Intro and Motivation: Closing the Gap Between Quantum Algorithms and Hardware through Software-Enabled Vertical Integration and Co-Design

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an NSF Expedition in Computing

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Tutorial Software Installation

- The USB drives with Docker tools and images are provided for you to complete the tutorial software installation.
- The instructions are in the USB drives.
- After you run the `tutorial_starter` script, your web browser will open the jupyter notebook automatically.
- If the jupyter notebook doesn’t run automatically, please copy/paste the URL, displayed in your terminal, to your web browser manually.
- Skip the step 4, “Edit IBM APIToken”, in the instruction since we don’t need to use IBM token for this tutorial.
- Disk space requirement: 12GB.

Raise your hand if you need any support.
Why Quantum Computing?

- Fundamentally change what is computable
  - The only means to potentially scale computation exponentially with the number of devices
- Solve currently intractable problems in chemistry, simulation, and optimization
  - Could lead to new nanoscale materials, better photovoltaics, better nitrogen fixation, and more
- A new industry and scaling curve to accelerate key applications
  - Not a full replacement for Moore’s Law, but perhaps helps in key domains
- Lead to more insights in classical computing
  - Previous insights in chemistry, physics and cryptography
  - Challenge classical algorithms to compete w/ quantum algorithms
Now is a privileged time in the history of science and technology, as we are witnessing the opening of the NISQ era (where NISQ = noisy intermediate-scale quantum).

– John Preskill, Caltech
The Algorithms to Machines Gap

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- Grover's Algorithm (Database search)
- Shor's Factoring Algorithm (Crypto)
The Algorithms to Machines Gap

Year

#Qubits

1 10 100 1000 10000 100000 1000000


#Qubits Needed

#Qubits Buildable

Gap!

Grover's Algorithm (Database search)
Shor's Factoring Alg. (Crypto)
Quantum Sim, Q Chem, QAOA
The Algorithms to Machines Gap

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- Shor's Factoring Algorithm (Crypto)
- Quantum Sim, Q Chem, QAOA
- Co-Design

Gap!
Closing the Gap: Software-Enabled Vertical Integration and Co-Design

- Grover's Algorithm (Database search)
- Shor's Factoring Algorithm (Crypto)
- Quantum Sim, Q Chem, QAOA


Gap!

- Algorithms
- Prog Lang
- Compiler
- Architecture
- Modeling
- Devices

Co-Design
Goal

Develop co-designed algorithms, SW, and HW to close the gap between algorithms and devices by 100-1000X, accelerating QC by 10-20 years.
Space-Time Product Limits

Gate Error \sim 10^{-3}

Gates

Qubits

1x1024

32x32

1024x1
Space-Time Product Limits

![Diagram showing qubits and gates with gate error ~ 10^{-5} and 128x1024 product limits]
“Good” Quantum Applications

- Compact problem representation
  - Functions, small molecules, small graphs
- High complexity computation
- Compact solution
- Easily-verifiable solution
- Co-processing with classical supercomputers
- Can exploit a small number of quantum kernels
Quantum Compiler Optimizations

- Similar to circuit synthesis for classical ASICs
- Program inputs often known at compile time
- Manage errors and precision
- Scarce resources
  - Every qubit and gate is important
Tool Flow

Scaffold tools, 41K lines of code, open source
epiqc.cs.uchicago.edu

https://github.com/epiqc/ScaffCC
Increasing Parallelism

- Compiler Optimizations:
  - Loop unrolling, constant propagation, inlining, function cloning, DAG scheduling

[Heckey+ ASPLOS 2015]
Breaking ISA Abstraction

- Multi-Qubit Operators for QAOA
  - Direct translation from compiler to control pulses

[Joint work with David Schuster]
Static vs Dynamic: Mapping Data

- Static spectral and graph partitioners
- Map for clustering
  - Probably necessary to get to 1000 qubits
- Map for irregular physical constraints
  - Qubit couplings, hardware defects
- Granularity of mappings
- Interaction with qubit reuse

Spectral communities for 2-level Bravyi-Haah magic-state factory
How do I know if my QC program is correct?

- Check implementation against a formal specification
- Check general quantum properties
  - No-cloning, entanglement, uncomputation
- Checks based on programmer assertions (quantum simulation)
- Heuristic bug-finding systems [Altadmri SIGCSE15]
- Can we check useful properties in polynomial time for programs with quantum supremacy?
What are the right abstractions?

- Specification Languages
  - Coq, Hamiltonians
- Programming Languages
  - Scaffold, Quipper, Q#, Quil …
- Instruction-Set Architectures
  - OpenQASM
- Physical Control
  - OpenPulse
Specialization vs Abstraction

Gap?

Short-term SW  Long-term SW

100  1000  10000  100000

qubits