Dance with Noise in NISQ Era
— A NASA Perspective on Quantum Computing

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ICCAD 2019, West Minster, CO
Quantum Computing:
Explore “bizarre” features of quantum mechanics

Superposition

Entanglement

Quantum Tunneling
The Noisy Intermediate-Scale Quantum (NISQ) Era

**Hardware Limitations:**
- up to 100 physical qubits
- (some) planar connectivity
- Limited in circuit depth
- Little to no error correction

**Are NISQ devices useful?**
- Quantum supremacy
- Optimization
- Quantum chemistry
- Quantum machine learning
- …
Quantum supremacy through random circuit

- **Advantage** Sampling the output of a pseudo-random quantum circuit
- **qFlex**: state of art classical simulator
  [https://github.com/ngnrsaa/qflex](https://github.com/ngnrsaa/qflex)
  [Villalonga et. al., accepted on NPJ QIP 2019]

- **Application** random-number generator
- **Why achievable in NISQ era**

  “Random circuits are a suitable choice for benchmarking because they do not possess structure and therefore allow for limited guarantees of computational hardness”

  — Randomness is desired

  Signature is resilient against noise.
Where to look next?

NISQ era: Challenging for fault tolerant quantum computing

Need to find ways to deal / live with noise

√ Quantum Supremacy: random circuit

Two other (out of many) NASA QuAIL efforts:

• Advanced qubit-routing (quantum circuit compilation)

• Variational quantum heuristics for optimization and quantum chemistry
  — like Quantum Alternating Operator Ansatz (QAOA), Variational Quantum Eigensolver (VQE)

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Noise-aware qubit routing / circuit compilation

Circuit for an algorithm is usually written at a hardware-agnostic level

— Non-commuting gates should obey the ordering dictated by the algorithm (circuit)

— When a set of 2-qubit gates commute but cannot be executed at the same time, E.g., $[ZZ(q_1, q_2), ZZ(q_2, q_3)] = 0$
  
  Does not matter ideally, ordering can affect circuit length/depth, and therefore the effect of noise.

— On hardware with restricted qubit connectivity, SWAPs are needed.
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Pioneered temporal planning & for compilation for NISQ devices
  - Collaborating with domain experts at NASA, utilizing state of the art temporal planners

For superconducting qubits
  — Taking Rigetti and Google h/w constraints
  — Minimizing makespan (gate-duration aware)
  — Including Crosstalk
  — Logical-to-Physical mapping/allocation

Venturelli, Do, Rieffel, Frank., Quantum Science and Technology (2018)
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— Benchmarking against analytical bounds
— Demonstrating effect of native gate sets
— Raising challenges and inspiring new planning/scheduling algorithms

Venturelli, Do, Rieffel, Frank., Quantum Science and Technology (2018)
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Noise-aware qubit routing / circuit compilation

Beyond superconducting qubit platform, noise and gate infidelity are posing other challenges. We are looking to
— Develop hardware specific models and goals
— Further exploiting planners for compilation

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**NISQ era: Challenging for fault tolerate quantum computing**

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Quantum Computing for NASA Applications

**Objective:** Find “better” solution
- Faster
- More precise
- Not found by classical algorithm

**Common Feature:** Intractable problems on classical supercomputers

- Data Analysis and Data Fusion
- Air Traffic Management
- Mission Planning, Scheduling, and Coordination
- Anomaly Detection and Decision Making
- V&V and Optimal Sensor Placement
- Robust Network Design for UAV

Image from P. Kopardekar et. al., Unmanned Aircraft System Traffic Management (UTM) Concept of Operations, DASC 2016
Quantum Approximate Optimization Algorithms (QAOA)

Cost Hamiltonian
encoding cost function

Mixer Hamiltonian
generating transitions
between different states

Variational parameters: \((\gamma_1, \gamma_2, \ldots, \beta_1, \beta_2, \ldots)\)

Work principle: constructive interference

Case shown speedup: reproduces quantum speedup in Grover’s algorithm for needle-in-a-haystack search

Farhi, Goldstone, and Gutmann, arXiv:1411.4028

Zhang, Rieffel, and Wang, PRA 2017
—> Symmetry Preserving Quantum Alternating Operator Ansatz (QAOA)

Exploit local or global symmetries in the problem

E.g., QAOA for constrained optimization

Design a mixer that contains the quantum evolution in the subspace that satisfies the constraints.

One-hot encoding:

\[ \sum_{c=1}^{k} x_{v,c} = 1 \iff \sum_{c=1}^{k} \sigma_{v,c}^z = k - 2 \]

Symmetry (constraints): preserve Hamming weight of subset

Standard mixer: \( X \)

symmetry-preserving mixer: \( XX + YY \)

Wang, Rubin, Dominy, Rieffel, arXiv:1904.09314

Hadfield, Wang, O'Gorman, Rieffel, Venturelli, Biswas, arXiv 1709.03489
XY complete-graph mixer in linear depth $\kappa-1$

Special for the Hamming-1 subspace:

\[
\begin{align*}
\exp[-i\beta \sum_{c,c'\in[0,3]} (XY)_{c,c'}] = \\
\exp[-i\beta((XY)_{0,1} + (XY)_{2,3})] \\
\exp[-i\beta((XY)_{0,2} + (XY)_{1,3})] \\
\exp[-i\beta((XY)_{0,3} + (XY)_{1,2})].
\end{align*}
\]

1D XY model in logarithmic depth

Through Jordan-Wigner transformation

\[
H_{XY} = \sum_{c=1}^{\kappa} (\sigma_c^x \sigma_{c+1}^x + \sigma_c^y \sigma_{c+1}^y)
\]

\[
\downarrow
\]

\[
H_{XY} = 2 \sum_{c=1}^{\kappa} (a_c^\dagger a_{c+1} + \text{h.c.}),
\]

and Fermionic Fourier transform,

\[
\hat{a}_c^\dagger = \text{FFFT}^\dagger \hat{f}_k^\dagger \text{FFFT} \equiv \frac{1}{\sqrt{\kappa}} \sum_c e^{i2\pi c k} \hat{f}_k^\dagger
\]

\[
H_{XY} = \sum_{k=1}^{\kappa} E_k f_k^\dagger f_k \quad H_{XY}^{(k)} = \sum_{k=1}^{\kappa} E_k (1 - \sigma_k^z) / 2
\]

FFFT : $O(\log(\kappa))$ depth

Wang, Rubin, Dominy, Rieffel, arXiv:1904.09314
Performance Comparison: Penalty vs XY

XY wins over X

(a) Penalty + X-mixer

(b) XY mixer

Small problems solved at low-depth with XY

Optimal results for the Prism graph

XY wins over X

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Small problems solved at low-depth with XY

Optimal results for the Prism graph

- Size of search space
  - Penalty + X-mixer: Full Hilbert space
  - XY mixer: Feasible subspace
  - Ratio: \( \left( \frac{k}{2^k} \right)^n \)

The feasible space **shrinks exponentially** with \( n \).

Symmetry-preserving QAOA circuits for noise characterization

Subspace for one vertex
Noise exponentially shrinks the probability of staying in the desired subspace with problem size and QAOA level

Probability of staying in the desired subspace is exactly computable under noise—can be used for experimental noise characterization

\[
\langle P_{\text{feas}} \rangle = \text{Tr}[\rho_0 U_1 \mathcal{E}(U_2 \mathcal{E}(U_3 \cdots \mathcal{E}(P_{\text{feas}}^i) \cdots )U_2)U_1]
\]

\[
= \text{Tr}[\rho_0 \mathcal{E}(\cdots \mathcal{E}(P_{\text{feas}}^i) \cdots )]
\]

Symmetry-preserving QAOA circuits for noise characterization, Streif, Rieffel, Wang, in preparation
Summary

Things we study to live with noise in NISQ era

• Using planning tools for qubit routing / quantum circuit compilation

• Symmetry-preserving QAOA circuits for more efficient optimization

• Symmetry-preserving QAOA circuits for noise characterization