

Building a Compiler for Quantum Computers

Matthew Treinish

Software Engineer - IBM Research

mtreinish@kortar.org

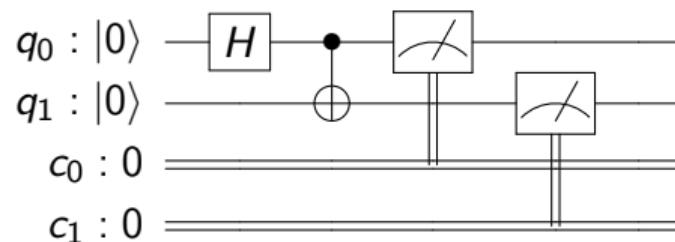
`mtreinish` on Freenode

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

January 17, 2020

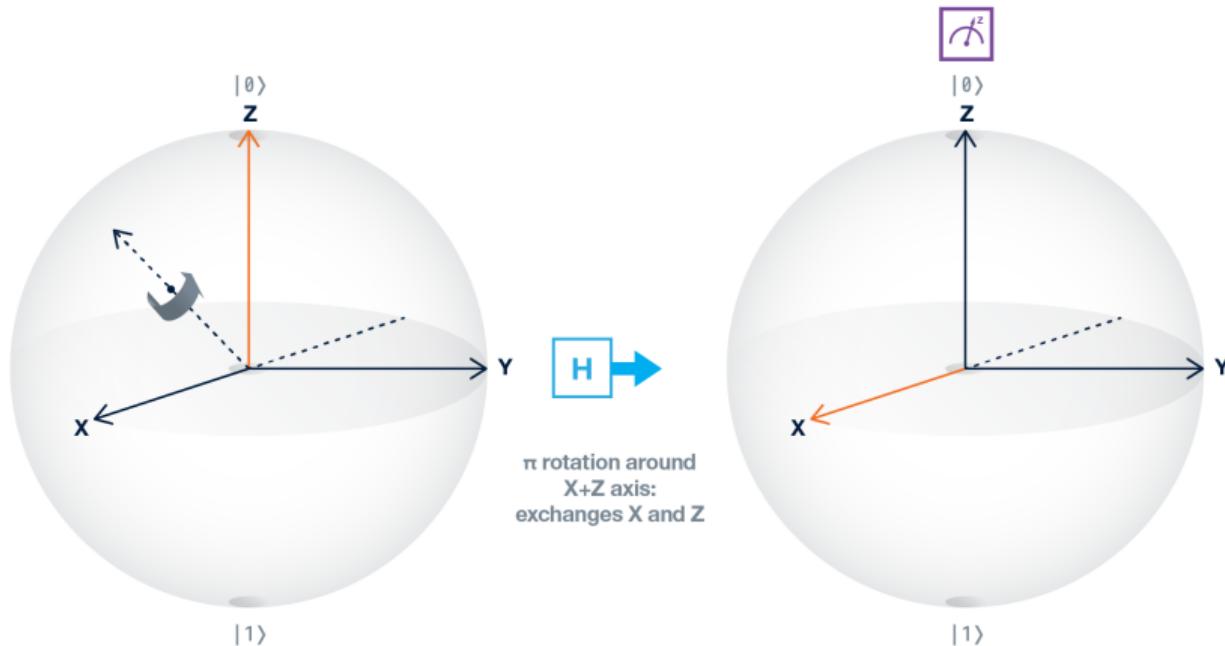
Quantum Circuits

- ▶ 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



Some Quantum Gates

Gate	Symbol	Unitary	Gate	Symbol	Unitary
Pauli X		$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$	U1		$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\lambda} \end{bmatrix}$
Pauli Y		$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$	U2		$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -e^{i\lambda} \\ e^{i\phi} & e^{i(\phi+\lambda)} \end{bmatrix}$
Pauli Z		$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$	U3		$U(\theta, \phi, \lambda)$
Hadamard		$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$	Z Rotation		$\begin{bmatrix} e^{-\frac{i\phi}{2}} & 0 \\ 0 & e^{\frac{i\phi}{2}} \end{bmatrix}$
CNOT		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$	SWAP		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

OpenQASM¹²

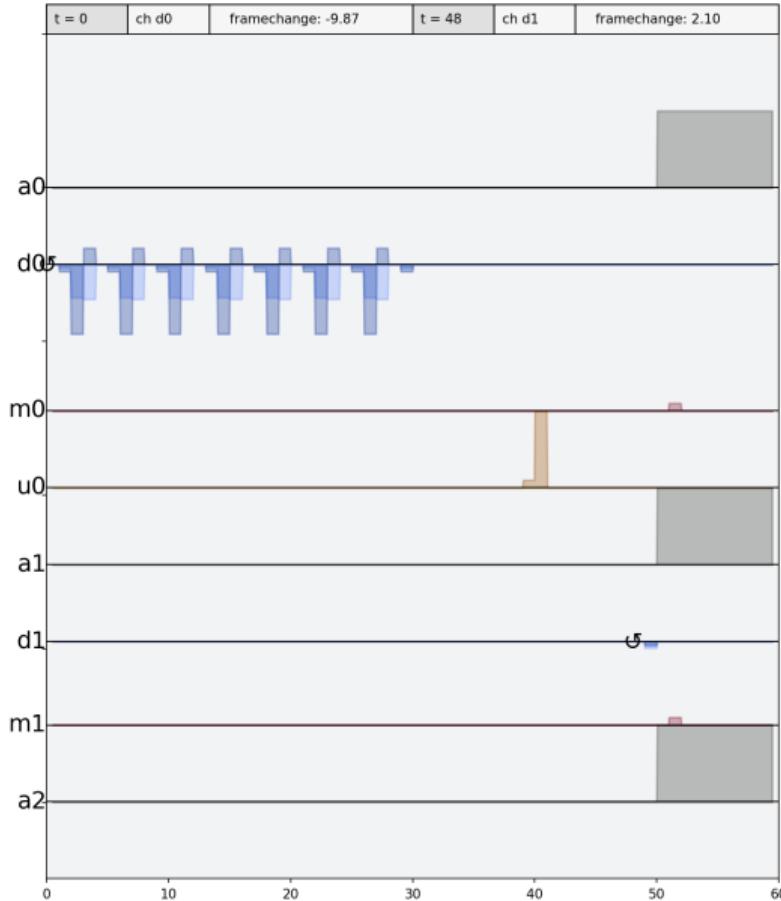
```
OPENQASM 2.0;
include "qelib1.inc";
qreg q[2];
creg c[2];
h q[0];
cx q[0],q[1];
measure q[0] -> c[0];
measure q[1] -> c[1];
```

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

¹<https://arxiv.org/abs/1707.03429>

²<https://github.com/Qiskit/openqasm>

Pulse Level Programming

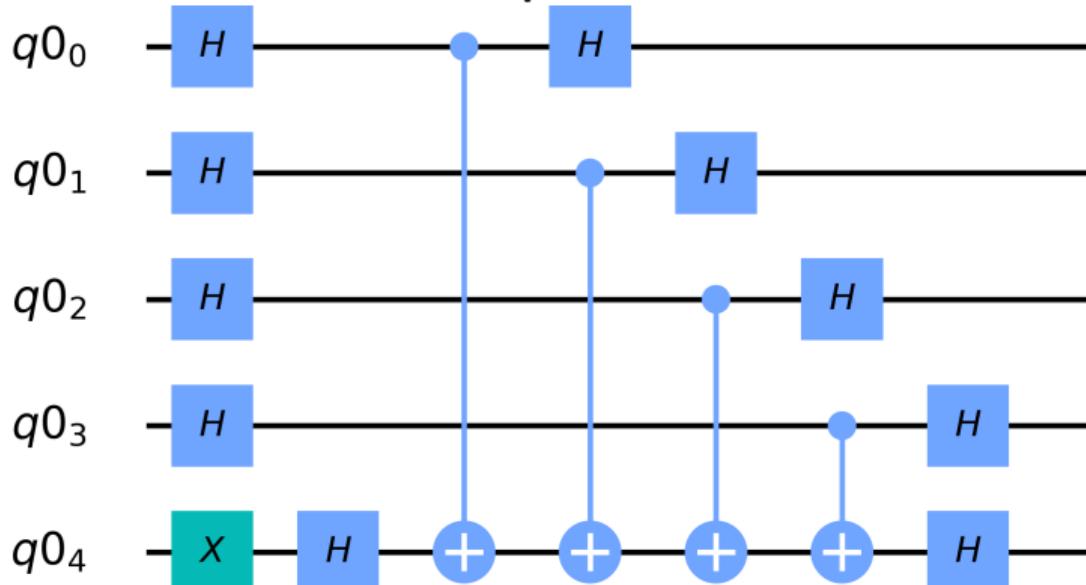


- ▶ A layer below the circuit model is to use pulses
- ▶ Each quantum gate is defined as a pulse that gets applied to the qubits
- ▶ Enables you to tweak the definition of gates for an existing circuit
- ▶ Also can just define a custom pulse schedule and run that directly
- ▶ Mostly used for physics research or hardware characterization

Why do we need compilers?

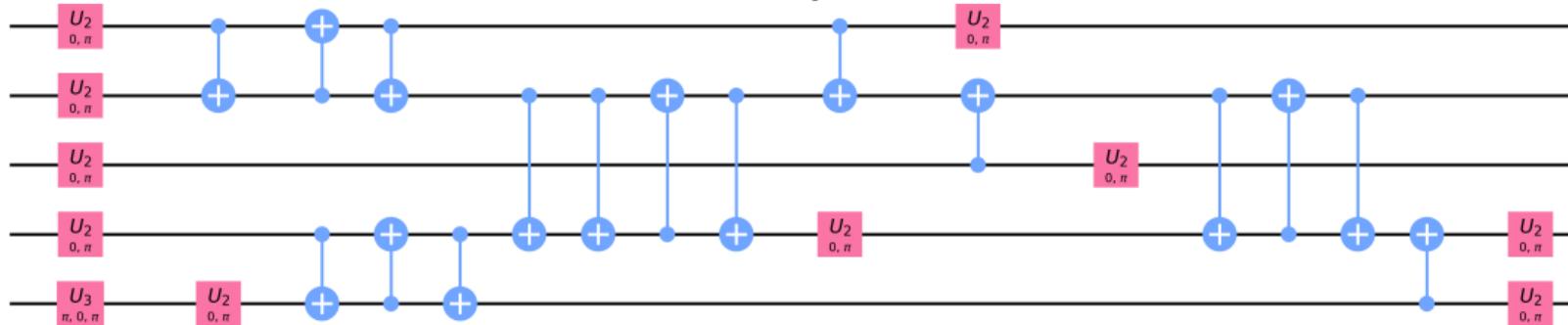
- ▶ Despite programming at a low (per bit) level this is still abstracted from the hardware. i
- ▶ NISQ devices have a number of limitations
- ▶ The compiler is used to enable running logical abstract circuit on an actual device

Example Circuit:

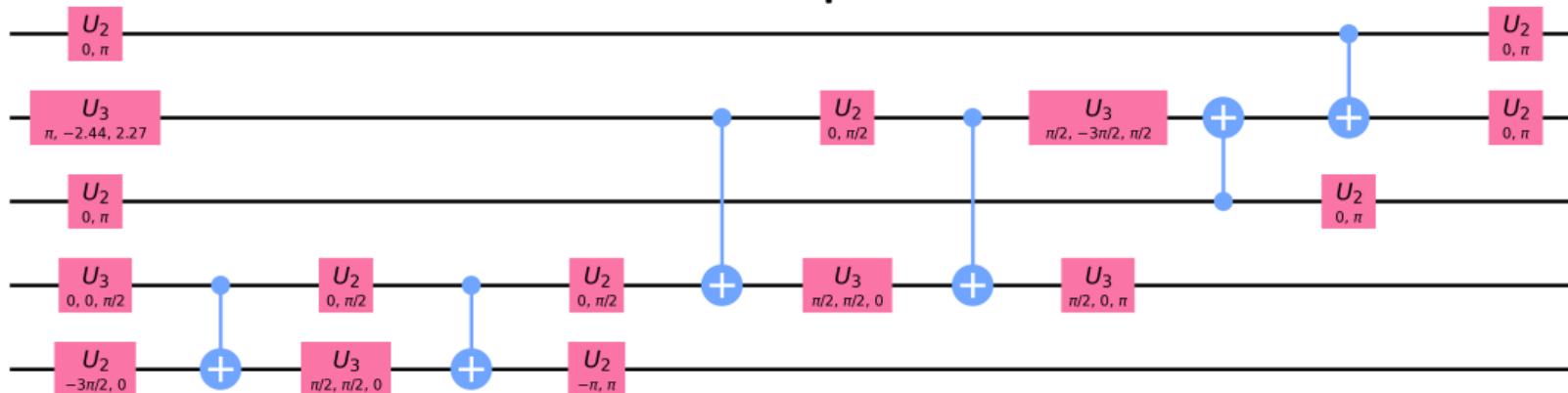


Why do we need compilers?

Bad Compilation

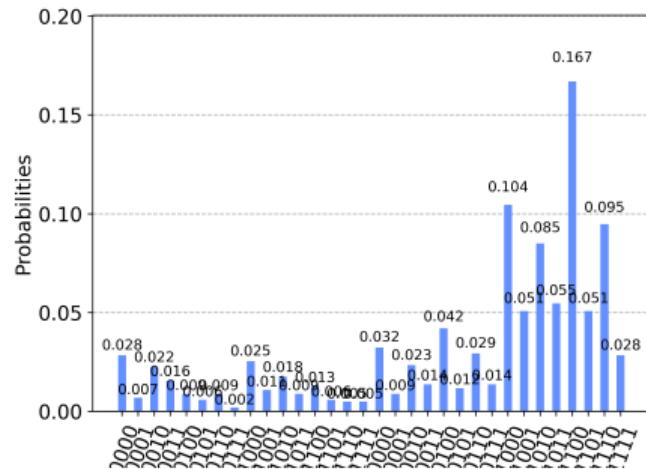


Good Compilation

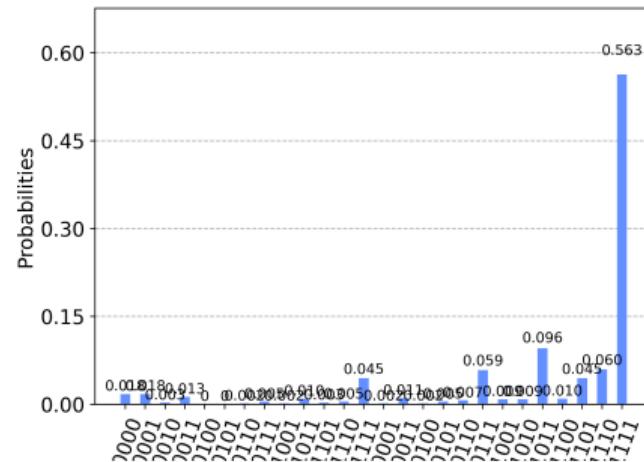


Why do we need compilers?

Bad Compilation



Good Compilation



Basis Gates

- ▶ Each Quantum Computer only supports a set of basis gates
- ▶ These gates can be used to implement all other gates
- ▶ Prior to running on a quantum computer the gates must be defined using the basis set

Superconducting Qubits:

Cx, U3, id

Trapped Ion Qubits:

Ms, Rx, Ry

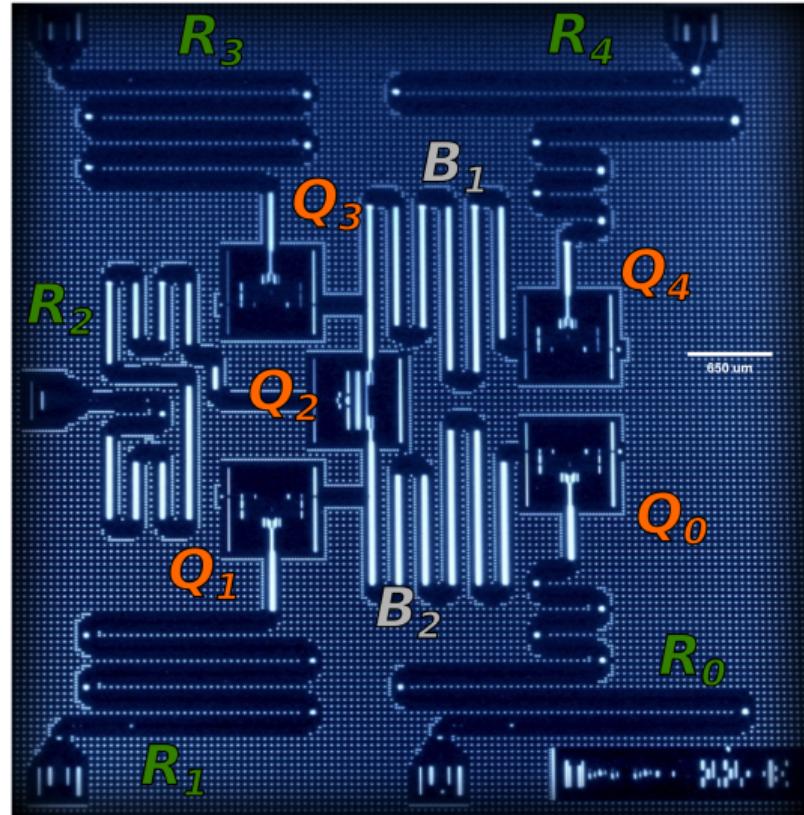
Simulator:

U1, U2, U3, Cx, Cz, Id, X, Y, Z, H, S, Sdg, t, tdg, swap, ccx, unitary, initialize, cu1, cu2, cu3, swap, mcx, mcz, mcu1, mcu2, mcu3, mcswap, multiplexer

Qubit Connectivity

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

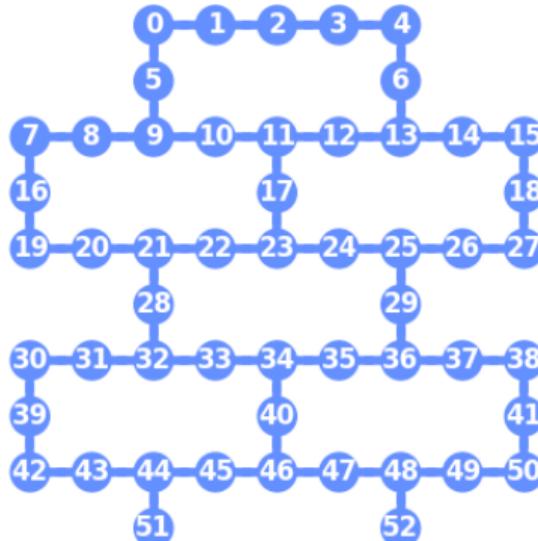
IBM Q 5 Yorktown



Qubit Connectivity

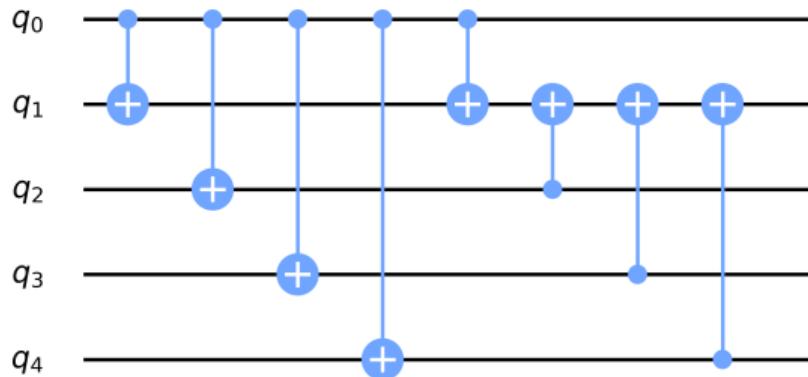
IBM Q 53 Rochester Coupling Map

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



Not Enough Connectivity?

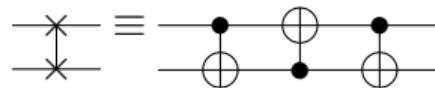
- ▶ Connectivity is not always sufficient to fully map logical circuit
- ▶ Use SWAP gate to move state around between qubits
- ▶ Adding swaps are potentially expensive from noise perspective



Not Enough Connectivity?

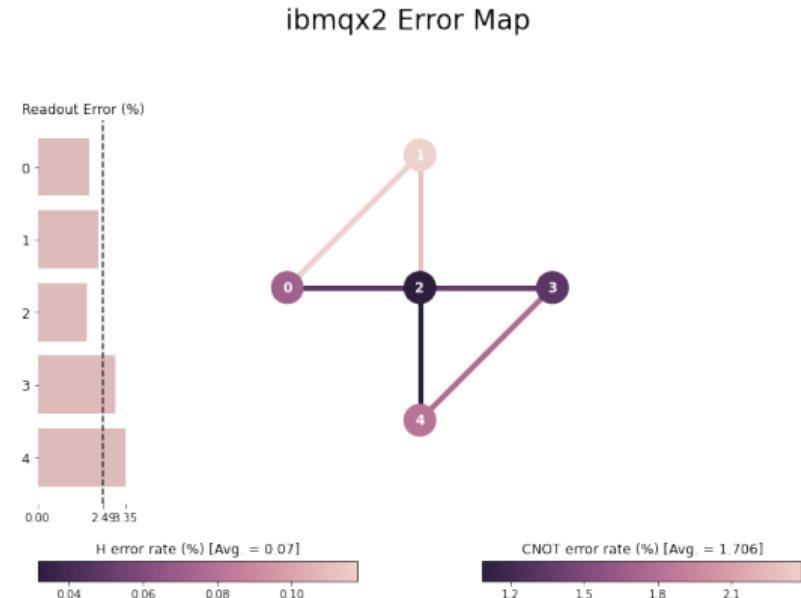
- ▶ Connectivity is not always sufficient to fully map logical circuit
- ▶ Use SWAP gate to move state around between qubits
- ▶ Adding swaps are potentially expensive from noise perspective

SWAP Gate



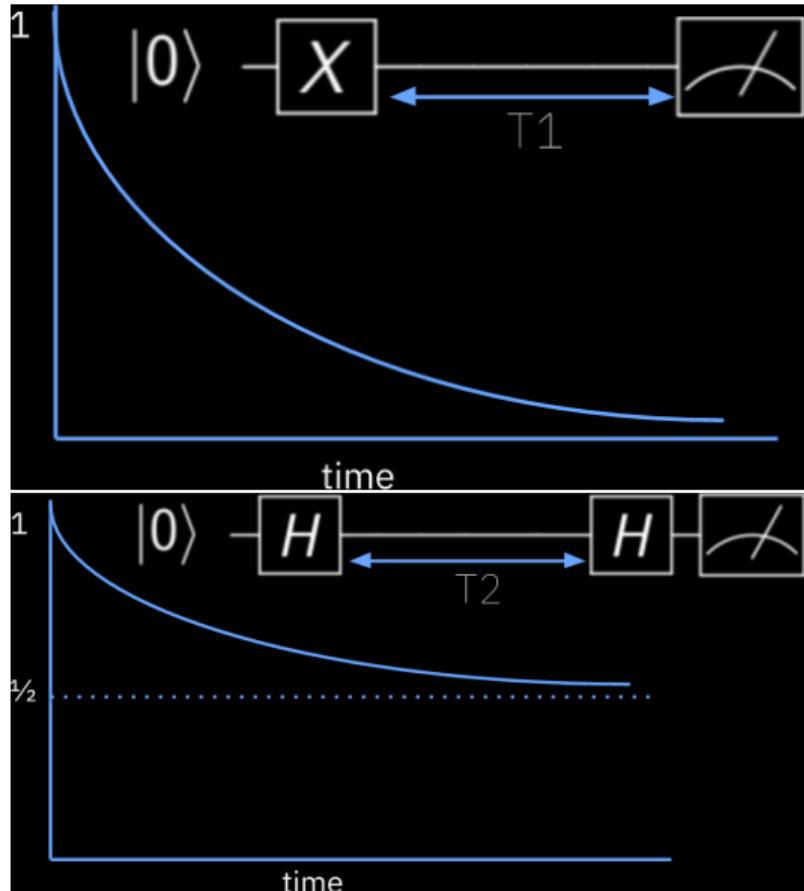
Noise

- ▶ 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

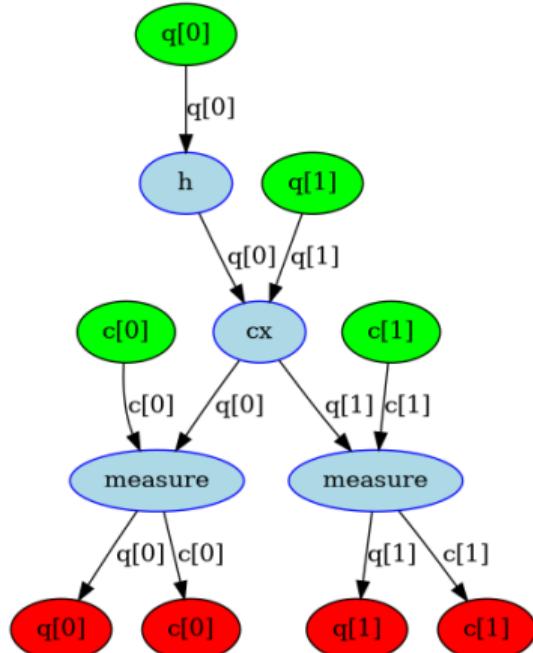
- ▶ Is the base layer for working with quantum computers provides interface to hardware and simulators
- ▶ Provides an SDK for working with quantum circuits
- ▶ Compiles circuits to run on different backends
- ▶ Designed to be backend agnostic and work with any quantum hardware or simulator
- ▶ Written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



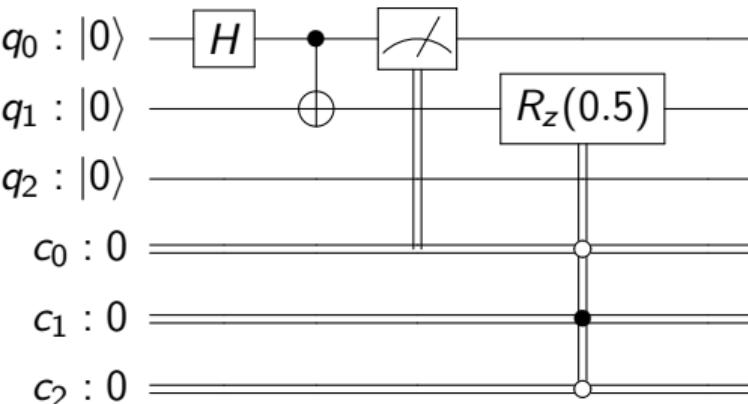
¹<https://github.com/Qiskit/qiskit-terra>

The DAG

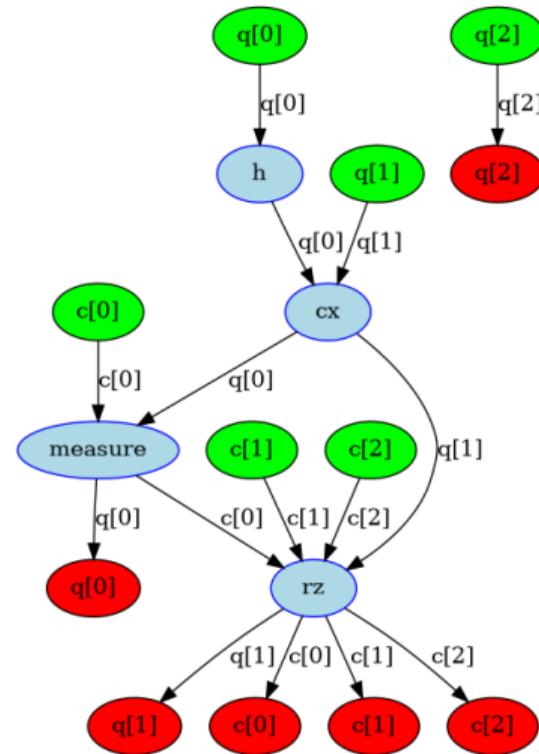
- ▶ Compiler represents circuits as a DAG
- ▶ Each node in the DAG is an operation, an input, or an output
- ▶ Each edge indicates data flow between nodes
- ▶ Makes flow of information between operations explicit



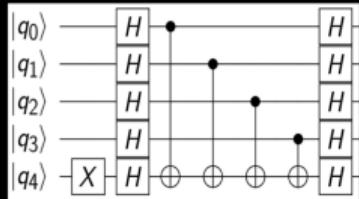
The DAG



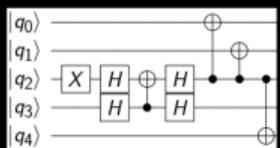
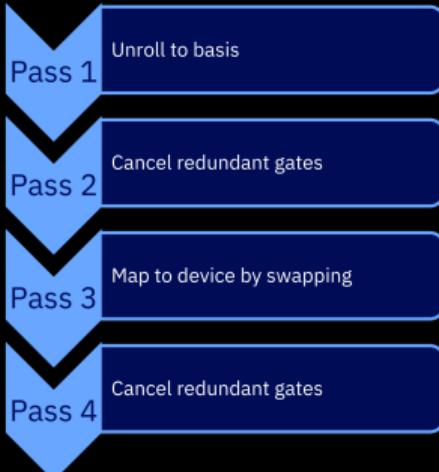
→



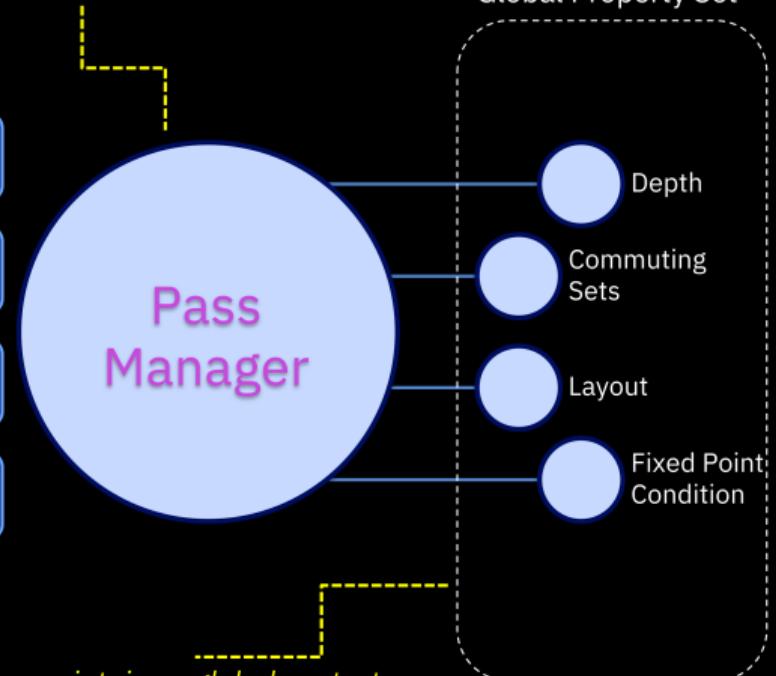
Transpiler Architecture



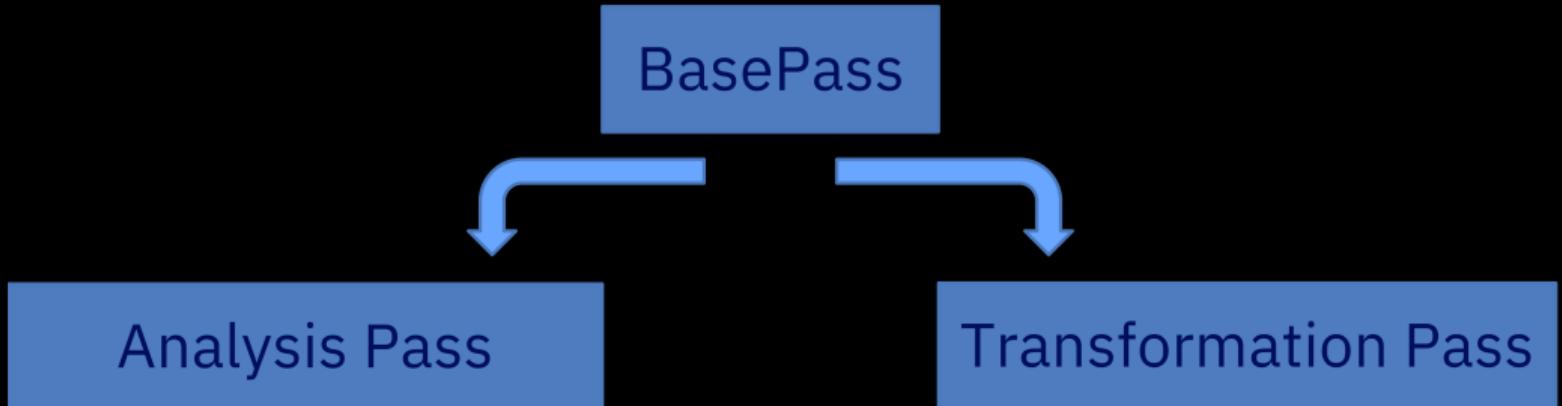
Each pass does one small, well-defined task.



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



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):

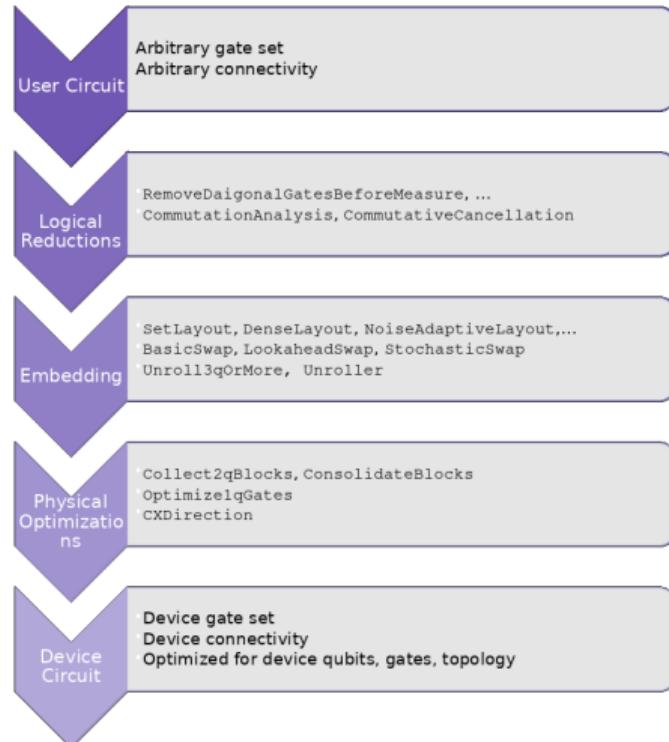
Pass A is an Analysis Pass that inspects the graph and finds nodes that can commute.

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

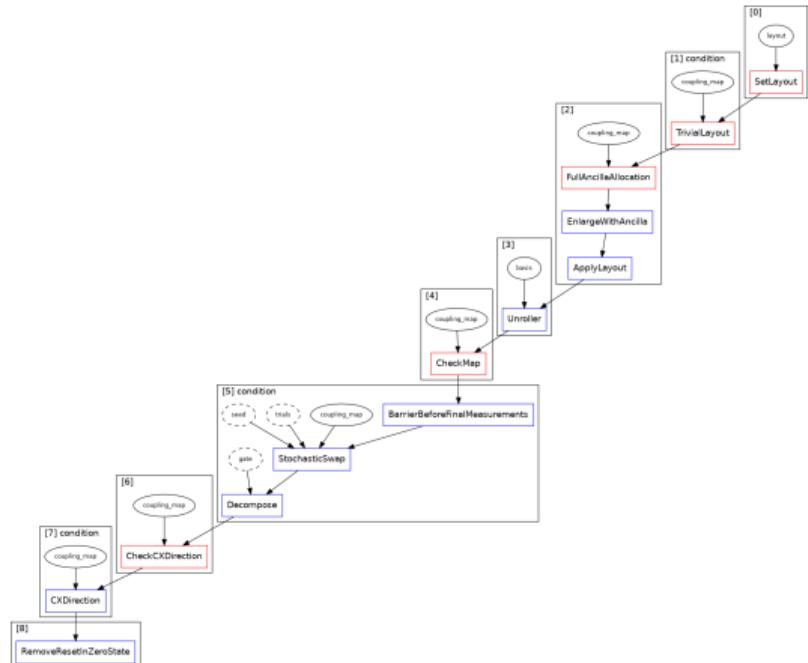


Preset Pass Managers

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

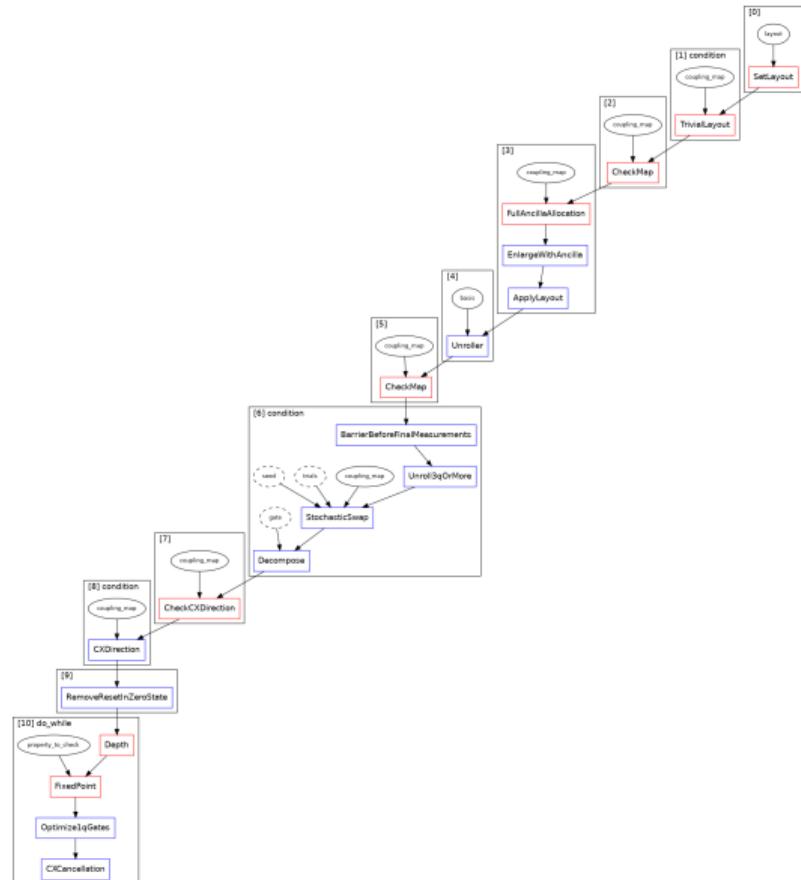
Optimization Level 0

- ▶ No Optimization
- ▶ Unroll
- ▶ Trivial Layout
- ▶ Swap Mapping



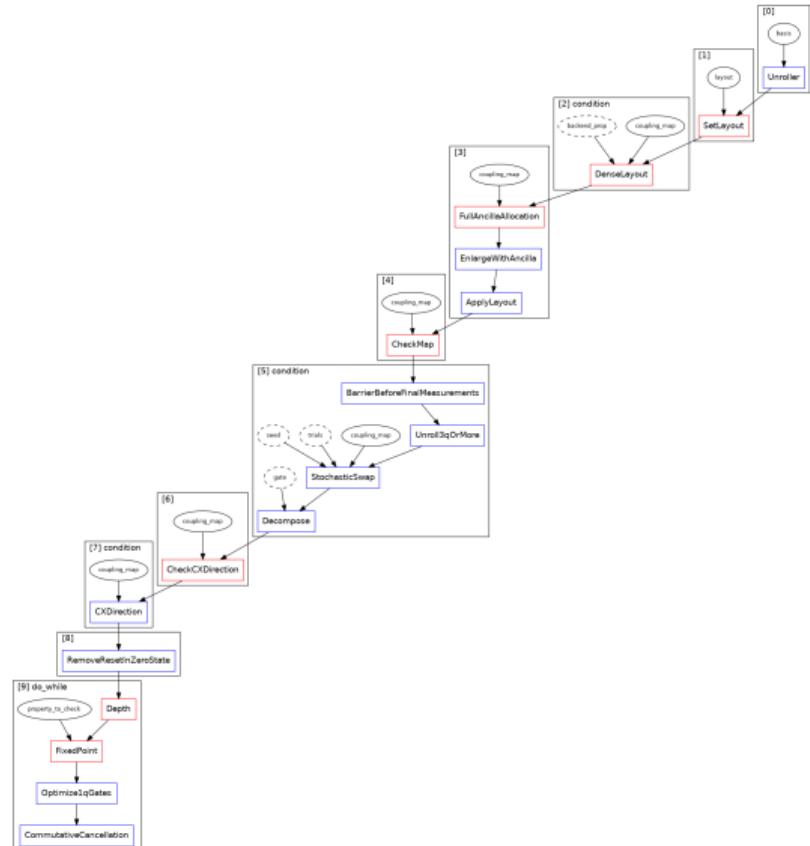
Optimization Level 1

- ▶ Unroll
- ▶ Trivial Layout
- ▶ Swap Mapping
- ▶ Optimization
 - ▶ Optimize 1Q
 - ▶ CX Cancellation



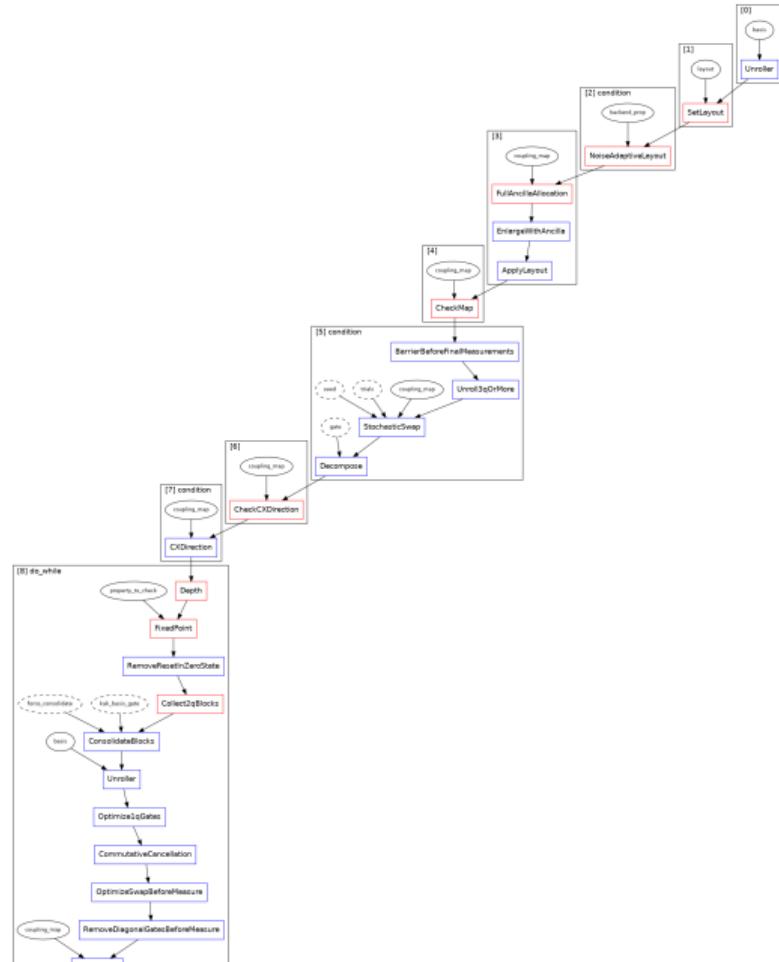
Optimization Level 2

- ▶ Unroll
- ▶ Dense Layout
- ▶ Swap Mapping
- ▶ Optimization
 - ▶ Optimize 1Q
 - ▶ Commutative Cancellation



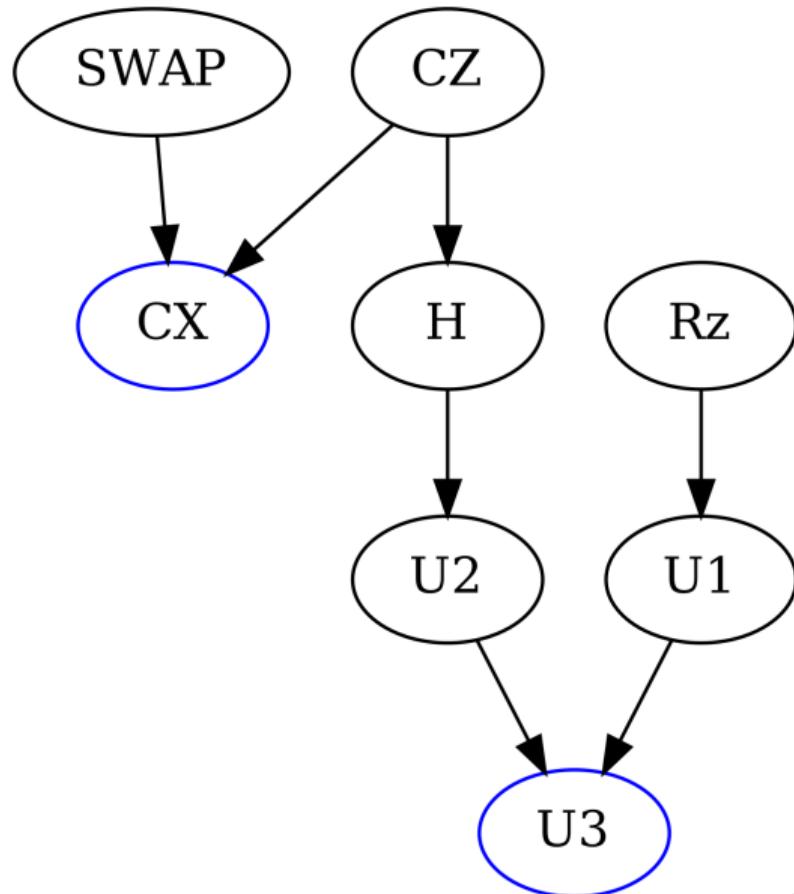
Optimization Level 3

- ▶ Unroll
- ▶ Noise Aware Layout
- ▶ Swap Mapping
- ▶ Optimization
 - ▶ Optimize 1Q
 - ▶ Commutative Cancellation
 - ▶ Consolidate Blocks
 - ▶ Remove Reset in 0 State
 - ▶ Optimize Swap before measure
 - ▶ Remove Diagonal Gates before measure



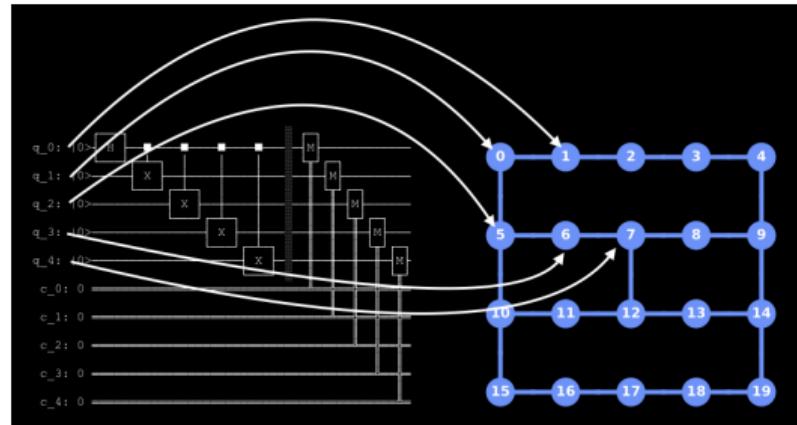
The Unroller

- ▶ 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

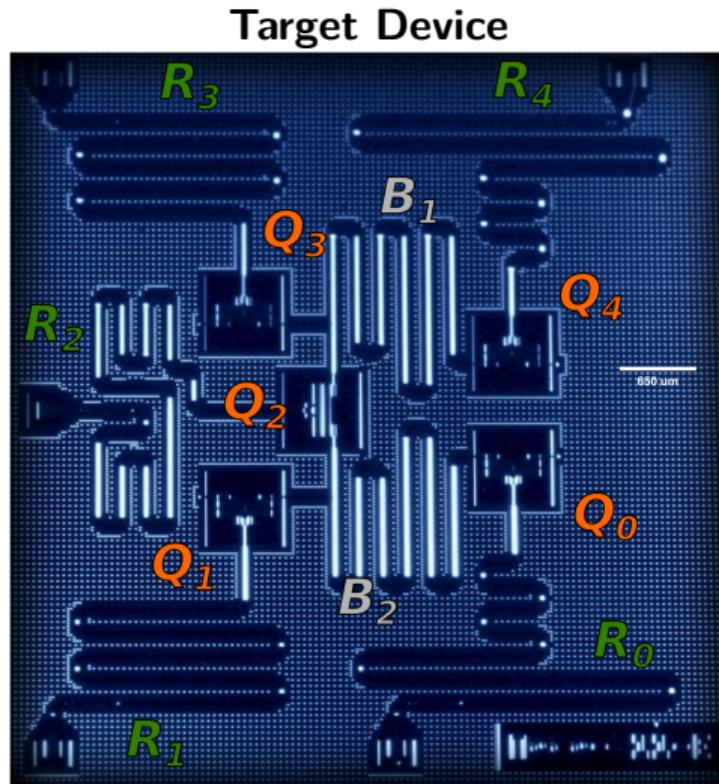
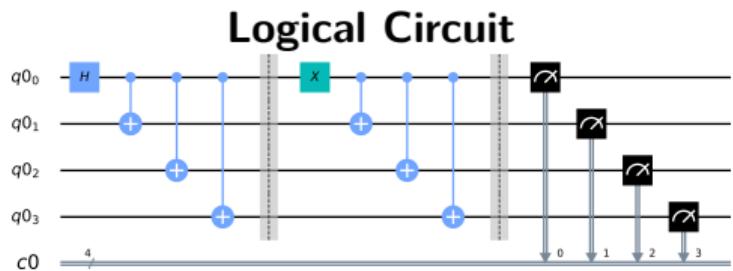


Layout

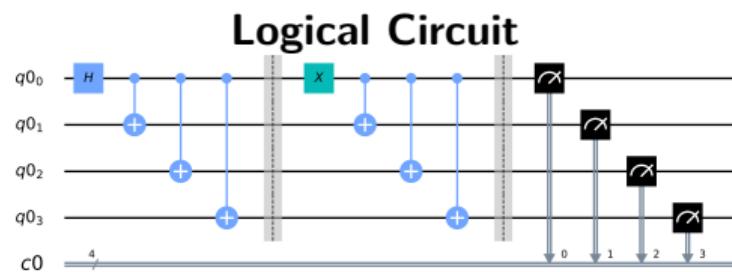
- ▶ Initial mapping to physical qubits
- ▶ Multiple options included
 - ▶ TrivialLayout
 - ▶ DenseLayout
 - ▶ NoiseAdaptiveLayout



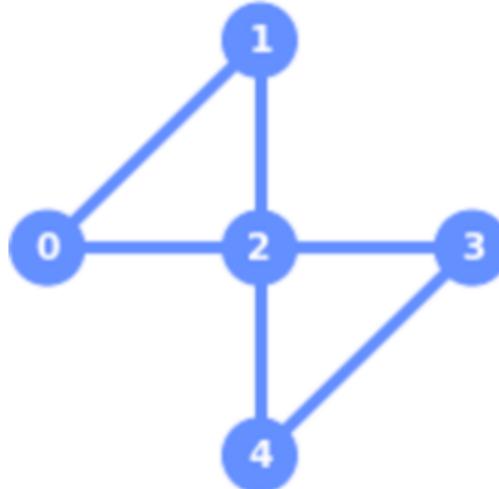
Layout Example



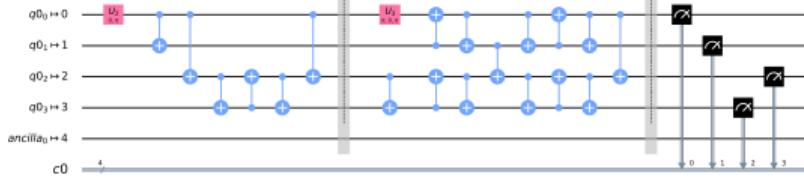
Layout Example



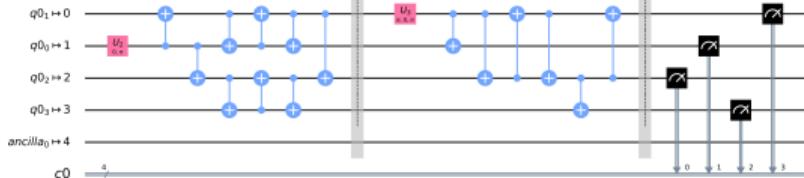
Target Device



optimization_level=1
TrivialLayout



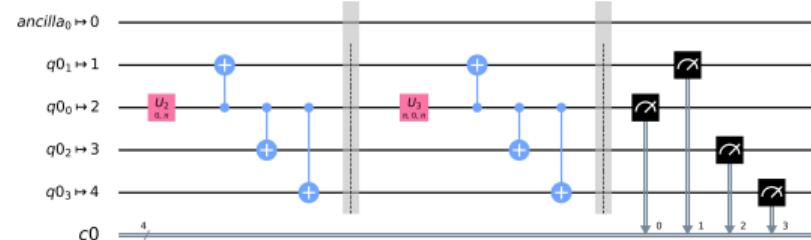
optimization_level=2
DenseLayout



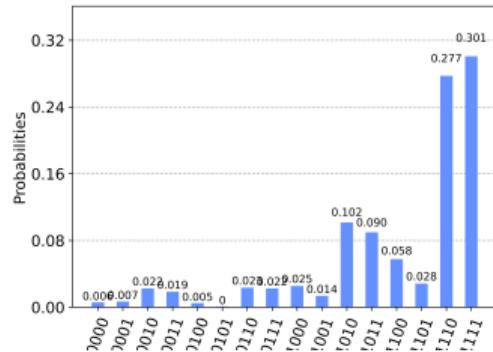
optimization_level=3
NoiseAdaptiveLayout



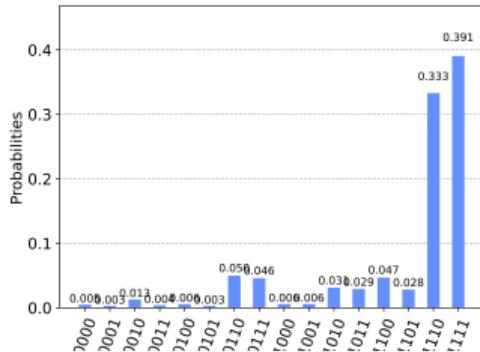
Custom Layout
(optimization_level=1)



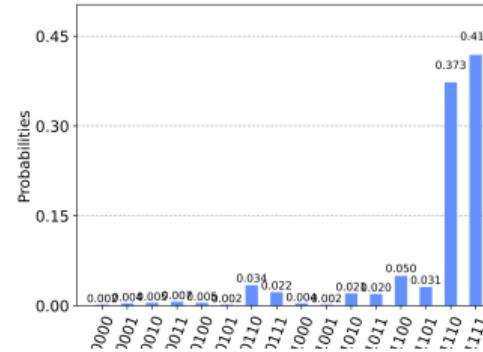
optimization_level=1
TrivialLayout



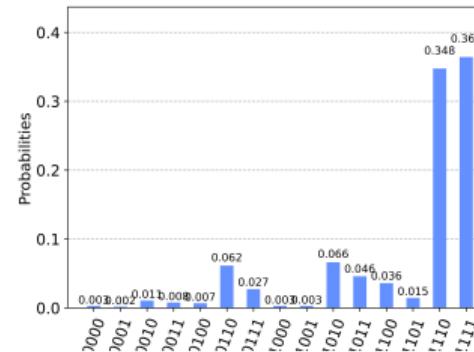
optimization_level=2
DenseLayout



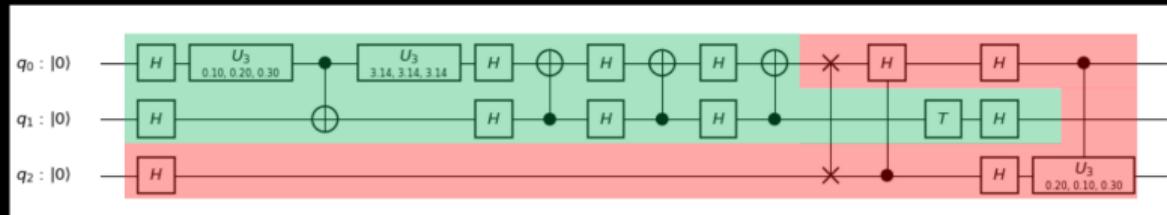
optimization_level=3
NoiseAdaptiveLayout



Custom Layout
(optimization_level=1)

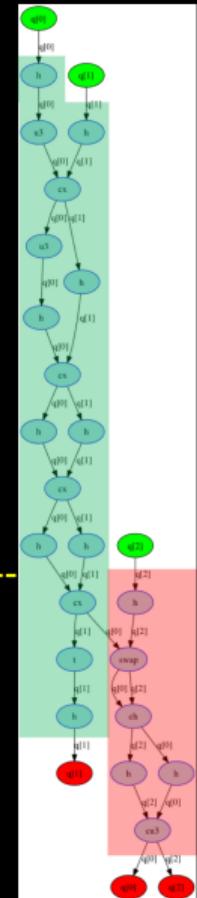


2-qubit Block Collection



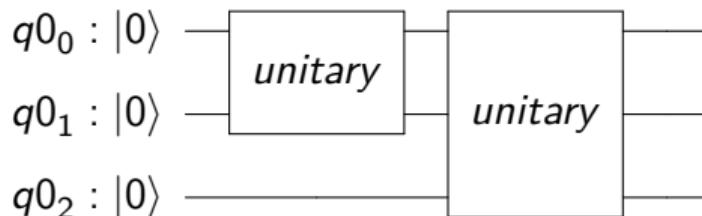
Efficient graph traversal on the DAG.

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



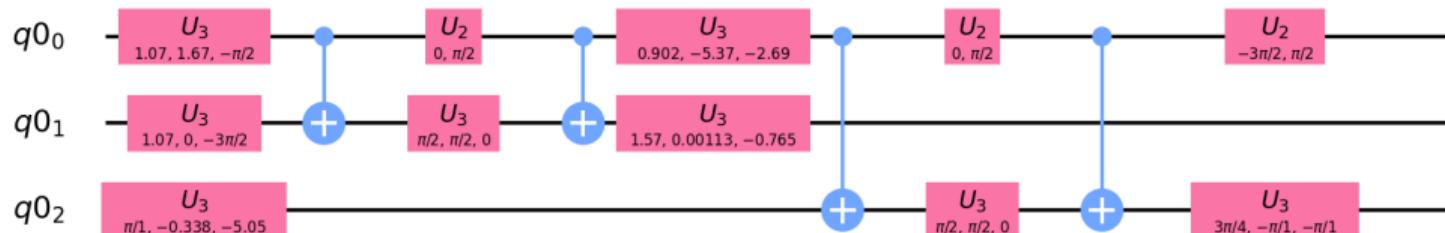
Consolidate Blocks

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
4. Decompose unitary to basis gates with unroller



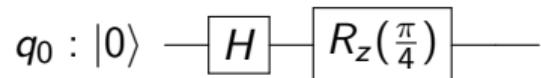
Consolidate Blocks

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
4. Decompose unitary to basis gates with unroller



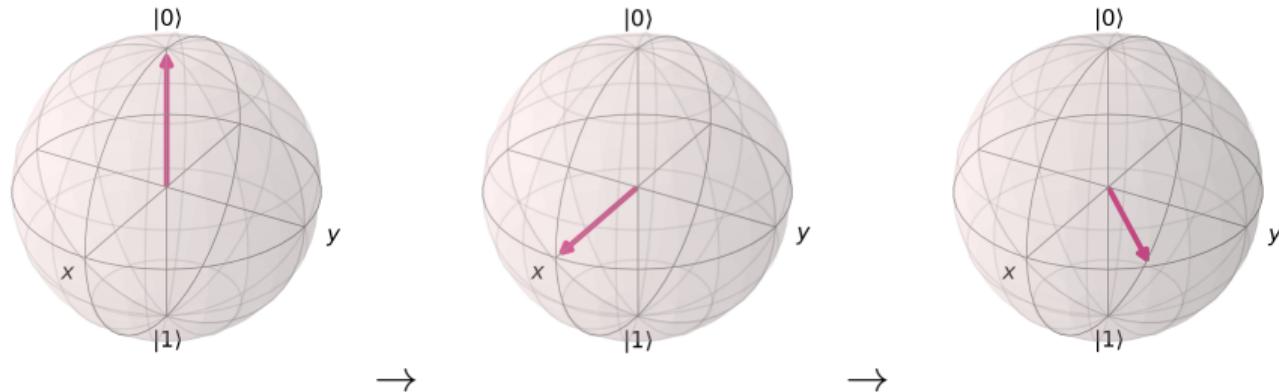
Optimize 1Q Operations

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



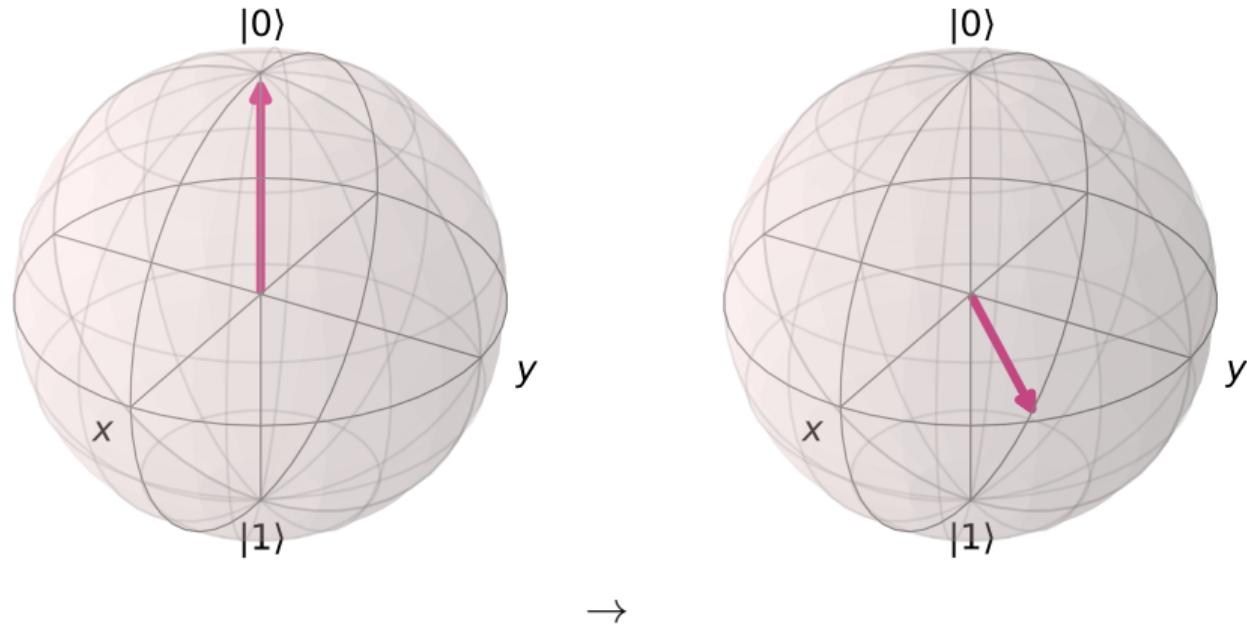
Optimize 1Q Operations

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

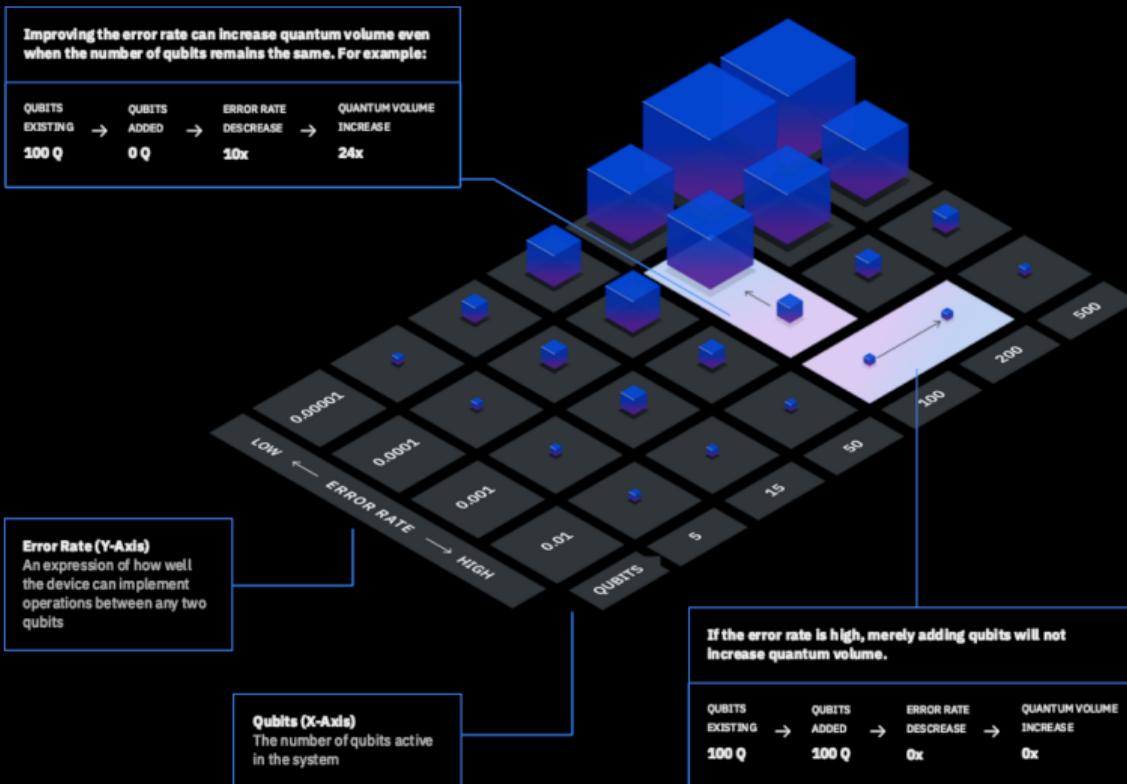
1. Find all runs of 1Q operations on each Qubit in the dag
2. For each run calculate the end state rotation
3. Replace all 1Q operations with a single rotation gate to that end state

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

Swap Mapping/Routing

- ▶ After the layout step we need to ensure connectivity between qubits
 - ▶ 3 Algorithms included in Qiskit
 - ▶ BasicSwap
 - ▶ LookaheadSwap
 - ▶ StochasticSwap
 - ▶ StochasticSwap is used in all presets
- 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 (sign up to get access to public quantum computers):
<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
- ▶ Qiskit Textbook: <https://qiskit.org/textbook/>
- ▶ My Talk from Last Year: <https://www.youtube.com/watch?v=th4TDYX6xoc>

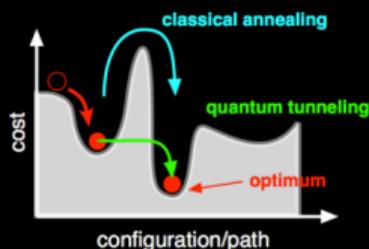
BACKUP SLIDES

Types of Quantum Computing

Quantum Annealing

Optimization Problems

- Machine learning
- Fault analysis
- Resource optimization
- etc...

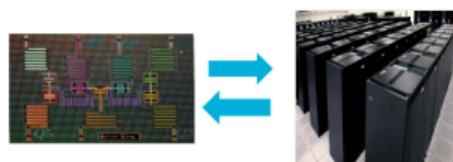
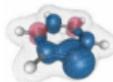


Many ‘noisy’ qubits can be built;
large problem class in optimization;
amount of quantum speedup unclear

Approximate Q-Comp.

Simulation of Quantum Systems, Optimization

- Material discovery
- Quantum chemistry
- Optimization
(logistics, time scheduling,...)
- Machine Learning

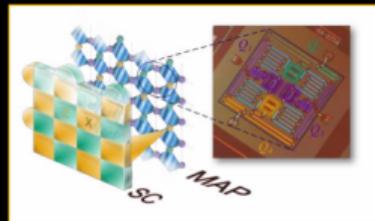


Hybrid quantum-classical approach;
already 50-100 “good” physical qubits
could provide quantum speedup.

Fault-tolerant Universal Q-Comp.

Execution of Arbitrary Quantum Algorithms

- Algebraic algorithms
(machine learning, cryptography,...)
- Combinatorial optimization
- Digital simulation of quantum systems



Surface Code: Error correction in a Quantum Computer

Proven quantum speedup;
error correction requires significant qubit
overhead.