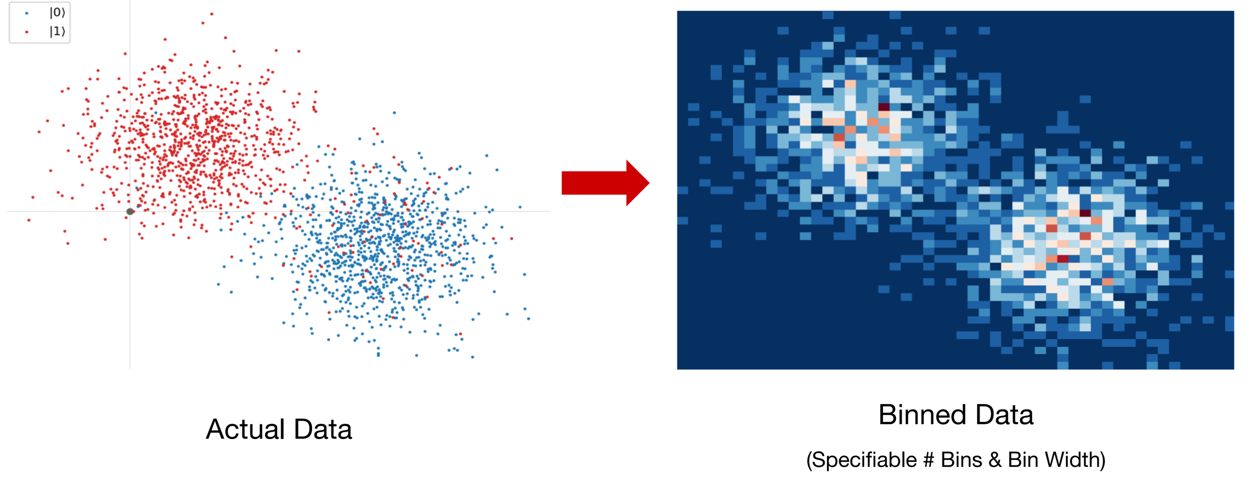
FPGA MEASUREMENT SPEED-UP

with Megan Yamoah



2D HISTOGRAM

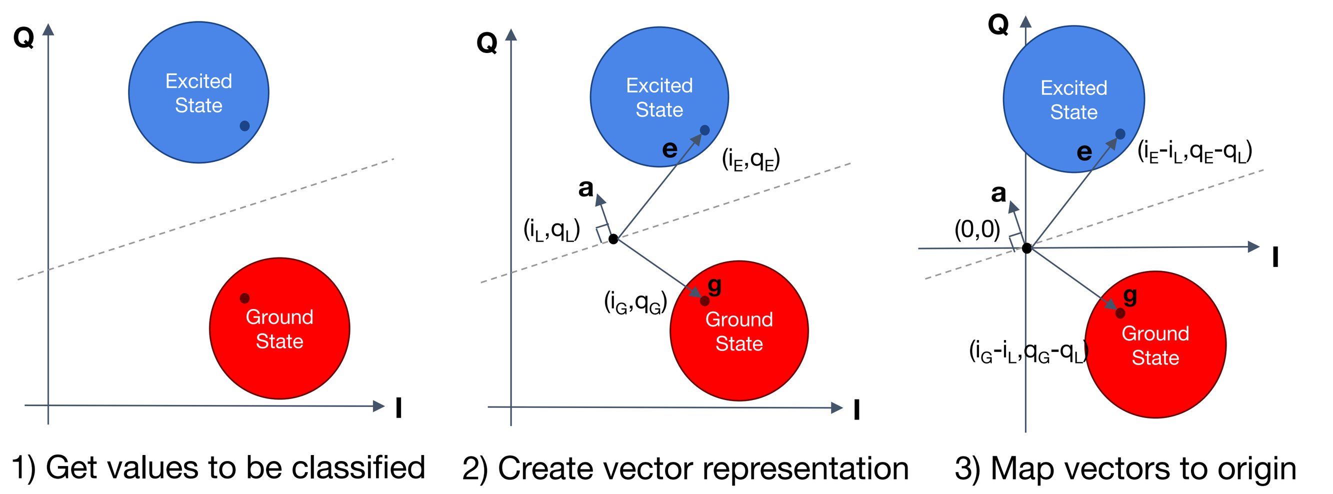
- Divide I-Q plane (user-defined resolution) & continuously bin values
- Once measurement is over, report count for each bin
- Decreased resolution reduces amount of data sent to computer & increases processing speed



Actual Data

Binned Data (Specifiable # Bins & Bin Width)

LINEAR CLASSIFICATION



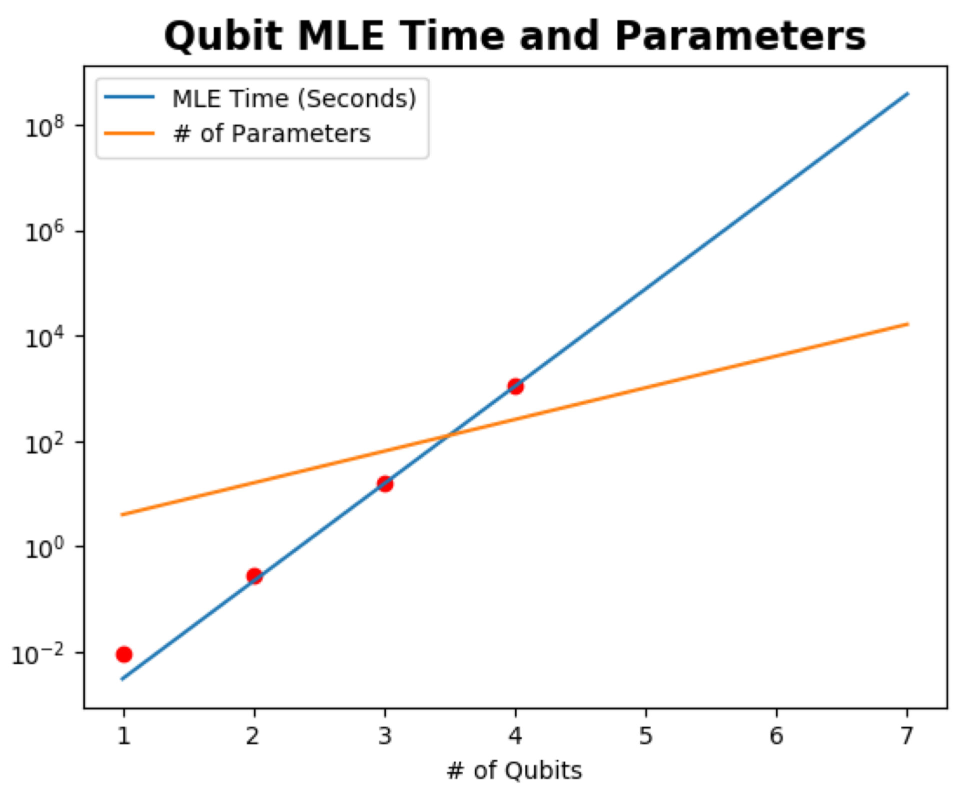
1) Get values to be classified

2) Create vector representation

3) Map vectors to origin

4) Compute dot products and bin values $\vec{a}\cdot\vec{b}: \begin{cases} > 0, & if\ \vec{b} = \vec{e} \rightarrow \textbf{bin as 1} \\ = 0, & if\ point\ on\ classifier \\ < 0, & if\ \vec{b} = \vec{g} \rightarrow \textbf{bin as 0} \end{cases}$

FUTURE WORK



Current tomography implementation is not scalable *O(4ⁿ)* !

- Optimize speed/accuracy of MLE
  - Improve initial guess
  - Find best minimizer

Maximum Likelihood Estimation is inadmissible! [5]

- Implement other QST methods
  - Other statistical methods
  - Machine learning
  - Deep learning
- Comparison of Methods
- Test 3-qubit QST on experimental data
- Finish and extend FPGA integration

REFERENCES

1. Original 1- and 2- qubit tomography implementation by Morten Kjaergaard.
2. Photo by Nathan Fiske.
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4. Cramer, J. 2012. *Algorithmic speedup and multiplexed readout inscalable circuit QED*. Delft University of Technology, Delft, Netherlands.
5. Ferrie, C., & Blume-Kohout, R. (2018). *Maximum likelihood quantum state tomography is inadmissible*. arXiv preprint arXiv:1808.01072.
6. Schmied, R. (2016). *Quantum state tomography of a single qubit: comparison of methods*. Journal of Modern Optics, 63(18), 1744-1758.