Mitigating Noise in Quantum Hardware #1

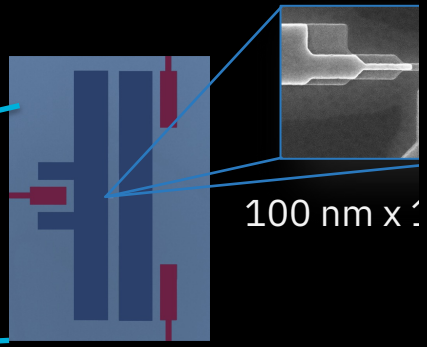
Nick Brønn, Ph.D.

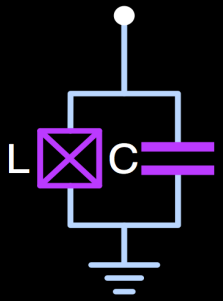
Qiskit | Global Summer School 2023

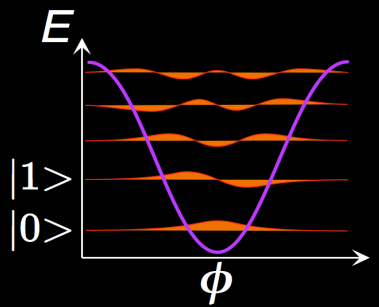
Anatomy of a Superconducting Qubit

Superconducting Qubit:

- Josephson Junction as a nonlinear inductor



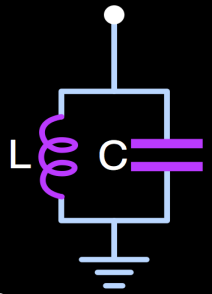


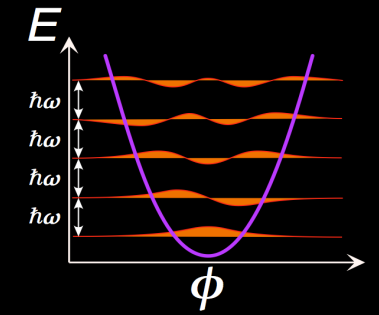


$E_{01} \approx 5\ \text{GHz} \approx 240\ \text{mK}$

Superconducting Microwave Resonators:

- read-out of qubit states
- multi-qubit quantum bus
- filters at qubit freq

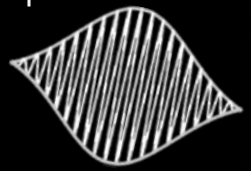


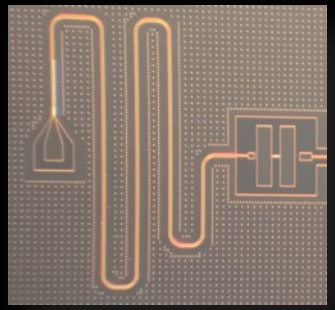


Single Qubit Control

Microwave pulses rotate qubit

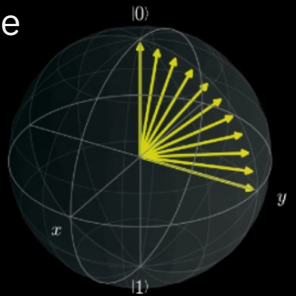
around the Bloch sphere



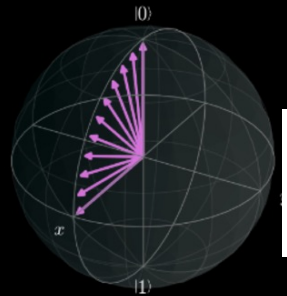


Axis of rotation in Bloch sphere

depends on phase

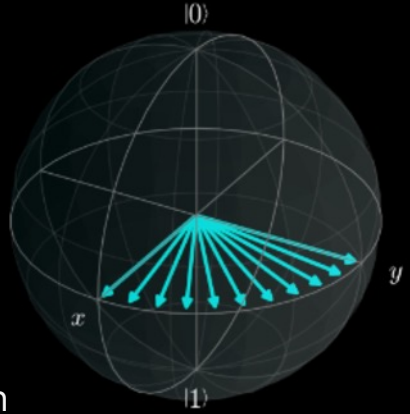


X90



Y90

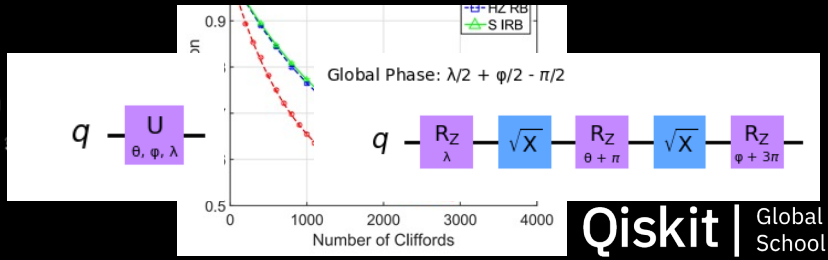
Z Rotations



Arbitrary 1Q rotation

Rotations come for free:

Just $U3(\theta,\phi,\lambda) = \begin{pmatrix} \cos\left(\frac{\theta}{2}\right) & -e^{i\lambda}\sin\left(\frac{\theta}{2}\right) \\ e^{i\phi}\sin\left(\frac{\theta}{2}\right) & e^{i(\phi+\lambda)}\cos\left(\frac{\theta}{2}\right) \end{pmatrix}$

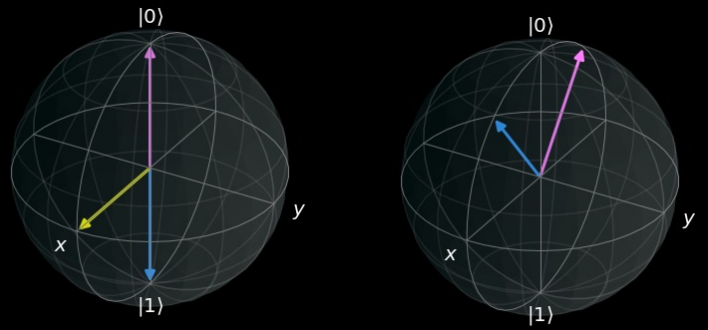


[DC McKay *et al*, *PRA* **96**, 022330 (2017)]

Two Qubit Control: Cross Resonance

- Cross Resonance: ZX Operation
- Rotation of Target Qubit depends on state of Control Qubit

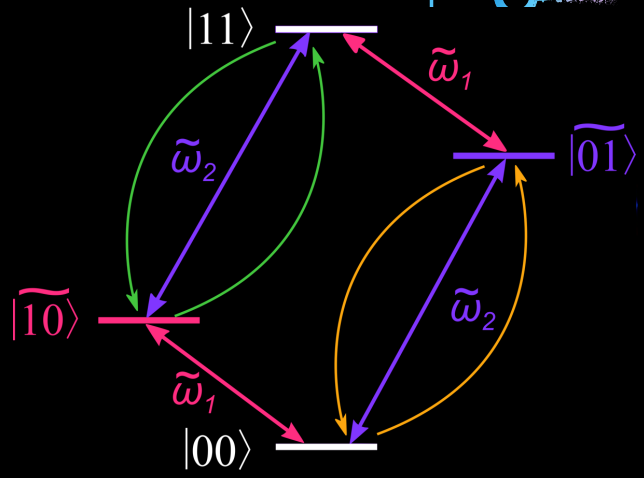
$$ZX = Z \otimes X = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \otimes \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \end{pmatrix}$$

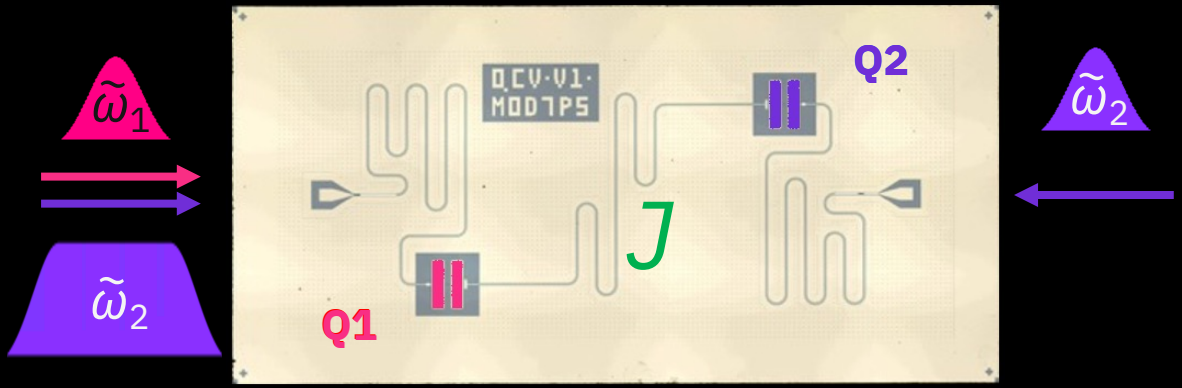


$$U_{\mathrm{CR}}(\theta) = \exp\{-i(\theta/2)ZX\} = \begin{pmatrix} \cos(\theta/2) & -i\sin(\theta/2) & 0 & 0 \\ -i\sin(\theta/2) & \cos(\theta/2) & 0 & 0 \\ 0 & 0 & \cos(\theta/2) & i\sin(\theta/2) \\ 0 & 0 & i\sin(\theta/2) & \cos(\theta/2) \end{pmatrix}$$

Two Qubit Control: Cross Resonance

- Cross resonance is an all-microwave entangling gate
- Static *J*-coupling hybridizes the qubit levels
- Drive the control qubit at the target qubit's frequency





[Rigetti *et al*, PRB (2010)] [Chow *et al*, PRL (2011)]

$|\widetilde{10}\rangle \rightarrow |10\rangle - J/\Delta|01\rangle$

$|\widetilde{01}\rangle \rightarrow |01\rangle + J/\Delta|10\rangle$

sign difference

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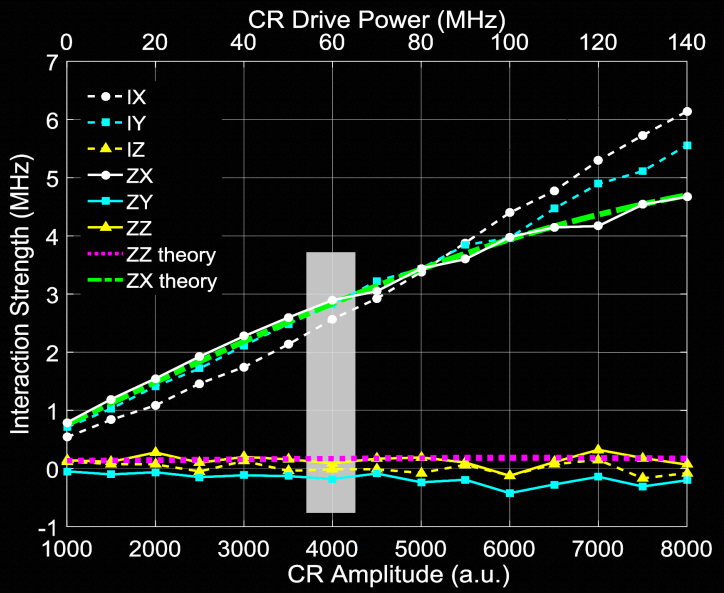
Cross Resonance Interaction

- Measure Cross Resonance Hamiltonian as function of drive strength
- “Qubit” terms
  - *ZX*: useful interaction ~ CX
  - *ZI*: Stark shift on control
  - *IX*: uncontrolled target rotation
- “Crosstalk” terms
  - *IY*: classical crosstalk, i.e. microwaves leaking
  - *ZZ*: quantum crosstalk (due to transmon)



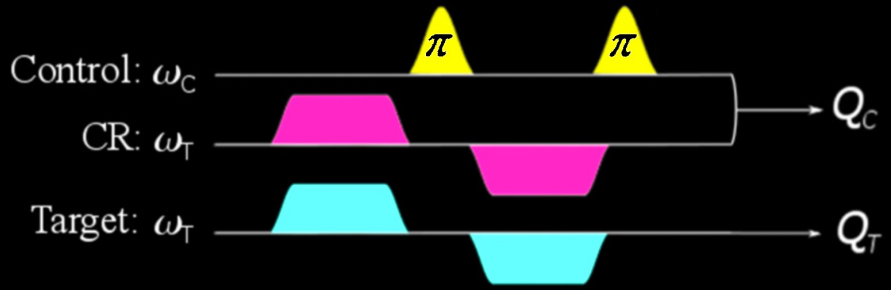
[S Sheldon *et al*, *PRA* **93**, 060302 (2016)]

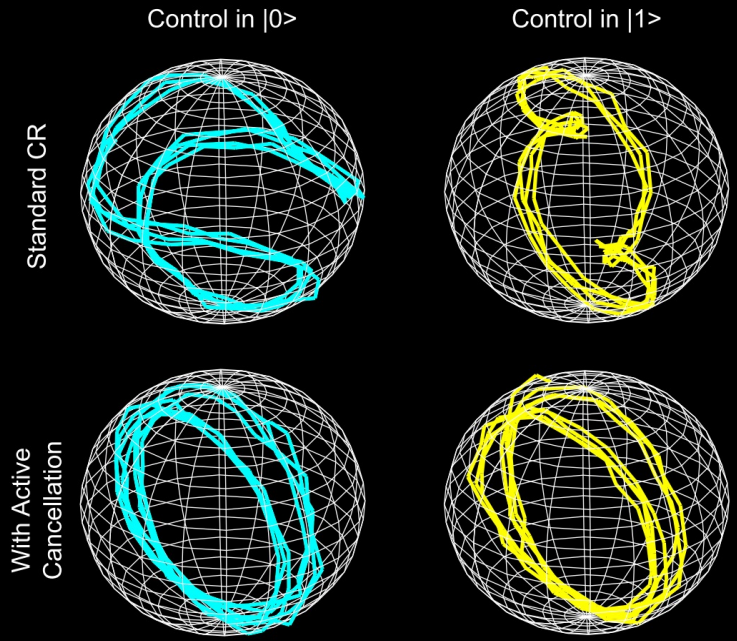
$$H_{CR} = \hbar\Omega(t)(ZI + \nu(\cos(\theta)\, IX + \sin(\theta)\, IY) + \mu ZX) + \hbar\alpha ZZ + \hbar\beta IZ$$

Cross Resonance Interaction

This work implemented

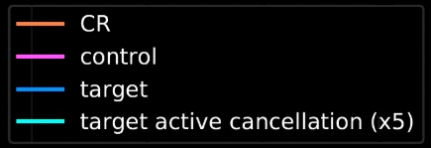
- Echo pulse: cancels *ZI*, *IX*
- Cancellation tone: cancels *IY*





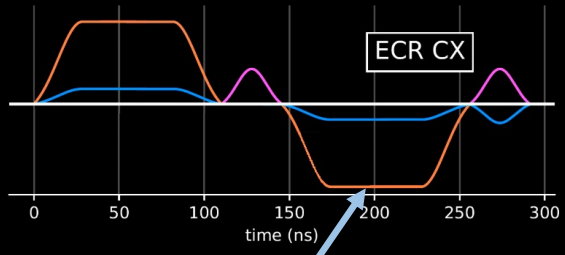
[S Sheldon *et al*, *PRA* **93**, 060302 (2016)]

Maximal Entanglers



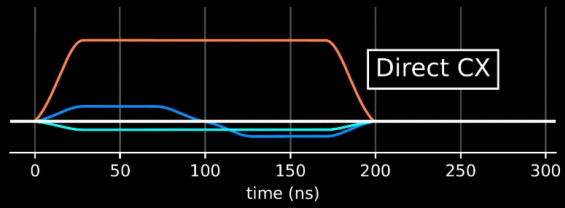
Know your target gate

`cx`



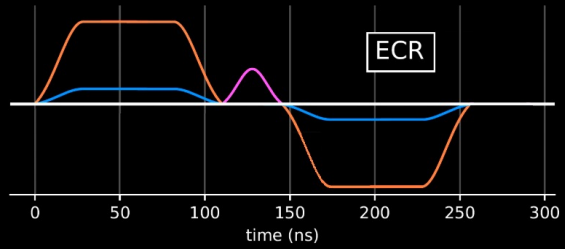
`GaussianSquare` or
`GaussianSquareDrag`

Echoed Cross Resonance + Singles



Direct CX

`ecr`



Echoed Cross Resonance

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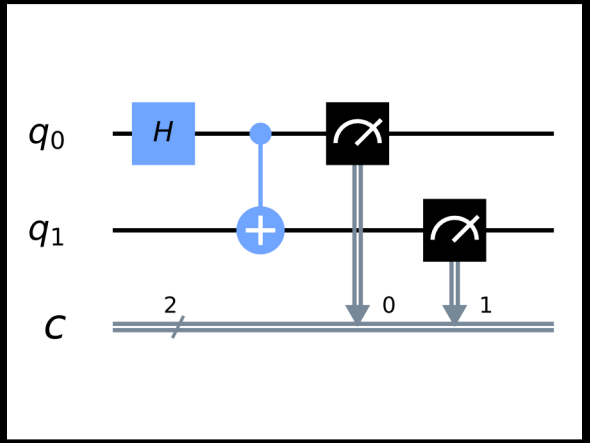
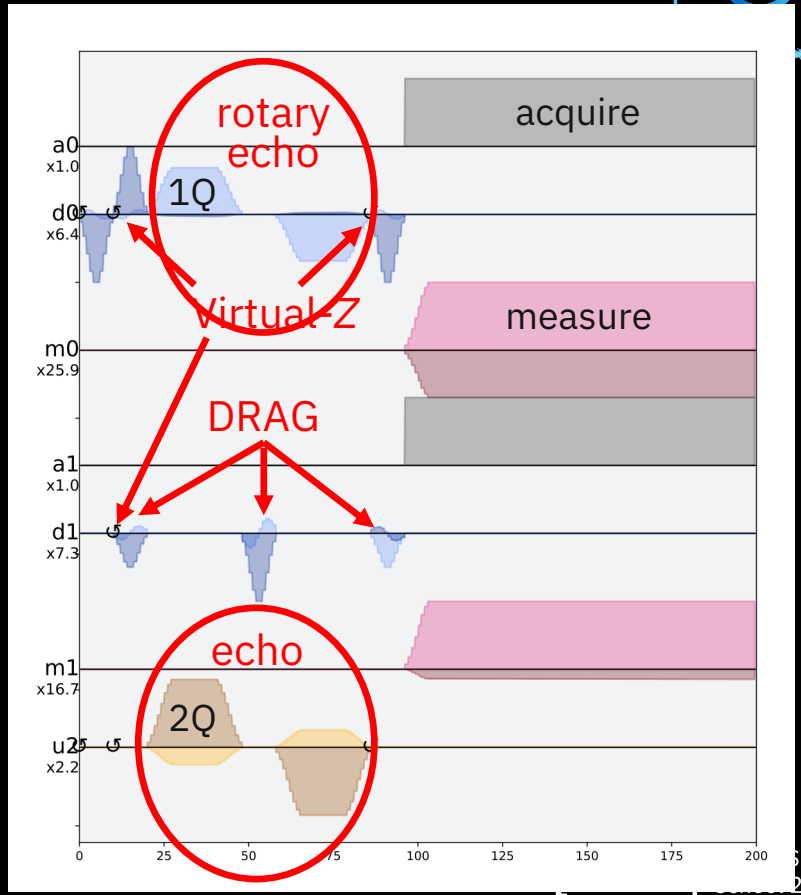
[P Jurcevic *et al*, *Quant Sci & Tech* **6**, 025020 (2021)]

Circuit vs Pulse Model





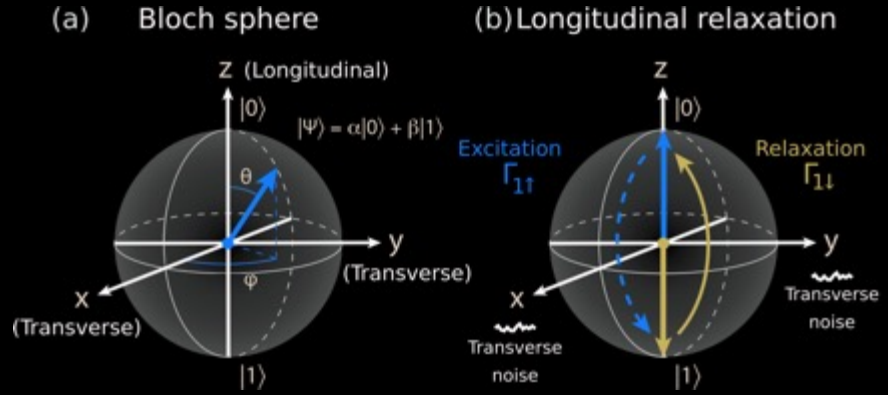
[F Motzoi *et al*, *PRL* **103**, 110501 (2009)]

[DC McKay *et al*, *PRA* **96**, 022330 (2017)]

[S Sheldon *et al*, *PRA* **93**, 060302(R) (2016)]

[N Sundaresan *et al*, *PRX Quantum* **1**, 020318 (2020)]

Relaxation and Decoherence



Relaxation (T_1):

- Coupling to two level systems and adsorbants
- Spontaneous emission due to Purcell effect
- Superconducting phenomena: quasiparticles and vortices

Pure Dephasing (T_φ):

- Fluctuations in energy levels due to thermal broadening or magnetic noise
- Measurement, whether intentional or not

Decoherence (T_2):

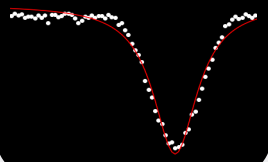
- Combined T_1 and T_φ

[P Krantz *et al*, *Appl Phys Rev* **6**, 021318 (2019)]

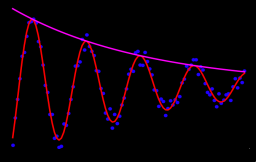
From Device Physics to Quantum Computation

Device Metrics

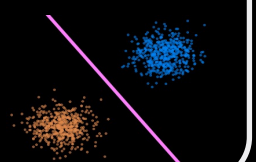
frequency



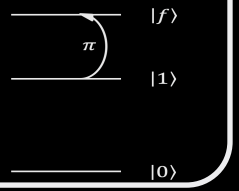
decoherence



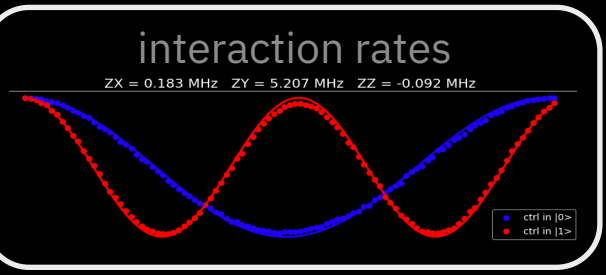
measurement



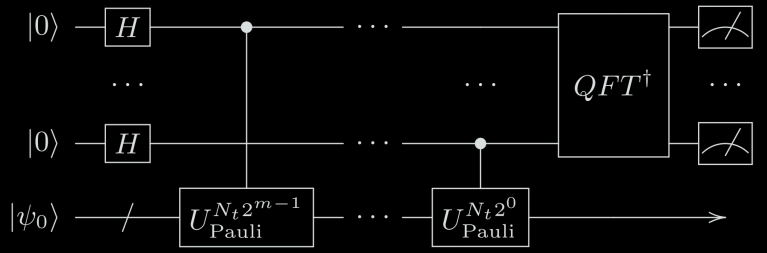
anharmonicity

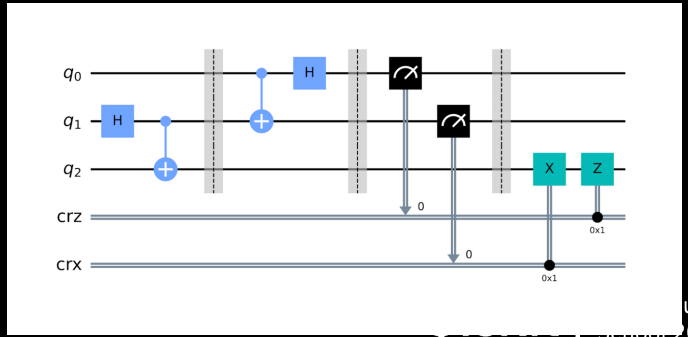


interaction rates



Algorithmic Desires





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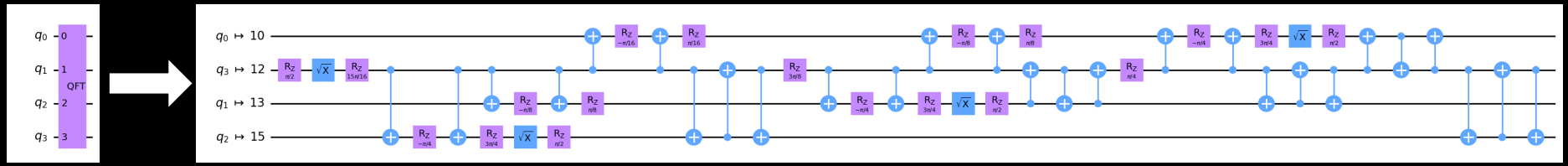
Qiskit Transpiler: where Circuits meet the HW

- Circuit transformations that take *abstract* quantum circuit to *physical* quantum circuit
- Each transformation is a Pass, the PassManager combines Passes and possibly control flow
- Operates on a Directed Acyclic Graph (DAG) representation of the circui
- Model for understanding mitigating errors on noisy quantum hardware

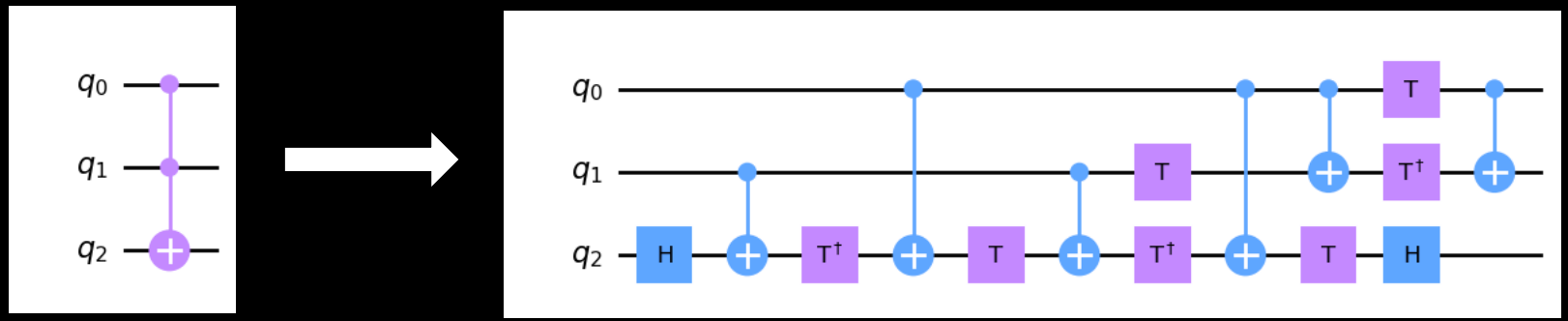


Initialization

IBM Backends only operate with single- and two-qubit gates

- Must decompose three-or-greater-qubit gates

```
pm.init.run(qc)
```

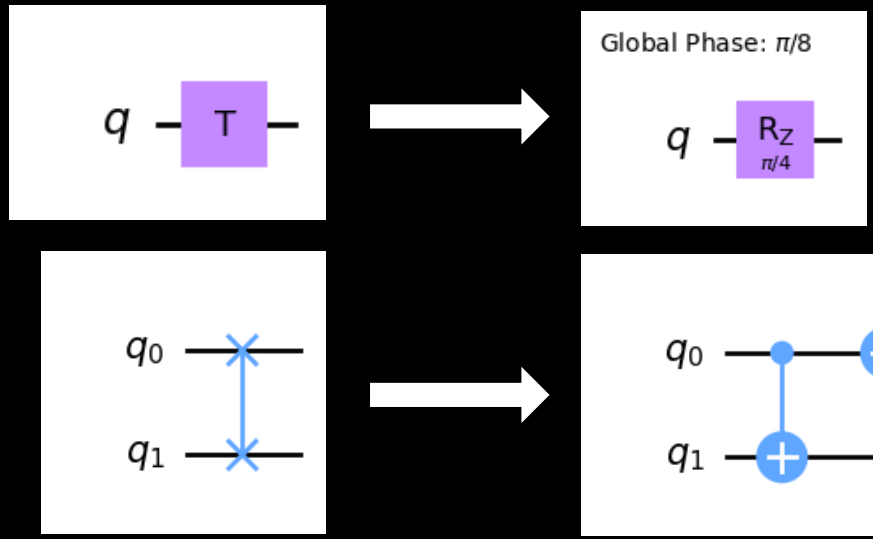


Translation

Only basis gates native to the backend can be used

- (exception are pulse gates that provide their own Schedule)

```
pm.translation.run(qc)
```



Most backends support `cx`
Some backends support `ecr`
Future backends support `cz`

[J Stehlik *et al*, *PRL* **127**, 080505 (2021)]

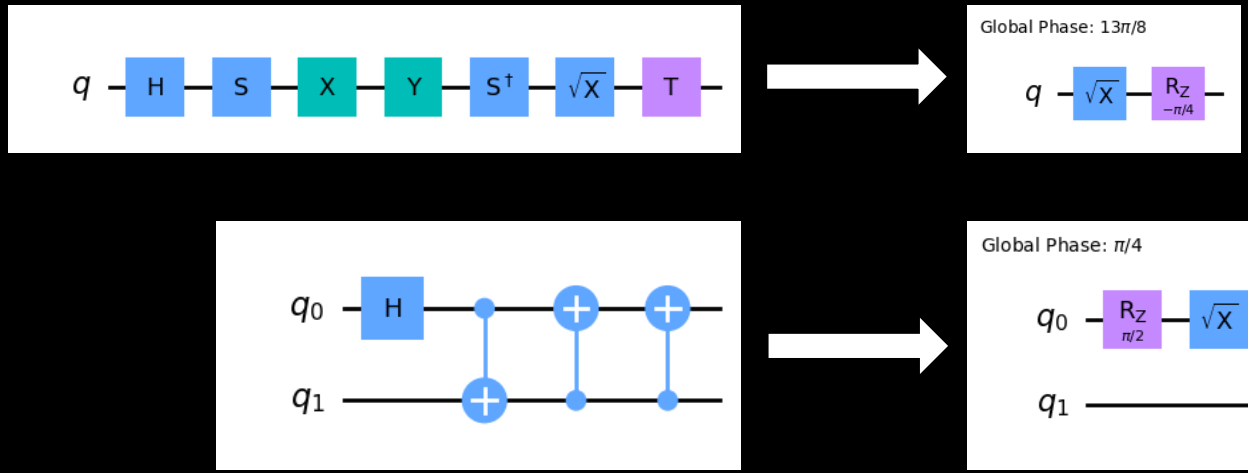
Error Correction Aside

- CXs are protected
- T gates are not

Optimization

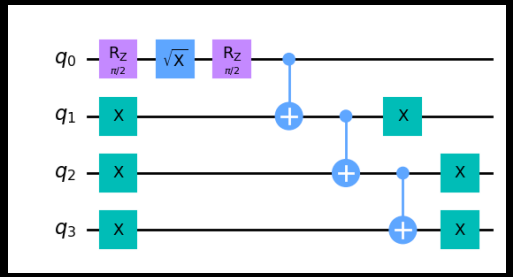
Combine 1Q gates, cancel redundant CXs

```
pm.optimization.run(qc)
```



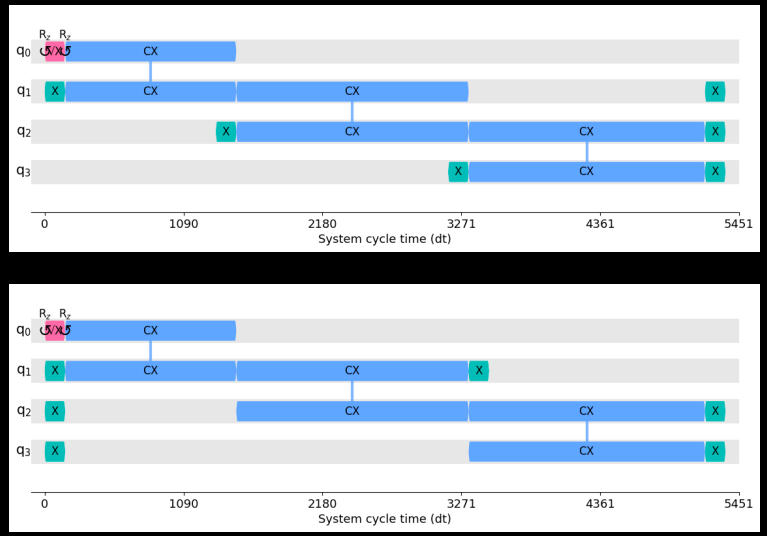
Scheduling

- Puts backend's timing information into circuit
- As-late-as-possible scheduling allows qubits to remain initially in |0> state



ALAP

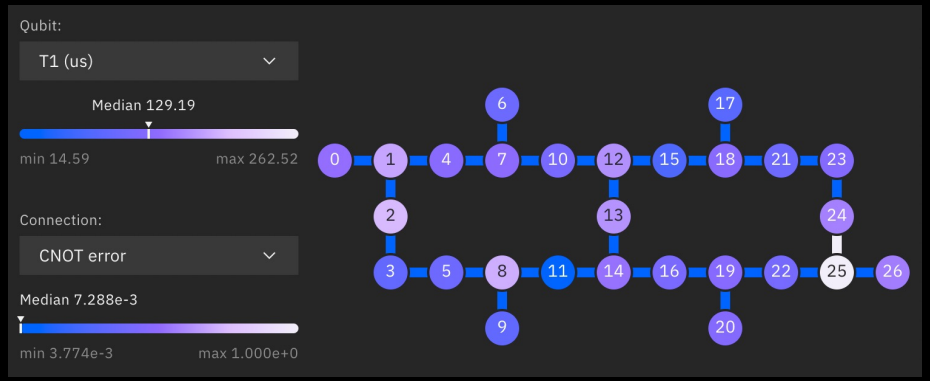
ASAP



Know thy Errors

IBM Quantum Services

ibmq_kolkata



Qiskit

```
backend.properties().t1(12)
    0.00018349695332505513

backend.properties().gate_error('cx', qubits=[0, 1])
    0.004620645864212458

backend.properties().readout_error(12)
    0.01200000000000001

backend.properties().general
    ...jq_1213, GHz, 0.0018740190228742494)
    ...zz_1213, GHz, -4.195867945992644e-05),

backend.configuration().coupling_map
    [[0, 1], [1, 0], [1, 2], [1, 4], [2, 1],...

backend.defaults().instruction_schedule_map
```

`qiskit & qiskit-partners`

`qiskit-research & qiskit-ibm-runtime`

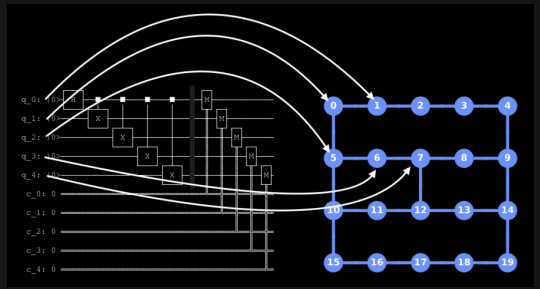
`qiskit-ibm-runtime`

Transpilation: take circuit to “smarter” circuit

Qubit Mapping

(be smart about the qubits you use)

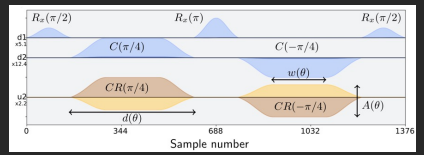
- Routing
- Layout



Error Suppression

(use physics to reduce errors)

- Parallelization
- Pulse Scaling
- Dynamical Decoupling
- Pauli Twirling
- Measure Error Mitigation

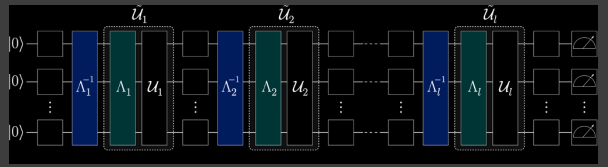


Transpile differently + Analyze

Error Mitigation

(analyze circuit run in multiple ways)

- Zero Noise Extrapolation
- Probabilistic Error Cancellation



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Installation

qiskit-partners

```
>>> pip install mapomatic
```

- Layout

```
>>> pip install mthree
```

- Matrix-free Measurement (Error) Mitigation

qiskit-research

```
>>> git clone https://github.com/qiskit-research/qiskit-research
```

```
>>> cd qiskit-research
```

```
>>> pip install -e .
```

- Parallelization
- Pulse Scaling
- Dynamical Decoupling
- Pauli Twirling

qiskit-ibm-runtime

```
>>> pip install qiskit-ibm-runtime
```

- Twirled Readout Error eXtinction
- Zero Noise Extrapolation
- Probabilistic Error Cancellation

Thank you