SAND2022-2506C

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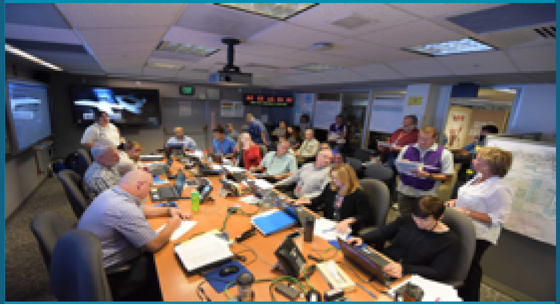
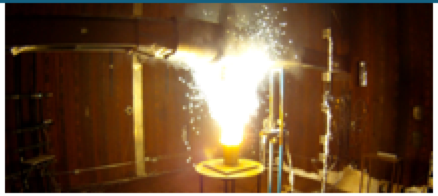
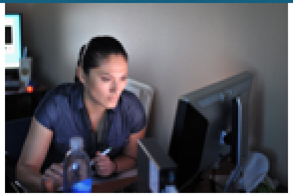
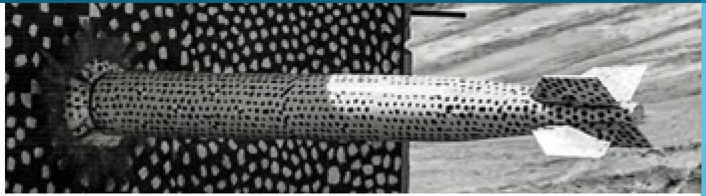
Scalable verification of quantum algorithm circuits









Mohan Sarovar

Stefan Seritan, Erik Nielsen, Kenneth Rudinger, Kevin Young, Robin Blume-Kohout, **Tim Proctor**

Sandia National Laboratories

APS March Meeting 2022

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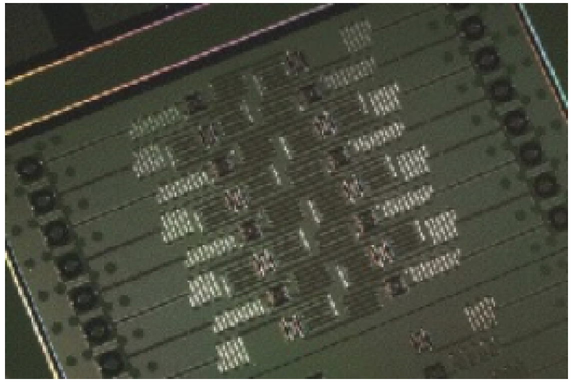
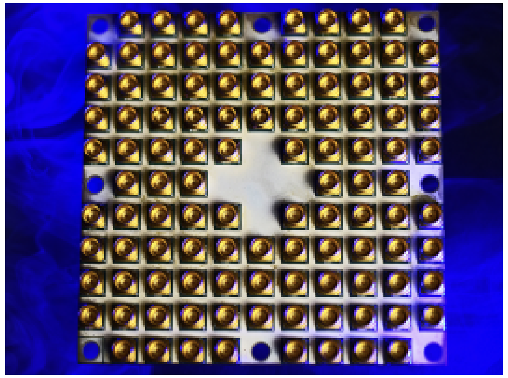
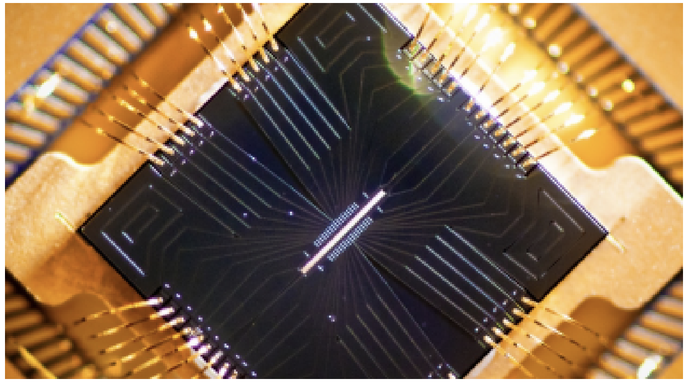
Verification of quantum computer output


IBM


Intel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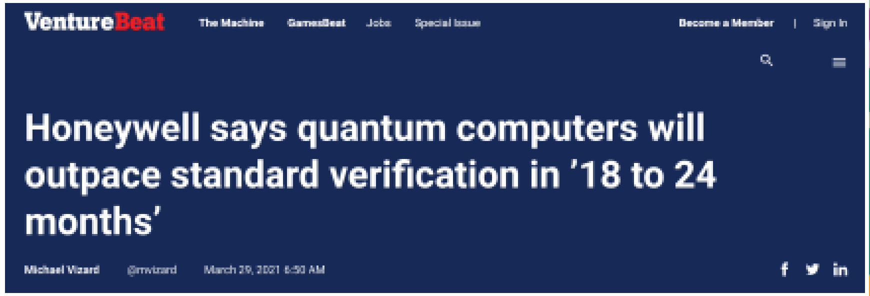
In the next decade: 100s – 1000s of qubits + poly depth circuits

- How do we verify the correctness of the output of such systems?
  - Many interesting applications will have output that is not efficiently verifiable by classical computers
  - Microscopic modeling will be impossible



March 29, 2021

Scalable verification

Verification goal: estimate fidelity of actual circuit with ideal circuit

We are given a circuit of interest C, which must contain only:

- Arbitrary single-qubit gates
- Two-qubit gates that are self-inverse and Clifford (not an essential assumption).

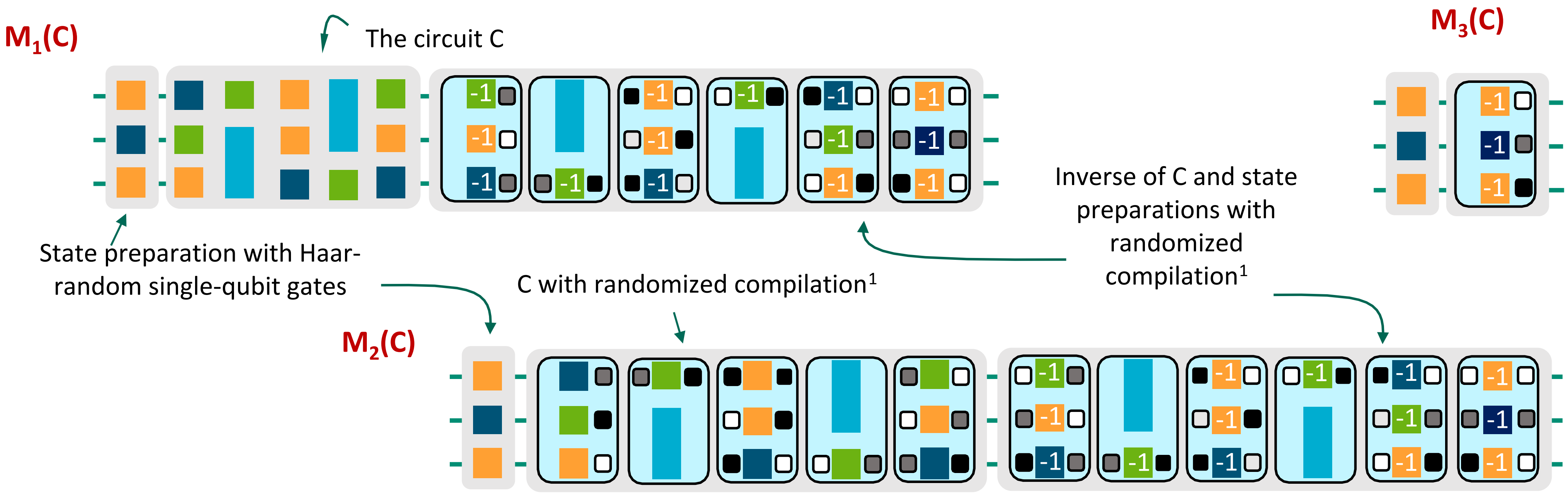
Estimate fidelity of an implementation of this circuits using data from executing circuits sampled from **three different mirror circuit [1] ensembles**

- Each ensemble is a slight variation of the circuit followed by its inverse

[1] Proctor et al. "Measuring the capabilities of quantum computers" Nature Physics, **18**, 75 (2022)

The three ensembles

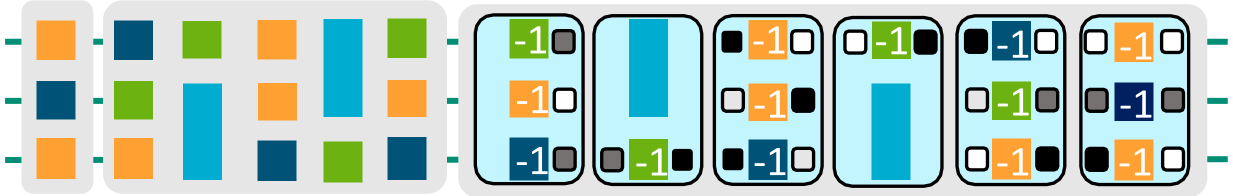
Original circuit



1Wallman, PRA 94 052325 (2016)

The three ensembles

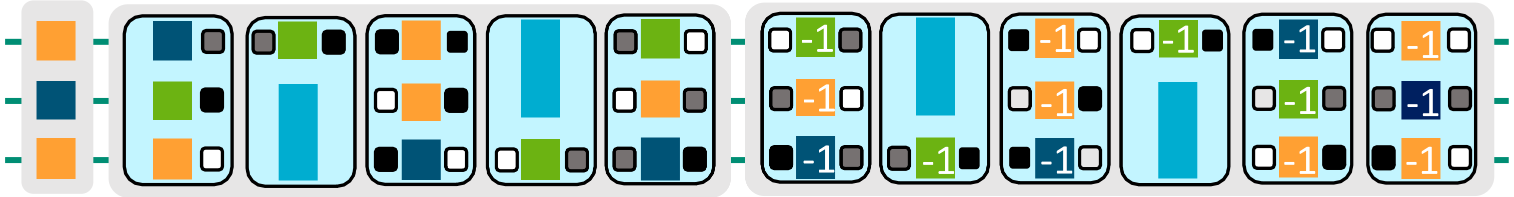
$M_1(C)$



S_1 = Success Prob(M_1(C)) ≈ F(SPAM) * F(C) * F(RC[C^{-1}])]

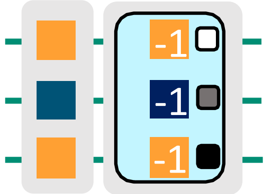
F(C) = The process fidelity with which C is implemented

$M_2(C)$



S_2 = Success Prob(M_2(C)) ≈ F(SPAM) * F(RC[C]) * F(RC[C^{-1}]) ≈ F(SPAM) * F(RC[C^{-1}])^2

$M_3(C)$



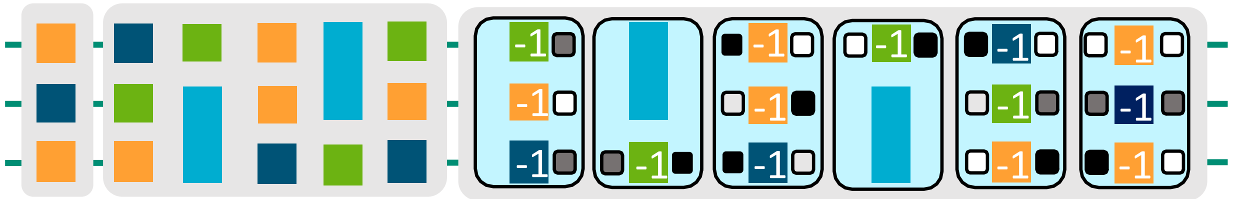
S_3 = Success Prob(M_3(C)) ≈ F(SPAM)

$F(C) \approx S_1 / (S_2 \times S_3)^{1/2}$

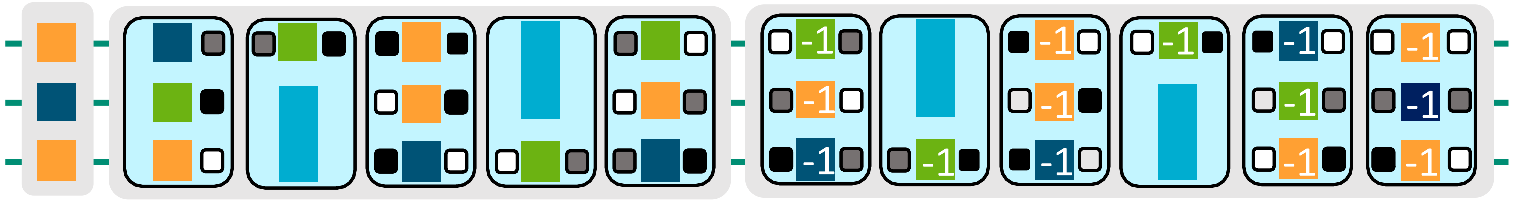
The actual formula we use is slightly more complex, because (process) fidelities don't multiply…

Circuit fidelity estimate

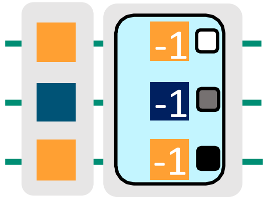
$M_1(C)$



$M_2(C)$



$M_3(C)$



Our estimate for F(C)

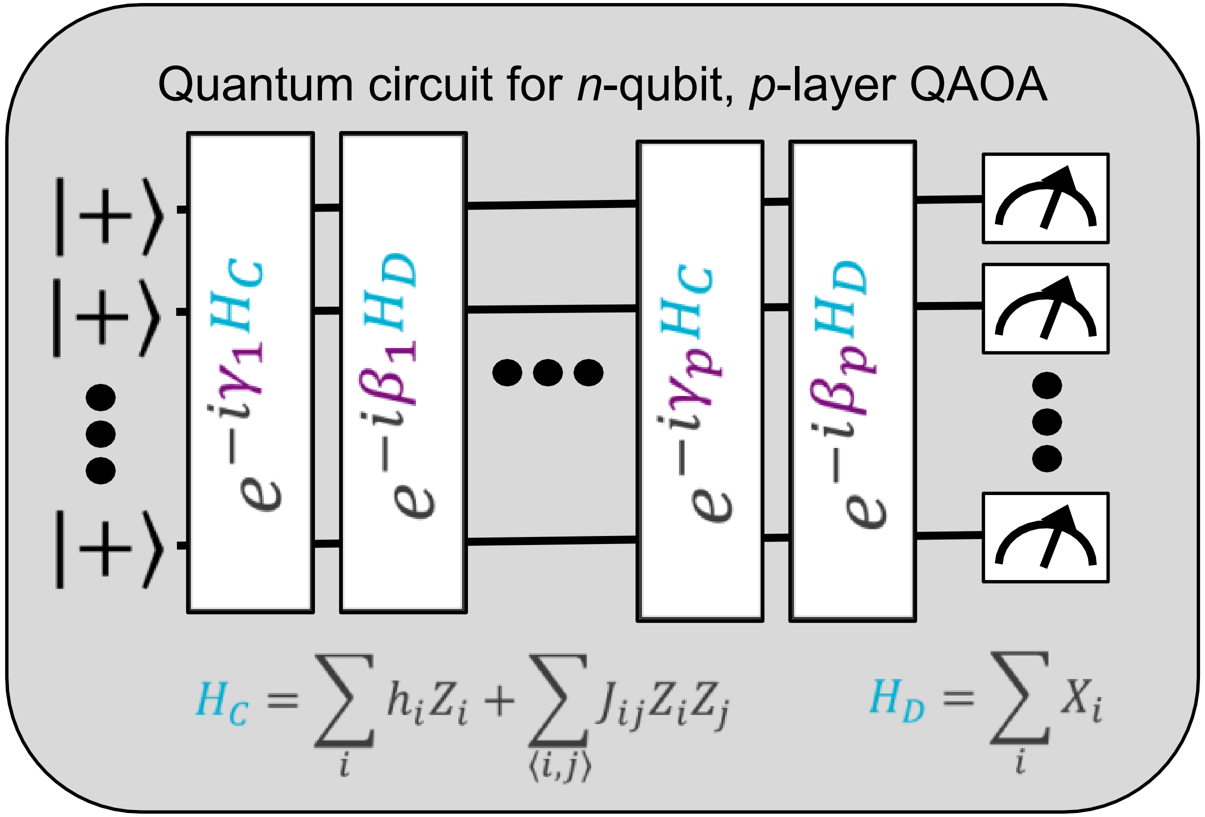
$$\chi_F(c) = 1 - \frac{4^n - 1}{4^n}\left(1 - \frac{\mathbb{E}[\gamma(M_1(c))]}{\sqrt{\mathbb{E}[\gamma(M_2(c))]\mathbb{E}[\gamma(M_3(c))]}}\right)$$

This is efficient to estimate, for any number of qubits, except when F(C) is very small!

$$\gamma = \frac{4^n}{4^n - 1}\left[\sum_{k=0}^{n}\left(-\frac{1}{2}\right)^k h_k\right] - \frac{1}{4^n - 1},$$

Illustrations

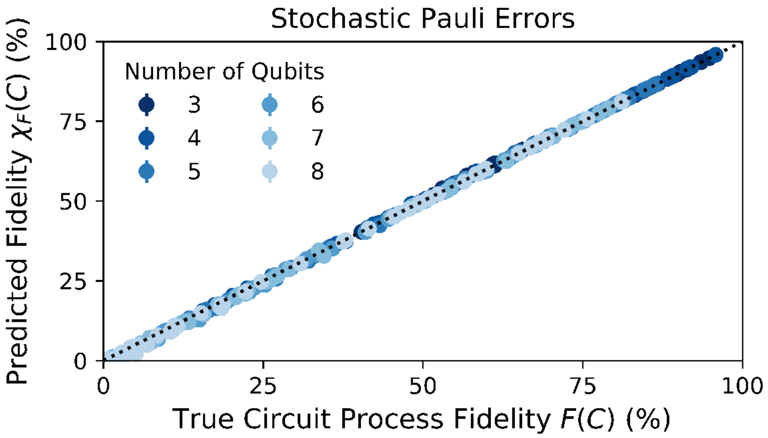
Quantum approximate algorithm (QAOA) circuits



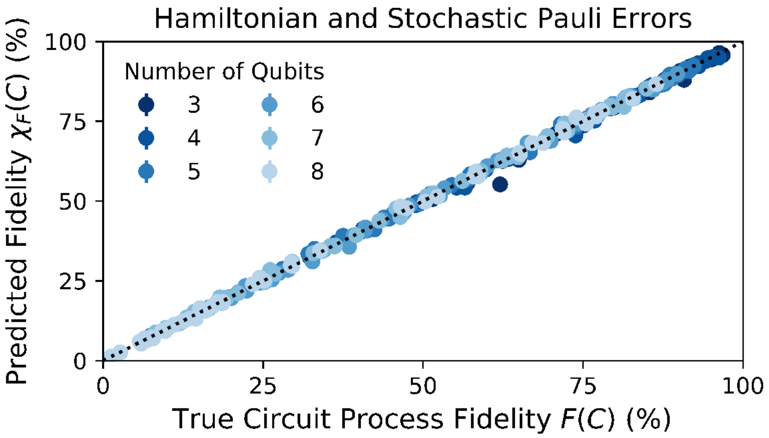
- Variable number of qubits, QAOA layers ranging from p=1 to p=10

Illustrations

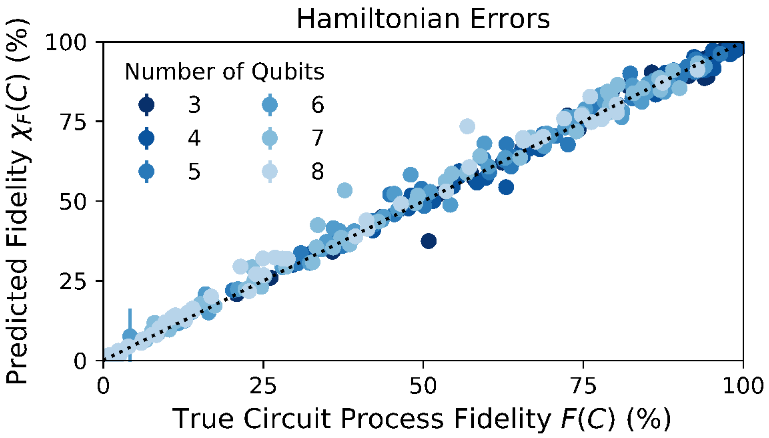
Comparison of estimated process fidelity to actual process fidelity



Perfect correlation under stochastic noise model



Excellent correlation under noise model with equal stochastic and Hamiltonian contributions



Good correlation, with some outliers, under noise model with *only* Hamiltonian/coherent errors

— n = 3 - 8 qubits
— p = 1,2,5,8,10 QAOA layers
— For each (n, p) there are 10 problem instances (300 total circuits).
—1000 of each type of mirror circuit for each QAOA circuit.
— Each QAOA instance (+ the 3000 corresponding mirror circuits) has it's own randomly sampled error model.

Summary

- We have developed a *scalable* way to verify accuracy of quantum circuit implementations

- Scalability:
  - No classical simulation of quantum circuits necessary
  - Requires execution of an ensemble of auxiliary circuits of roughly twice the depth
  - Analysis and sample complexity have weak dependence on *number of qubits, circuit depth*

- Solves one of the major challenges emerging in the NISQ era of quantum computing

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