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

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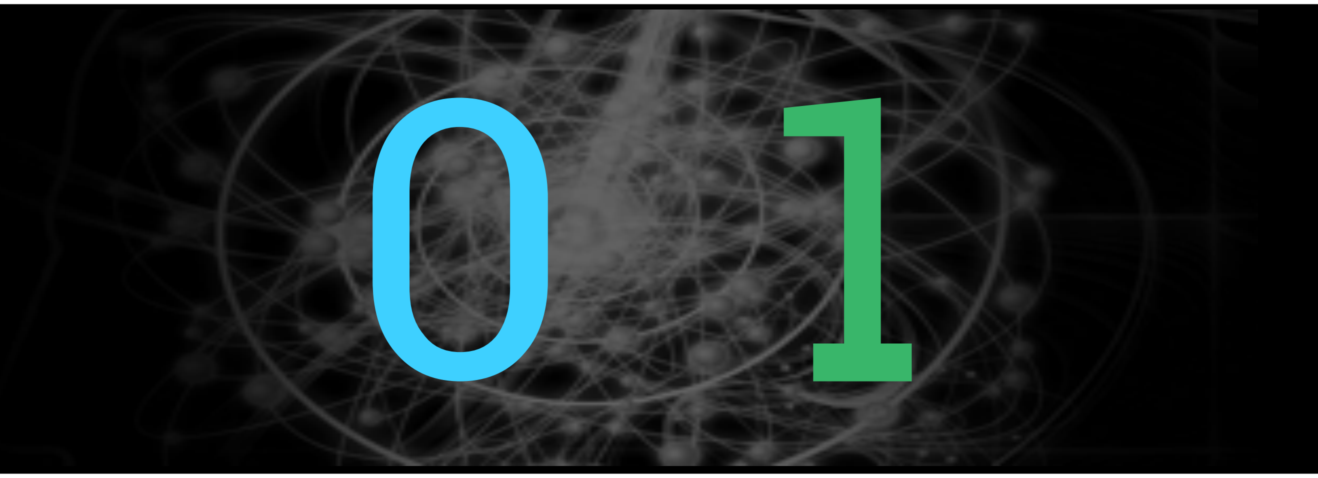
ICCAD 2019, West Minster, CO

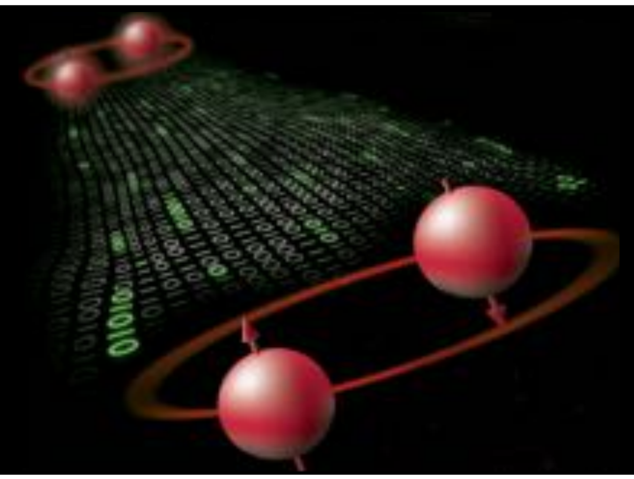
Quantum Computing:

Explore “bizarre” features of quantum mechanics

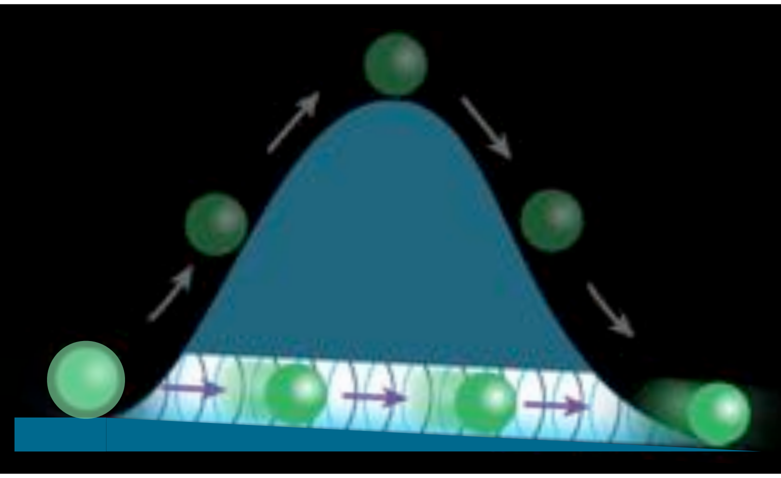
Superposition



Entanglement

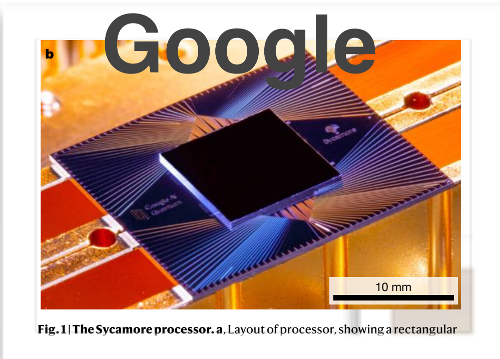


Quantum Tunneling

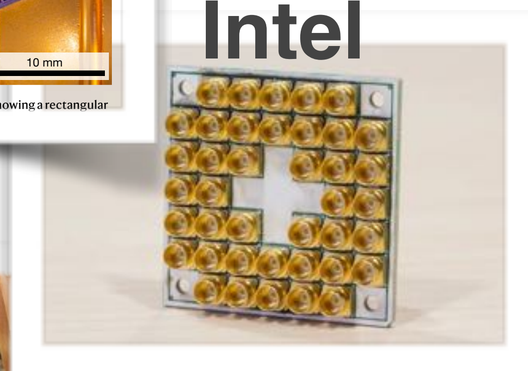


The Noisy Intermediate-Scale Quantum (NISQ) Era

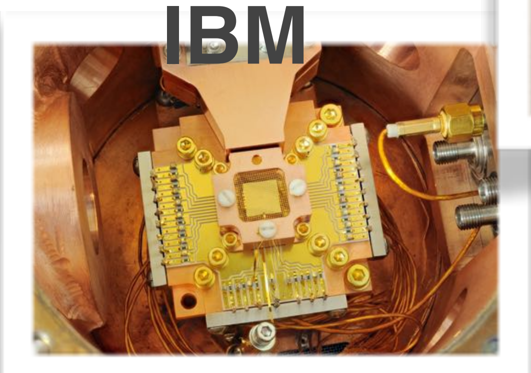
Google



Intel

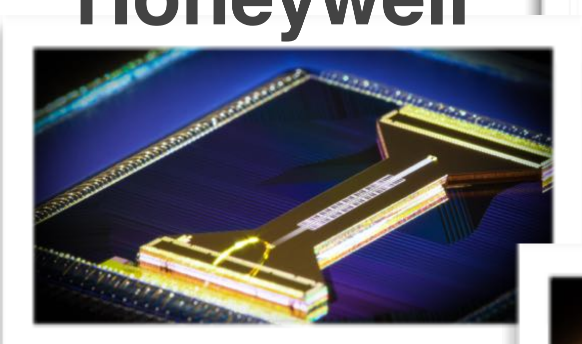


IBM



Rigetti

Honeywell



IonQ

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
- …

National Aeronautics and Space Administration

Ames

Discovery Innovations Solutions

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

  [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.

nature

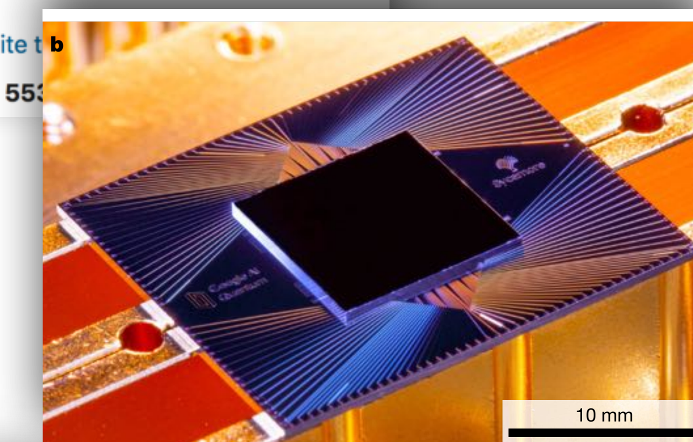
Article | Published: 23 October 2019

Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, [...] John M. Martinis

Nature **574**, 505–510(2019) | Cite t

551k Accesses | **2** Citations | 55



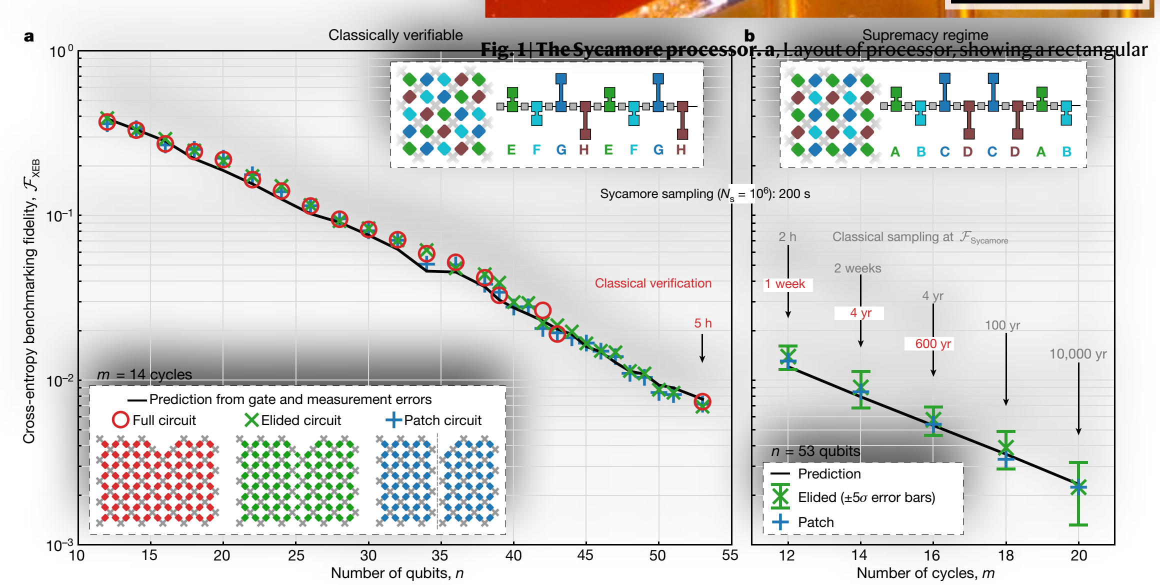


Fig. 1 | The Sycamore processor. a, Layout of processor, showing a rectangular

Where to look next?

NISQ era: Challenging for fault tolerate quantum computing

Need to find ways to deal / live with noise

√ Quantum Supremacy: random circuit

***qFlex**: state of art classical simulator*
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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(q1, q2), ZZ(q2, q3)] = 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

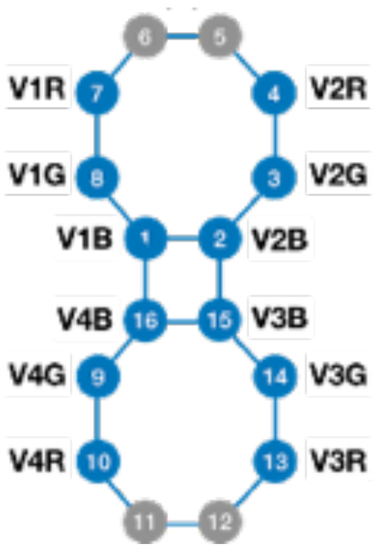
— Minimizing makespan (gate-duration aware)

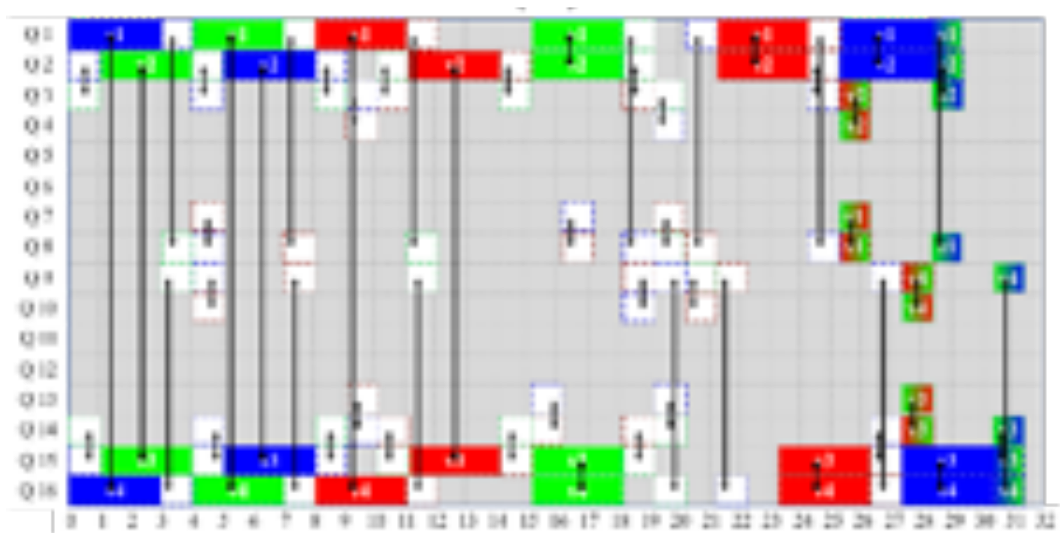
— Including Crosstalk

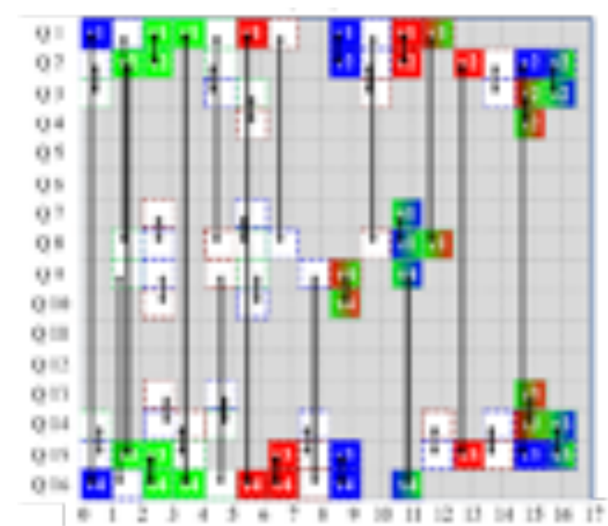
— Logical-to-Physical mapping/allocation

Venturelli, Do, Rieffel, Frank., Quantum Science and Technology (2018)

Noise-aware qubit routing / circuit compilation







Do et. al., Planning for quantum circuit compilation for graph coloring, In preparation

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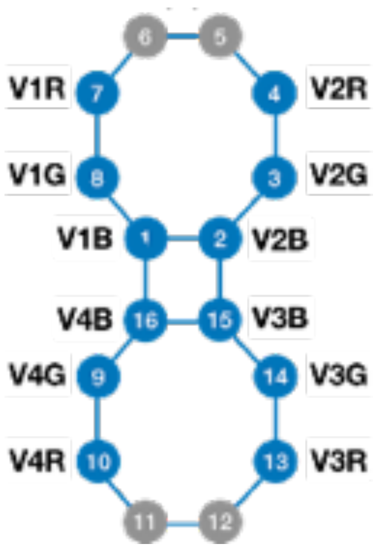

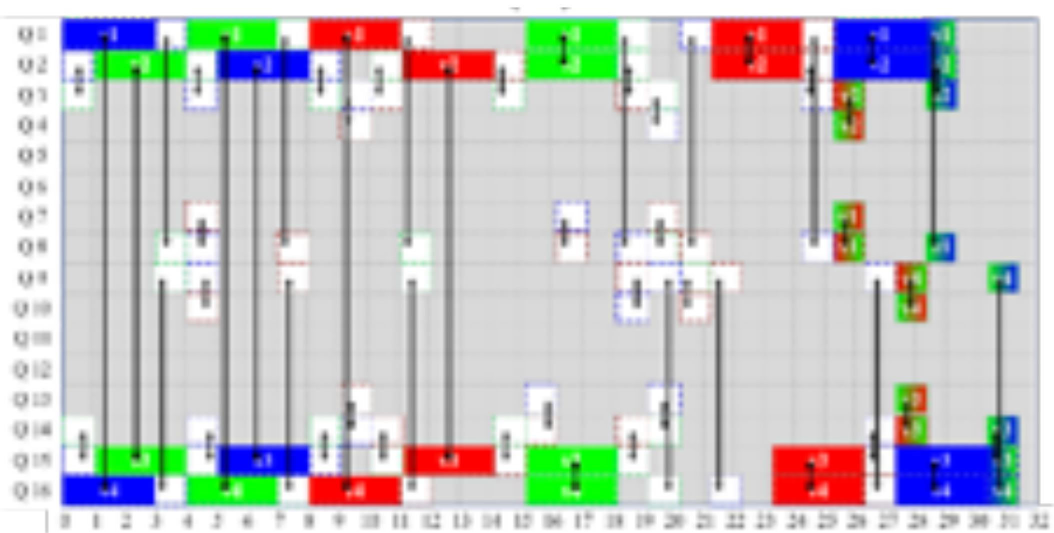

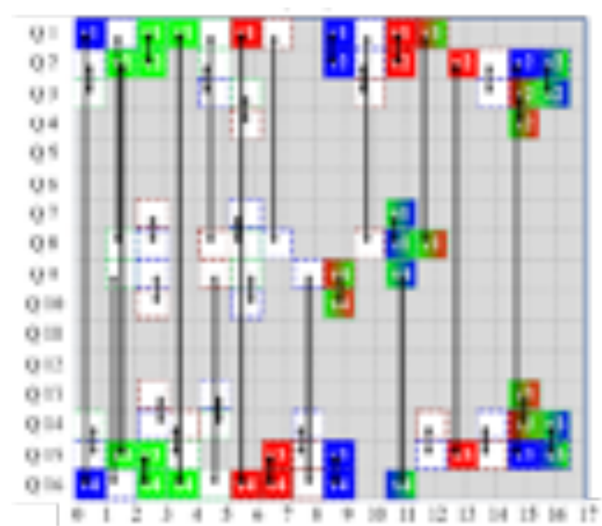

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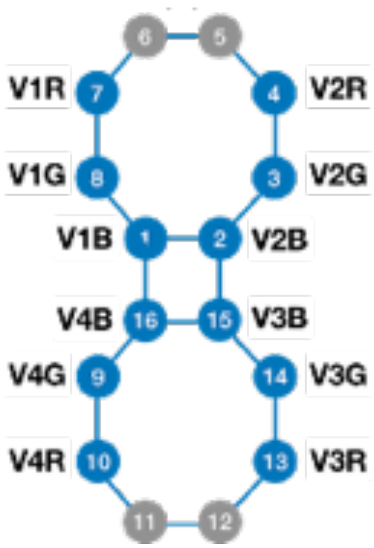
— Benchmarking against analytical bounds
— Demonstrating effect of native gate sets
— Raising challenges and inspiring new planning/scheduling algorithms

Venturelli, Do, Rieffel, Frank., Quantum Science and Technology (2018)

Generalized swap networks for near-term quantum computing, B O'Gorman 2019]

Noise-aware qubit routing / circuit compilation



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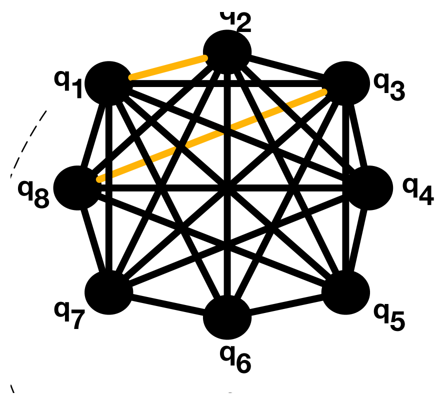

Beyond superconducting qubit platform, noise and gate infidelity are posing other challenges. We are looking to
— Develop hardware specific models and goals
— Further exploiting planners for compilation

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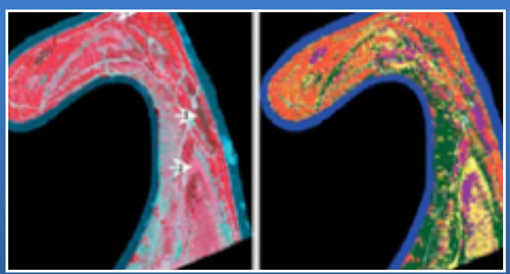
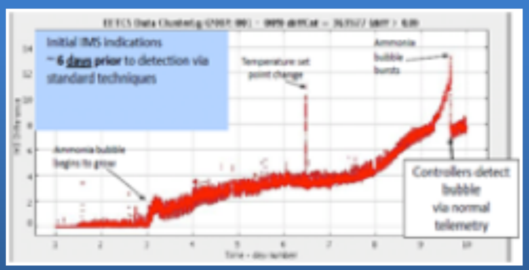
Quantum Computing for NASA Applications

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

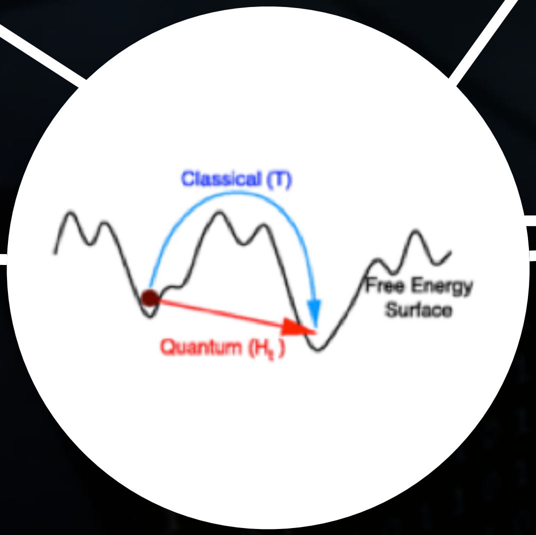


Data Analysis and Data Fusion

Anomaly Detection and Decision Making



Air Traffic Management



V&V and Optimal Sensor Placement

Mission Planning, Scheduling, and Coordination

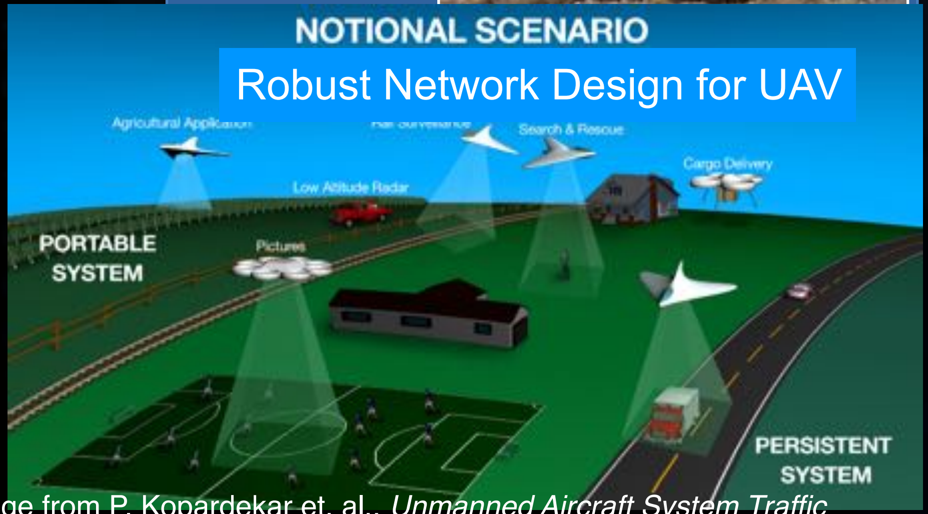
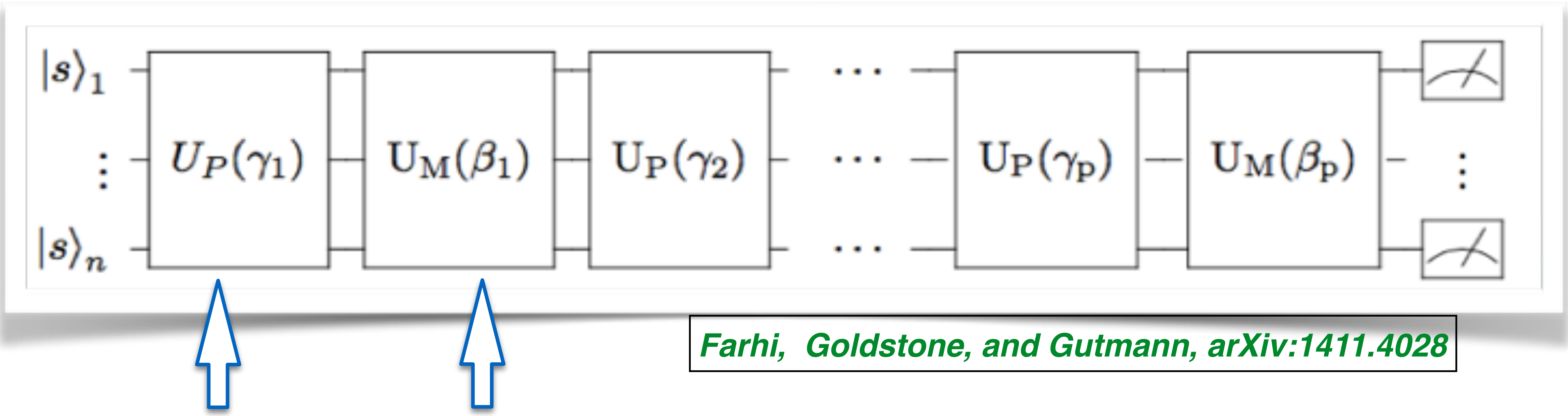


Image from P. Kopardekar et. al., *Unmanned Aircraft System Traffic Management (UTM) Concept of Operations, DASC 2016*

Common Feature: Intractable problems on classical supercomputers

Quantum Approximate Optimization Algorithms (QAOA)



Farhi, Goldstone, and Gutmann, arXiv:1411.4028

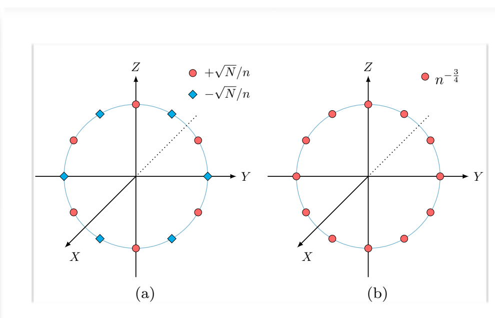
Cost Hamiltonian encoding cost function

Mixer Hamiltonian generating transitions between different states

Variational parameters: $(\gamma_1, \gamma_2, \cdots, \beta_1, \beta_2, \cdots)$

Work principle: constructive interference

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



query complexity of our algorithm is

$$T(n) \simeq \frac{2\pi}{\arg(\alpha)} \simeq \frac{\pi}{2\sqrt{2}} 2^{n/2}$$

Zhang, Rieffel, and Wang, PRA 2017

—> Symmetry Preserving Quantum Alternating Operator Ansatz (QAOA)

Exploit local or global symmetries in the problem

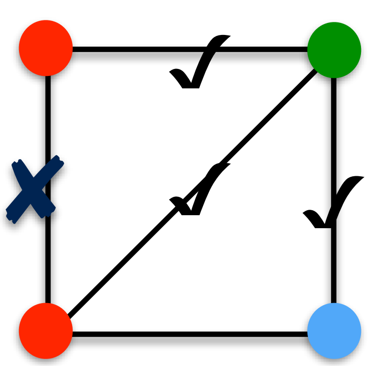
E.g., QAOA for constrained optimization

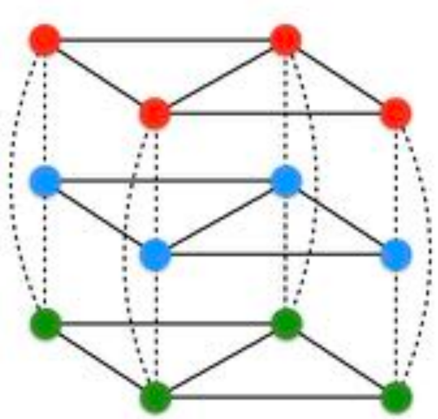
Hadfield, Wang, O'Gorman, Rieffel, Venturelli, Biswas, arXiv 1709.03489

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

One-hot encoding: $$\sum_{c=1}^{k} x_{v,c} = 1 \Longleftrightarrow \sum_{c=1}^{k} \sigma^z_{v,c} = k-2$$

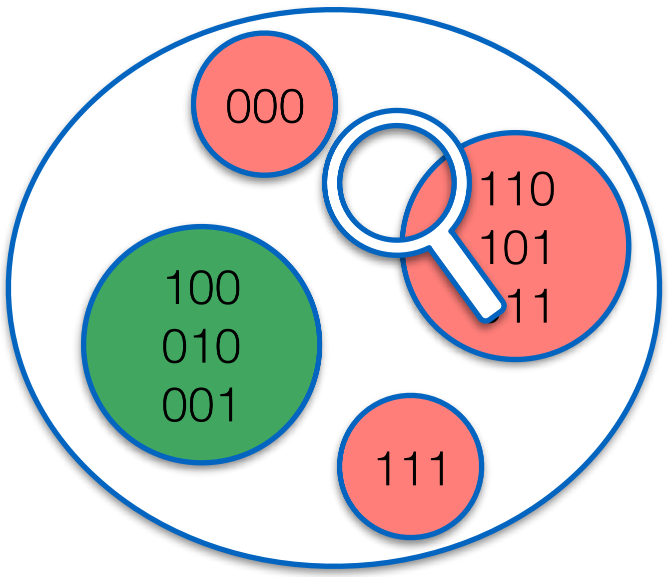
Symmetry (constraints): preserve Hamming weight of subset





Standard mixer: *X*

symmetry-preserving mixer: *XX+YY*



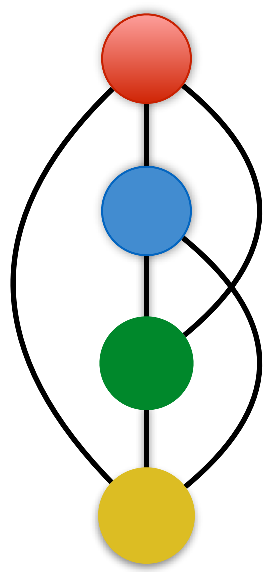
Wang, Rubin, Dominy, Rieffel, arXiv:1904.09314

Efficient Implementation

XY **complete**-graph mixer in **linear depth** *κ-1*

Special for the Hamming-1 subspace:

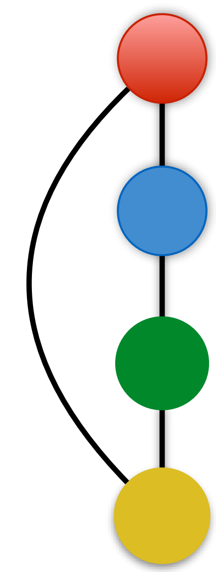
$$\exp[-i\beta \sum_{c,c'\in[0,3]} (XY)_{c,c'}] =$$
$$\exp[-i\beta\big((XY)_{0,1}+(XY)_{2,3}\big)]$$
$$\exp[-i\beta\big((XY)_{0,2}+(XY)_{1,3}\big)]$$
$$\exp[-i\beta\big((XY)_{0,3}+(XY)_{1,2}\big)]\ .$$



1D XY model in **logarithmic** depth

Through Jordan-Wigner transformation

$$H_{XY} = \sum_{c=1}^{\kappa} \left(\sigma_c^x \sigma_{c+1}^x + \sigma_c^y \sigma_{c+1}^y\right)$$
$$\downarrow$$
$$H_{XY} = 2\sum_{c=1}^{\kappa} \left(a_c^\dagger a_{c+1} + \text{h.c.}\right)\ ,$$



and Fermionic Fourier transform,

$$\hat{a}_c^\dagger = \text{FFFT}^\dagger \hat{f}_k^\dagger \text{FFFT} \equiv \frac{1}{\sqrt{\kappa}} \sum_c e^{i2\pi ck} \hat{f}_k^\dagger$$

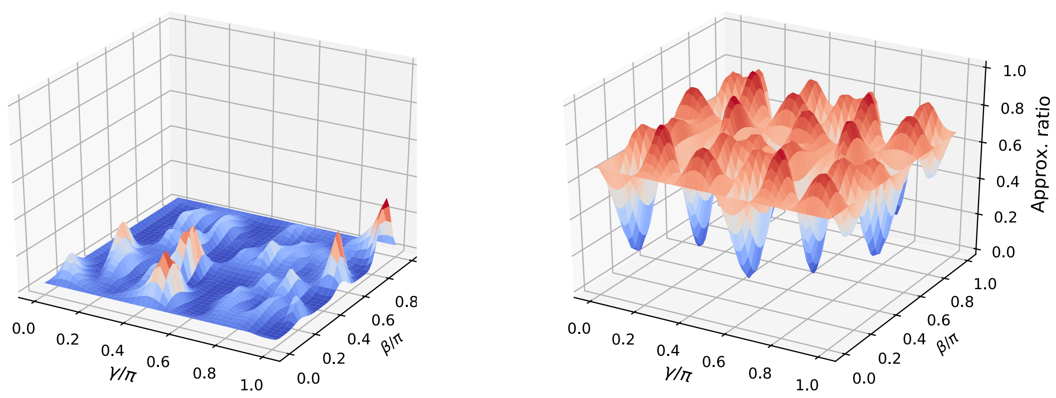
$$H_{XY} = \sum_{k=1}^{\kappa} E_k f_k^\dagger f_k \qquad H_{XY}^{(k)} = \sum_{k=1}^{\kappa} E_k \left(1-\sigma_k^z\right)/2$$

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

Wang, Rubin, Dominy, Rieffel, arXiv:1904.09314

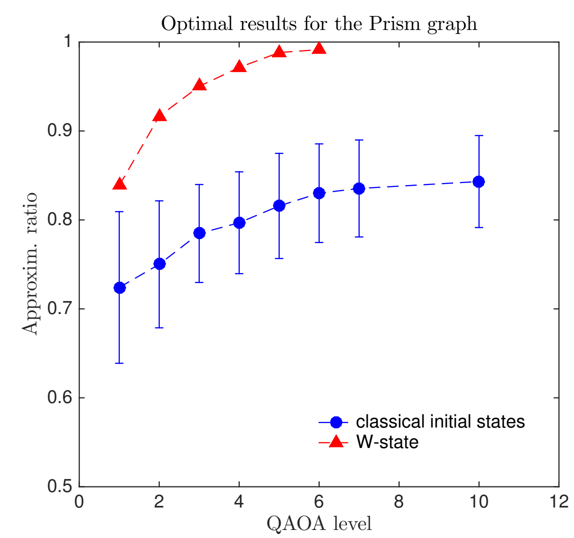
Performance Comparison: Penalty vs XY

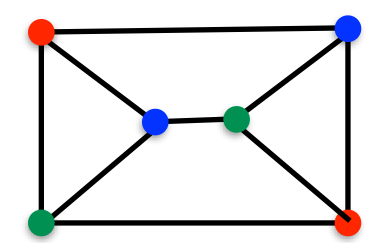
XY wins over X

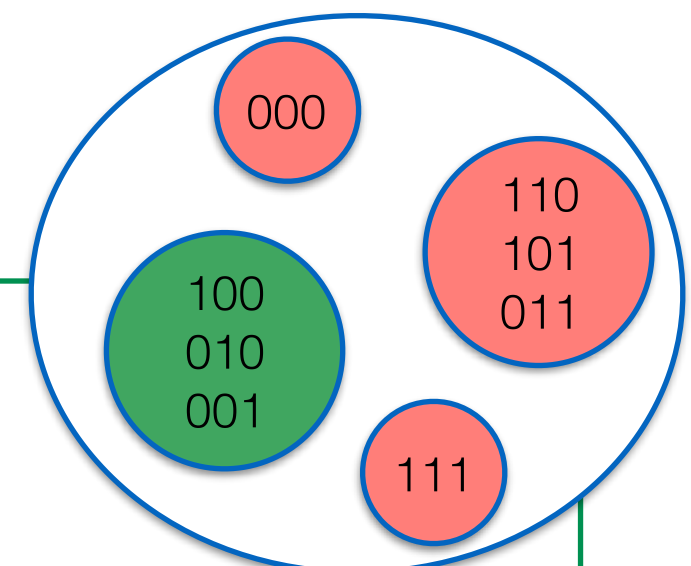


(a) (b)

Small problems solved at low-depth with XY





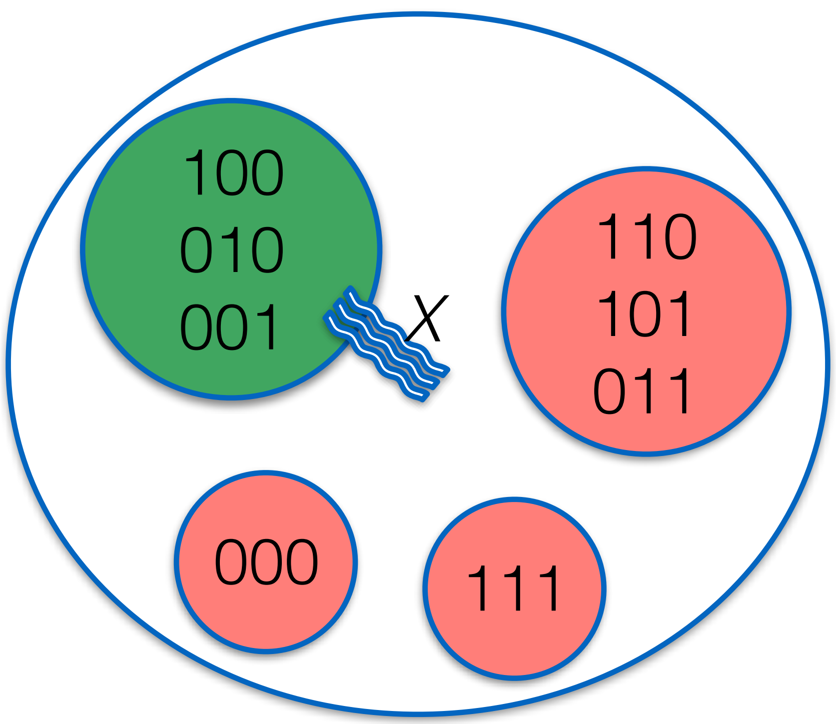


- Size of search space

Penalty + X-mixer		Full Hilbert space	2^{nk}
XY mixer		Feasible subspace	k^n
Ratio:	$\left(\frac{k}{2^k}\right)^n$	The feasible space **shrinks exponentially** with *n*.	

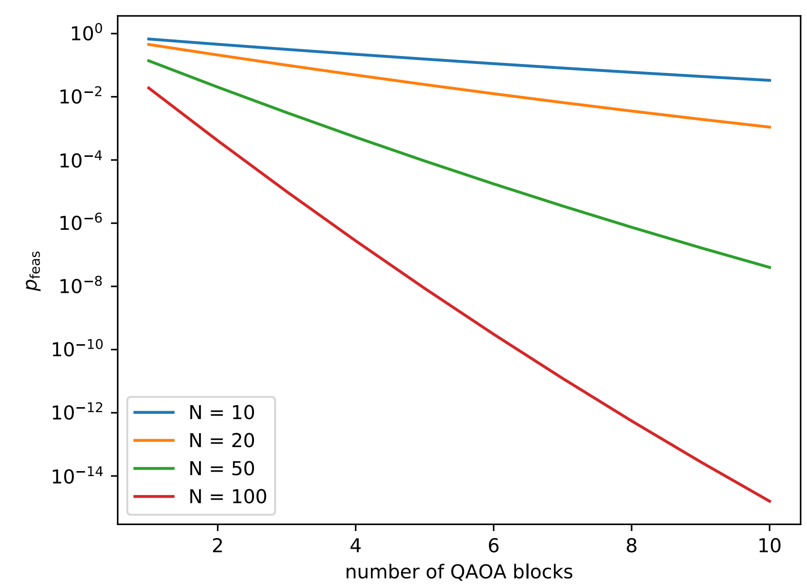
[Wang, Rubin, Dominy, Rieffel, arXiv:1904.09314]

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



(a) $p_{\text{noise}} = 0.01$

$$\begin{aligned}\langle \mathcal{P}^i_{\text{fea}} \rangle &= \text{Tr}[\rho_0 U_1^\dagger \mathcal{E}(U_2^\dagger \mathcal{E}(U_3^\dagger \cdots \mathcal{E}(U_l^\dagger \mathcal{E}(\mathcal{P}^i_{\text{fea}})U_l) \cdots U_3)U_2)U_1] \\ &= \text{Tr}[\rho_0 \mathcal{E}(\mathcal{E}(\cdots \mathcal{E}(\mathcal{P}^i_{\text{fea}})) \cdots)]\end{aligned}$$

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

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**


QuAIL NASA