Ensuring NASA's Quantum-Readiness

Lucas T. Braydwood (né Brady)

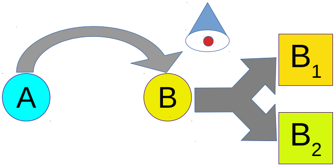
NASA Quantum Artificial Intelligence Lab (QuAIL)

July 17, 2025

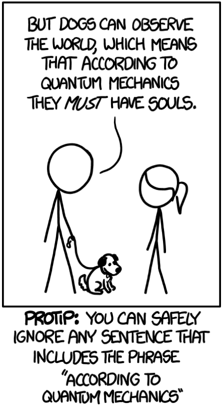
What is Quantum Mechanics

Quantum Mechanics governs the behavior of very small particles

- Weirdly probabilistic when you look
  but completely deterministic in dynamics

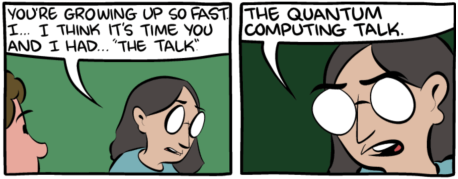


- Large objects rarely behave quantumly
- For a dog to exhibit quantum mechanical behavior you would have to wait longer than the age of the universe



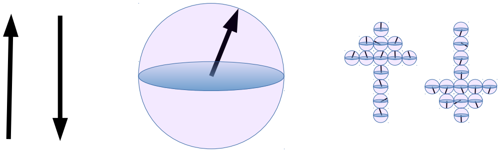
https://xkcd.com/1240/

What is a Quantum Computer



https://www.smbc-comics.com/comic/the-talk-3

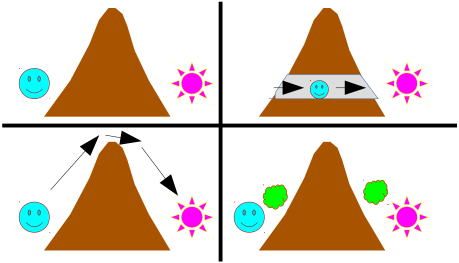
- All computers rely on quantum mechanics
- Classical info is stored in big things



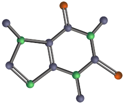
- Quantum information can be manipulated in more ways
- Quantum computers are **slower**

Why Would We Do That

Quantum Computers work fundamentally differently than traditional computers



- Even if a quantum computer is slower, its path is more direct
- This only works on some problems
- For most problems, faster is still better



We Have Quantum Advantage

Quantum Advantage

The accomplishment of a task on a quantum computer that is not possible to do on traditional computers in *reasonable*[a] amounts of time

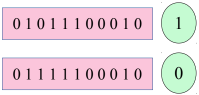
[a] e.g. Google wasn't able to do it in a month

- Accomplished in 2019; **the task was not useful**
- It will be years before quantum computers are big enough for useful tasks (e.g. artificial fertilizer production)

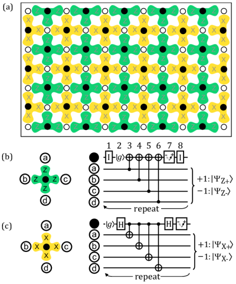
Error Rates

- Computers do basic “operations” (e.g. adding, subtracting)
- How often will an “operation” produce an error
  - Classical Error Rate: $\sim 10^{-15}\%$
  - Quantum Error Rate: $\sim 0.5\%$
- Classical computers run at gigaFLOPS rates - this means about one error a day
- Quantum Information is unique, it cannot be copied

Classical Error Detection/Correction



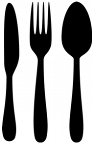
Quantum Error Detection/Correction



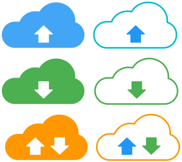
DOI: 10.1103/PhysRevA.86.032324

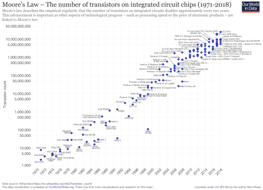
How Will Companies Make Money Off This

The smaller something is, the more machinery is needed to control it



Technology can only improve so much before it hits physical limits





Max Roser - ourworldindata.org

Quantum At NASA

Why Quantum Computing at NASA

- NASA confronts computational challenges and bottlenecks with missions, limiting scopes and aims

Even if every atom on earth were a processor, we could not run some quantum-able computations classically

- Quantum computers offer a potentially more efficient option for some problems
- We have a zoo of existing applications
- Near-term is a lot more heuristic
- This is potentially Green, with lower energy consumption

How We Approach Quantum Problems

Physics Insights

Fundamental research, Hardware co-design

Classical Solvers

Quantum-inspired Classical Algorithms, HPC Quantum Circuit Simulators

Quantum Tools

Error Mitigation, Compiling

Quantum Algorithms

Quantum Algorithm Design, Hybrid Approaches

Applications

Scheduling, Material Science, Machine Learning

Communication

Quantum Networking, Cryptography

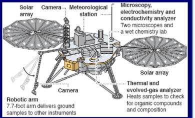
Ways to Apply Quantum Thinking

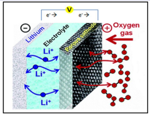
Quantum-Ready	Quantum-Inspired	Quantum-Enabled
Classical algorithms with pieces that can be exchanged for quantum components when ready	Classical-algorithms whose design was inspired by quantum phenomena	Quantum-ready algorithms that have had quantum pieces integrated
Implementable in full today	Implementable in full today	Implementable only on small systems today
Can mimic today's state-of-the-art with certification of quantum augmentation	Novel methods that have sometimes beaten existing state-of-the-art	Expected to eventually have scaling advantage
Have been deployed on real-world applications	Have been deployed on real-world application	Currently too small and noisy to benefit real-world applications

Quantum Ready Applications at NASA

Quantum ML for Earth Science Data Analysis

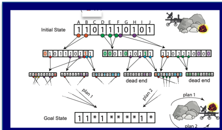
Resource Allocation and Scheduling for Space Exploration





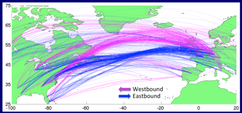
Quantum Simulations for Aerospace Materials

Secure Airspace Communication



Quantum Optimization for Mission Planning & Coordination

Air Traffic Management



The goal is never to just quantum-ify something. We seek **better** solutions in terms of time-to-solution or quality-of-solution

What is Quantum Good (and not Good) For

Limitations

Fixed with Engineering/Time

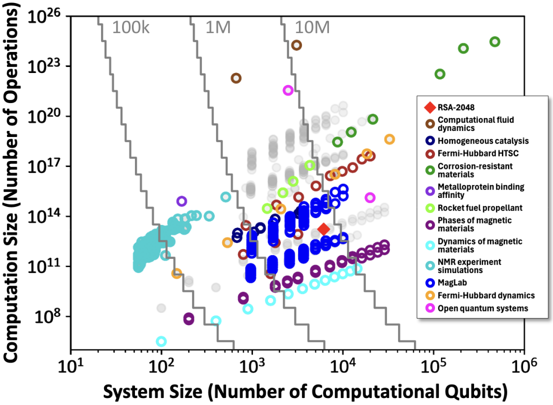
- Small system sizes - too small for practical applications yet
- Noisy - runs tell you more about the hardware than the problem

Will Never Do

- Speed up parallelization of easy tasks
- Solve NP-Hard problems efficiently
- Do time-travel, instantaneous communication, macroscopic teleportation, et cetera

Possible Applications

- Chemistry and Materials
- Computational Fluid Dynamics
- Optimization
- Many Body Physics
- High Energy Physics



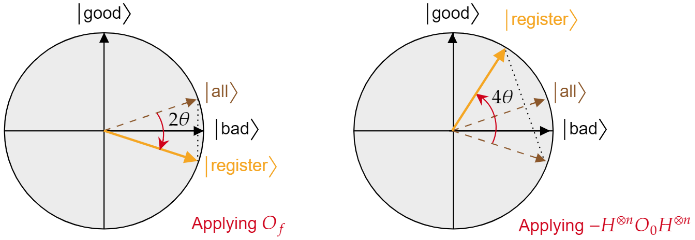
Grey solid circles represent pessimistic resource estimates. Colored circles are optimistic resource estimates based on known improvements. All points supported by detailed published pre-prints.

From the DARPA QB Program

https://www.darpa.mil/sites/default/files/attachment/2024-12/qbi-proposers-day-2024-program-manager.pdf

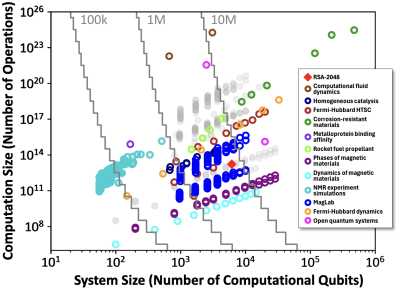
Not Restricted to Quantum-Native

- The first “killer-algorithm” for quantum computers was factoring
- Number theory natively doesn’t have anything to do with quantum
- Search algorithms also fall in this bucket



https://learn.microsoft.com/en-us/azure/quantum/concepts-grovers

Expected Timeline



Grey solid circles represent pessimistic resource estimates. Colored circles are optimistic resource estimates based on known improvements. All points supported by detailed published pre-prints.

- Successes will be piecemeal

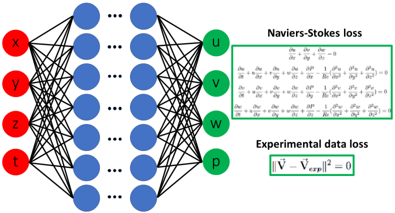
- Chemistry & Materials simulations are likely to be first (5-10 years)
- Factoring is likely 20-30 years out
- Optimization and machine learning are still being researched, but insight is leading to better classical methods

Quantum and AI

Areas in Classical AI

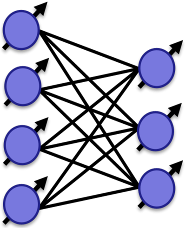
- Artificial Intelligence is a wide field that includes far more than just machine learning.
- Current trends, especially in LLMs and foundation models, are focused on large general-purpose models with lots of ingested data and broad use cases
- There are AI models for very specific tasks, where training data is hard to get and the core task

- Lots of scientific use cases: physics-informed neural networks and operator learning

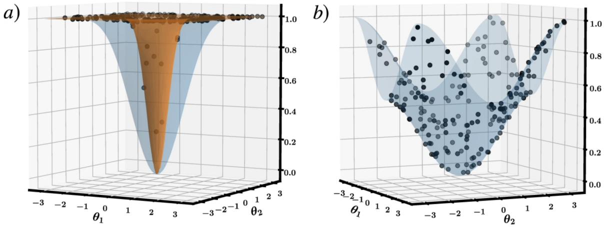


https://upload.wikimedia.org/wikipedia/commons/
informed_nerural_networks.png

Quantum AI



- Quantum computers are good at large complicated calculations, rather than many small easy calculatin
- Focus on hybrid approaches where quantum handles a small but difficult portion

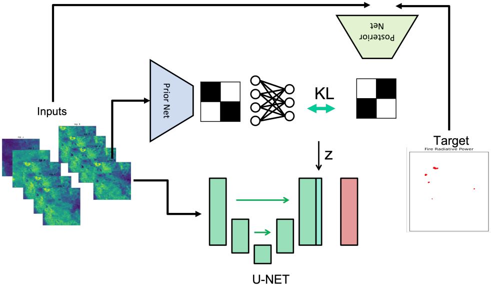


- The training landscape is a major difficulty

Cerezo, M., et al. Cost function dependent barren plateaus in shallow parametrized quantum circuits. Nat Commun 12, 1791 (2021).

Integration Points Between Quantum and AI

- Near-term hybrid approaches are going to be needed
- Quantum is good in situations where the task itself is hard not in situations where generality is needed
- Data ingestion is expected to be a problem
- Unlikely to be helpful with large foundation models and general methods



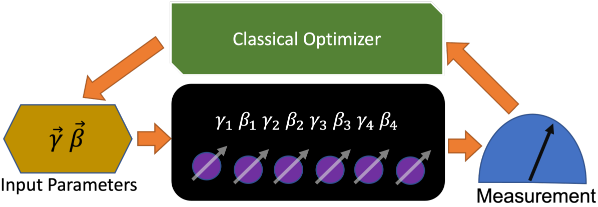
Deep Dive into One Application[1]

[1]Lucas T. Brady, Ata Akbari Asanjan, Zoe Gonzalez Izquierdo, Milad Memarzadeh, P. Aaron Lott, Shon Grabbe, Eleanor Rieffel

Variational Quantum Algorithms

Hybrid Algorithms

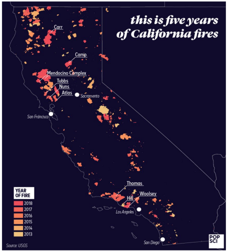
Algorithms that rely on both quantum and classical components



- Often involves classical outer loop optimization of variational parameters
- This naturally evolved into Quantum Machine Learning

Problem Setup

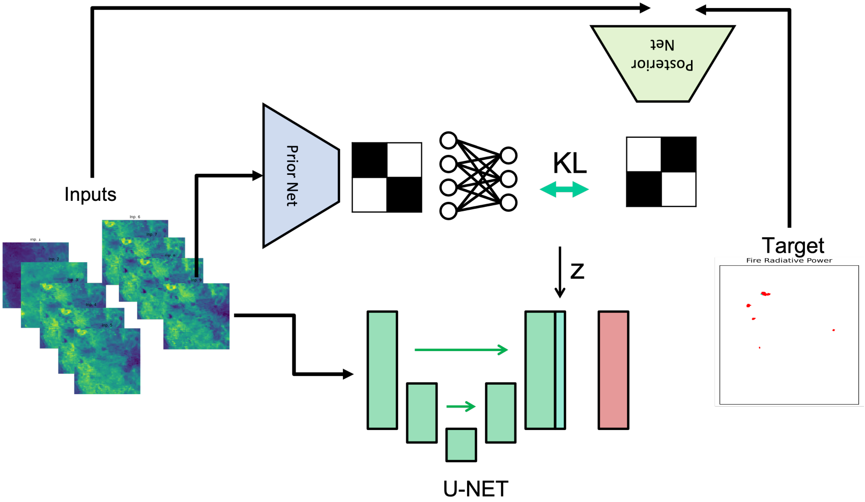
- We want to use quantum machine learning to analyze satellite imagery
- We are focusing on wildfires and vegetation properties that indicate risks
- We want to create a quantum-assisted image-to-image translation algorithm



Credit: USGS

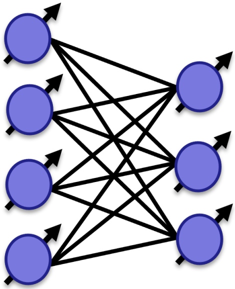
- We are starting with quantum-ready models and incorporating quantum where available
- Focus on Quantum Variational Autoencoder and later on Quantum Neural Networks

U-Net and Variational Autoencoder (Training Mode)



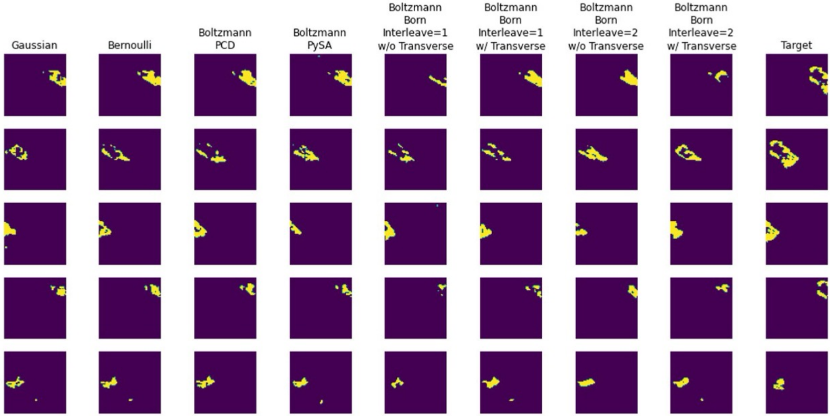
Quantum Latent Space

- The latent space is small and so the best place to plug in a small quantum computer
- We are using a Quantum Ising Born Machine (QIBM)
- The QIBM is the same connectivity as a Boltzmann machine but with quantum instead of thermal fluctuations
- The quantum computer automatically importance samples



- Training of a Born Machine is possible and relies only on easy to produce quantum measurements

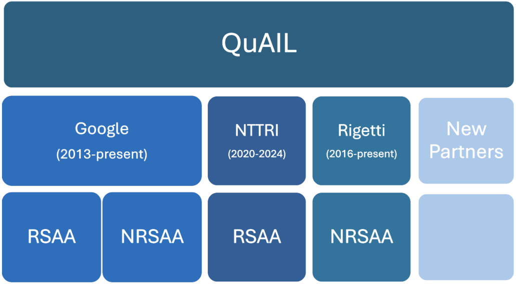
Initial Results and Efforts



Partnerships and Connections with Industry

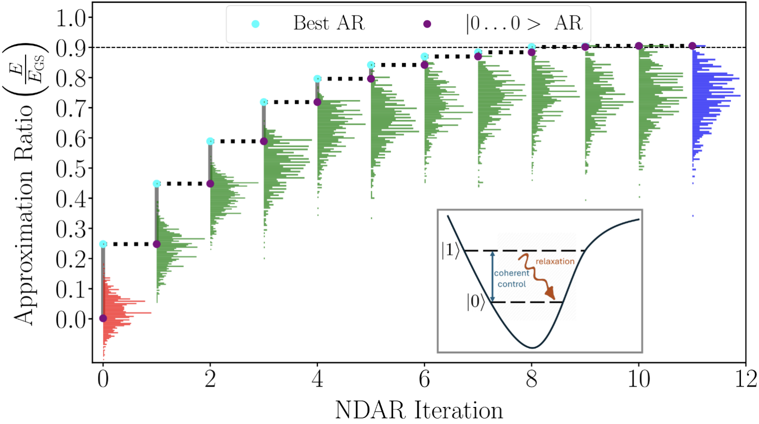
Partnerships

- We have connections to industry
- This is a two-way street with them gainining our expertise and us gaining compute time and co-design input
- We have used a wide variety of vehicles



Noise-Directed Adapative Remapping[2]

- Collaboration with industry can lead to new algorithms and ways of running the hardware



[2]Filip B. Maciejewski, Jacob Biamonte, Stuart Hadfield, and Davide Venturelli

Outlook

- Quantum insight and expertise can lead to classical successes today
- Quantum hardware is developing but is not ready for utility-scale applications yet
- It has been a wild decade of development that isn't slowing down