Application Performance Exploration using the QED-C Quantum Computing Benchmark Framework

Presentation prepared for the

2nd TQCI International Seminar on Benchmarks for Quantum Computers

4-5 June 2024 - REIMS

by

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** QED-C = Quantum Economic Development Consortium*

Agenda

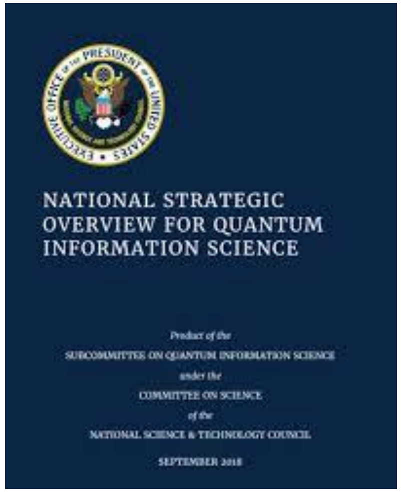
- Background – Quantum Economic Development Consortium (QED-C)
- Application-Oriented Benchmarks Project – Motivation and Goals
- Published Results
- Structure and Implementation
- Recent and Current Work
- Benchmarks – Future Directions

- *An active project for benchmarking, integrating the perspectives of representatives from multiple QED-C member companies*

Quantum Economic Development Consortium (QED-C)

- **25 Sep 2018** - Office of Science and Technology Policy (OSTP) announces the ***National Strategic Overview for Quantum Information Science***

- **28 Sep 2018** - National Institute of Standards and Technology (NIST) announces formation of the **Quantum Economic Development Consortium (QED-C)**


NATIONAL STRATEGIC OVERVIEW FOR QUANTUM INFORMATION SCIENCE

Product of the
SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE
under the
COMMITTEE ON SCIENCE
of the
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

SEPTEMBER 2018

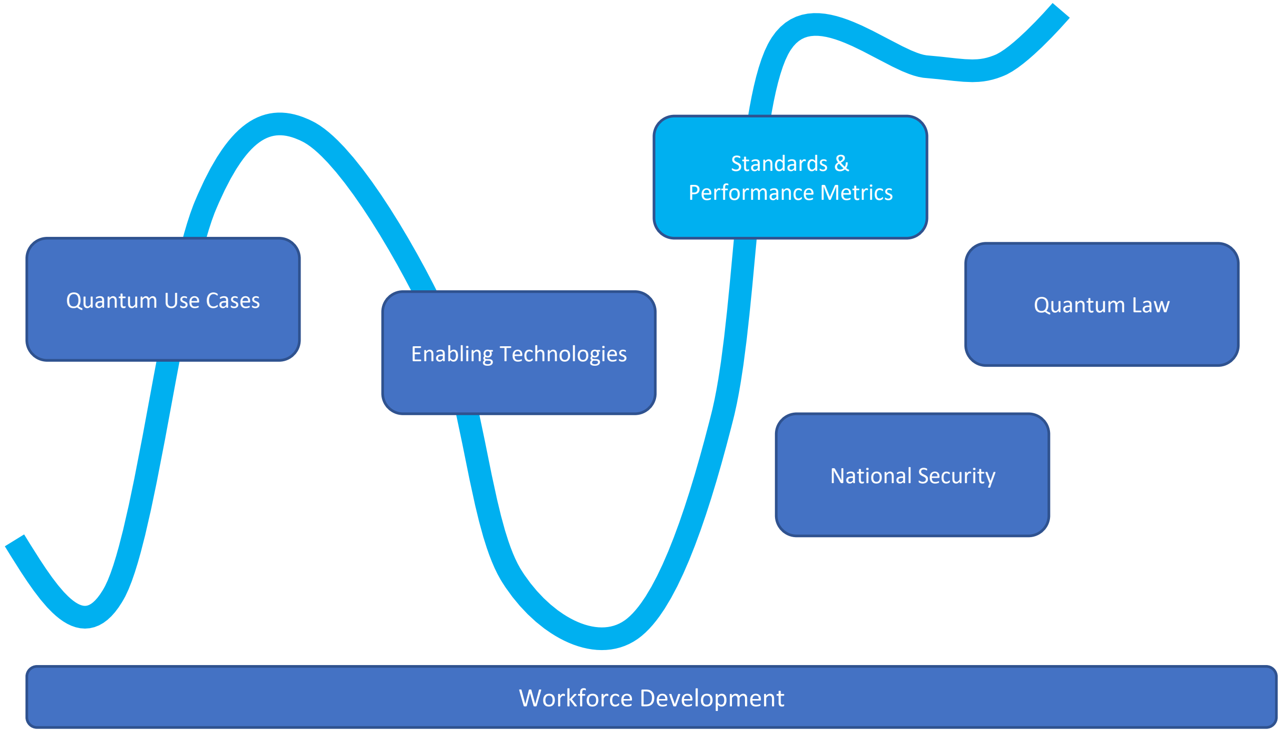
NIST
National Institute of Standards and Technology
U.S. Department of Commerce

QED-C

SRI International®

- **Encourage and facilitate** global quantum research and development and grow the emerging quantum industry in computing, communications and sensing.

- **Technical Advisory Committees**



QED-C Technical Advisory Committee – Standards and Performance Metrics

“The Standards TAC”

*Identify ways to **encourage development of standards and performance metrics** in Quantum Information Science to accelerate commercialization of quantum-based products and services..*

- **Primary Group**
  - Standards Landscape, Eco-System
  - Standards Information Web-Site
- **Quantum Sensing Group**
  - Standards in Quantum Sensing
- **Quantum Networking Group**
  - QKD Use Cases and Certification Challenges
  - Quantum Networking Interoperability
- **Quantum Computing Group**
  - Study Benchmarks/Standards as applied to Use Cases
  - *Application-Oriented Performance Benchmarks*

⇧

Our Effort

Observations

- A large body of high-quality work exists for evaluating performance of quantum computers
- T1, T2, QPT, RB, XEB -> SPAM, 1Q and 2Q Fidelity, Quantum Volume, CLOPS, …
- Focus on optimizations of techniques for characterizing
  1) component properties
  2) inter-component interactions
  3) aggregate behaviors

Factors important to building a quantum computer and presenting general performance measures!

How do we provide performance benchmarks in the context of usage in real applications?

QED-C Solution – "Application-Oriented Performance Benchmarks"

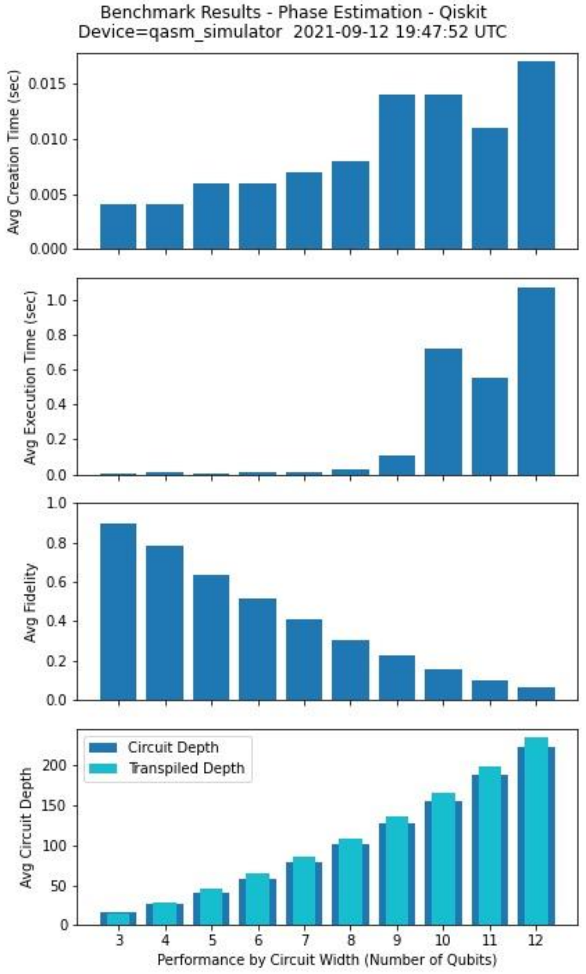
From a scientific perspective … Quality + Time + Resources can be predicted from component and system-level benchmarks.
Application-focused benchmarks are not strictly required to understand performance.

From a user perspective … "OK, I believe you … but I want to run some tests myself!"

To help the user accomplish this …

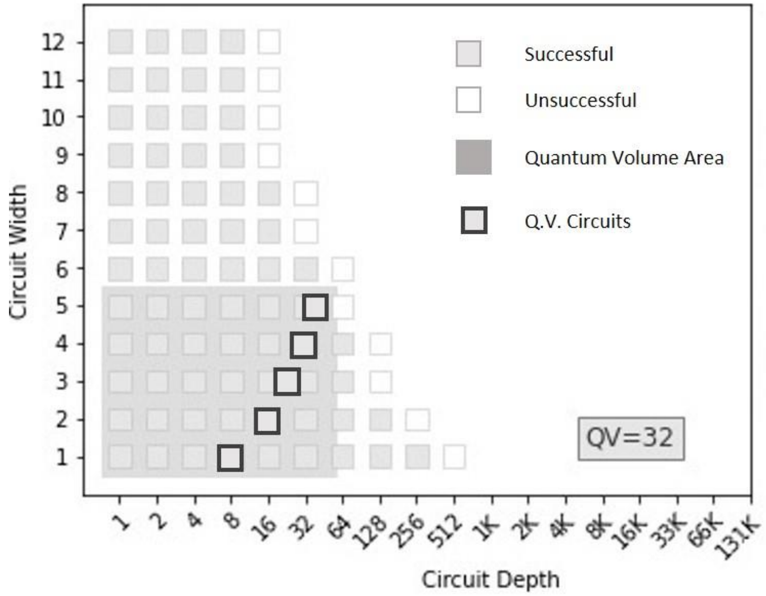
- Set up a **framework** to run small algorithms and applications as **"benchmarks"**
- Generalizes a **sweep** over a range of **problem sizes** (qubit widths)
- Systematize the collection, analysis and presentation of **result fidelity, execution time,** and other metrics
- Analyze results and produce **relevant reports and visuals**

Present Metrics Results in Bar Charts and Volumetric Charts by App



Quantum Phase Estimation
12 Qubits

+



Volumetric Benchmarking
Sandia Quantum
Performance Lab

(Blume-Kohout, Young, Proctor)

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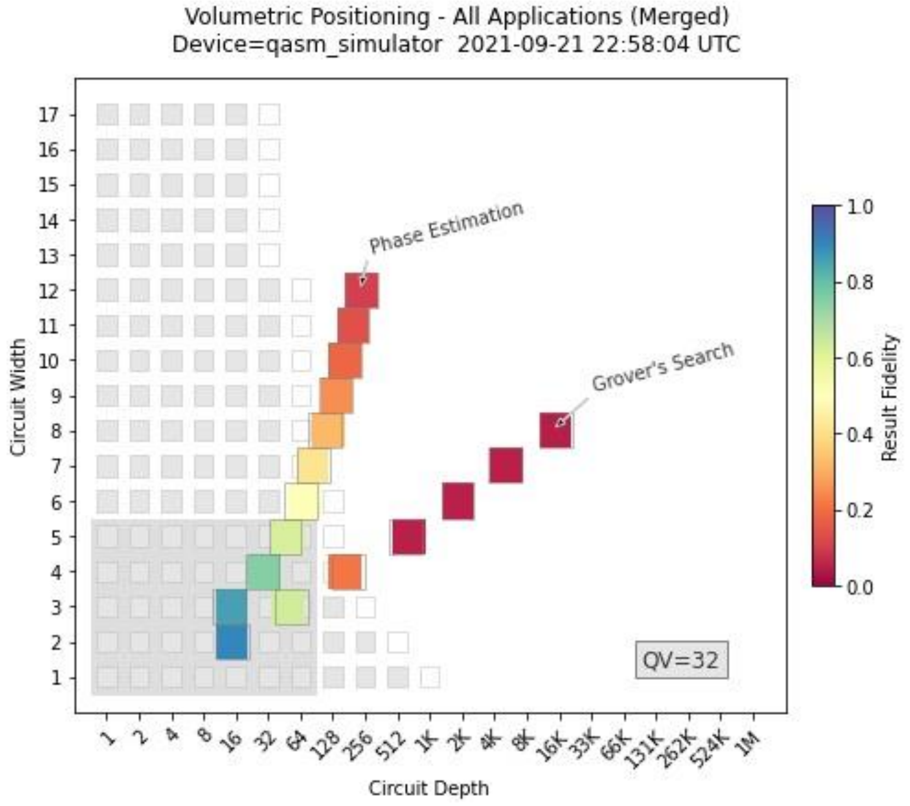


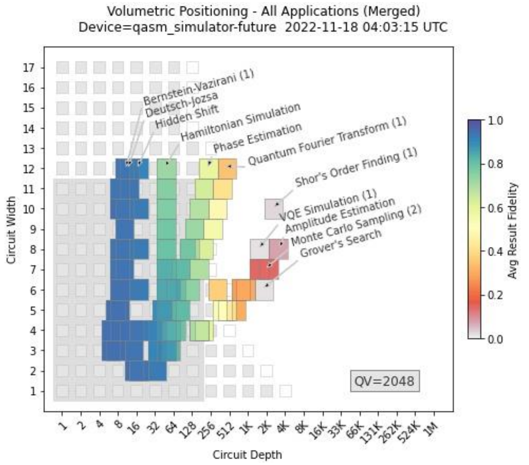
Volumetric Positioning
of
Application profile

Timeline of QED-C Benchmark Efforts

Application-Oriented Performance Benchmarks

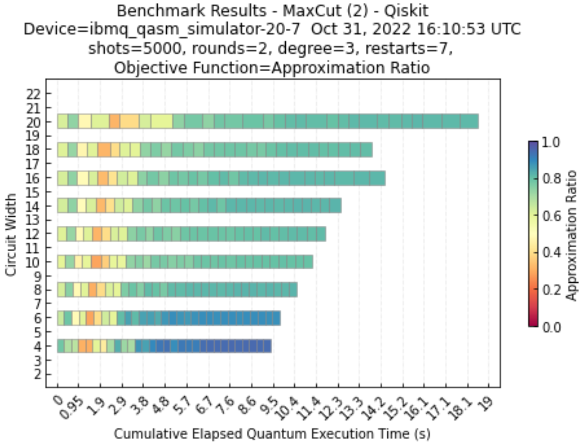
https://ieeexplore.ieee.org/document/10061574

https://arxiv.org/abs/2110.03137



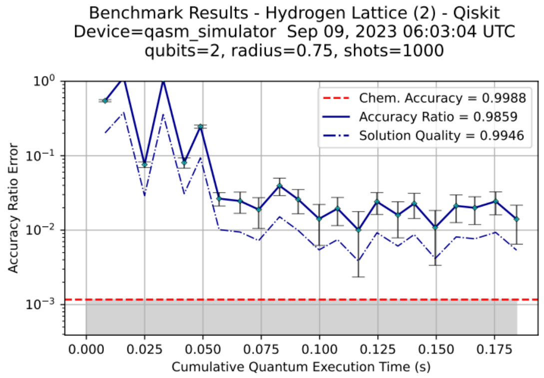
Optimization Applications as Quantum Benchmarks

https://arxiv.org/abs/2302.02278



Quantum Algorithm Exploration with A.O. Benchmarks

https://arxiv.org/abs/2402.08985



Benchmarking Applications of Hamiltonians using HamLib (WIP)

Conception + Planning

2020	2021	2022	2023	2024
	Algorithm Execution Fidelity and Run Time	*Throughput and Application Metrics*	*Increase Coverage Exploration Features*	*Simulation and Applications*

15+ Benchmark Programs (w/ variants)

Tutorial	Qiskit	Cirq	Braket
Deutsch-Jozsa	X	X	X
Bernstein-Vazirani	X	X	X
Hidden-Shift	X	X	X

Subroutine	Qiskit	Cirq	Braket
Quantum-Fourier-Transform	X	X	X
Phase Estimation	X	X	X
Amplitude Estimation	X	X	

Functional	Qiskit	Cirq	Braket
Hamiltonian Simulation	X	X	X
Grover's Search	X	X	X
Monte Carlo Sampling	X	X	
Variational Quantum Eigensolver	X		
Shor's Order Finding Algorithm	X		

Application	Qiskit	Cirq	Braket
HHL Linear Solver	X		
MaxCut QAOA Algorithm	X		
Hydrogen Lattice VQE Algorithm	X		
Image Recognition	X		

Quantum Program APIs: Qiskit, Cirq, Braket, CUDA Quantum, Q#

Quantum Backends: IBM Quantum, IonQ, Quantinuum, Rigetti, BlueQubit, NVIDIA

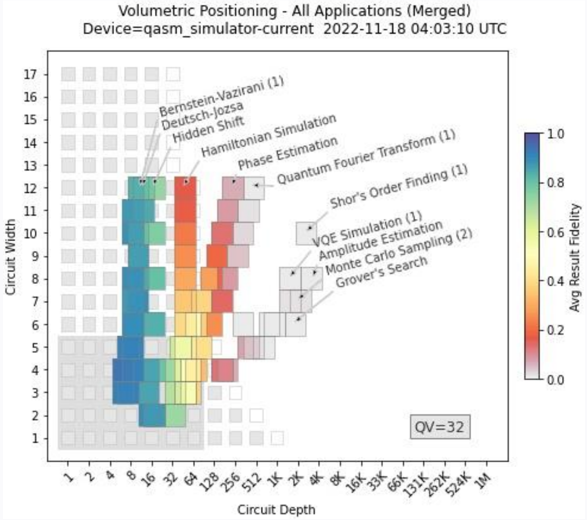
Code Repository: https://github.com/SRI-International/QC-App-Oriented-Benchmarks

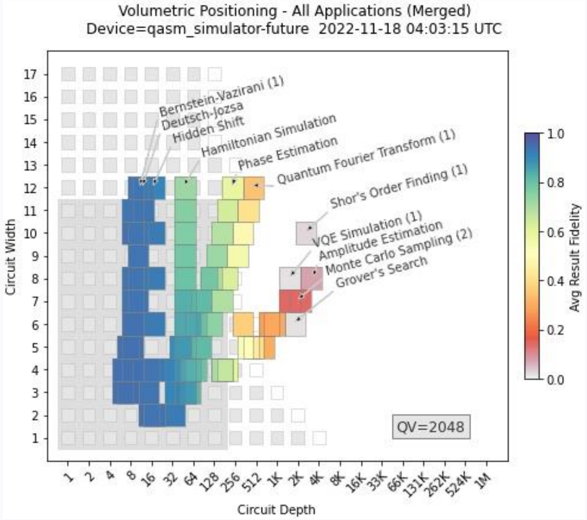
Benchmark Results (Simulator + Hardware) – Now and in the Future ?

https://arxiv.org/abs/2110.03137

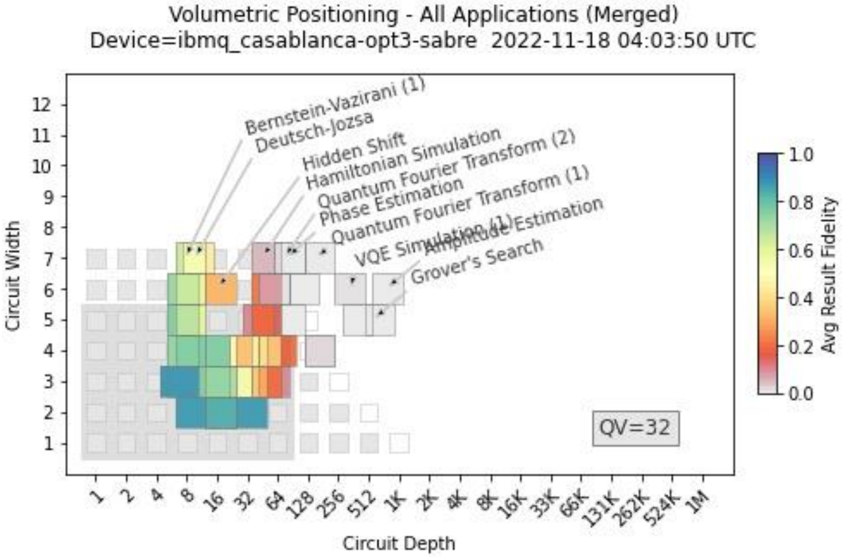
Simulator

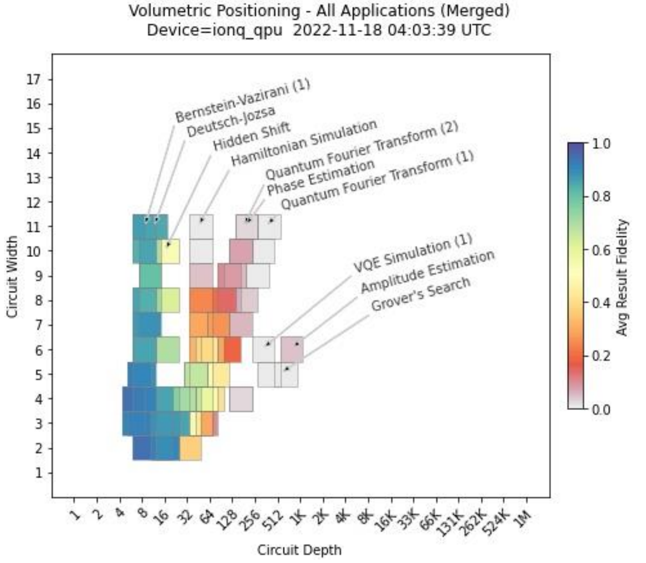
Current devices
(QV=32)

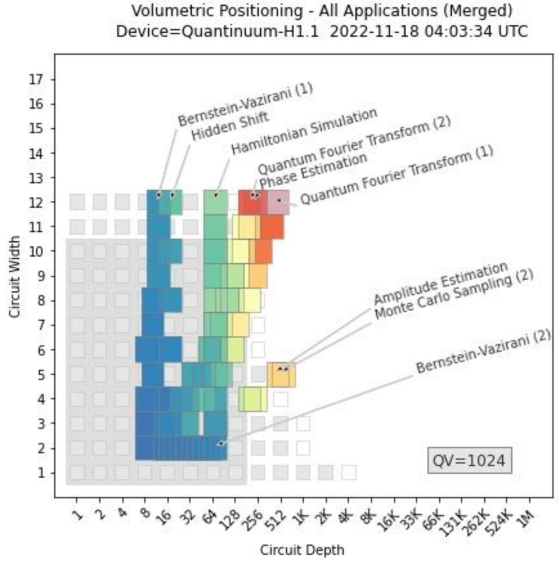




Future devices
(QV=2048)?



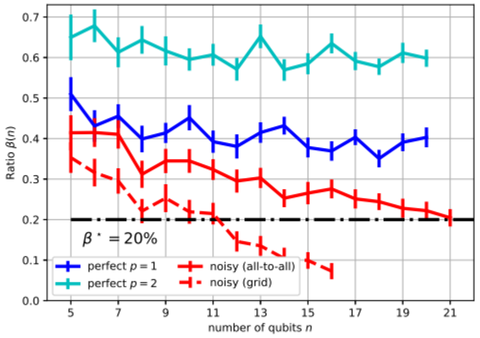




Other Application-Focused Benchmarks (Single Organization)

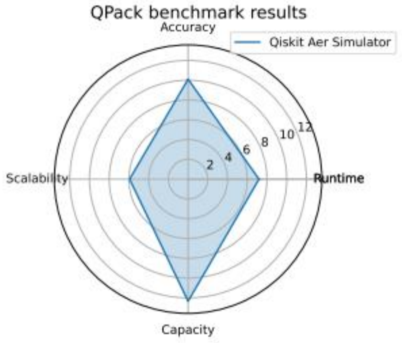
Q-score (Atos)

https://arxiv.org/abs/2102.12973



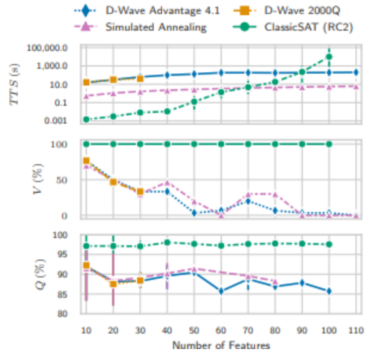
QPack-Scores (Delft)

https://arxiv.org/abs/2205.12142



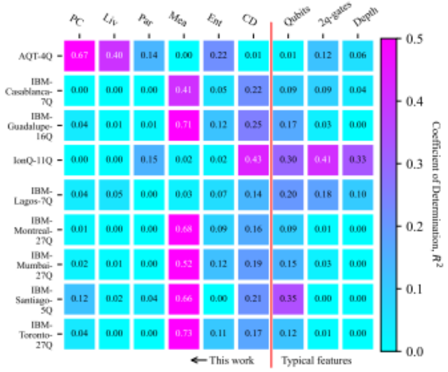
QUARK (BMW)

https://arxiv.org/abs/2202.03028



SupermarQ (Infleqtion)

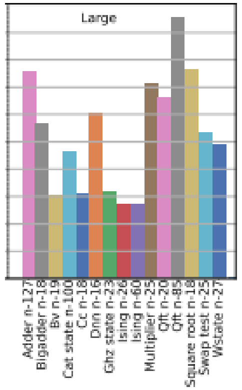
https://arxiv.org/abs/2202.11045



(a) Including error-correction benchmarks.

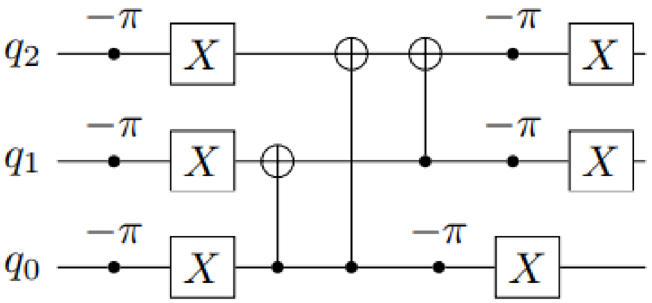
QASMBench (PNNL)

https://arxiv.org/abs/2005.13018

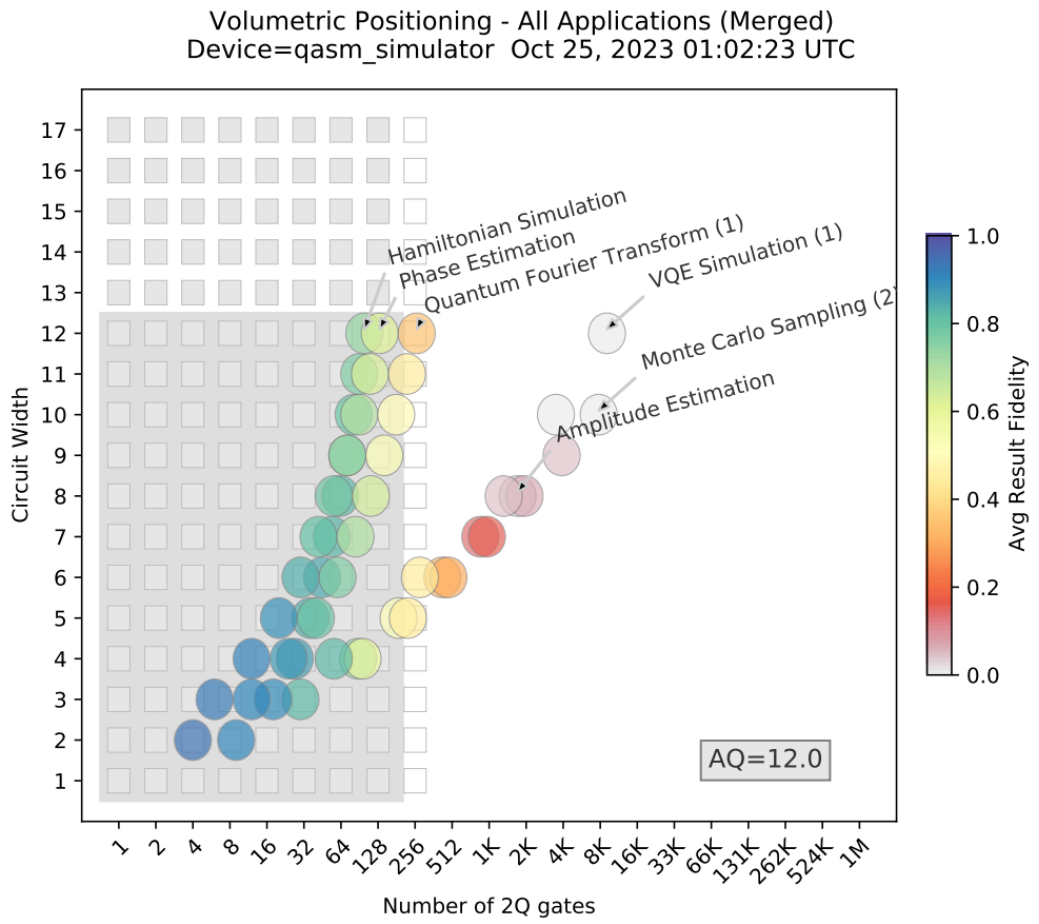


MQT Bench (U. Munich)

https://arxiv.org/abs/2204.13719



Algorithmic Qubits (introduced by IonQ)



NOTES:

AQ based on QED-C Benchmarks

Adds computation of AQ number

(similar to N in QV's 2^N)

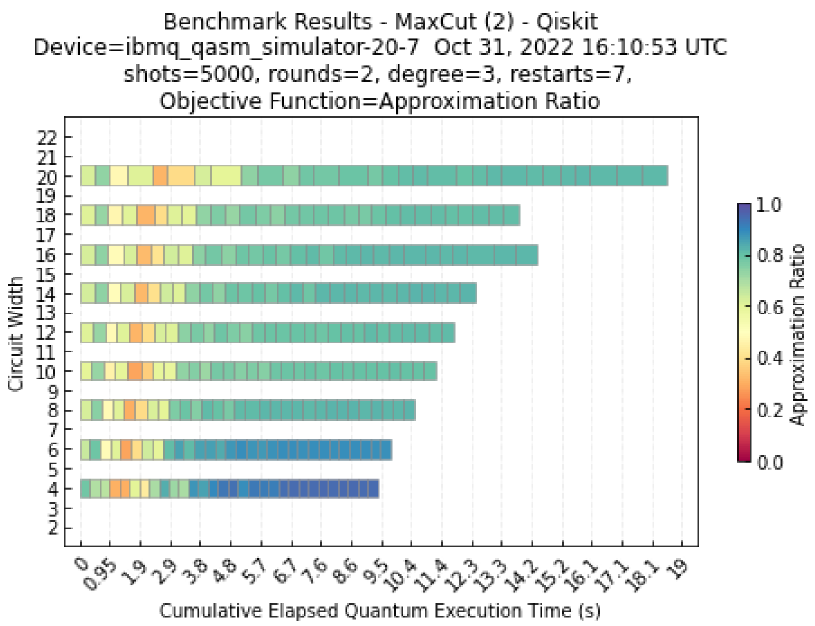
Adds Number of 2Q gates in X-axis

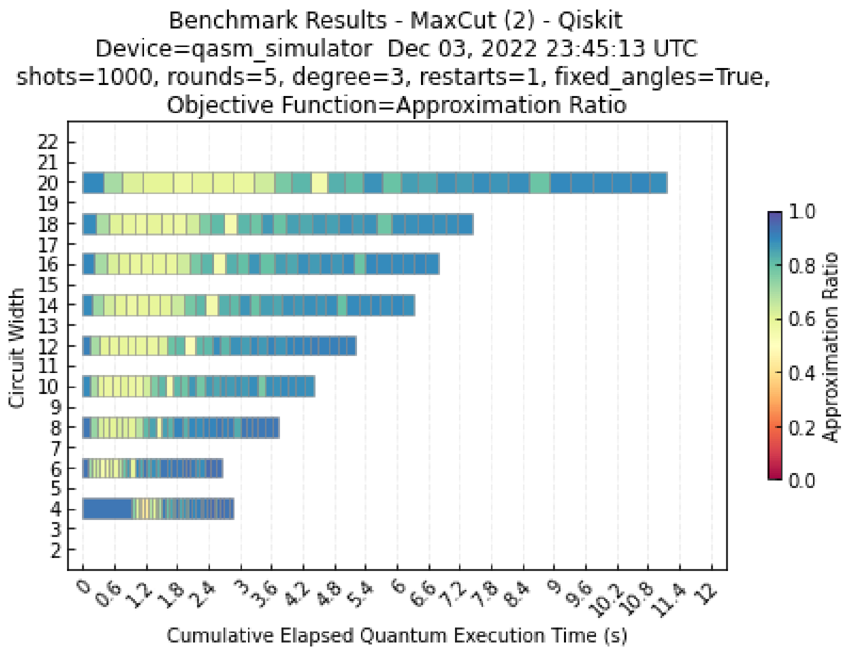
(instead of normalized gate count)

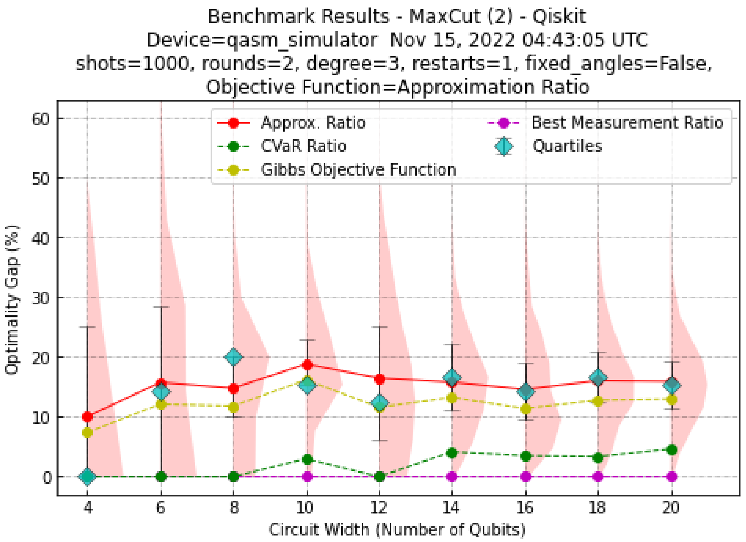
The QED-C repo includes the AQ option

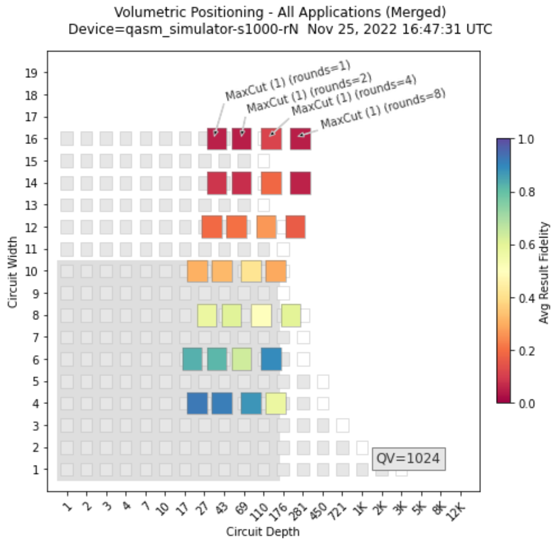
More on issues with AQ in later slide

Benchmarking Hybrid Algorithms – QAOA Example





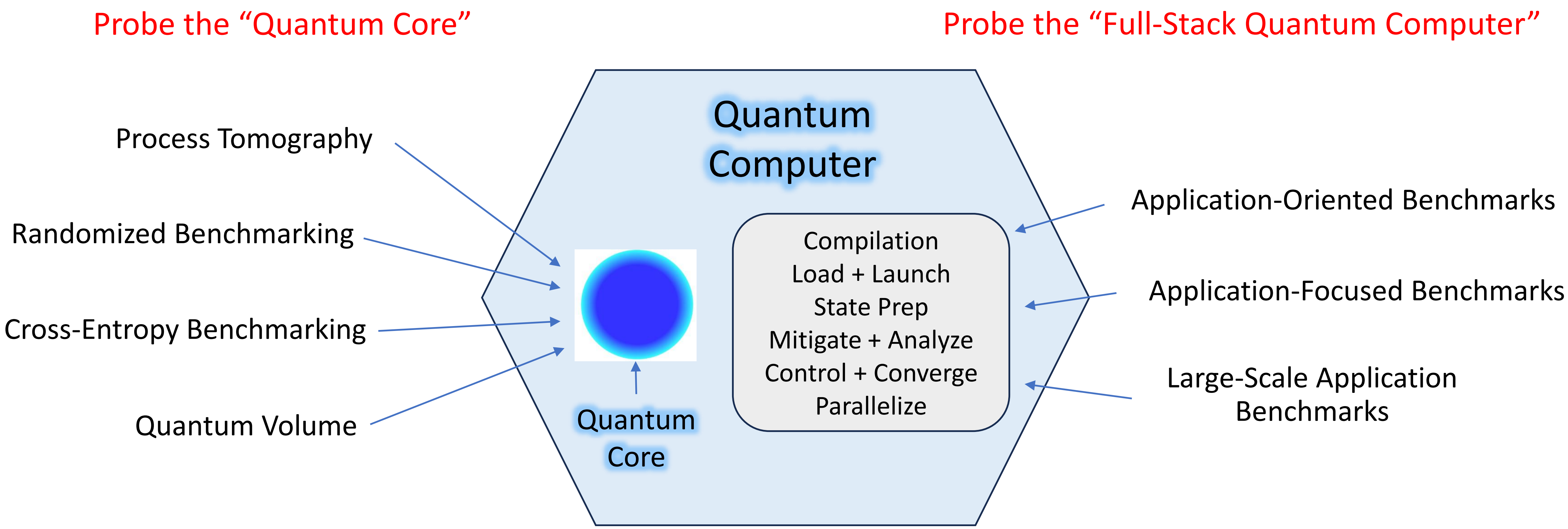




The paper (2) includes hardware results with emphasis on throughput assessment

https://arxiv.org/abs/2302.02278

Properly Positioning Application-Oriented Benchmarks

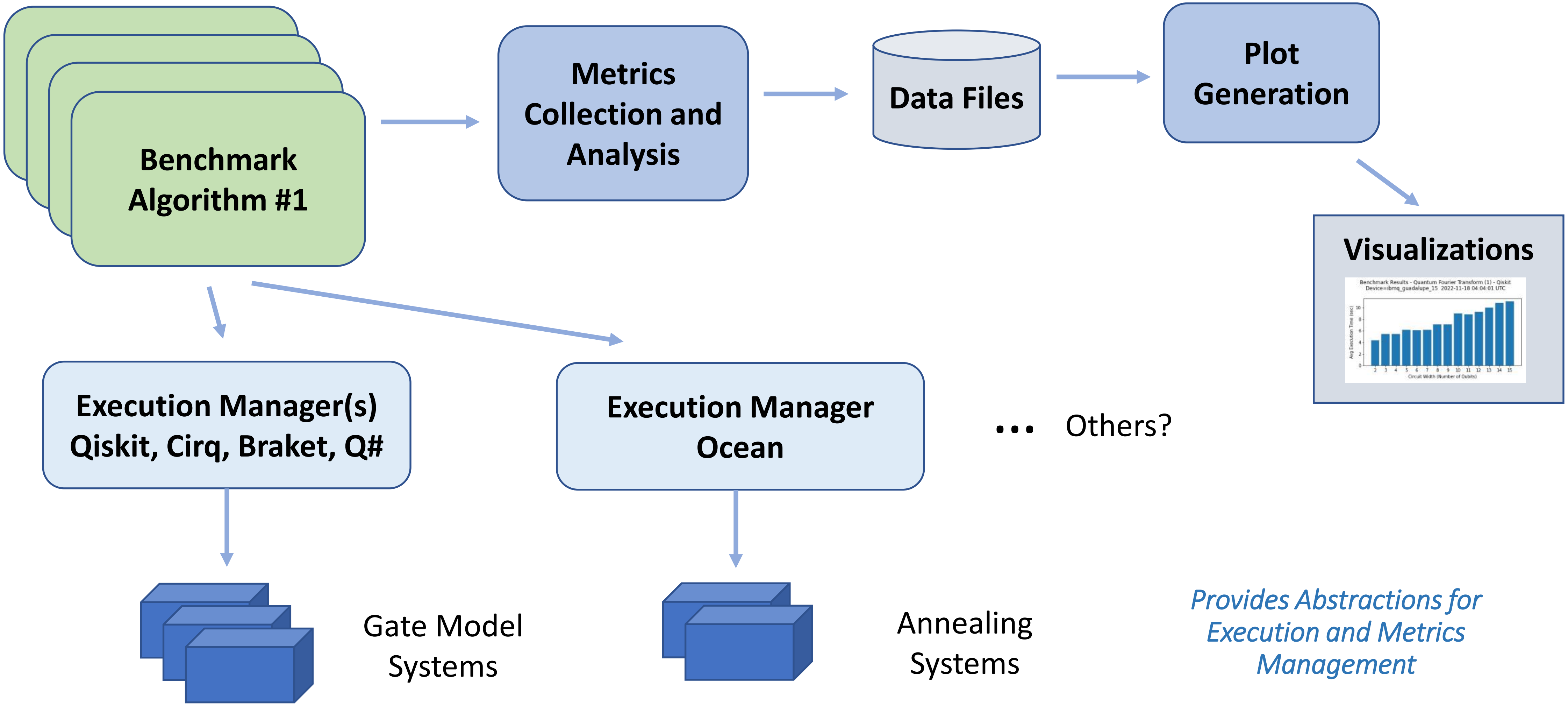


Two Ways to use Application-Oriented Benchmarks

- Benchmarking the Quantum Computer itself
  - Same benchmark run on different targets or hardware variations
  - Should align with predictions from component metrics
  - Critical to identify classical techniques used, e.g. error mitigation, which affects results

- Use Benchmarks to Explore Variations on Quantum Algorithms
  - Run a benchmark on the same machine but change parameters
  - Two directions this can take:
    - Modify properties of the quantum circuits used
    - Modify properties of the classical code, e.g. optimizer, pre- and post-processing

Benchmarking Framework – Architecture



Provides Abstractions for Execution and Metrics Management

Characterizing Quantum Application Performance

- **Resources**
  - Algorithmic Circuit Depth
  - Normalized Depth – in normal basis gates
  - Number of 2-qubit gates
  - Xi Factor – 2-qubit gates / total
  - Circuit Width

- **Execution Time**
  - Quantum Circuit Creation Time – API time
  - Quantum Execution Time – QPU time
  - Elapsed Execution Time – compile/transfer/enhance
  - Classical Execution Time – everything non-quantum

- **Result Quality**
  - Hellinger Fidelity
  - Normalized Hellinger Fidelity
  - Application-Specific Metrics

    Optimization - Approximation Ratio / Optimization Gap

    Simulation - Energy / Accuracy Ratio Error (Chem)

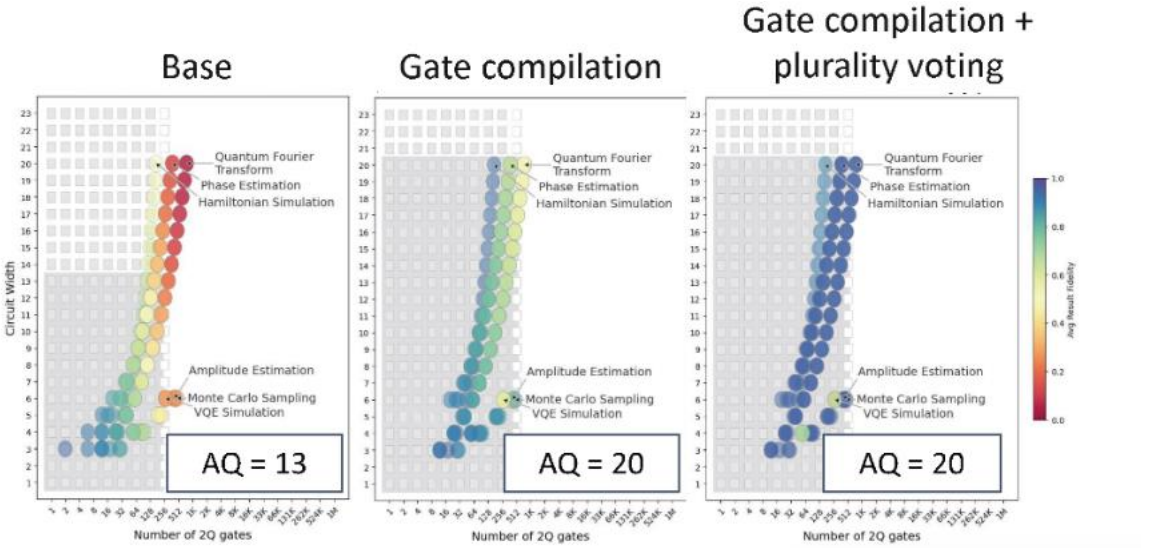
    Computation - Solution Quality (Algebraic)

Exploration of Quantum Algorithm Variations - Benchmark Weaknesses

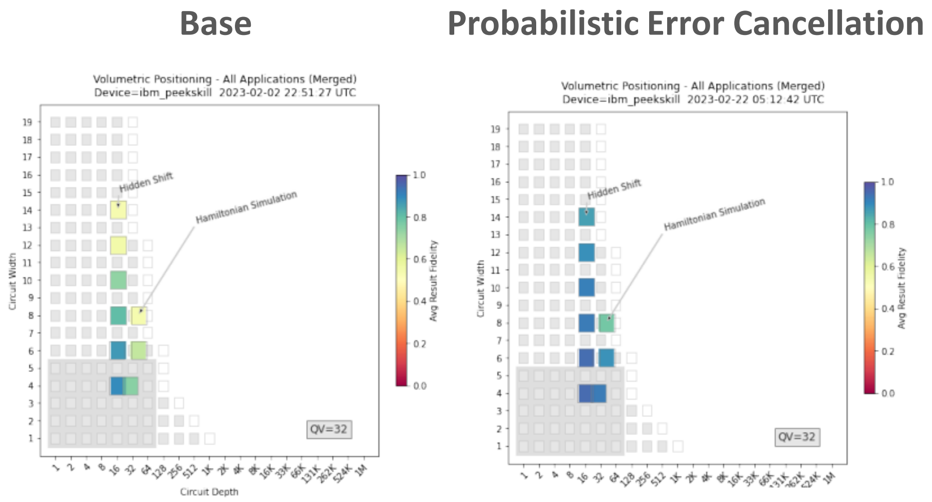
- Various External Efforts identified simple program processing techniques that produce misleading or erroneous results (e.g. ignores run-time).

- **Debunking Algo Qubits**
  - https://www.quantinuum.com/news/debunking-algorithmic-qubits

2Q fidelity = 0.995
QV = 2^{12} = 4096



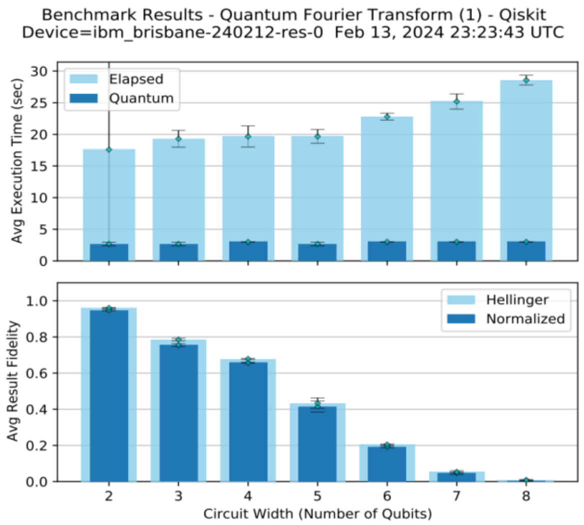
- **Defining Best Practices for Quantum Benchmarks**
  - https://www.computer.org/csdl/proceedings-article/qce/2023/432301a692/1SuQzXPjnDW

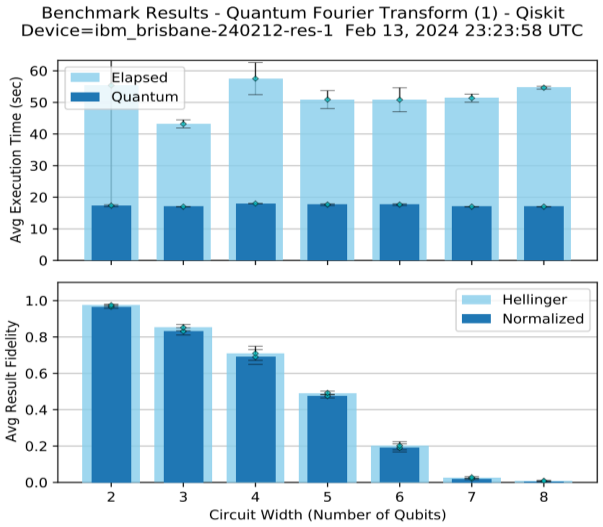


- Leads QED-C to a study of compilation / mitigation techniques

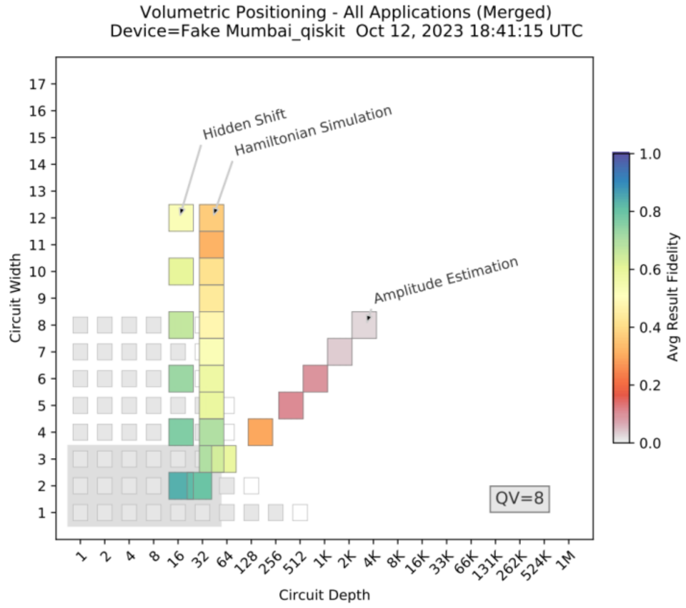
Exploration of Quantum Algorithm Variations - Program Optimizations

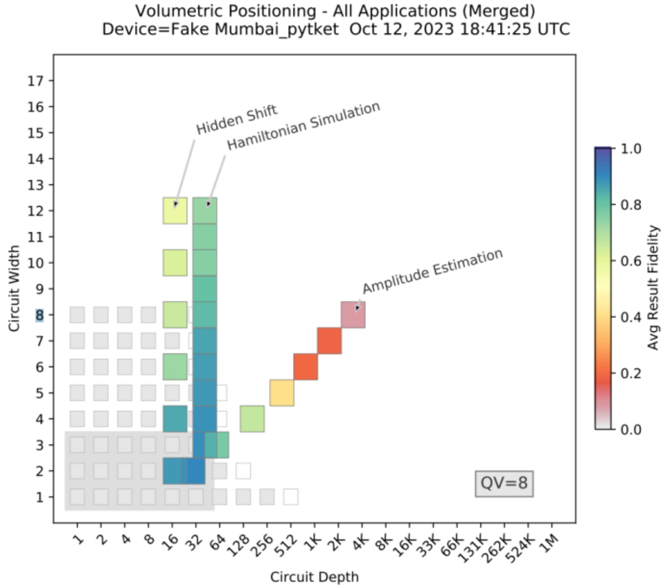
- Compare Results with error mitigation, showing run-time cost





- Compare results with special optimizations, showing algorithm-specific results





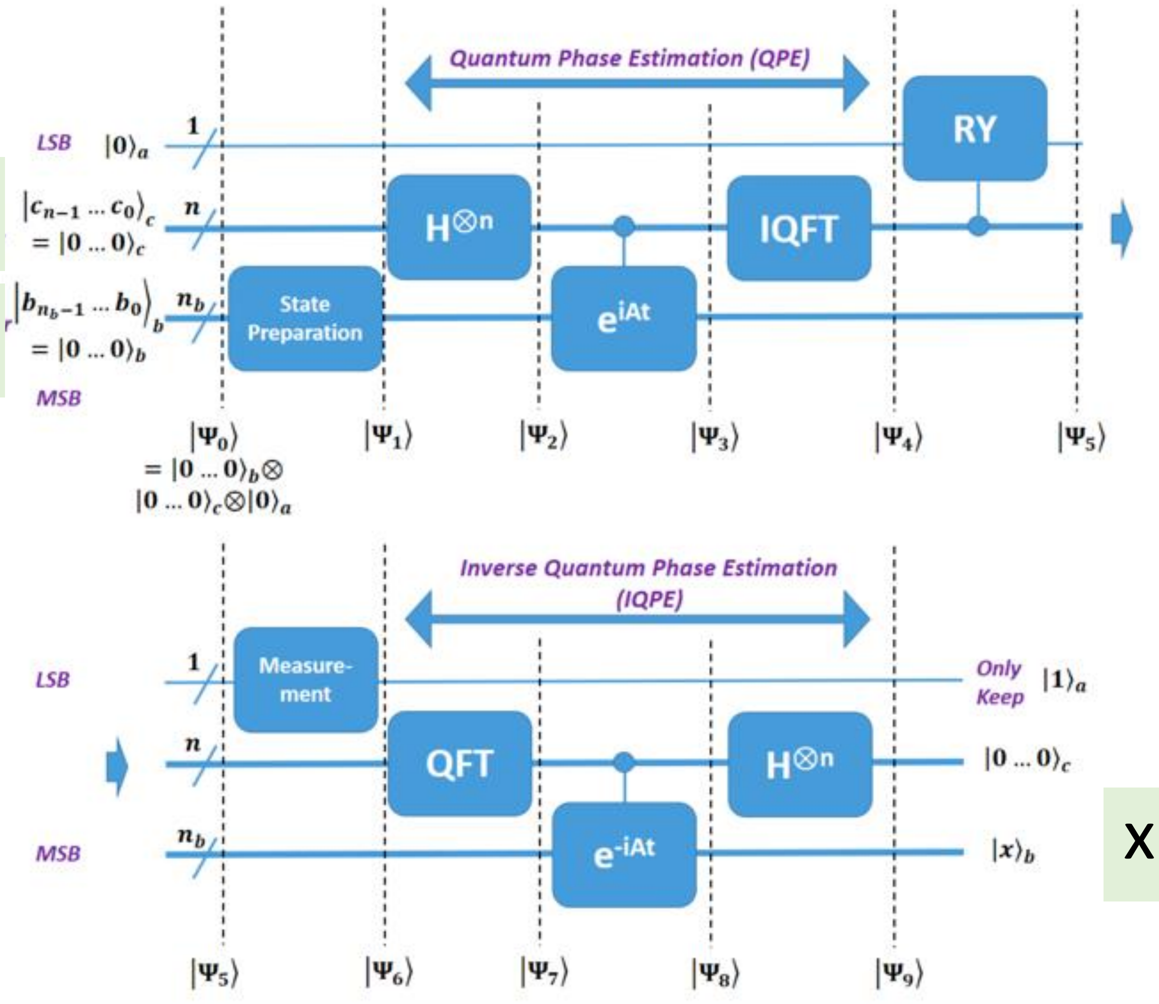
https://arxiv.org/abs/2402.08985

Exploration of Quantum Algorithm Variations (1) HHL

- Vary Circuit Construction Parameters in HHL Solver (*Ax = b, find x*)

A:clock

b:input



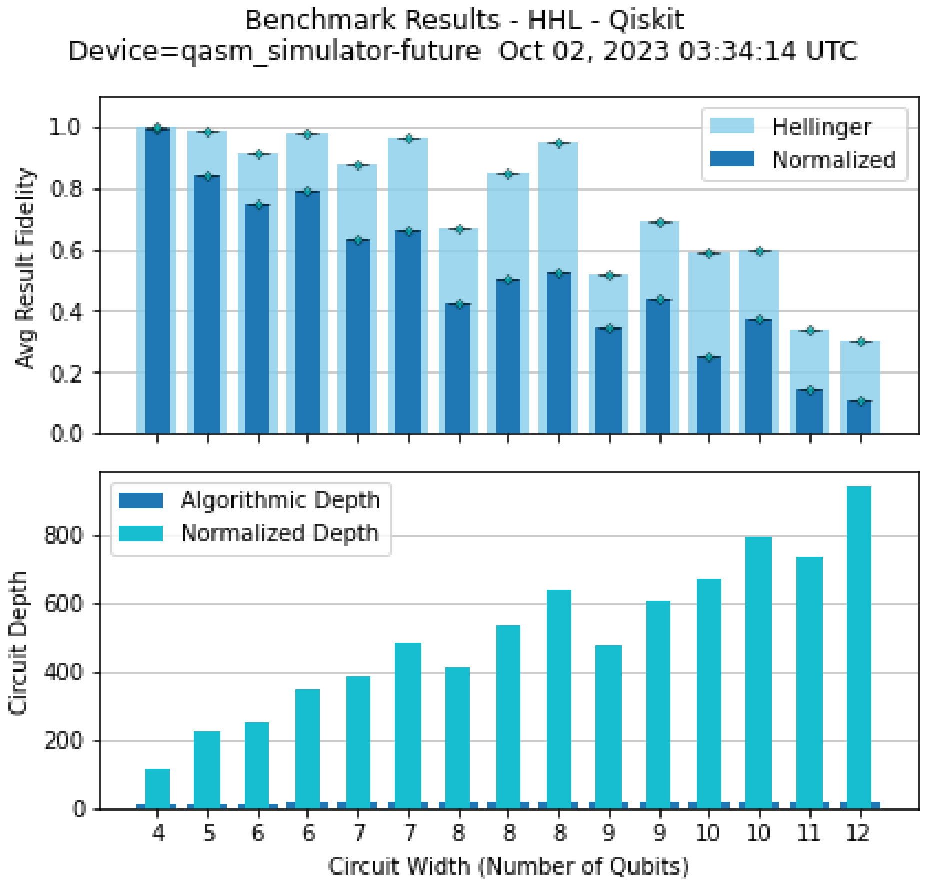
x:result

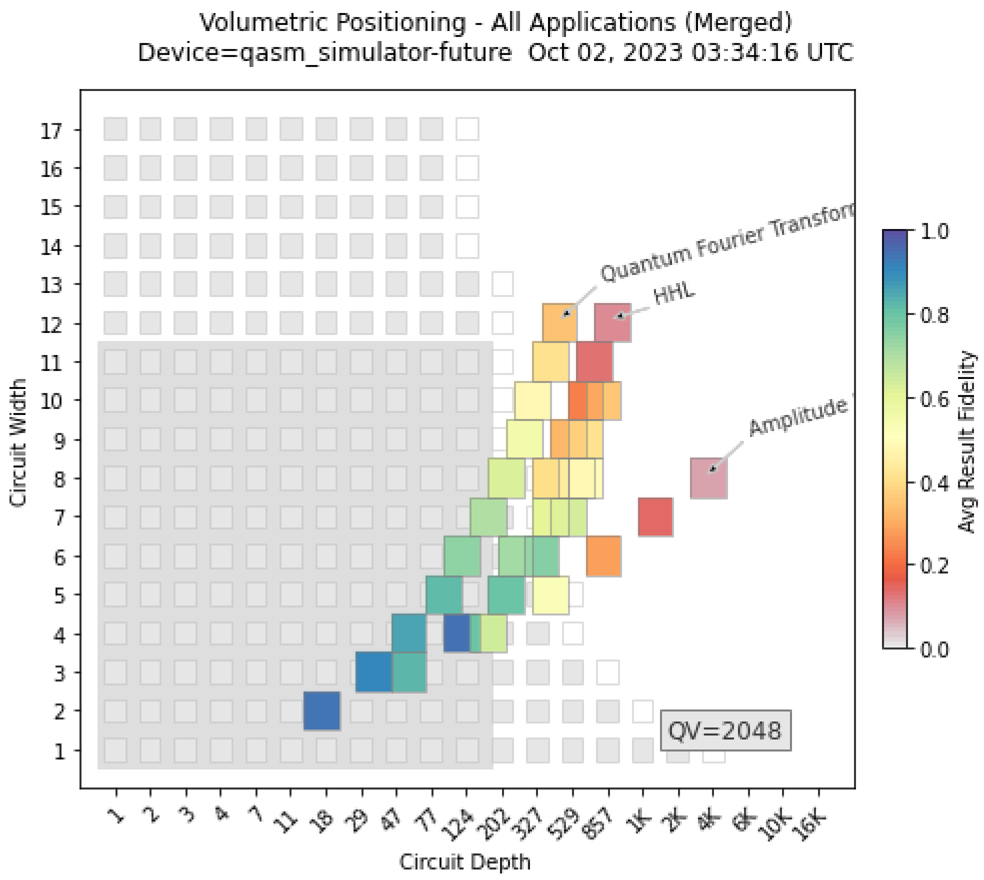
- What is the impact of modifying the clock and input size to the resources required and quality of result?

https://arxiv.org/abs/2108.09004

Exploration of Quantum Algorithm Variations -- (1) HHL

HHL Scaling Rule: $N_{total} >= 2 \times N_{input} + N_{clock} + 1$ → Multiple execution groups at some widths



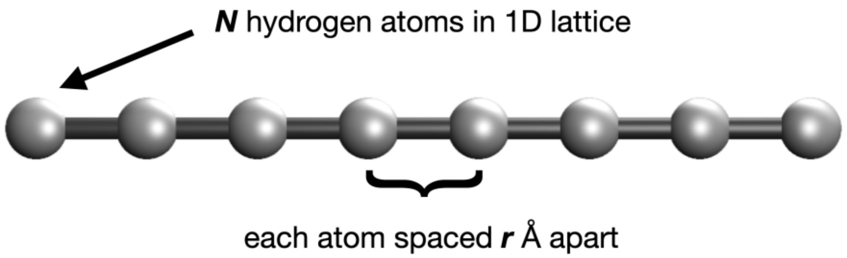


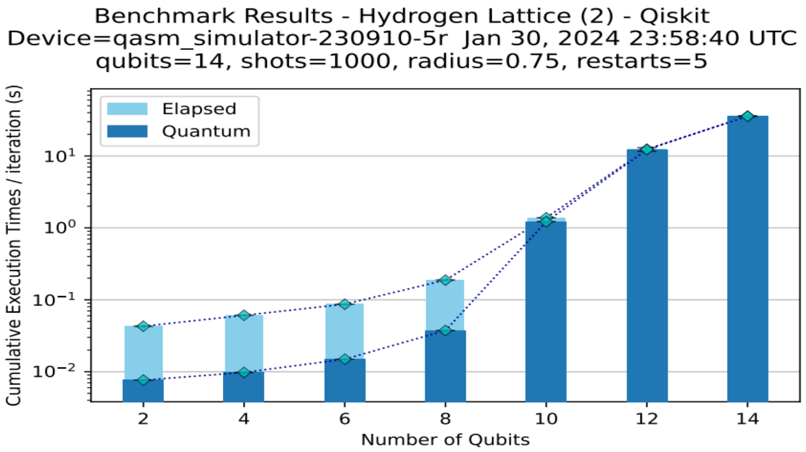
https://arxiv.org/abs/2402.08985

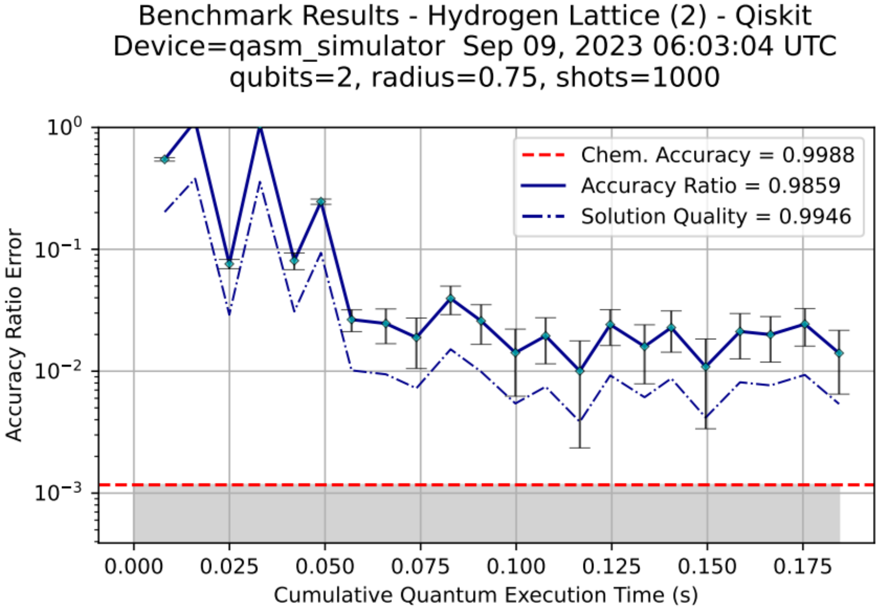
Question – why do shallower circuits in HHL perform worse?
We conjecture it is related to the number of 2 qubit gates differing.

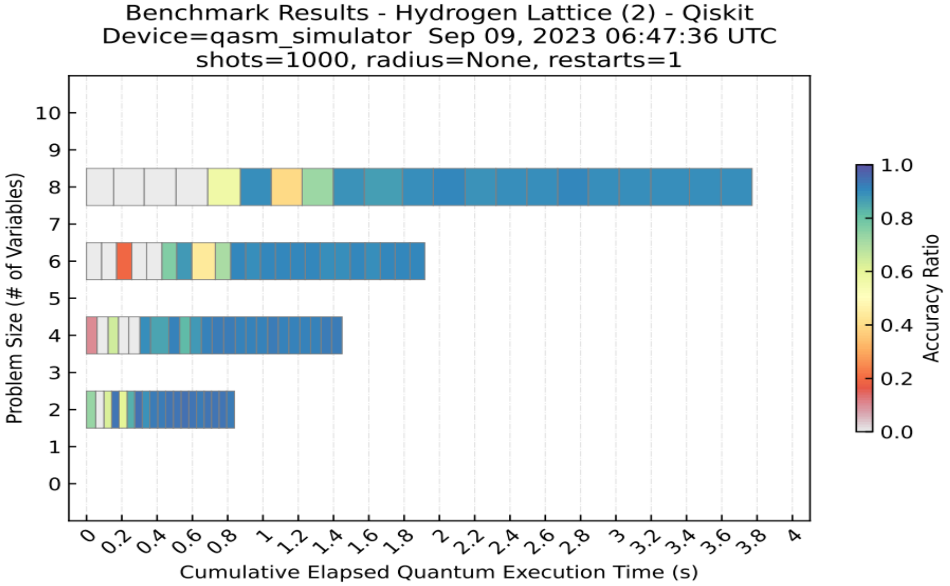
Exploration of Quantum Algorithm Variations (2) Simulation

- Vary Ansatz Parameters, Classical Optimizer, Application-Specific Simulation Metrics







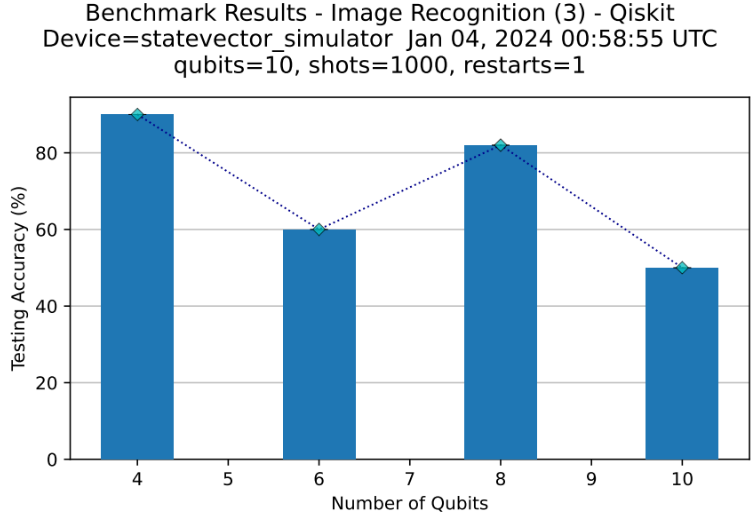


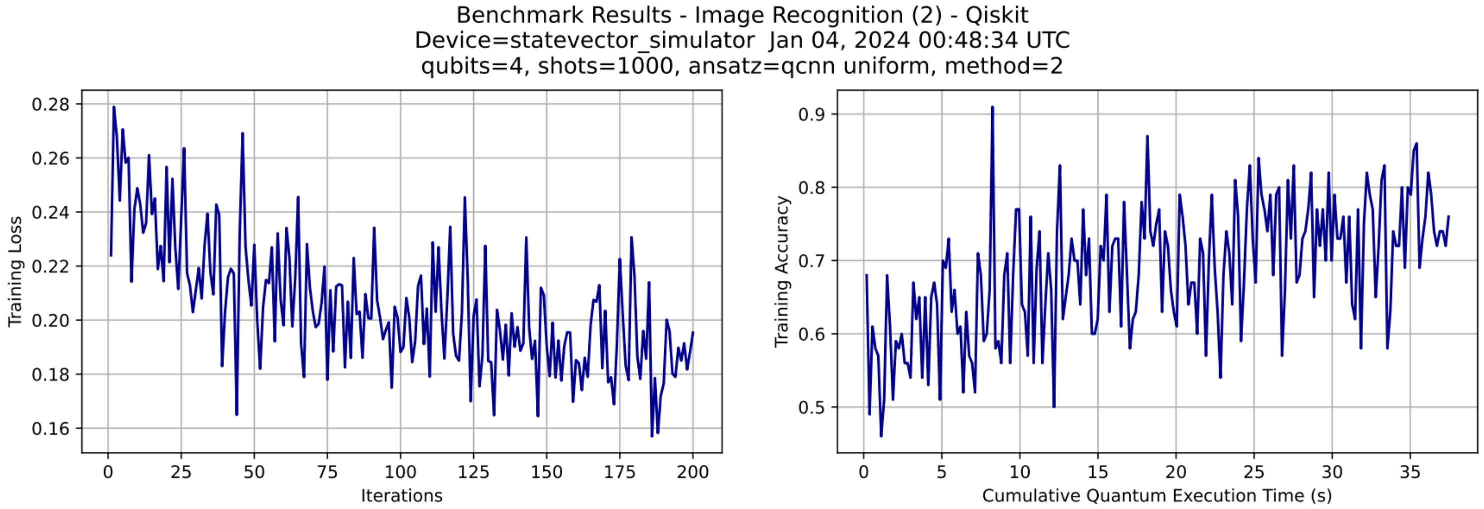
https://arxiv.org/abs/2402.08985

Exploration of Quantum Algorithm Variations (3) Machine Learning

- Image Recognition - Data Encoding, Batch Processing, Training and Execution

Recognize 1s and 7s





https://arxiv.org/abs/2402.08985

Upcoming Projects

- Build Out Hamiltonian Simulation Benchmarking
  - Improve Resilience against gross optimizations, e.g. small angle removal
  - Integrate large library of pre-computed Hamiltonians for different applications from HamLib - https://arxiv.org/abs/2306.13126

- Explore and Benchmark Advanced Quantum-Classical Algorithms
  - FALQON Feedback-based quantum optimization - https://arxiv.org/pdf/2103.08619
  - Random Walk Phase Estimation - https://www.frontiersin.org/articles/10.3389/fphy.2022.940293/full
  - LAQCC Feed-forward state preparation - https://arxiv.org/pdf/2307.14840

Incorporate Software Engineering Practices

- Primary Focus has been quantum algorithms and benchmarking

- Need - Software Engineering Improvements
  - Task Tracking, Testing, and Release Procedures
  - Delivery mechanisms beyond repo cloning and Jupyter notebooks
  - High-level website and proper documentation

- Need - Software Execution Improvements
  - Data storage and archival
  - Background processing and job management
  - User configuration management

Benchmarking – A few Key Points

Why the focus on benchmarking?

Providers and Users have lots to draw on and can do it themselves.

Provides industry validation and build credibility for continued investment

A Platform for Exploration that saves Time and Money

Express applications with consistent design patterns

How do algorithms/applications scale?

How do various evolving programming APIs differ?

Take advantage of common abstractions for execution, metrics, visualization

The End

Questions and Comments ?