

Building a Compiler for Quantum Computers

Matthew Treinish

Software Engineer - IBM Research

mtreinish@kortar.org

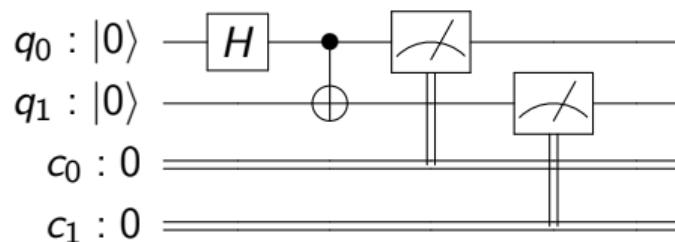
`mtreinish` on Freenode

<https://github.com/mtreinish/quantum-compilers>

January 17, 2020

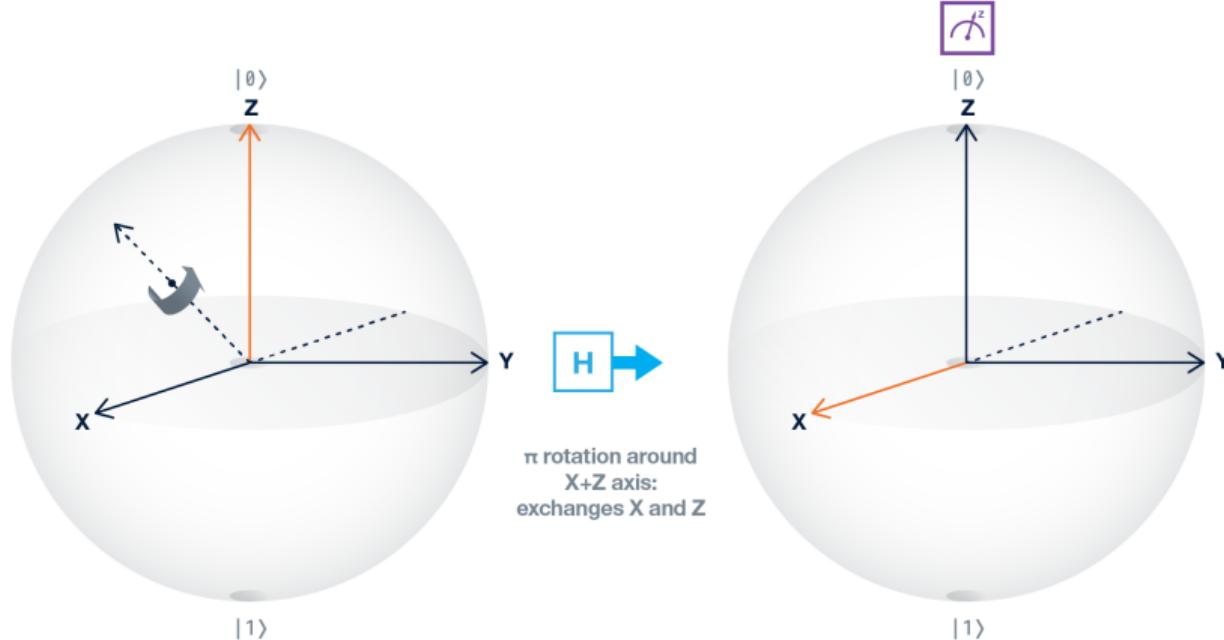
Quantum Circuits

- ▶ Used to describe operations on a quantum computer
- ▶ Each row represents a bit (either classical or quantum)
- ▶ Shows dependency of operation



Quantum Gates

- ▶ Quantum gates
- ▶ Gates are reversible
- ▶ Each gate can be represented as a unitary matrix



OpenQASM¹²

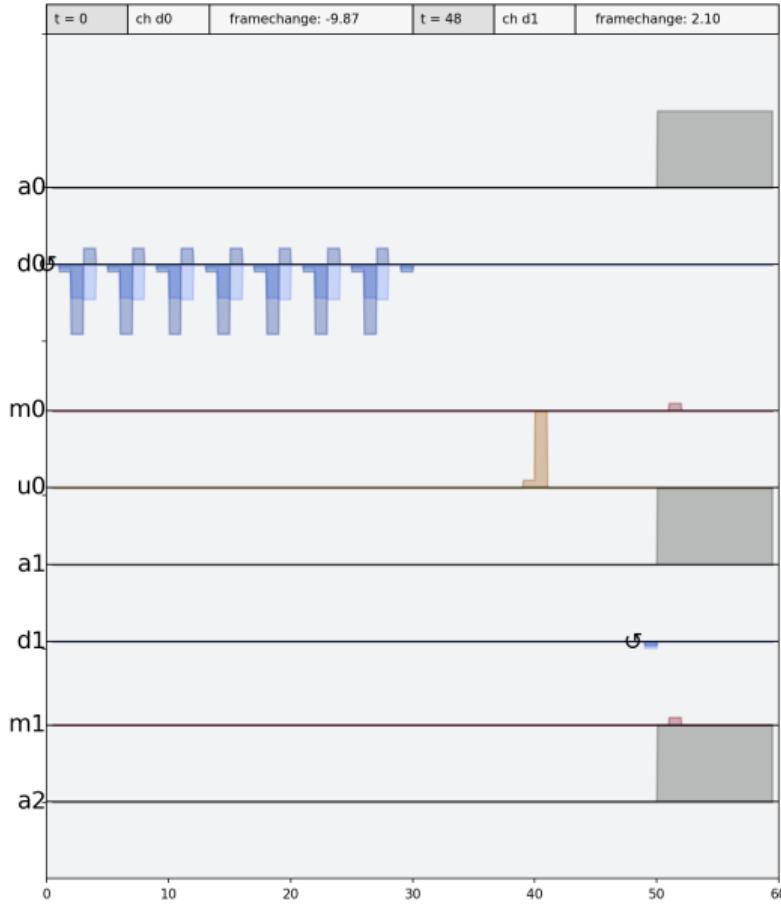
```
OPENQASM 2.0;
include "qelib1.inc";
qreg q[2];
creg c[2];
h q[0];
cx q[0],q[1];
measure q[0] -> c[0];
measure q[1] -> c[1];
```

- ▶ Open Quantum Assembly Language
- ▶ Can be used to write circuits
- ▶ Mostly used as a transport layer to save circuits or as a transport

¹<https://arxiv.org/abs/1707.03429>

²<https://github.com/Qiskit/openqasm>

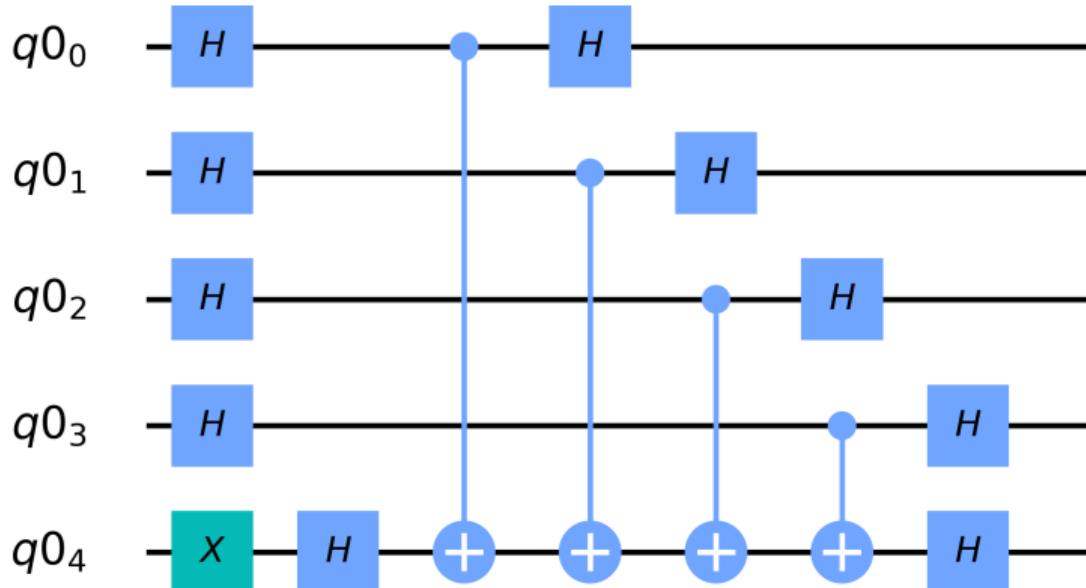
Pulse Level Programming



- ▶ A layer below the circuit model is to use pulses
- ▶ Each quantum gate is defined as a pulse that gets applied to the qubits
- ▶ Enables you to tweak the definition of gates
- ▶ Mostly used for physics research or hardware characterization

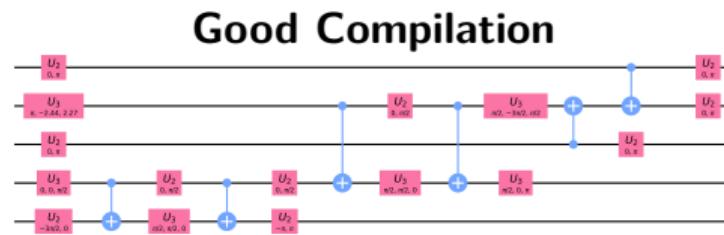
Why do we need compilers?

- ▶ Despite programming at a low level there are lots of constraints with programming a quantum computer
- ▶ The compiler is used to enable running logical abstract circuit on an actual device
- ▶ the performance of the compiler can be the difference between getting a result and not



Why do we need compilers?

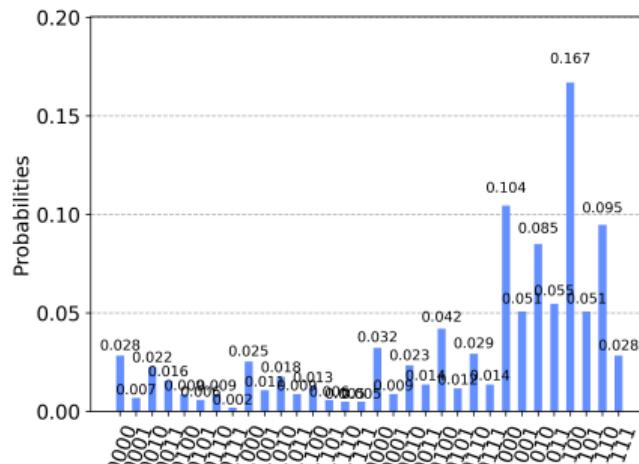
- ▶ Despite programming at a low level there are lots of constraints with programming a quantum computer
- ▶ The compiler is used to enable running logical abstract circuit on an actual device
- ▶ the performance of the compiler can be the difference between getting a result and not



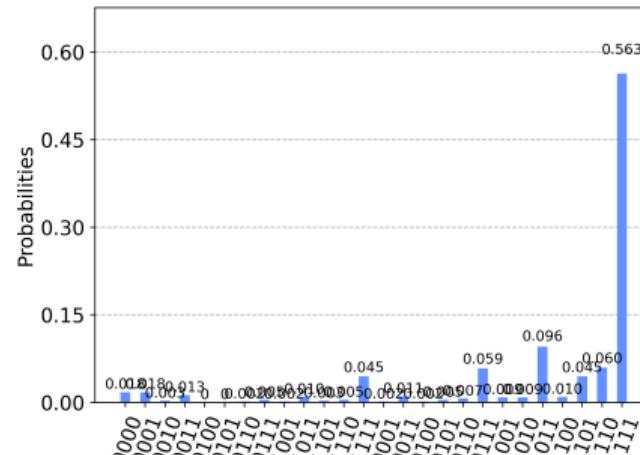
Why do we need compilers?

- ▶ Despite programming a low level there are lots of constraints with programming a quantum computer
 - ▶ The compiler is used to enable running logical abstract circuit on an actual device
 - ▶ the performance of the compiler can be the difference between getting a result and not

Bad Compilation



Good Compilation



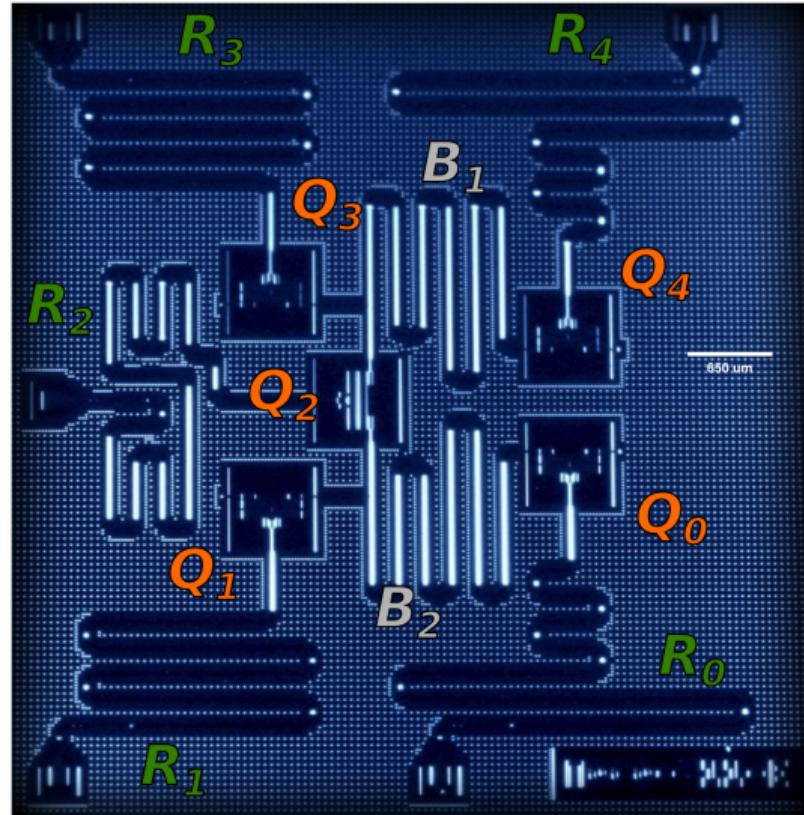
Basis Gates

- ▶ Each Quantum Computer only supports a small set of basis gates
- ▶ These gates can be used to implement any other
- ▶ For circuits to be executable by a quantum computer they must be expressed in terms of their basis gates

Qubit Connectivity

- ▶ Qubits in a device have limited connectivity
- ▶ For multi-qubit gates this means we can only run them between those qubits

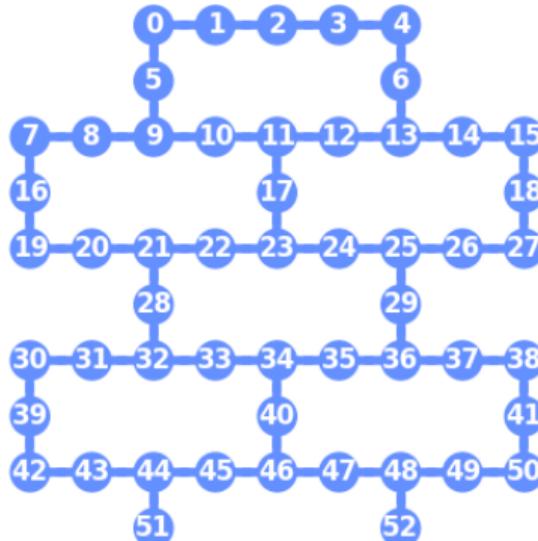
IBM Q 5 Yorktown



Qubit Connectivity

IBM Q 53 Rochester Coupling Map

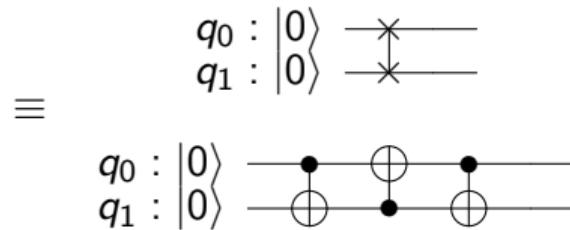
- ▶ Qubits in a device have limited connectivity
- ▶ For multi-qubit gates this means we can only run them between those qubits



Not Enough Connectivity

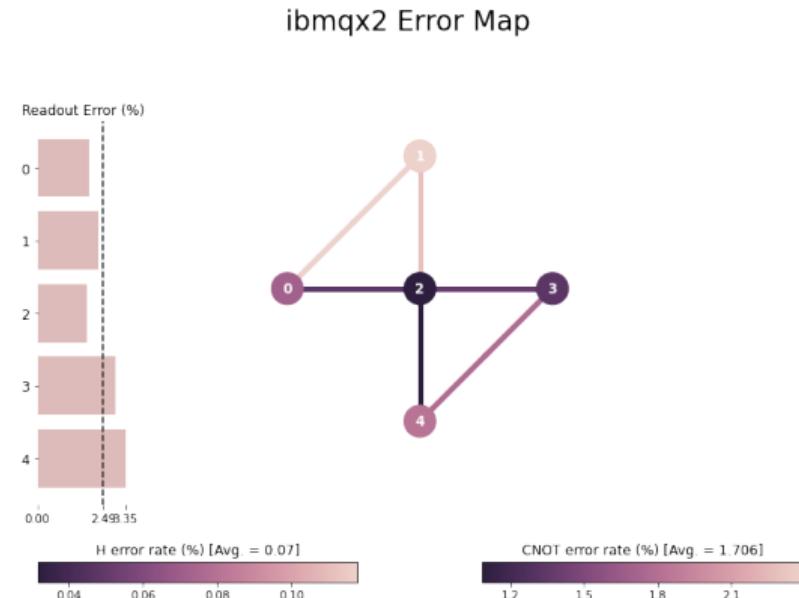
- ▶ If there
- ▶ Use SWAP gate to move state around

SWAP Gate



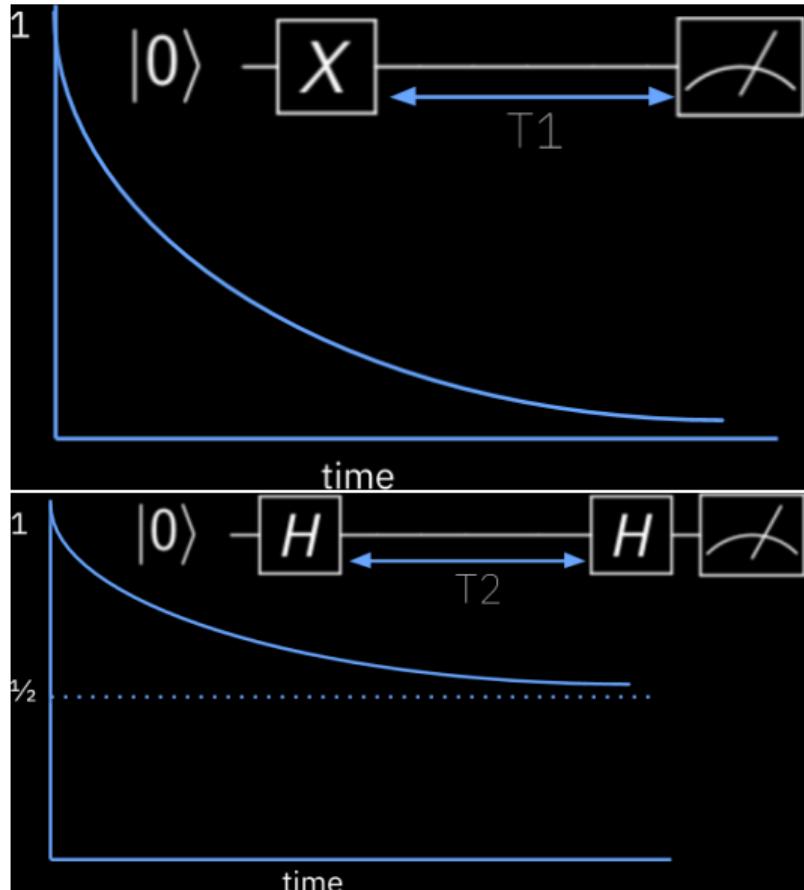
Noise

- ▶ Gate Errors
 - ▶ Single Qubit Errors
 - ▶ Multiqubit Errors
- ▶ Decoherence
 - ▶ T1: Energy relaxation, the time for a qubit at $|1\rangle$ to decay to ground state $|0\rangle$
 - ▶ T2: dephasing of a qubit in superposition state
- ▶ Readout Error



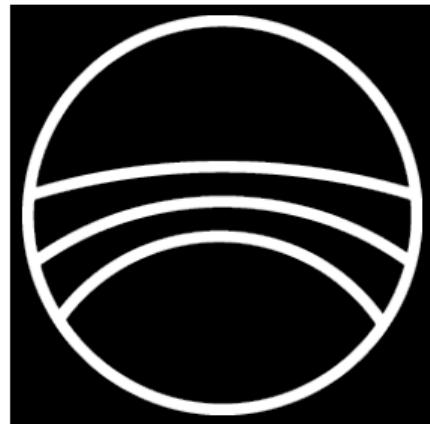
Noise

- ▶ Gate Errors
 - ▶ Single Qubit Errors
 - ▶ Multiqubit Errors
- ▶ Decoherence
 - ▶ T1: Energy relaxation, the time for a qubit at $|1\rangle$ to decay to ground state $|0\rangle$
 - ▶ T2: dephasing of a qubit in superposition state
- ▶ Readout Error



Qiskit Terra¹

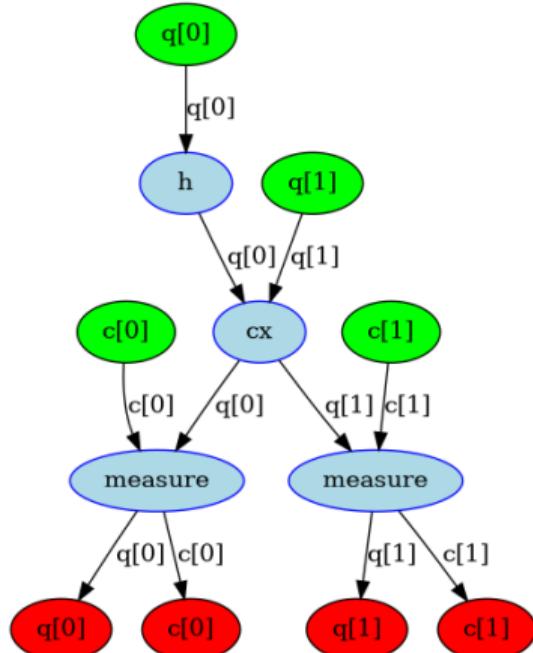
- ▶ Is the base layer for working with quantum computers provides interface to hardware and simulators
- ▶ Provides an SDK for working with quantum circuits
- ▶ Compiles circuits to run on different backends
- ▶ Designed to be backend agnostic and work with any quantum hardware or simulator
- ▶ Written in Python
- ▶ Apache 2.0 Licensed

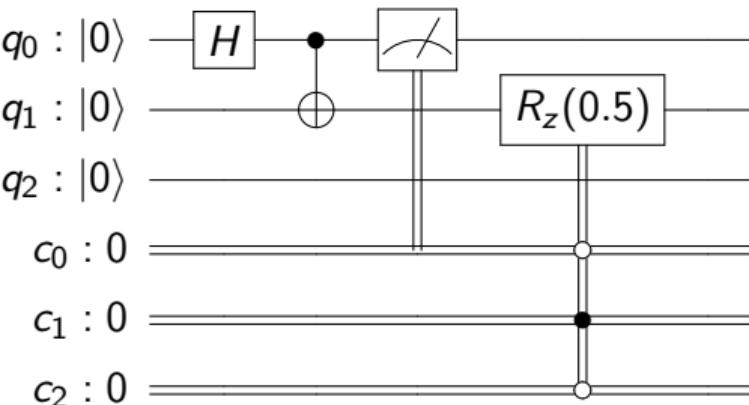


¹<https://github.com/Qiskit/qiskit-terra>

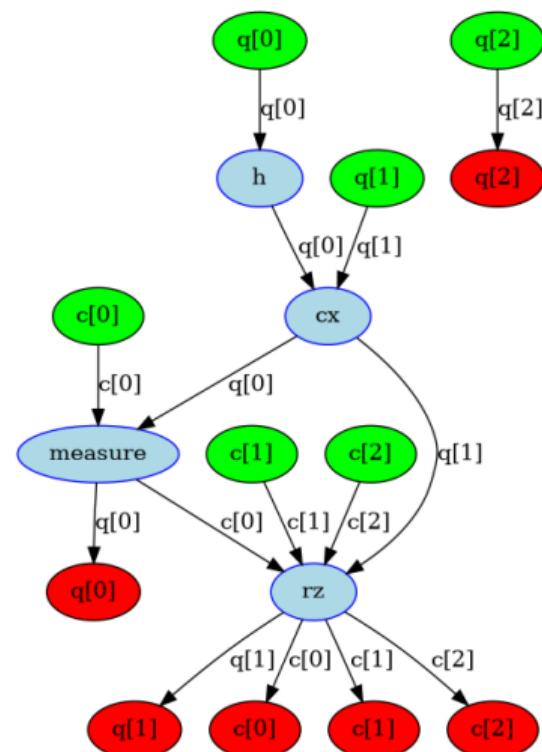
The DAG

- ▶ Compiler represents circuits as a DAG
- ▶ Each node in the DAG is an operation, an input, or an output
- ▶ Each edge indicates data flow between nodes
- ▶ Makes flow of information between operations explicit

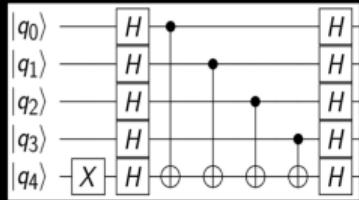




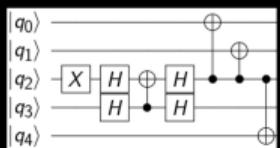
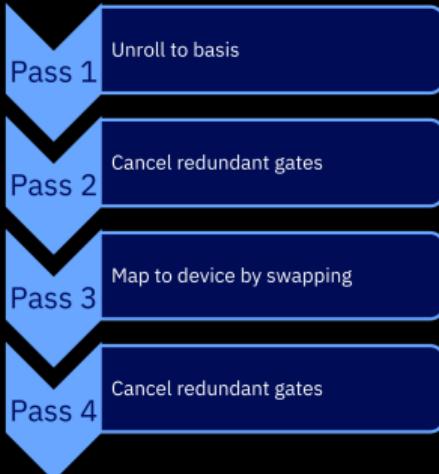
\rightarrow



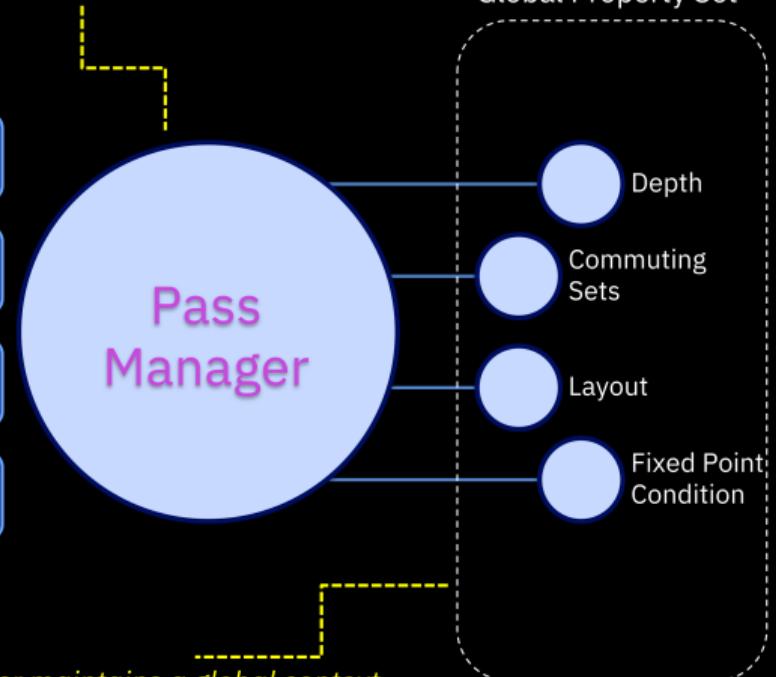
Transpiler Architecture



Each pass does one small, well-defined task.

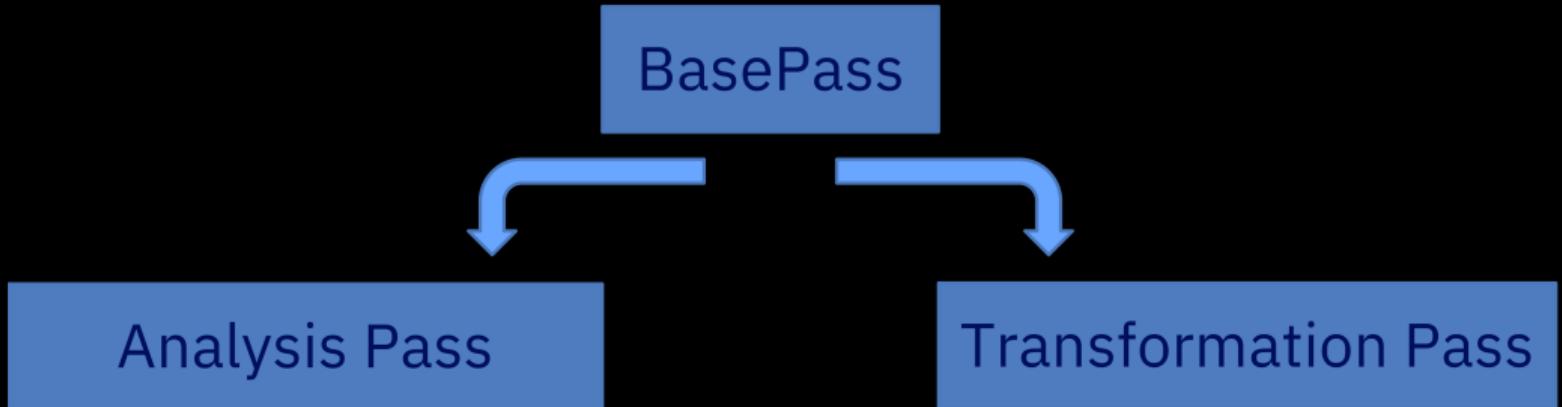


The complexity of scheduling is solely in the pass manager, to keep passes simple



The pass manager maintains a global context about the circuit as it runs through the pipeline

Transpiler Architecture



- Read-only Access to DAG
- Write Access to Property Set

- Write Access to DAG
- Read-only Access to Property Set

Example (commutation relationships):

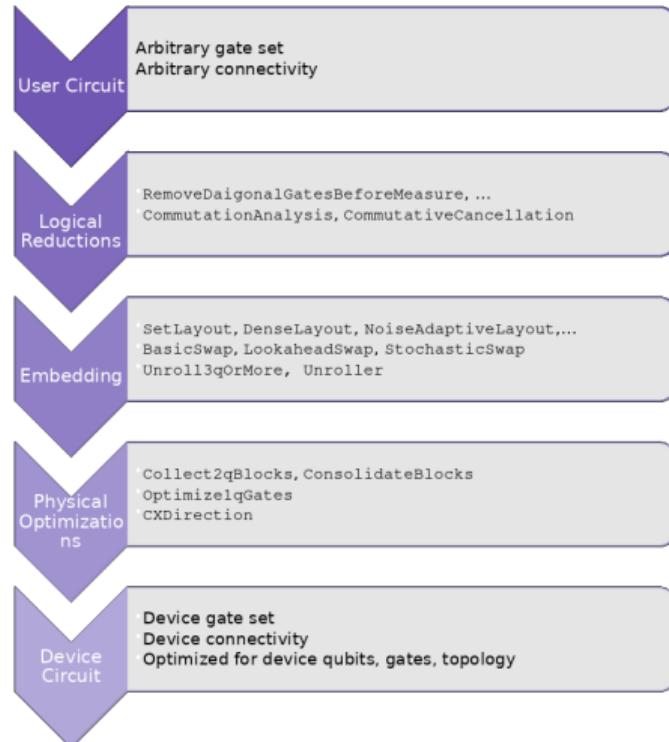
Pass A is an Analysis Pass that inspects the graph and finds nodes that can commute.

Pass B is a Transformation Pass that dissolves those edges that commute (are false dependencies).

Pass B requires Pass A, and indicates this to the Pass Manager

Passmanager Stages

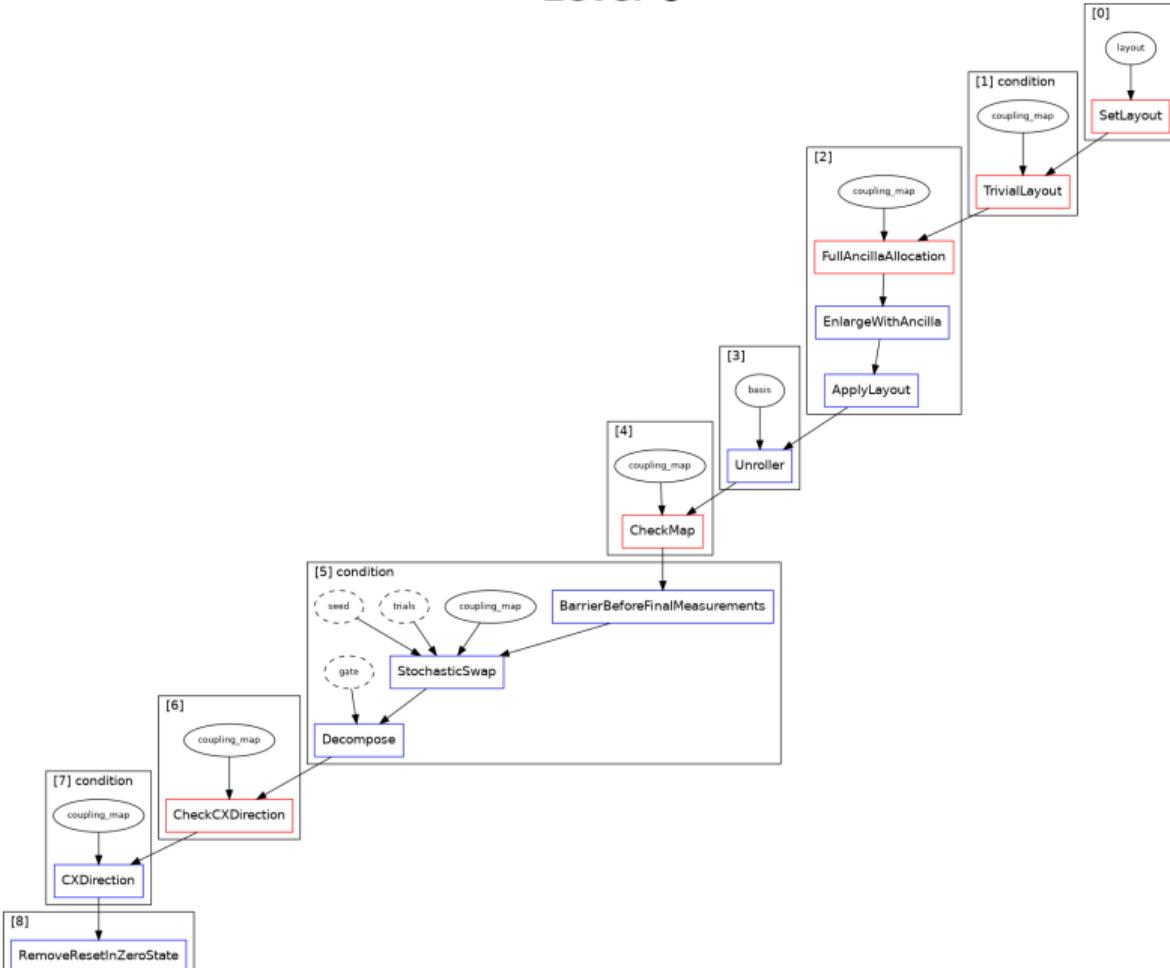
- ▶ Stages
 - ▶ Logical Reductions
 - ▶ Embedding
 - ▶ Layout
 - ▶ Mapping/Routing
 - ▶ Unrolling
 - ▶ Physical Reductions
- ▶ Pluggable and extensible



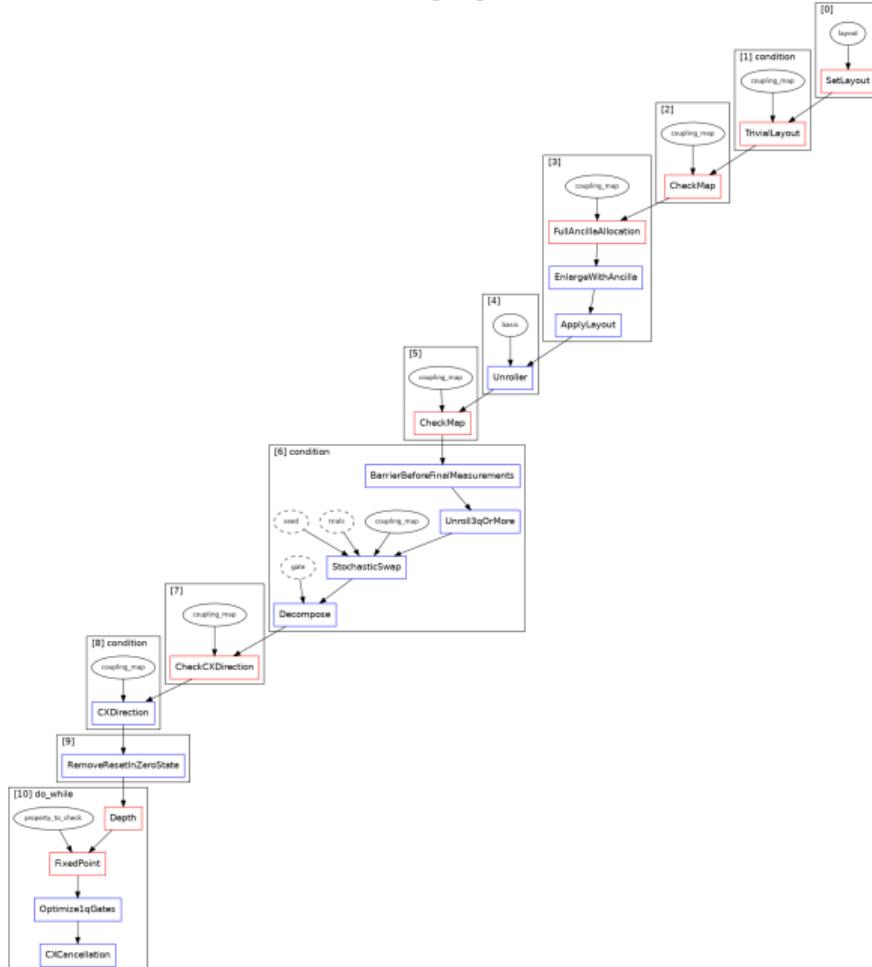
Preset Pass Managers

- ▶ Out of the box 4 optimization levels (0-3) with preset pass managers
- ▶ Increasing levels of optimization vs execute time

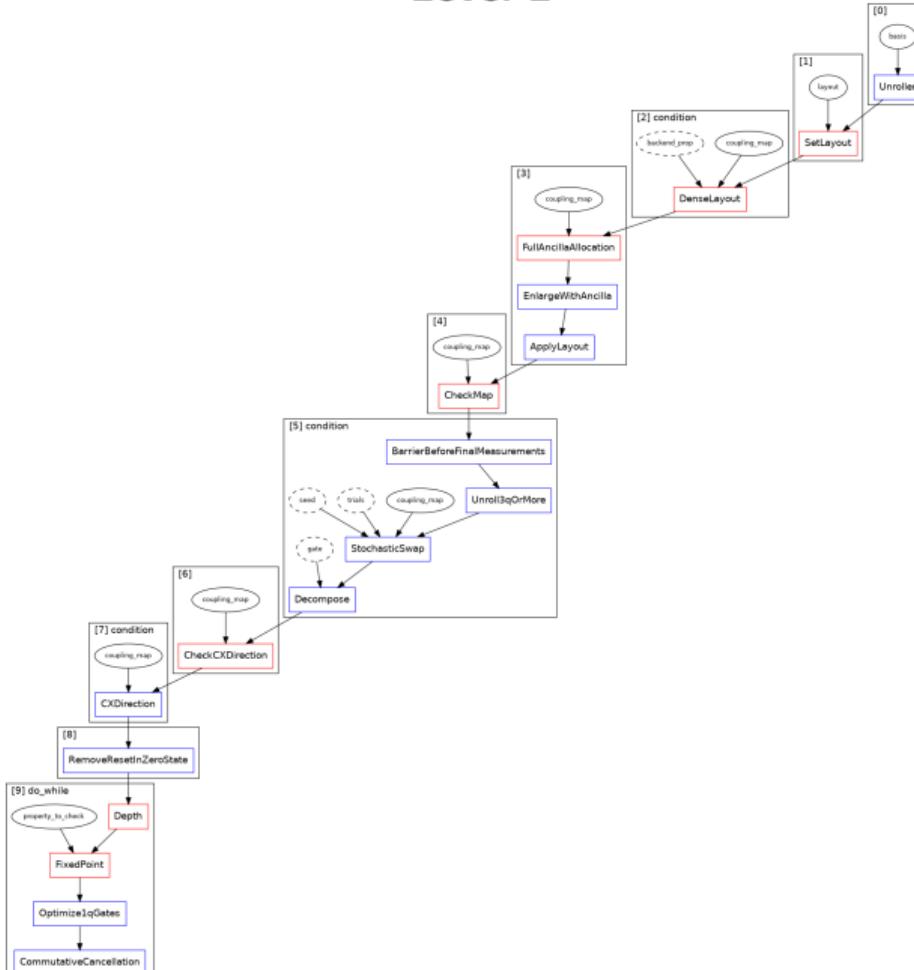
Level 0



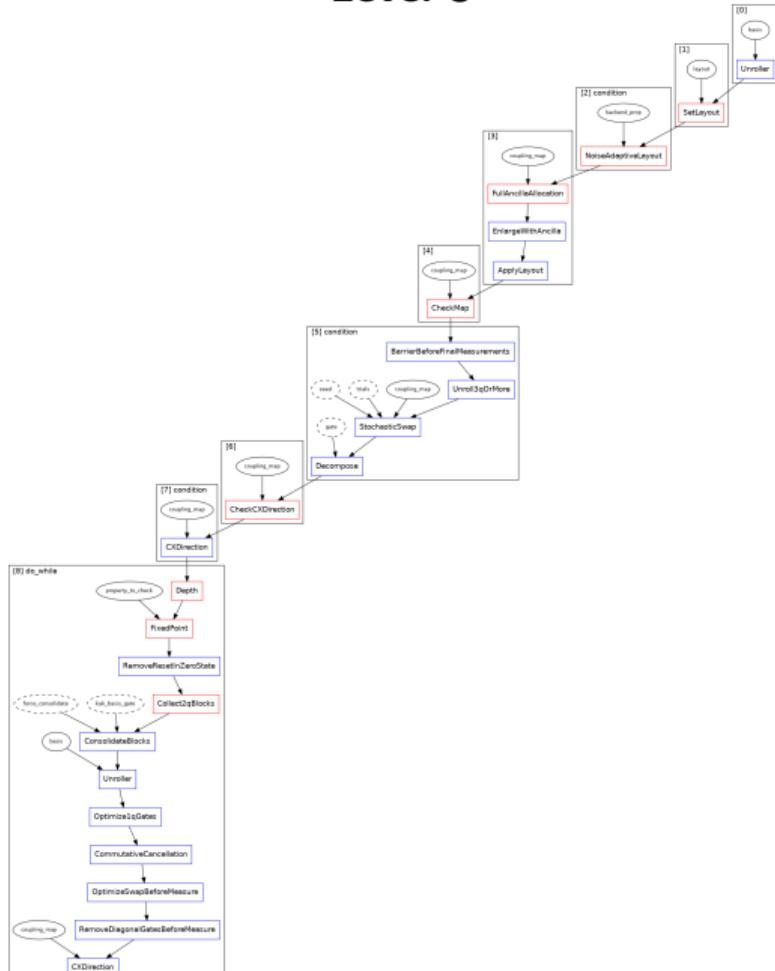
Level 1



Level 2



Level 3



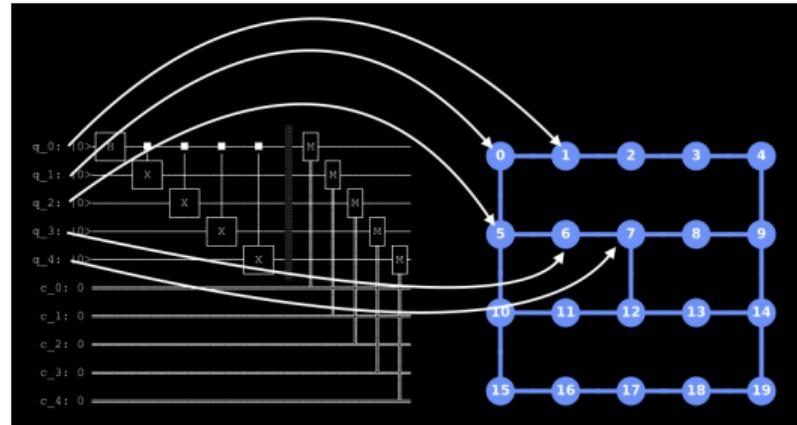
The Unroller

- ▶ The first stage of any compilation is to unroll the gates to the basis set
- ▶ Currently this is done using a descent tree
- ▶ Mainly works for superconducting qubit basis
- ▶ Other types of devices support is hardcoded extra path

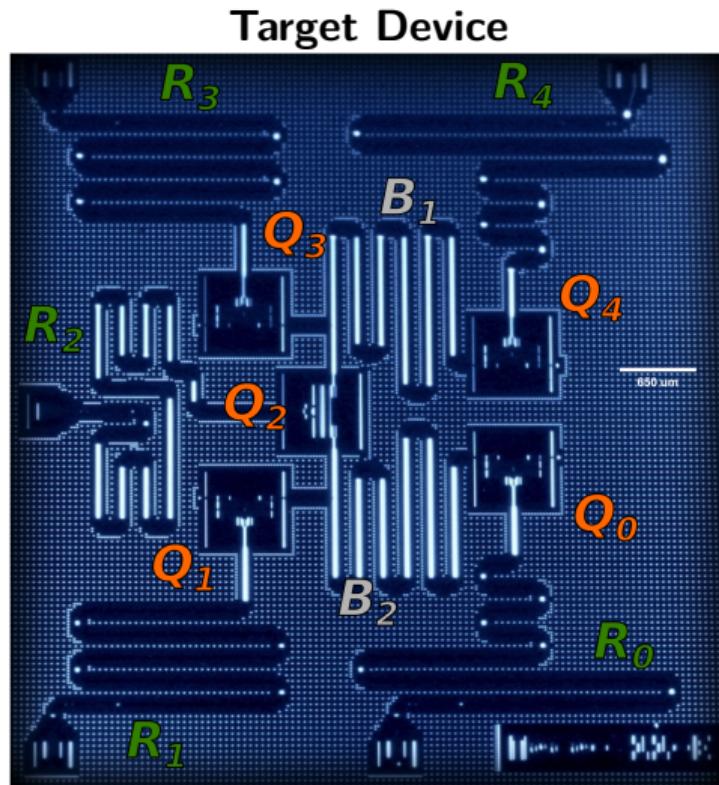
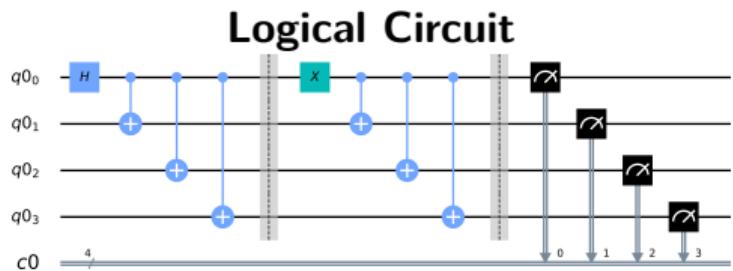
Insert Diagram of Descent Tree

Layout

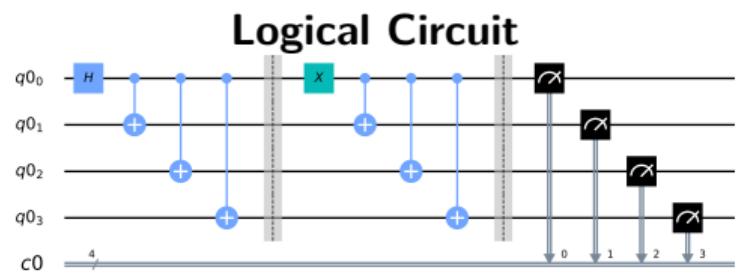
- ▶ Initial mapping to physical qubits
- ▶ Multiple options included
 - ▶ TrivialLayout
 - ▶ DenseLayout
 - ▶ NoiseAdaptiveLayout



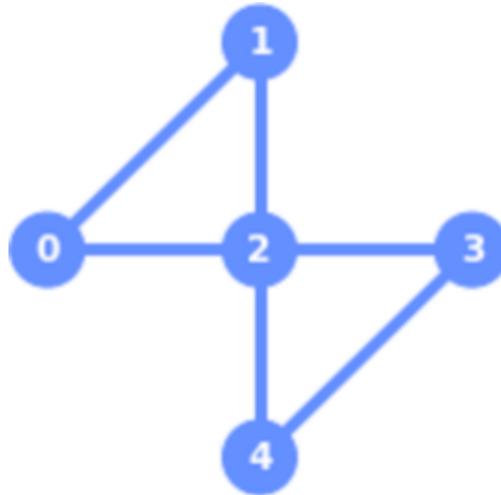
Layout Example



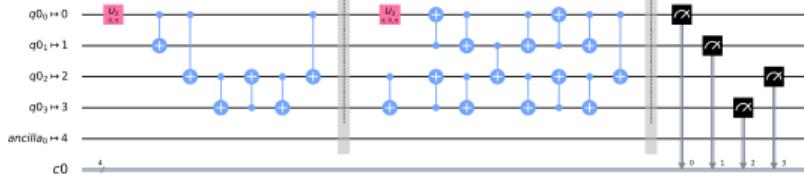
Layout Example



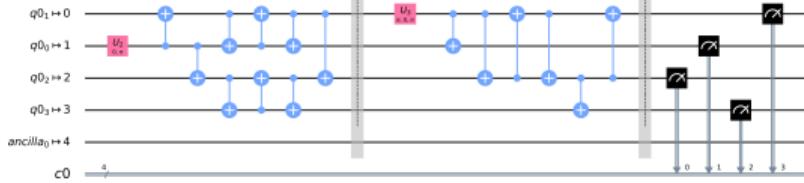
Target Device



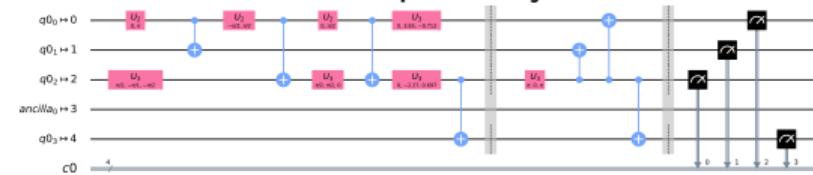
optimization_level=1
TrivialLayout



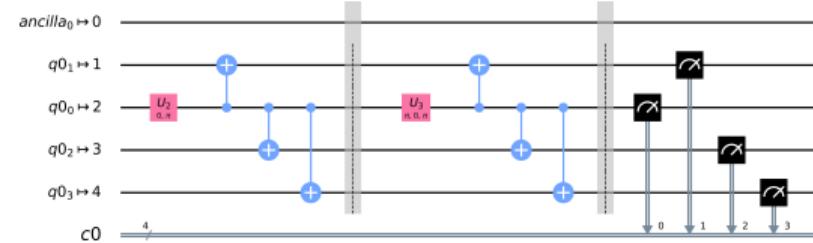
optimization_level=2
DenseLayout



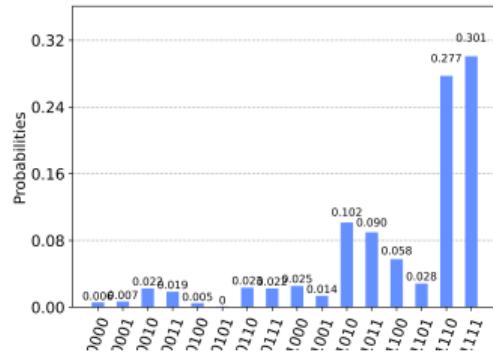
optimization_level=3
NoiseAdaptiveLayout



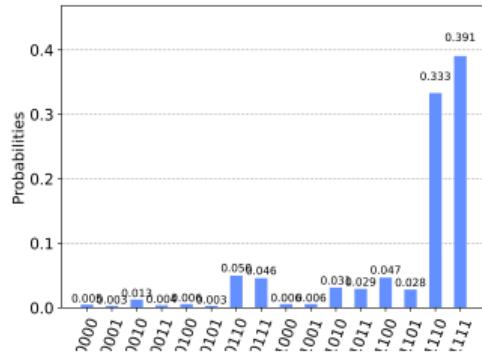
Custom Layout
(optimization_level=1)



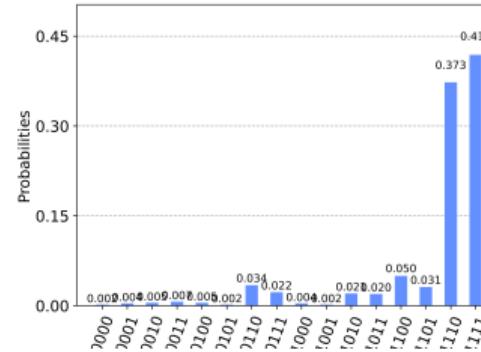
optimization_level=1
TrivialLayout



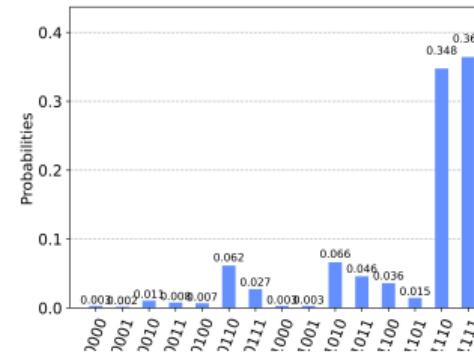
optimization_level=2
DenseLayout



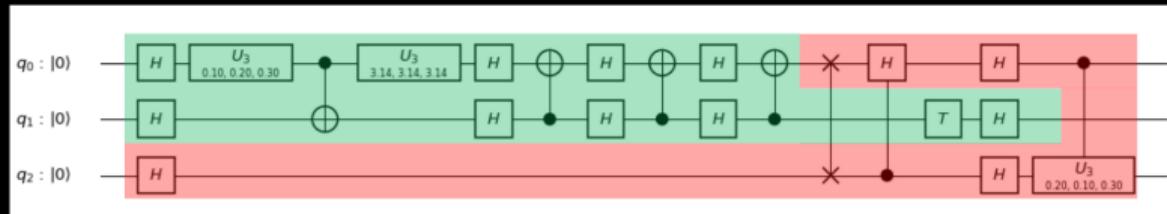
optimization_level=3
NoiseAdaptiveLayout



Custom Layout
(optimization_level=1)

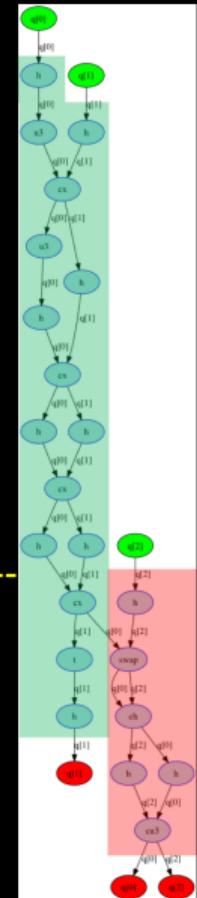


2-qubit Block Collection



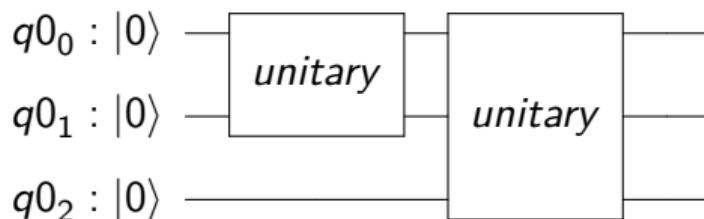
Efficient graph traversal on the DAG.

For each CNOT, collect ancestors and predecessors until a branch.



Consolidate Blocks

1. Loop over 2Q blocks collected from analysis pass
2. Run a simulation to find unitary matrix of each block
3. Replace block with unitary matrix



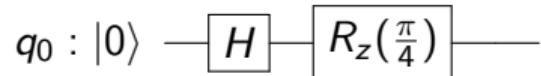
Consolidate Blocks

1. Loop over $2Q$ blocks collected from analysis pass
2. Run a simulation to find unitary matrix of each block
3. Replace block with unitary matrix



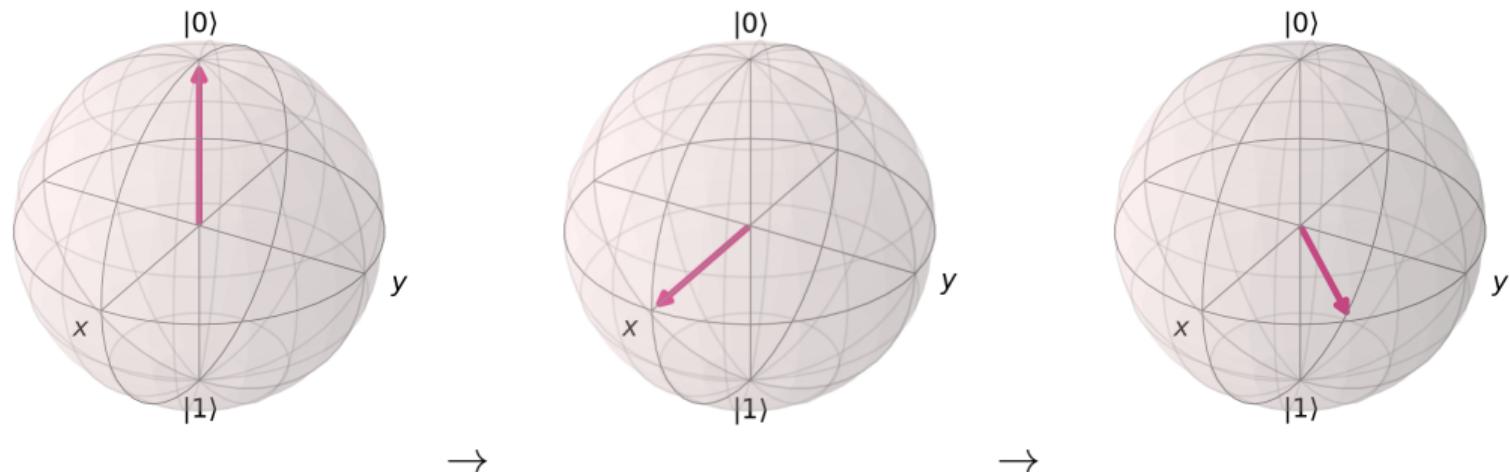
Optimize 1Q Operations

1. Find all runs of 1Q operations on each Qubit in the dag
2. For each run calculate the end state rotation
3. Replace all 1Q operations with a single rotation gate to that end state



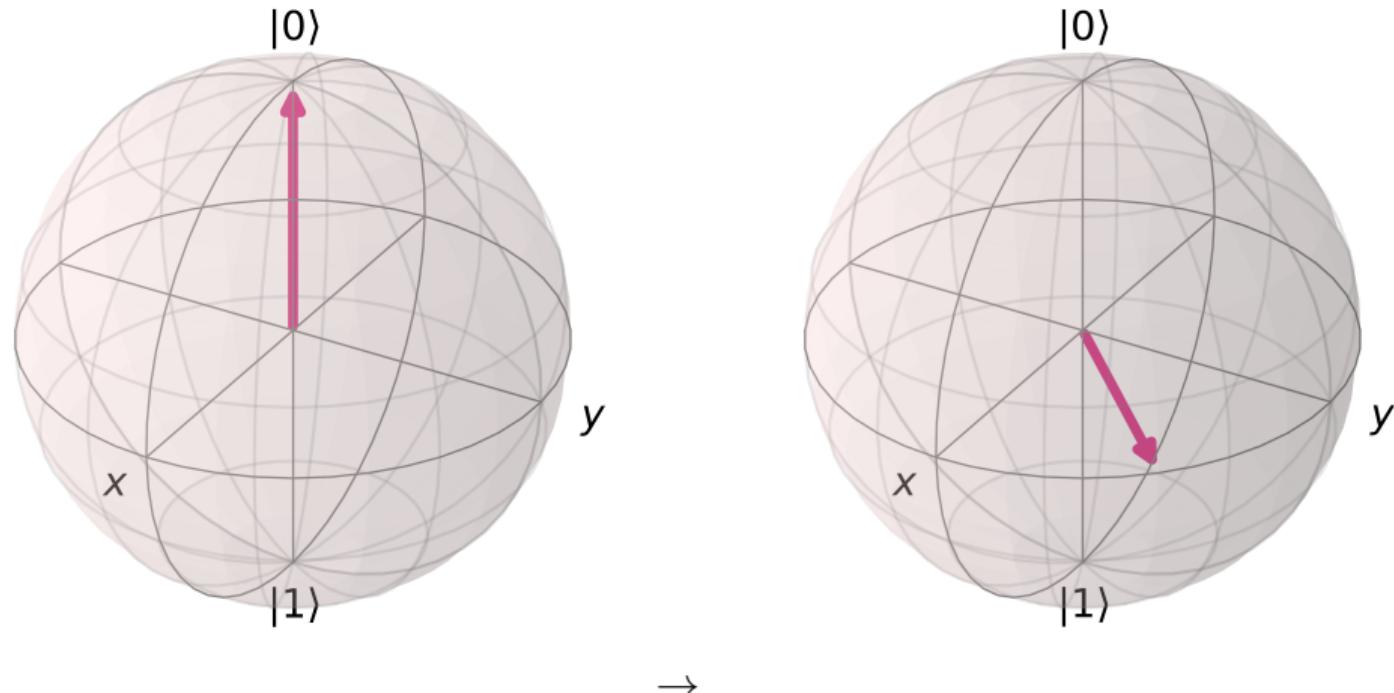
Optimize 1Q Operations

1. Find all runs of 1Q operations on each Qubit in the dag
 2. For each run calculate the end state rotation
 3. Replace all 1Q operations with a single rotation gate to that end state



Optimize 1Q Operations

1. Find all runs of 1Q operations on each Qubit in the dag
2. For each run calculate the end state rotation
3. Replace all 1Q operations with a single rotation gate to that end state



Optimize 1Q Operations

1. Find all runs of 1Q operations on each Qubit in the dag
2. For each run calculate the end state rotation
3. Replace all 1Q operations with a single rotation gate to that end state

$$q_0 : |0\rangle \xrightarrow{U_2\left(\frac{\pi}{4}, \pi\right)}$$

Swap Mapping

- ▶ After the layout step we need to ensure that

Insert Diagram of Swap Mapping

Quantum Volume¹

¹<https://arxiv.org/abs/1811.12926>

Conclusions

- ▶ Techniques used are similar to a classical compiler
- ▶ Implementation details are different because of uniqueness of quantum computing
- ▶ A good compiler can be the difference between a functional program and one that doesn't work

Where to get more information

- ▶ These Slides: <https://github.com/mtreinish/quantum-compilers>
- ▶ Qiskit: <https://qiskit.org/>
- ▶ Qiskit Terra on Github: <https://github.com/Qiskit/qiskit-terra>
- ▶ IBM Q Experience: <https://quantum-computing.ibm.com>
- ▶ Tutorial on using Passmanager: https://github.com/Qiskit/qiskit-iqx-tutorials/blob/master/qiskit/advanced/terra/4_transpiler_passes_and_passmanager.ipynb