SAND2018-1998C

Gate Set Tomography on more than two qubits

Erik Nielsen[1]

Robin Blume-Kohout[2], Timothy Proctor[1], Kenneth Rudinger[2], Mohan Sarovar[1], Kevin Young[1]

[1](Sandia National Laboratories)

[2](Center for Computing Research, Sandia National Laboratories)

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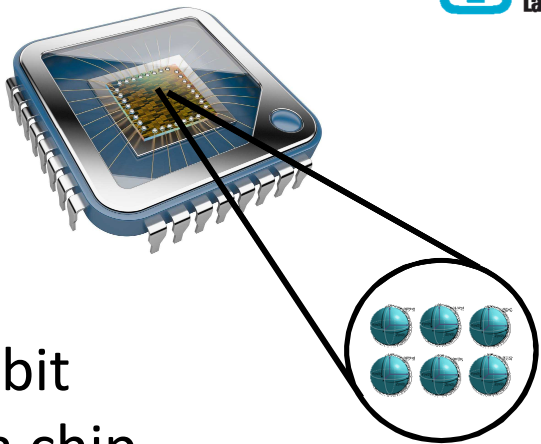
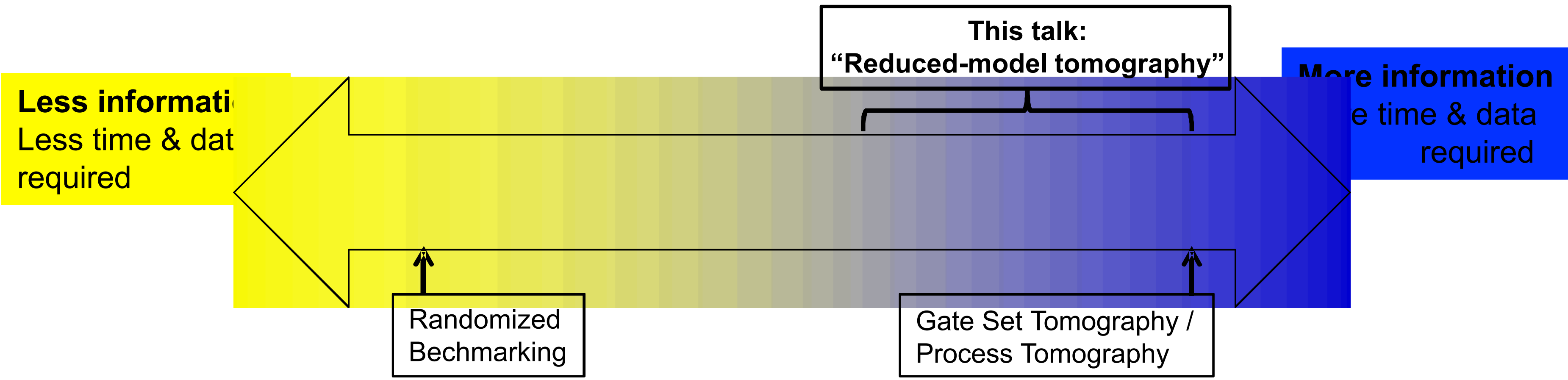
Background



- Ultimate goal is to produce working multi-qubit devices.
- State of the art has moved from single qubit demonstrations to handfuls of qubits on a chip.
- How do we best ensure these collections of qubits will work?
  - What does it mean to “work”?
    - perform algorithms?
    - perform error correction?
    - no “high-weight” errors?
  - Could just “see if they work”, but this is risky, and is difficult to extrapolate from.
  - Characterization? (but how?)

Characterization

- By extracting the information about the system we'd like to:
  - Rough gauge of performance (benchmarking)
  - "Debug" the system of qubits
  - Inform predictive simulations (model-based)
- **Tradeoff**: Information vs. Effort (but how in practice?)



- **Goal** of this work is to **allow us to make this tradeoff**.
- Within the context of model-based approaches, tradeoff is captured by the **number of model parameters**

Reduced-parameter models

This talk: "GST"-like characterization using reduced-parameter models.

- Starting point: standard-GST's very rich model
  - Gates are 4^N x 4^N matrices; $\approx 3N \cdot 16^N$ total parameters.
  - Hero computation at N=3; impossible beyond that.
  - Even if we could compute it, way too much information

$$G_i \text{ (gate)} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ \tau_x & \lambda_{xx} & \lambda_{xy} & \lambda_{xz} \\ \tau_y & \lambda_{yx} & \lambda_{yy} & \lambda_{yz} \\ \tau_z & \lambda_{zx} & \lambda_{zy} & \lambda_{zz} \end{pmatrix}$$

λ, τ parameters

- **Key idea**: (leading to natural reduction in #parameters)
  - Write gates as:

"Error generator"

$$G_i \text{ (gate)} = e^{\Gamma} U_0$$

Ideal unitary

$$\Gamma = \sum_i \theta_i H_i + \sum_{ij} \theta_{ij} S_{ij}$$

$$H_i \colon \rho \to -\frac{i}{\hbar}[A_i, \rho]$$

$$S_{ij} \colon \rho \to A_i \rho A_j^\dagger - \frac{1}{2}\left(\rho A_j^\dagger A_i - A_j^\dagger A_i \rho\right)$$

  - **Strategy: Limit terms in Γ to reduce the parameters of G_i**
    - Pauli-channel; limited weight; locality of terms; system-specific physics
    - **Nested** models allow application of standard selection criteria.

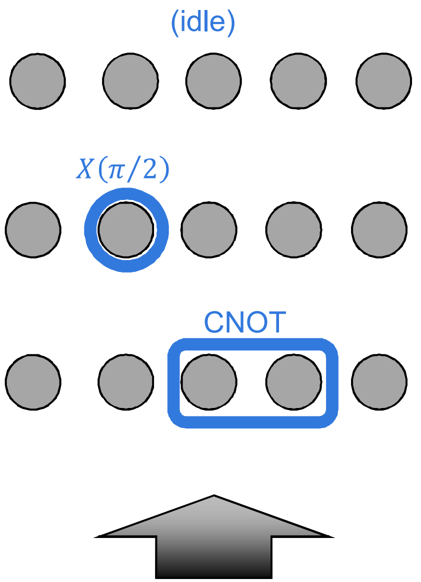
Linear-chain models

Recall:

$$G_i = e^{\Gamma} U_0$$

Consider a chain of N qubits.

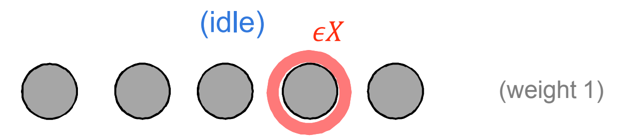
- Ideal operations:
  1. Global idle gate
  2. $X(\pi/2)$ and $Y(\pi/2)$ gates on each qubit
  3. CNOT gates between adjacent qubits.



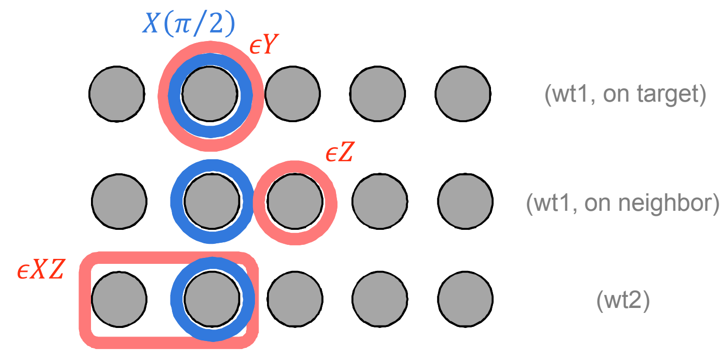
Example:
5-qubit chain

Linear-chain models (cont.)

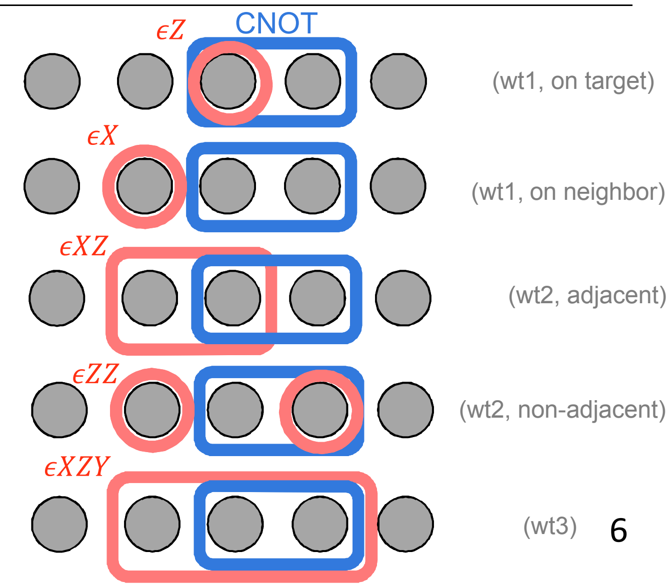
- Errors included in model:
  - Idle gate
    - weight-1 errors* on all qubits



  - X,Y gates:
    - weight-1 & 2 errors* on target qubit and its neighbors
    - Same weight-1 errors* as global idle on all other qubits



  - CNOT gates:
    - weight-1, 2 & 3 errors* on target qubits and their neighbors
    - Same weight-1 errors* as global idle on all other qubits



* "errors" = Hamiltonian + *Pauli*-stochcastic only

Sparse-model Gate Set Tomography

- **Method**:
  - Input:
    - Parameterized qubit error model
    - ouctome counts for a pre-defined set of gate sequences
  - Maximize Likelihood(model-parameters | data)
  - Output: best-fit model parameters (= qubit errors)

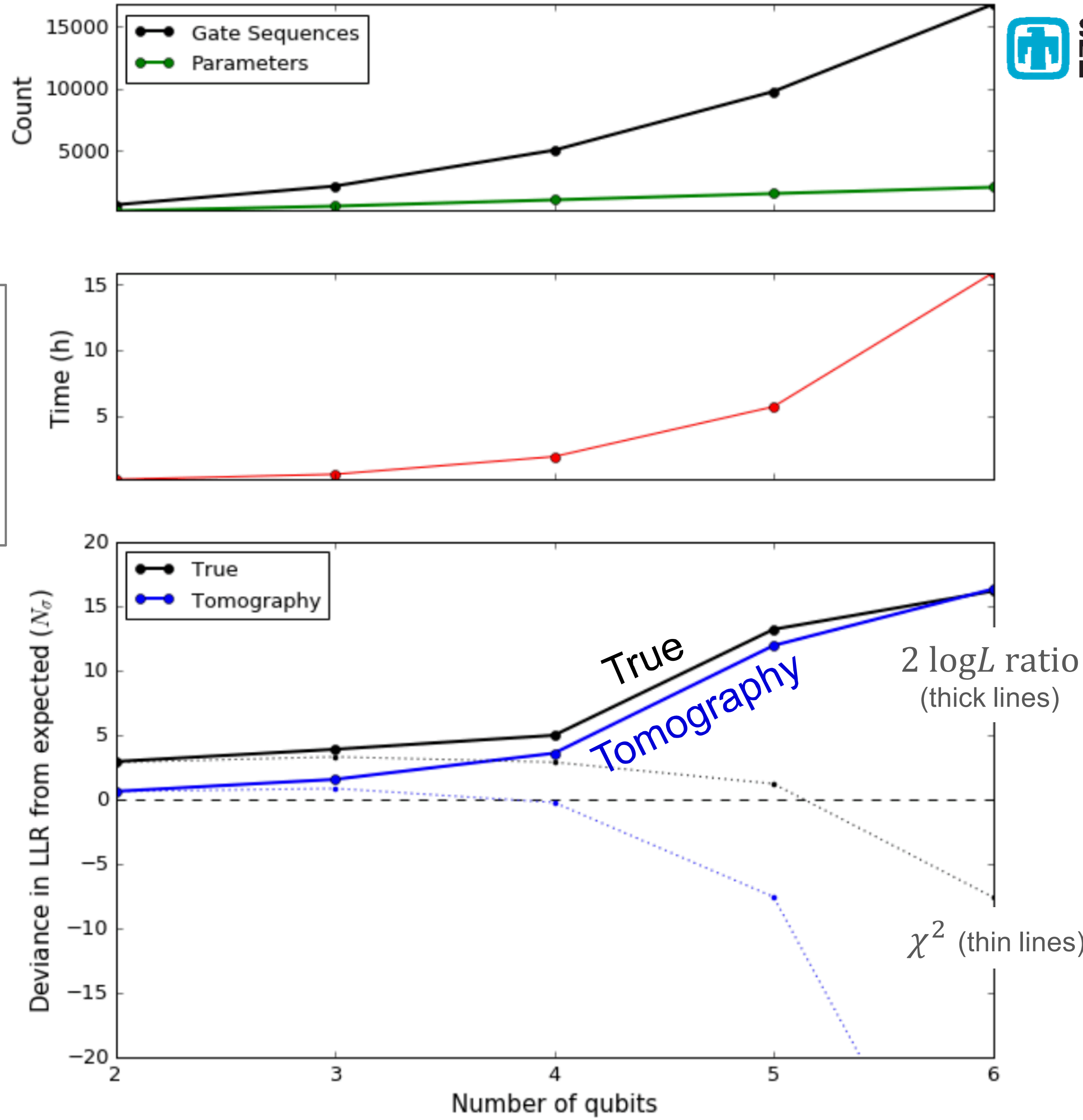
- **Result**:
  - Using the “base” model and an over-complete set of sequences, this **method succeeds in identifying the errors in simulated 3,4,5 & 6-qubit processors**.
  - Computation time: < 15 hours on < 100-cores.

- **Significance**:
  - **Proof of principle**: ML gradient ascent algorithms are able to fit simulated-processor data using the aforementioned models.
  - **Capability**: methods/framework in open-source pyGSTi package.

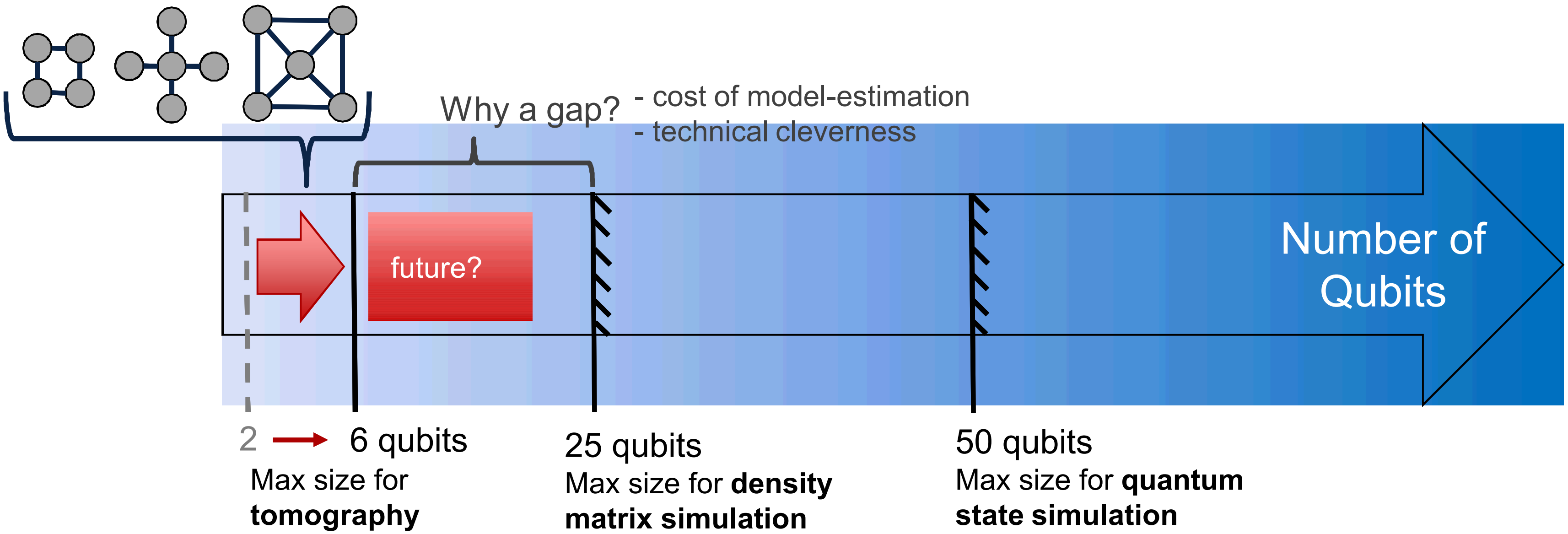
Results:
(more details)

Tomography results fit:

- Within what we expect (χ^2 theory)
- Better than the "**True**" processor model which generated the data.



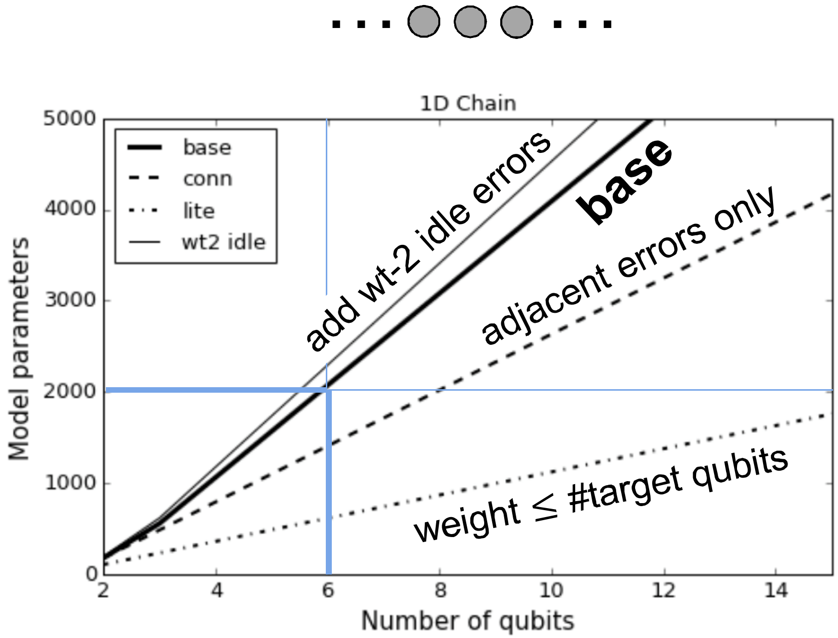
Significance

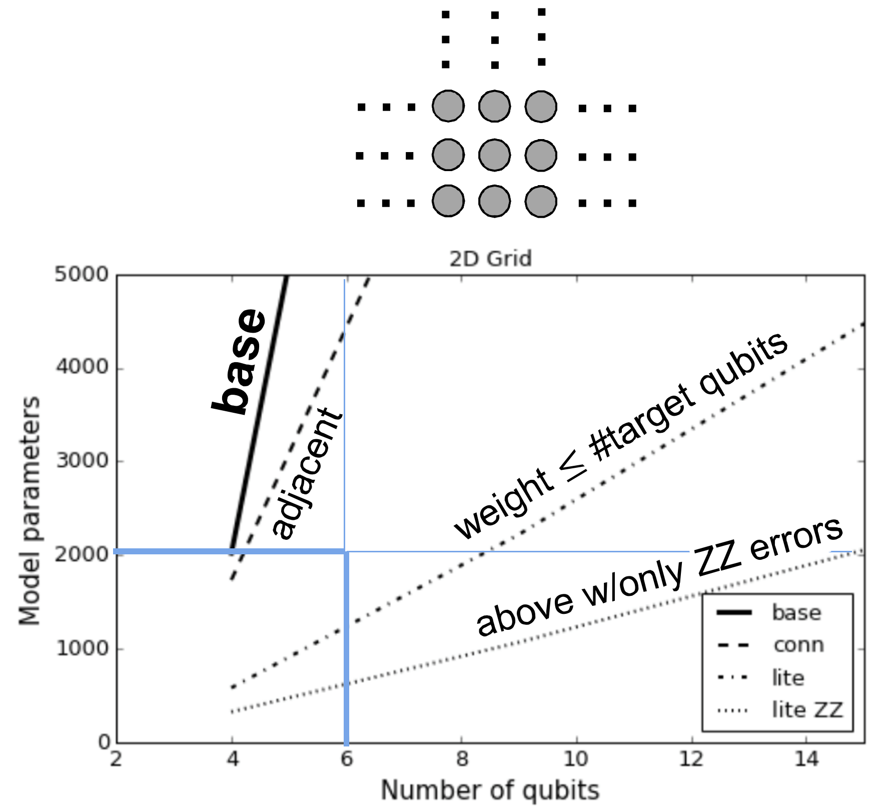


- Does:
  - Gives users access to the tradeoff space between tomographic detail and required data.
  - Pushed **“#qubits you can perform tomography on**” to > 2 (maybe ~ 6?)
  - Provide more direct link with predictive QEC simulations
- Doesn’t:
  - push **“#qubits you can simulate**” any higher – *still* limited by cost of forward simulation (density matrix propagation in our case)

[Quant-ph arXiv:1710.05867v1]

Parameter Scaling





- **Linear scaling** of parameters with #qubits
- Ability to tradeoff model richness with qubits or time.
  - Easy to create **nested** models
  - Practical for 2-8(?) qubits
- Pushes reason for tomography's exponential scaling to qubit simulation (*resources ~ parameters * simulation_cost*)

Next steps & open questions

- Faster quantum-state propagation
  - Currently use density-matrix propagation (4^N)
  - Alternatives: state-vector (2^N); compact representations?
  - …**Or** ways to perform tomography without state propagation.
- Sequence selection (how many & which ones)
- Gauge degrees of freedom
- Efficiency: precision vs. time, # of experiments
- Model selection criteria

Summary

- Suggested a way to construct **reduced-parameter, nested, multi-qubit models**.
- Showed that families of these models can easily have **parameter counts which are polynomial** (even linear) in the number of qubits.
- Showed that it is **possible to use standard likelihood maximization to fit a "base"-type model** to raw count data from a simulated N-qubit linear-chain processor, where N <= 6. (Essentially a "sparse quantum process tomography" on 6 qubits)

Excuses ☺

- Review and Approval
- Early march meeting
- My relatives
- Artic vortex
- El Niño