Enabling a Programming Environment for an Experimental Ion Trap Quantum Testbed

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Introduction

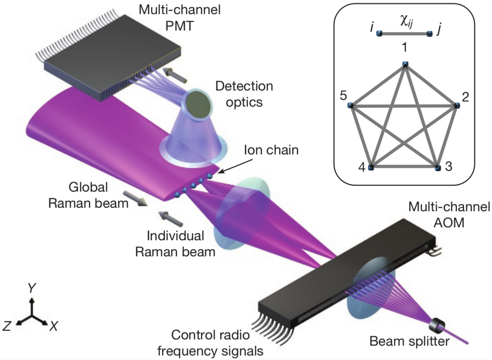
- Idea: connect an existing quantum compiler framework to the Georgia Tech Research Institute (GTRI) quantum testbed
- Motivation: Current approach is hardware expert–oriented and requires programming in assembly. Our backend introduces a more programmer-driven flow for programmers who may not be hardware experts
- Our contributions:
    - New compiler backend that interacts with the low-level testbed control software
    - Show multi-level optimizations: hardware-agnostic level and hardware-specific level
    - Performance evaluation of our backend
    - Investigation of the impact of future hardware upgrades

Background

Ion Trap Quantum Computers

- Ion trap quantum computers realize qubits by manipulating spin of trapped ions using electromagnetic radiation (e.g., lasers, microwaves)
- We consider two popular native gates on ion trap systems:
    - The single-qubit gate $R_\phi(\theta)$: A rotation of θ around the angle ϕ in the X-Y plane of the Bloch sphere
    - The two-qubit entangling gate $XX(\alpha)$: can perform a CNOT when combined with a few single-qubit gates

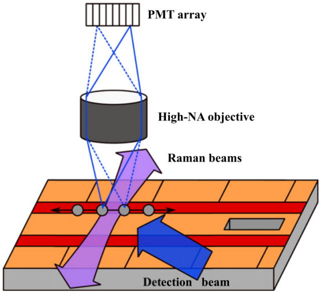
An early IonQ machine [1]:



GTRI Quantum Testbed

- The CIPHER Quantum Systems Division at Georgia Tech Research Institute (GTRI) has a quantum testbed based on an ion trap
  - Original 2016 configuration [3] (right) could only target two ions (qubits) simultaneously, but this has been upgraded to allow single-qubit addressing
  - Native operations: $R_\phi(\pi/2)$ and $XX(\pi/4)$
    - Rudimentary compiler exists for decomposing quantum assembly into a sequence of these operations
    - Control software also contains an ideal simulator originally used in calibration
  - Currently repurposed for domain-specific computations based on global operations [7]

GTRI testbed apparatus as of 2016 [3]:



QCOR

- QCOR: specification for compiler framework intended for heterogeneous quantum–classical algorithms on near-term hardware
- QCOR implementation:
  - Uses Clang syntax handler to allow running quantum circuits inline in C++ code (right)
  - Behind the scenes, uses the lower-level XACC compiler framework
    - We add a GTRI compiler backend to XACC, which surfaces it on the QCOR level

QCOR C++ program which generates and measures the GHZ state $\frac{1}{\sqrt{2}}|00\cdots0\rangle + \frac{1}{\sqrt{2}}|11\cdots1\rangle$:

```
__qpu__ void ghz(qreg q) {
  H(q[0]);
  for (int i = 1; i < q.size(); i++)
    CNOT(q[i-1], q[i]);
  Measure(q);
}

int main(int argc, char **argv) {
  auto q = qalloc(atoi(argv[1]));
  ghz(q);
  q.print();
}
```

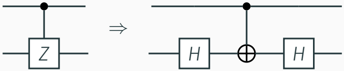
Compiler Backend Design

Backend Implementation

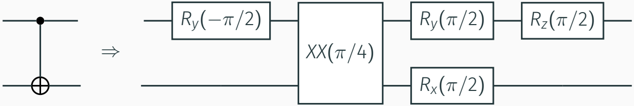
- Our XACC backend for the GTRI testbed takes XACC IR as input and:
    1. Runs an IR transformation for two-qubit gates
    2. Runs another IR transformation for single-qubit gates
    3. Writes a sequence (or table) of primitive operations to a file in a directory polled by the control software
    4. Parses simulation result written by control software and returns measurements

Two-Qubit Gate Compiler Pass

1. Decompose two-qubit gates in XACC IR into combinations of CNOT and single-qubit gates. For example,



2. Decompose CNOTs into $XX(\pi/4)$ native gates and single-qubit gates:



Single-Qubit Gate Compiler Pass

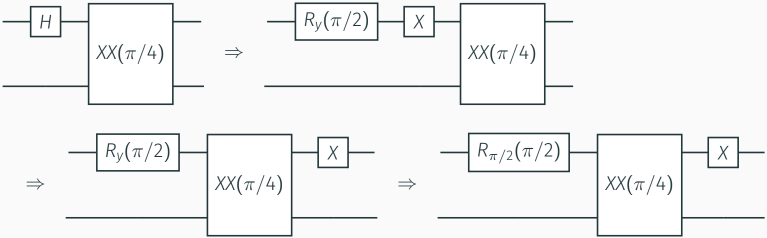
- Find adjacent single-qubit gates and multiply them together to get a goal unitary G
- Need to decompose G into the product of $R_\phi(\pi/2)$ gates
  - For example, up to a global phase, $H = XR_y(\pi/2) = R_0(\pi)R_{\pi/2}(\pi/2) = R_0(\pi/2)R_0(\pi/2)R_{\pi/2}(\pi/2)$, so

$$-\boxed{H}- \quad \Rightarrow \quad -\boxed{R_{\pi/2}(\pi/2)}-\boxed{R_0(\pi/2)}-\boxed{R_0(\pi/2)}-$$

- Use numerical optimizer to find the ϕ angles
- Start with 1 rotation and keep adding rotations until we get a sufficiently close decomposition
  - In our experiments, the maximum needed is 4 rotations

Single-Qubit Decomposition up to an X-Rotation

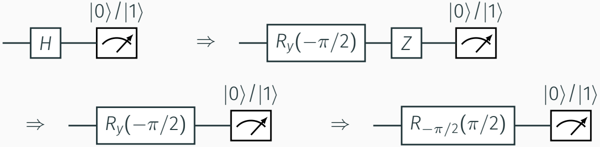
- We can ask the optimizer for a different decomposition in different situations
- Fun fact: XX commutes with X-rotations
- So when G ends at an XX gate, we can ask for a decomposition up to an X-rotation, and commute that final $R_x(\theta)$ to the other side of the XX. Example:



- Deal with the $R_x(\theta)$ in a later iteration

Single-Qubit Decomposition up to a Z-Rotation

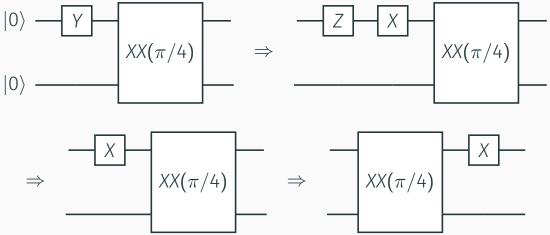
- Z-rotations do not change measurement outcomes when measuring in the $|0\rangle$ / $|1\rangle$ basis
- When the gates to decompose end at a measurement, we can ask optimizer for a decomposition up to a Z-rotation ($R_z(\theta)$ gate)
- Example using $H = ZR_y(-\pi/2)$:



- Can discard the ending $R_z(\theta)$

Single-Qubit Decomposition *from* a Z-Rotation

- Up to a global phase, $R_z(\theta)\,|0\rangle = |0\rangle$
- So when the gates start at the beginning of the circuit, we can ask the optimizer for a decomposition starting with a Z-rotation
- Example using $Y = XZ$ (up to a global phase):



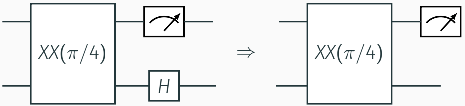
- Discard the leading $R_z(\theta)$
- Can combine with the previous two optimizations!

Single-Qubit Gate Compiler Pass: Two More Optimizations

Can skip the optimizer entirely in two situations:

1. If G is closer than the configured threshold to identity, we discard the sequence of gates. For example:

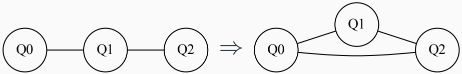
2. If the sequence of gates ends with the end of the circuit, without a measurement, then we can safely discard the gates without affecting measurement outcomes the programmer cares about:



Future Hardware Upgrades

What if the GTRI testbed had a tightly-focused beam for each ion as demonstrated by IonQ [2]? We consider the following two benefits:

1. **All-to-all connectivity:** Can reduce number of SWAP gates needed to execute logical circuit on linear chain of ions (qubits)
    - Easy: QCOR handles qubit placement, so have our `Accelerator` tell QCOR we have full connectivity instead of linear



2. **Parallel single-qubit operations:** Execute multiple $R_\phi(\pi/2)$ gates across different qubits in the same "cycle"
    - We use a greedy algorithm that takes resulting IR from two compiler passes and builds a table of native operations
    - Example for the Bell state circuit `H 0; CNOT 0,1`:

Operation	Ion	ϕ
$XX(\pi/4)$	0,1	
$R_\phi(\pi/2)$	0	$\pi/2$
$R_\phi(\pi/2)$	1	0

$\Rightarrow$

Operation	Ion 1	ϕ_1	Ion 2	ϕ_2
$XX(\pi/4)$	0,1			
$R_\phi(\pi/2)$	0	$\pi/2$	1	0

Experiments and Discussion

Evaluation

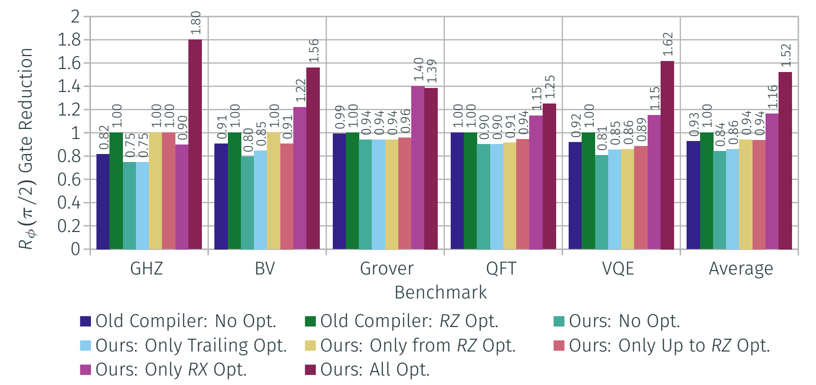
- Physical testbed hardware has been repurposed for domain-specific computations based on global operations, so we cannot test on hardware
- Instead, we:
  1. Validate results using the simulator already included in the control software
  2. Roughly estimate fidelity by counting native operations
- Benchmark QCOR programs on three-qubit programs:
  - GHZ, which generates the state $\frac{1}{\sqrt{2}} |000\rangle + \frac{1}{\sqrt{2}} |111\rangle$
  - Bernstein-Vazirani with secret string $s = 11$
  - Grover with one iteration and marked states $|101\rangle$ and $|110\rangle$
  - Quantum Fourier Transform using the `qft()` QCOR routine
  - VQE (Variational Quantum Eigensolver) on a three-qubit Hamiltonian using the QCOR tooling for VQE

Validation Results

- We compare probability distribution of measurements based on the final state vectors produced by our backend and the existing Quantum++ simulator backend.
- Why not compare final state vectors?
  - By design, the single-qubit pass will produce different final states, even considering global phase. Example: for Bernstein–Vazirani, our compiler discards a trailing Hadamard on the ancilla qubit, so the final state becomes $\frac{1}{\sqrt{2}}\left|110\right\rangle - \frac{1}{\sqrt{2}}\left|111\right\rangle$ rather than $\left|111\right\rangle$
    - The programmer measures only the other two qubits, so no observable difference

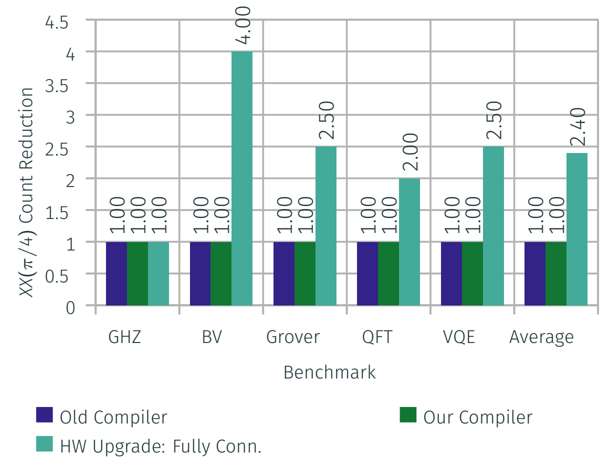
Gate Count Reduction

As expected, we saw no reduction in $XX(\pi/4)$. For $R_\phi(\pi/2)$ gates, we saw an average of 1.52× reduction:



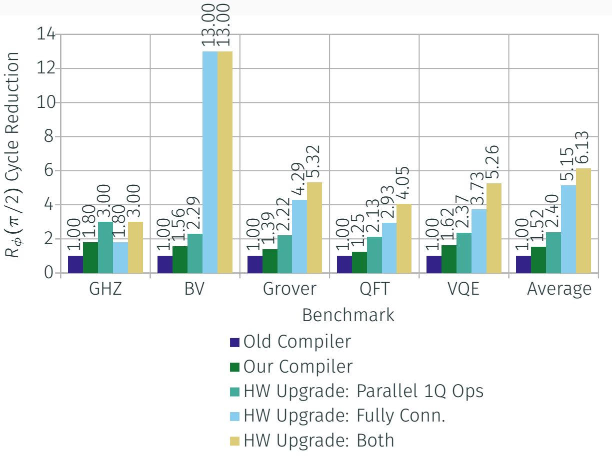
$XX(\pi/4)$ Gate Count Reduction: Hardware Upgrades

Full connectivity showed a 2.40× reduction in $XX(\pi/4)$ native operations:



$R_\phi(\pi/2)$ Gate Count Reduction: Hardware Upgrades

Together, full connectivity and parallel operations showed a 6.13× reduction in $R_\phi(\pi/2)$ native operations:



Adaption to Other Hardware

- The $XX(\alpha)$ and $R_\phi(\theta)$ are common native gates for ion trap hardware
  - See: IonQ hardware [1], Sandia QSCOUT testbed [4]
- But does other hardware restrict the θ angle in $R_\phi(\theta)$?
  - Aforementioned hardware does not, but it's not an uncommon choice. For example, the 2021 Honeywell machine limits θ to π or $\pi/2$ [6]
  - Adjusting our optimizer-based decomposition for these machines would be straightforward
- What about hardware with only global operations? (E.g., the current configuration of the GTRI testbed)
  - Possible with XACC, but our current backend is not totally compatible
  - However, any hardware programmed with a typical quantum gateset will benefit from existing high-level optimizations in QCOR [5]

Future Work

- Run this on actual hardware!
- Consider parallel two-qubit gates [2], non-$R_\phi(\pi/2)$ operations, make decompositions consider parallelism
- What about different hardware, like the 2021 Honeywell QCCD machine? Or TILT hardware? [6, 8]

Thank you!

- QCOR website: `https://qcor.ornl.gov/`
- Backend source code: `https://github.com/ausbin/xacc/tree/ion-trap-backend/`

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