



A NASA perspective on quantum AI, error correction, and beyond

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Lead

*Quantum Artificial Intelligence Lab (QuAIL)
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NASA QuAIL mandate: *Determine the potential for quantum computation to enable more ambitious and safer NASA missions in the future*

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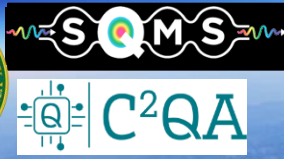
Ryan LaRose (Michigan State)

Sarah Muschinske (MIT)

Bryan O’Gorman (UC Berkeley)

Anthony Polloreno (Univ. Colorado, Boulder)

+ active year-round intern program



Quantum Computing R&D at NASA Ames



Communication & Networks

Quantum networking

Distributed QC

Application Focus Areas

Planning and scheduling

Material science

Fault diagnosis

Machine learning

Software Tools & Algorithms

Quantum algorithm design

Compiling to hardware

Mapping, parameter setting, error mitigation

Hybrid quantum-classical approaches

Solvers & Simulators

Simulation of quantum systems, under noise

HPC quantum circuit simulators

Physics Insights

Co-design quantum hardware

New Era for Quantum Computing

Quantum supremacy achieved

- Perform computations not possible on even largest supercomputers in reasonable time
- Google – NASA – ORNL collaboration



F. Arute et al. (2019), Quantum supremacy using a programmable superconducting processor, Nature 574, 505-510

... but so far only for a toy problem

- Quantum hardware currently too small and non-robust to solve practical problems intractable on classical computers
- These devices need to scale up and become more reliable

So what to do in the interim?

- Unprecedented opportunity to invent, explore, and evaluate quantum algorithms *empirically*

2023 Update

A. Morvan, B. Villalonga, X. Mi, S. Mandrà, et al., (2023) Phase transition in Random Circuit Sampling, arXiv:2304.11119

Exp.	1 amp.	1 million noisy samples		
	FLOPs	FLOPs	XEB fid.	Time
SYC-53 [9]	$6.44 \cdot 10^{17}$	$2.60 \cdot 10^{17}$	$2.24 \cdot 10^{-3}$	6.18 s
ZCZ-56 [10]	$6.24 \cdot 10^{19}$	$6.40 \cdot 10^{19}$	$6.62 \cdot 10^{-4}$	25.3 min
ZCZ-60 [11]	$1.32 \cdot 10^{21}$	$1.41 \cdot 10^{23}$	$3.66 \cdot 10^{-4}$	38.7 days
This work	$4.74 \cdot 10^{23}$	$6.27 \cdot 10^{25}$	$1.68 \cdot 10^{-3}$	47.2 yr

NASA QuAIL Focus

- **Algorithms and applications** to enable safer, more ambitious, and greater time- and energy-efficient missions
- **Tools** for advancing quantum computing, from quantum circuit simulation, noise characterization, error correction, compilation to realistic hardware

Status of Quantum Algorithms

Quantum computing can do everything a classical computer can do *and*

Provable quantum advantage known for a few dozen quantum algorithms and subroutines

Unknown quantum advantage for everything else

Status of classical algorithms

- Provable bounds hard to obtain
 - Analysis is just too difficult
- Best classical algorithm not known for most problems
- Empirical evaluation required
- Ongoing development of classical heuristic approaches
 - Analyze empirically: run and see what happens
 - E.g. SAT, planning, machine learning, etc. competitions
- **NISQ era supports unprecedented means for empirical analysis of quantum algorithms**
 - Quantum heuristics come into their own

A handful of proven limitations on quantum computing

Conjecture: Quantum Heuristics will significantly broaden applications of quantum computing

Utility-scale quantum computers

Utility-scale quantum computers will resemble supercomputers

Many quantum processing units (QPUs), and classical processing units (CPUs)

Quantum and classical communication

Potentially heterogeneous quantum components

Memory

Magic state factories

Special purpose components targeted at common quantum subroutines

May have 2D local structures, higher dimensional comm at larger scales

Surface code is not the end of the story

Many breakthroughs in QEC in the past few years

New code types

e.g. Dynamical qubit or Floquet codes

Better decoders

e.g. For good LDPC codes



Quantum Error Correction: Rough Beginnings (1990s)

Is Shor's factoring algorithm anything more than a theoretical curiosity?

- If nature doesn't allow robust quantum computing, then no one will be able to ever run it

“unless some unforeseen new physics is discovered, the implementation of error-correcting codes will become exceedingly difficult as soon as one has to deal with more than a few gates”

- Haroche & Raimond

“if error correction is needed, this is inevitably dissipative and incoherent, and prevents quantum parallelism”

“error correction in quantum computation cannot follow the recipes we learned for classical digital computers. ... we cannot, in general, tell whether two arbitrary quantum states differ, or not. Even if we were able to recognize errors, we cannot throw away the description of the error”

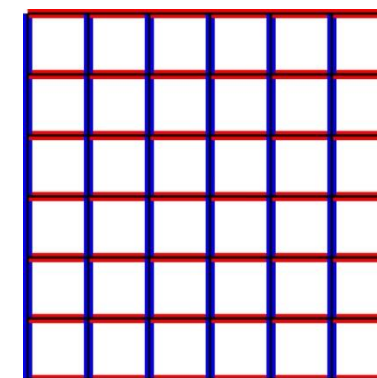
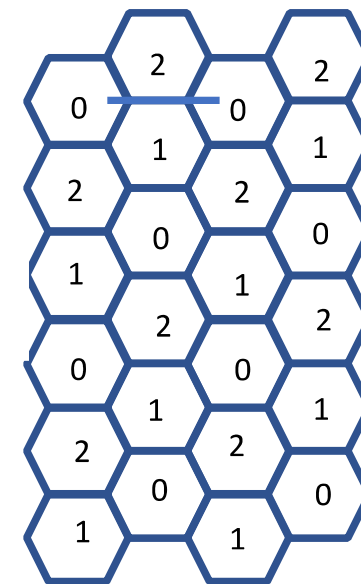
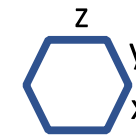
- Landauer

New family of Floquet codes

- On a square lattice rather than a trivalent graph
- Add defects to Bacon- Shor codes to obtain dynamical logical qubits
- Four rounds of measurement, alternating between X measurements and Z measurements

This work is part of a larger program trying to understand when one can define Floquet codes, when it is useful to do so, and subtleties with regard to defining their distance

First code with dynamical qubits:
Floquet honeycomb code



Bacon-Shor subsystem code

Floquet-Bacon-Shor code

To free up space for an additional logical qubit in a Bacon-Shor code

We refrain from fixing one of the gauge degrees of freedom

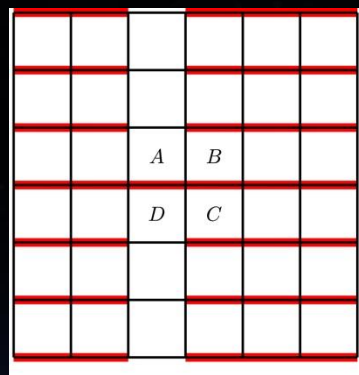
We introduce a “gauge defect”

We need to do so carefully to ensure all Bacon-Shor stabilizers get measured

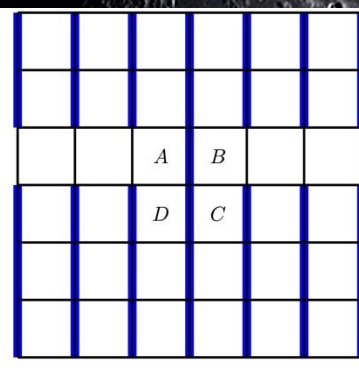
Measurement schedule

Provides insights into design space and design strategies for dynamical codes

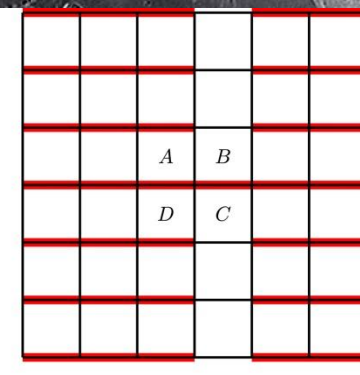
Potential for early experimental realization of a dynamical code



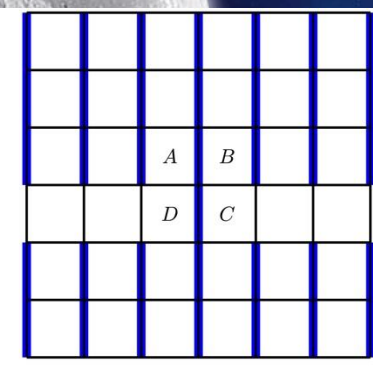
Subset of horizontal XX checks



Subset of vertical ZZ checks



Subset of horizontal XX checks



Subset of vertical ZZ checks



Mind the constants and log factors!

Quantum Algorithms Intrinsically Distributed problems

Algorithms for problems that are distributed by nature

- each node in the graph has information; no node has all the information
- all nodes need to work together to solve the problem
- minimize number of communication rounds

Novel quantum distributed algorithms for Survivable Network Design Problems

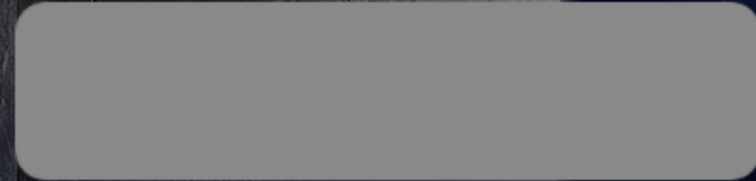
- Broad class that includes Approximate Steiner Tree Problem, K-Connected Network Problem
- Asymptotic improvement with respect to the current best known classical algorithm in terms of computational rounds in the CONGEST CLIQUE model
- Detailed analysis to understand at what scales these algorithms and their classical counterparts out perform a simpler approach

Approximate Steiner Tree in CONGEST CLIQUE can always be solved in n rounds

To be practical, need roughly

$$3200 \cdot n^{\frac{1}{4}} \log_2(n)^6 < n$$

for which





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10^{11} for classical $\tilde{O}\left(n^{\frac{1}{3}}\right)$ counterpart.



QuAIL simulation software and theory



HybridQ: A Hybrid Quantum Simulator for Large Scale Simulations

- Hardware agnostic circuit simulator
- Tensor contraction simulations, direct evolution, and Clifford+T simulations
- CPU/GPU and/or TPU, either on single or multiple nodes (MPI) for large scale simulations, using same syntax
- Commutations rules are used to simplify circuits (useful for QAOA)

Open source code available at <https://github.com/nasa/HybridQ>

S. Mandrà, J. Marshall, E. G. Rieffel, R. Biswas, HybridQ: A Hybrid Simulator for Quantum Circuits, QCS 2021, arXiv:2111.06868

Open Quantum System Simulation

- e.g. N Suri, J Barreto, S Hadfield, N Wiebe, F Wudarski, J Marshall, Two-Unitary Decomposition Algorithm and Open Quantum System Simulation, Quantum 7, 1002 (2022)

Simulation of Photonic Quantum Systems

- J Marshall, N Anand, Simulation of quantum optics by coherent state decomposition, arXiv:2305.17099
- J Saied, J Marshall, N Anand, S Grabbe, EG Rieffel, Advancing quantum networking: some tools and protocols for ideal and noisy photonic systems, Quantum Computing, Communication, and Simulation IV (2024)

Mitigating distinguishability errors

- J Marshall, Distillation of Indistinguishable Photons Phys. Rev. Lett. (2024)
- J Saied, J Marshall, N Anand, EG Rieffel, General protocols for the efficient distillation of indistinguishable photons, arXiv:2404.14217 (2024)



One Area of Quantum Computing is Underhyped



These algorithms are the only ones coming out of quantum computing that are useful today



They are applications of quantum computing but not of quantum computers

Quantum-inspired classical algorithms and hardware



Quantum Monte Carlo

Improved classical techniques for simulating quantum systems

De-quantized quantum algorithms

e.g. for E3Lin2

e.g. certain sampling and quantum ML algorithms

Quantum proofs for classical theorems
(Survey: Drucker & Wolf arXiv:0910.3376)

Quantum Inspired Classical Hardware

Digital Annealers

Coherent Ising Machines

DARPA's Quantum-Inspired Classical Computing (QuICC) program

Quantum Computing for Earth Science



Quantum-assisted variational autoencoder

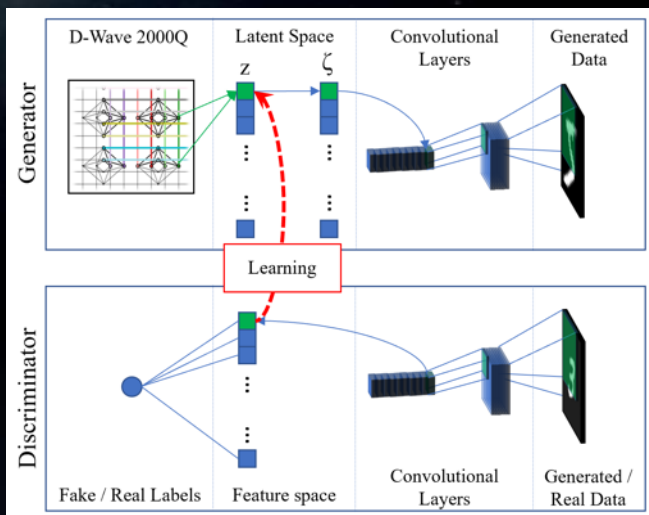
- “Similarity” search applied to NASA’s MODIS dataset
- Multi-variate time series of land cover change
- 17 years of satellite observations over 36 spectral bands
- Extend to segmentation, reconstruction, super-resolution

N. Gao *et al.* (2020), High-dimensional similarity search with quantum-assisted variational autoencoder, *KDD '20*, 956-964

Quantum inspired classical algorithms

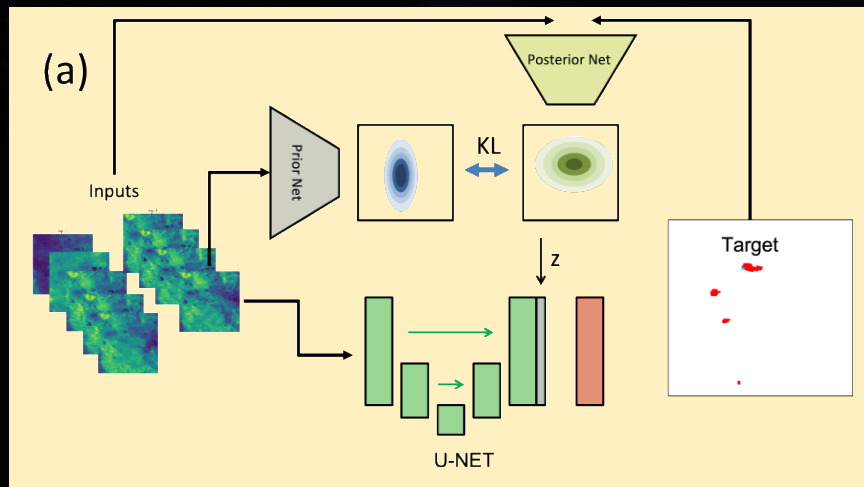
Quantum-ready classical algorithms

Generative Machine Learning for Wildfire Image Processing



Quantum-assisted associative adversarial network

M. Wilson *et al.* (2021), Quantum-assisted associative adversarial network: Applying quantum annealing in deep learning, *Quantum Machine Intelligence*



A. Asanjan *et al.* (2023), *Probabilistic Wildfire Segmentation Using Supervised Deep Generative Model from Satellite Imagery, Remote Sensing*



What can Quantum Computing tell us about Fundamental Physics?

Wigner's Friend Inequalities and Future Experiments

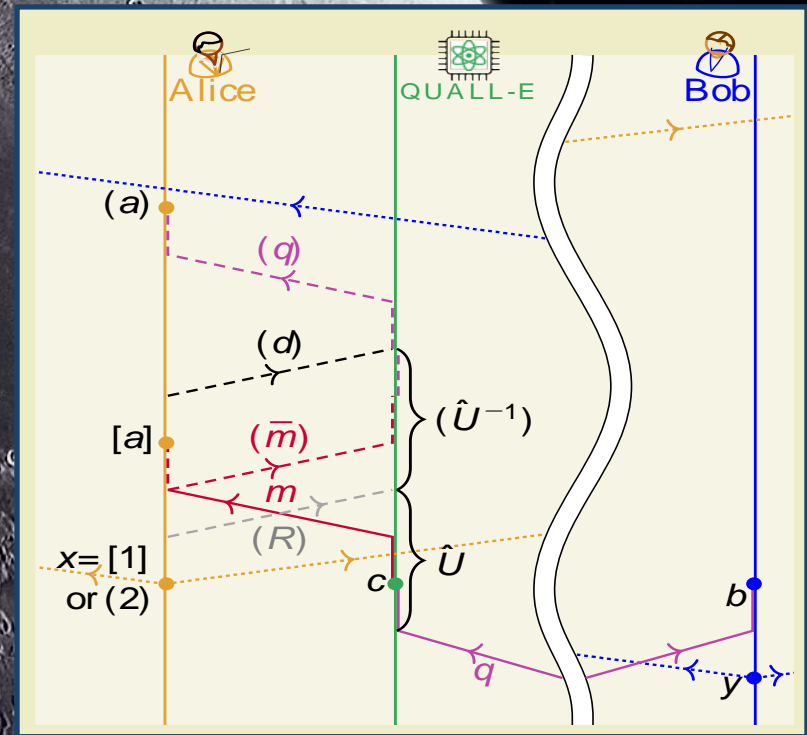
New inequalities, with weaker assumptions than Bell's inequalities, stemming from Wigner's friend scenario

Wigner's friend is less famous than Schrödinger's cat, but equally intriguing

2022 Nobel prize in physics: "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

Design of an experiment testing for violations of these inequalities would combine Artificial Intelligence and Quantum Computing

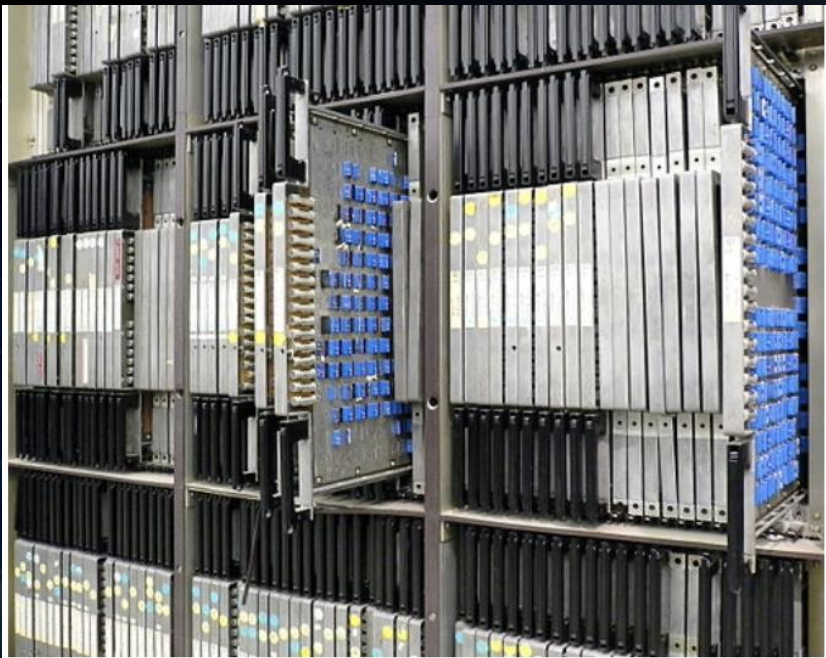
Collaboration between NASA and Australian researchers
Ultimate experiment requires space-based experiments



QUALL-E, an artificial intelligence running on a quantum computer plays a key role WF experiments testing fundamental aspects of quantum physics

H.M. Wiseman, E.G. Cavalcanti, E.G. Rieffel, *A "thoughtful" Local Friendliness no-go theorem: a prospective experiment with new assumptions to suit*, Quantum 7, 1112, 20204
A. Ananthaswamy, *Can AI Save Schrödinger's Cat?*, Scientific American, July/August issue, 2024

A Historical Perspective



Illiac IV – first massively parallel computer

- 64 64-bit FPUs and a single CPU
- 50 MFLOP peak, fastest computer at the time

Finding good problems and algorithms was challenging

Questions at the time:

- How broad will the applications be of massively parallel computing?
- Will computers ever be able to compete with wind tunnels?



NASA Ames director Hans Mark brought Illiac IV to NASA Ames in 1972



For more info

Eleanor Rieffel, Ph.D.

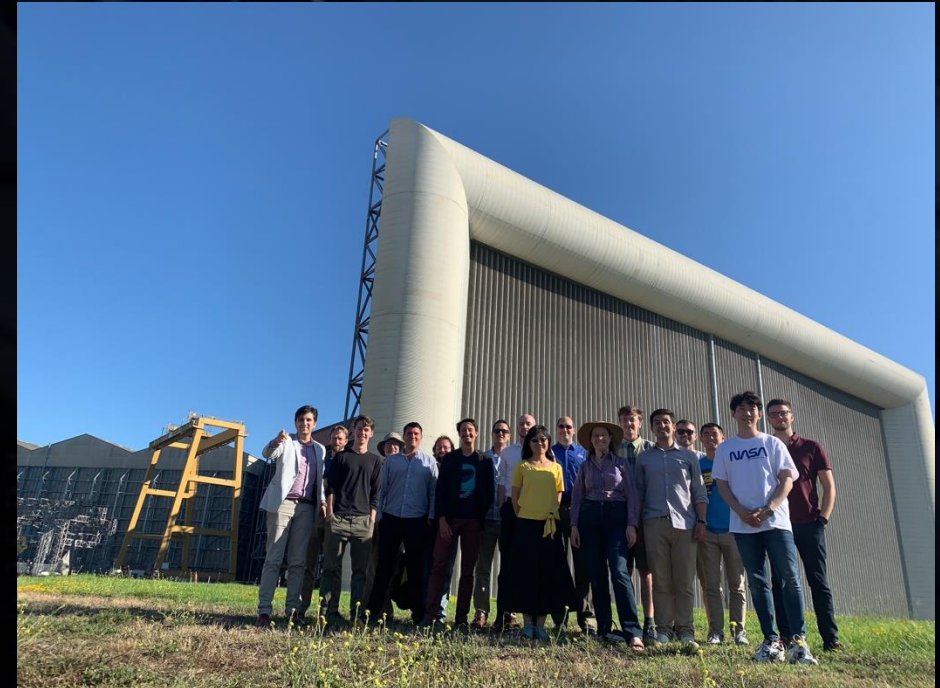
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<https://www.nasa.gov/intelligent-systems-division/discovery-and-systems-health/nasa-quail/>