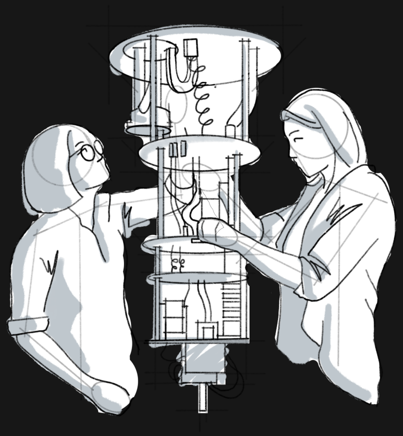
Quantum Hardware Introduction

Nathan Earnest-Noble, Ph.D.
Quantum Computing Application Researcher



Overview

- Brief Review of Superconducting Qubits and circuit Quantum Electrodynamics (cQED)
- Typical Device Errors and Error Mitigation Techniques
- Quantum Process Tomography

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I will introduce the “forest” of superconducting hardware.

In the process I hope to direct you the resources to study the details

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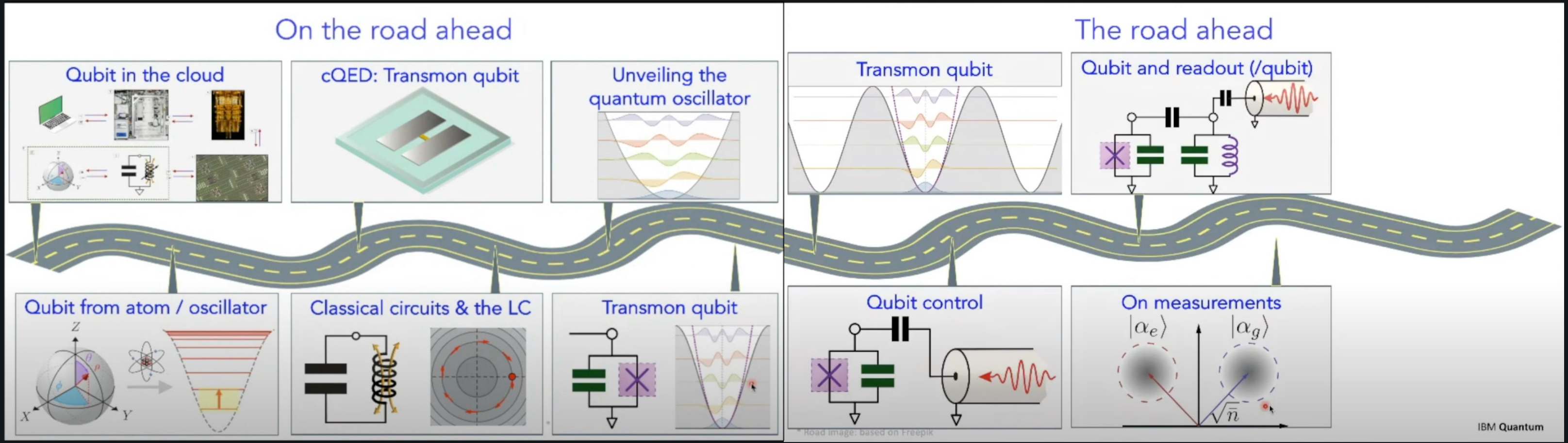
- Brief Review of Superconducting Qubits and circuit Quantum Electrodynamics (cQED)
- Typical Device Errors and Error Mitigation Techniques
- Quantum Process Tomography

Check out Zlatko's Talks from QGSS 2020 (Lectures 16-21)– Covers many of the details



Overview

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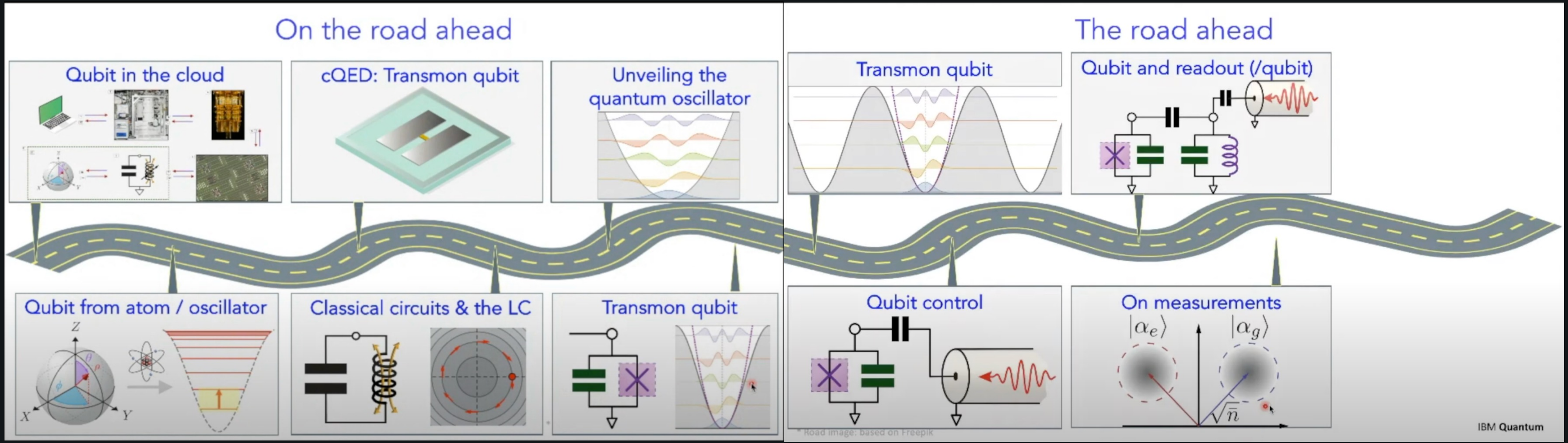


Superconducting Qubits are Made from Three Essential Components

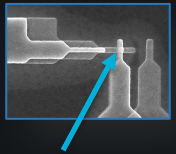
Component:

Circuit Drawing:

Physical Realization:

Hamiltonian Description:

Superconducting Qubits are Made from Three Essential Components

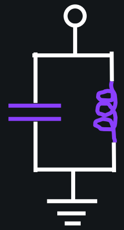
Component:	Capacitors	Inductors	Josephson Junction
Circuit Drawing:			
Physical Realization:			 **100 nm X 100 nm**
Hamiltonian Description:	$\frac{\hat{Q}^2}{2C}$	$\frac{\hat{\phi}^2}{2L}$	$E_J \cos(\hat{\phi})$

Combining the Linear Elements Gives Rise to a Simple Harmonic Oscillator

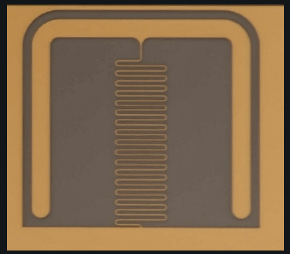
Qiskit

Component: Simple Harmonic Oscillator | Josephson Junction

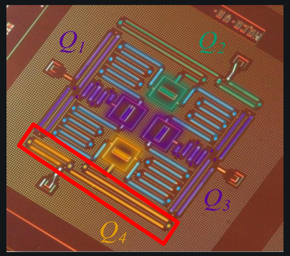
Circuit Drawing:



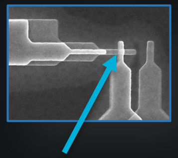
Physical Realization:



Lumped Element Resonator



CPW Resonator (length and boundary conditions determine resonate frequency)



100 nm X 100 nm

Hamiltonian Description:

$$H = \frac{\hat{Q}^2}{2C} + \frac{\hat{\phi}^2}{2L}$$

$$E_J \cos(\hat{\phi})$$

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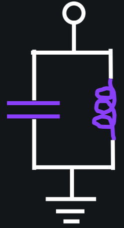
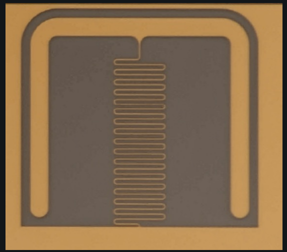


Physical Realization:



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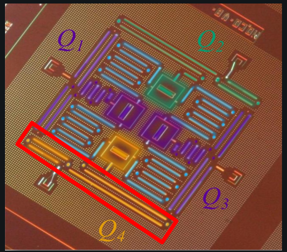

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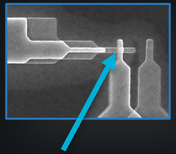

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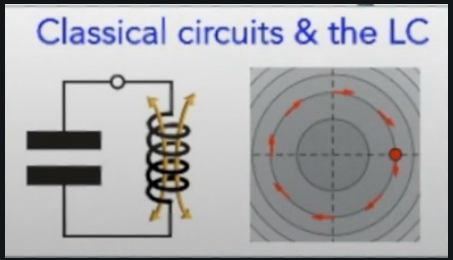


QGSS 2020 - Lecture 17

Covers:

- Kirchhoff's Laws and "Newtonian" mechanics for motion
- Hamiltonian and Lagrangian Mechanics

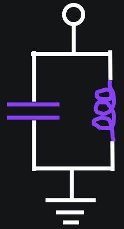
$$E_J \cos(\hat{\phi})$$

Combining the Linear Elements Gives Rise to a Simple Harmonic Oscillator

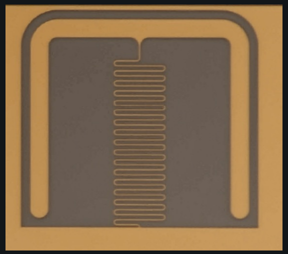
Qiskit

Component: Simple Harmonic Oscillator | Josephson Junction

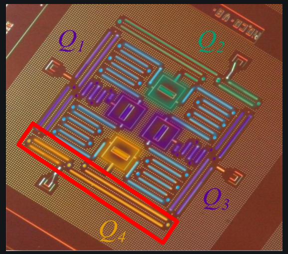
Circuit Drawing:



Physical Realization:



Lumped Element Resonator



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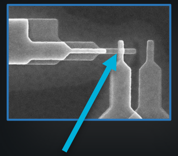


100 nm X 100 nm

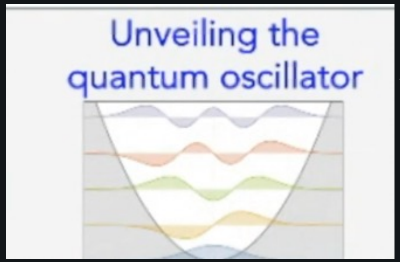
Hamiltonian Description:

$$H = \frac{\hat{Q}^2}{2C} + \frac{\hat{\phi}^2}{2L}$$

QGSS 2020 - Lecture 18

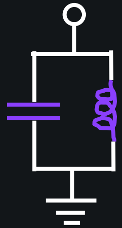
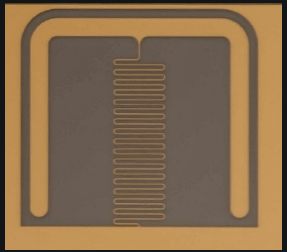
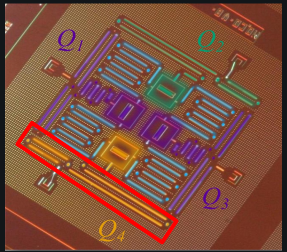
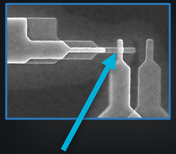
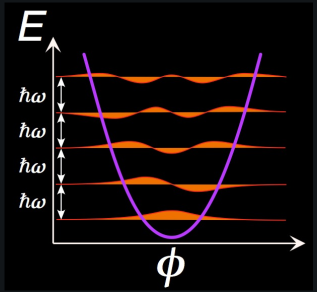
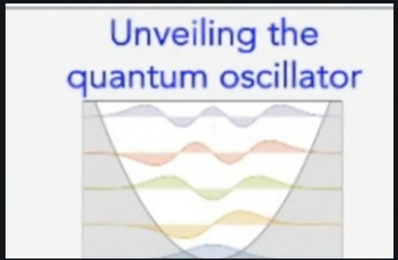
Covers:

- Definition of ‘Ladder Operators’
- Quantum Energy and Zero Point Fluctuations



$$E_J \cos(\hat{\phi})$$

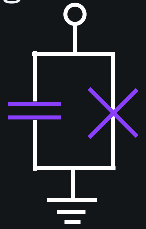
The Simple Harmonic Oscillator Alone Cannot be Coherently Controlled

Component:	Simple Harmonic Oscillator		Josephson Junction
Circuit Drawing:			
Physical Realization:	 Lumped Element Resonator	 CPW Resonator (length and boundary conditions determine resonate frequency)	 **100 nm X 100 nm**
Hamiltonian Description:	$H = \frac{\hat{Q}^2}{2C} + \frac{\hat{\phi}^2}{2L}$ 		$E_J \cos(\hat{\phi})$

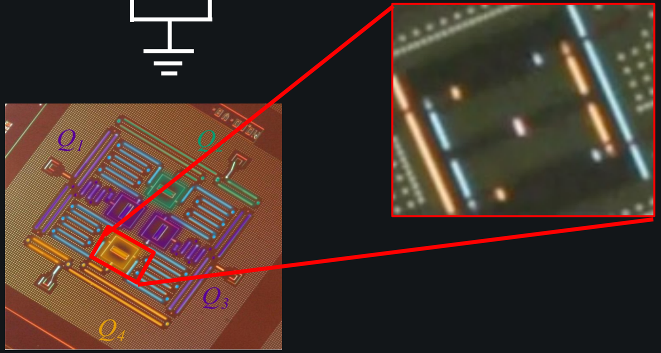
Replacing the Inductor with a Non-Linear Josephson Junction Enables Coherent Control

Component: Charge Based Anharmonic Osccilator

Circuit Drawing:



Physical Realization:



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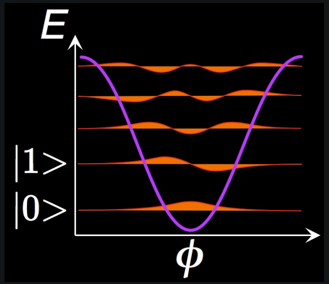

$$H = 4E_C n^2 - E_J \cos(\hat{\phi})$$

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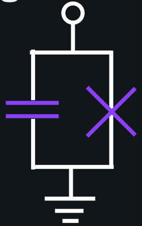

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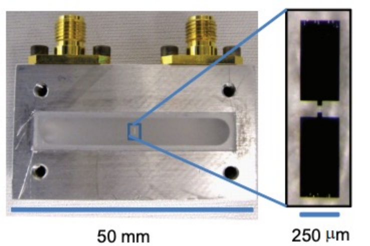

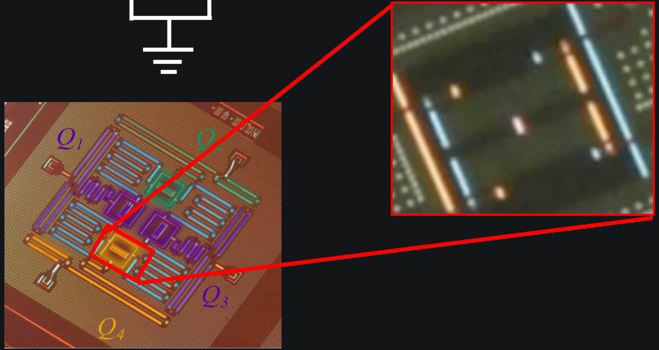

Paik, H. et al "Observation of high coherence in Josephson junction qubits measured in a three-dimensional circuit QED architecture." *Physical Review Letters* 107, no. 24 (2011): 240501.

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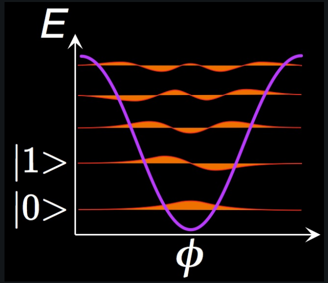

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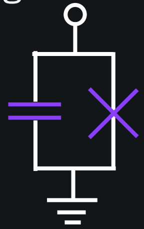

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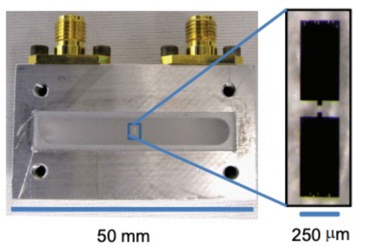

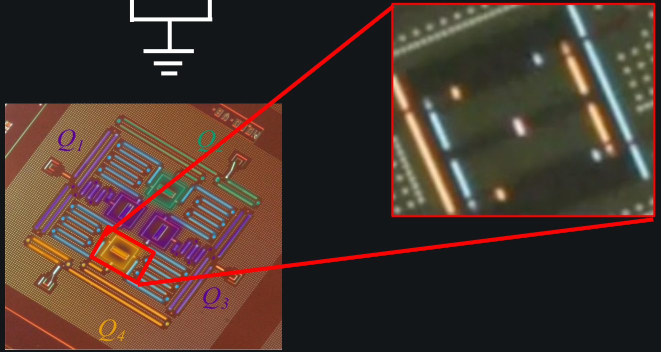

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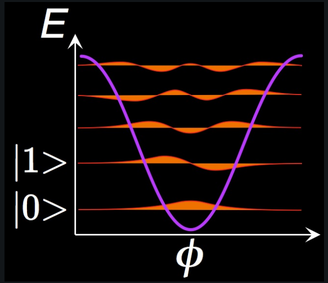
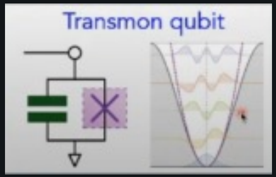




QGSS 2020 - Lecture 19

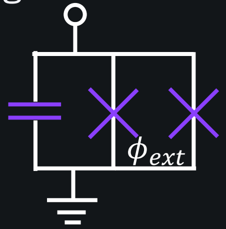
Covers:

- Derivation of Josephson Inductance
- Transmon Hamiltonian

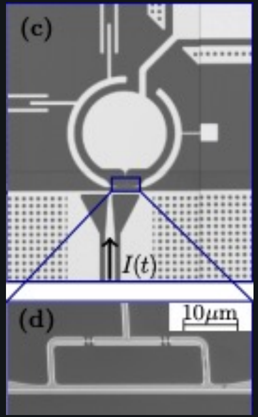
Making a Loop with Two Josephson Junction Allows for a Tunable Qubit

Component: Charge Based Anharmonic Osccilator

Circuit Drawing:

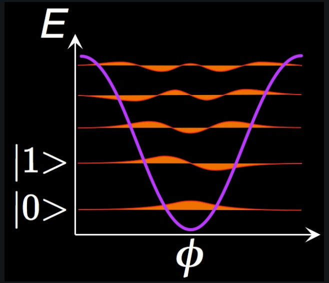


Physical Realization:



Caldwell, S. A., et al "Parametrically activated entangling gates using transmon qubits." *Physical Review Applied* 10, no. 3 (2018): 034050.

Hamiltonian Description:



$$H = 4E_C n^2 - E_J(\phi_{ext})\cos(\hat{\phi})$$

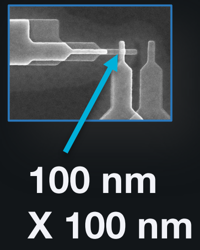
The Josephson Junction can be Carefully Engineered

Component:

Josephson Junction

Circuit Drawing:

Physical Realization:



Hamiltonian Description:

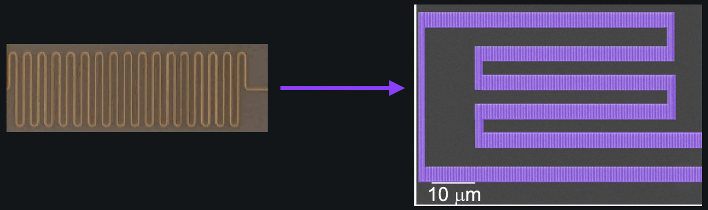
Large Josephson Junctions can be Made as a Linear ‘superinductance’

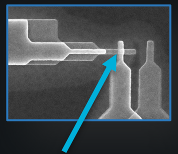
Qiskit

Component: | Superinductors Inductors | Josephson Junction

Circuit Drawing:

Physical Realization:



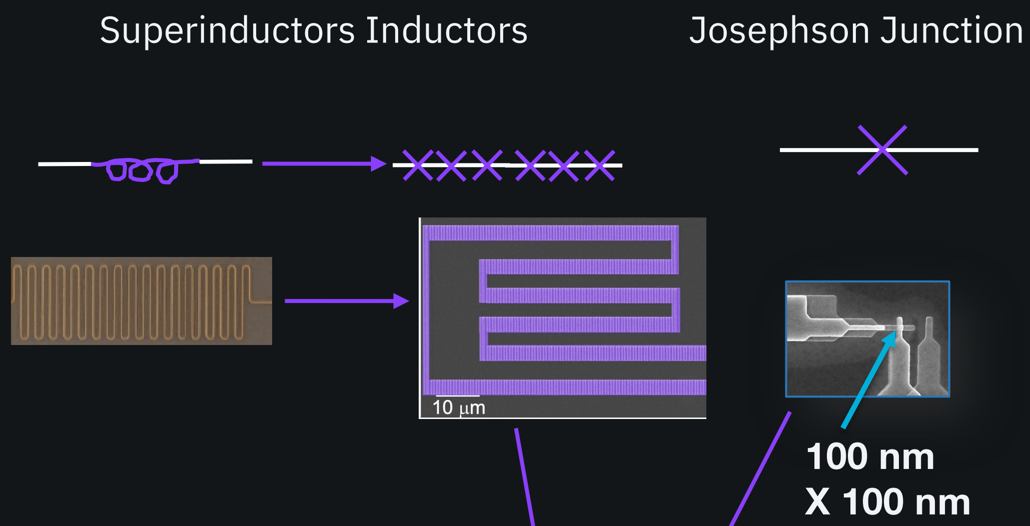


100 nm X 100 nm

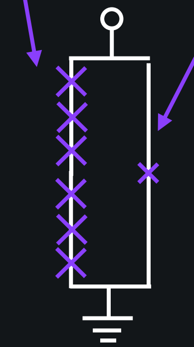
Hamiltonian Description:

Shunting a Non-Linear JJ with a Superinductor Create a Fluxonium Qubit

Qiskit



"Quantum Impurity Regime of Circuit Quantum Electrodynamics" | Seminar Series w/ Vladimir Manucharyan



Each of These Circuit Elements Can be Combined to Make Different Qubits

Capacitors

Inductors

Super Inductors

Josephson Junction

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Qiskit

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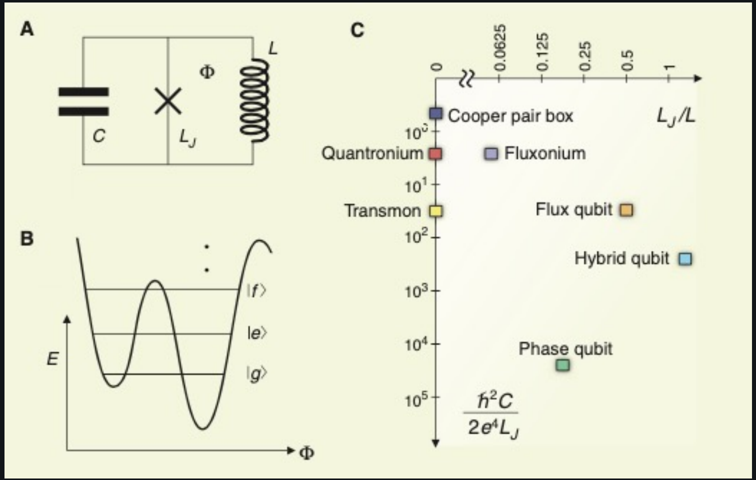


Devoret, Michel H., and Robert J. Schoelkopf. "Superconducting circuits for quantum information: an outlook." *Science* 339, no. 6124 (2013): 1169-1174.

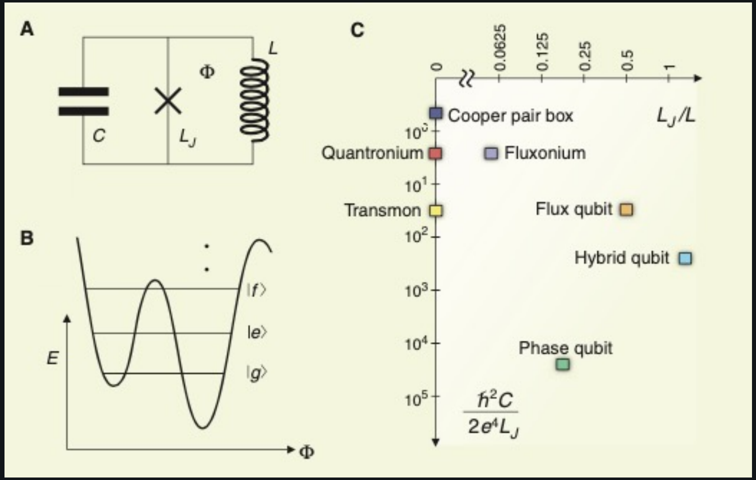
The Different Circuit Elements can be Combined in Sophisticated Manners to Give Rise to Special Properties for Inherent Noise Protection

Capacitors

Inductors

Super Inductors

Josephson Junction



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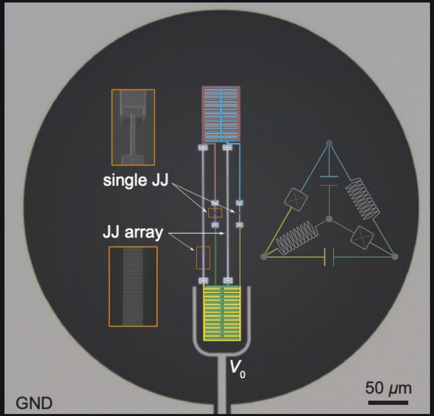
Protected 0-π qubit

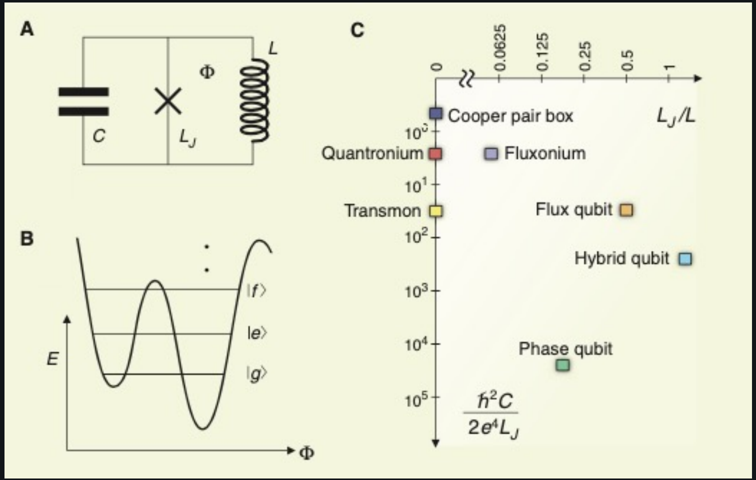


Gyenis, A., Pranav S. M. et al. "Experimental Realization of a Protected Superconducting Circuit Derived from the 0–π Qubit." *PRX Quantum* 2, no. 1 (2021): 010339.

The Different Circuit Elements can be Combined in Sophisticated Manners to Give Rise to Special Properties for Inherent Noise Protection

Qiskit

Capacitors	Inductors	Super Inductors	Josephson Junction
			



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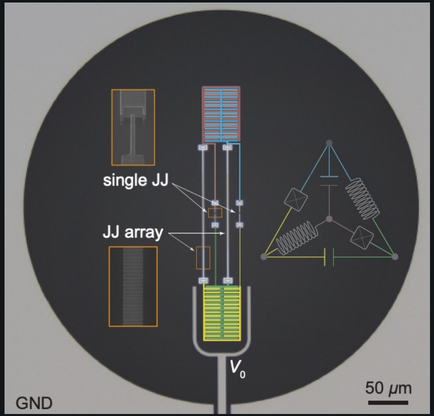
Protected 0-π qubit



Gyenis, A., Pranav S. M. et al. "Experimental Realization of a Protected Superconducting Circuit Derived from the 0–π Qubit." *PRX Quantum* 2, no. 1 (2021): 010339.

"Improving Qubit Performance – Design and Control " | Seminar Series w/ Pranav Mundada

Go Explore Different Superconducting Qubits and Corresponding Energy Landscapes!

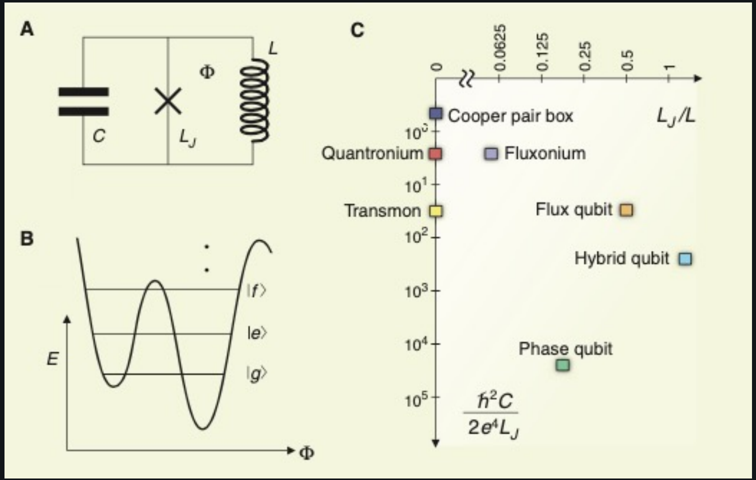
Qiskit

Capacitors

Inductors

Super Inductors

Josephson Junction



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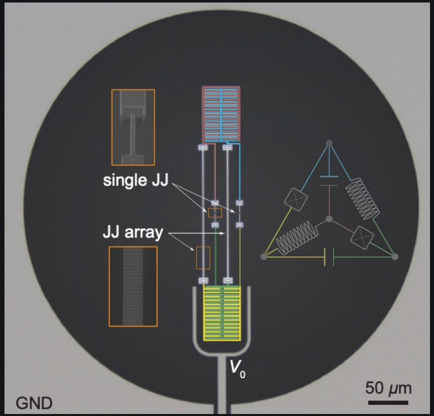

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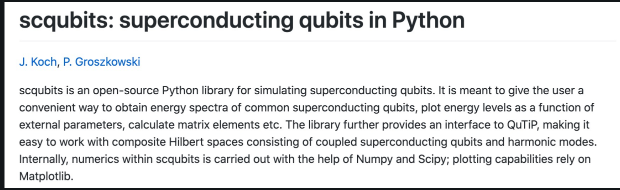


scqubits: superconducting qubits in Python

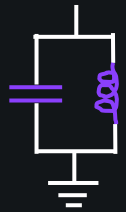
J. Koch, P. Groszkowski

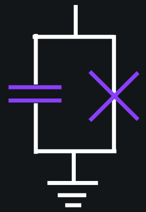
scqubits is an open-source Python library for simulating superconducting qubits. It is meant to give the user a convenient way to obtain energy spectra of common superconducting qubits, plot energy levels as a function of external parameters, calculate matrix elements etc. The library further provides an interface to QuTiP, making it easy to work with composite Hilbert spaces consisting of coupled superconducting qubits and harmonic modes. Internally, numerics within scqubits is carried out with the help of Numpy and Scipy; plotting capabilities rely on Matplotlib.

pip install scqubits

github.com/scqubits/scqubits

Circuit QED and Readout

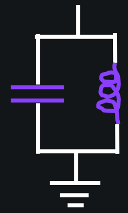


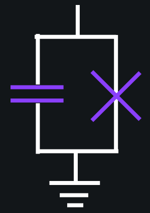


$$H = \frac{\hat{Q}^2}{2C} + \frac{\hat{\phi}^2}{2L}$$

$$H = 4E_C n^2 - E_J \cos(\hat{\phi})$$

Circuit QED and Readout

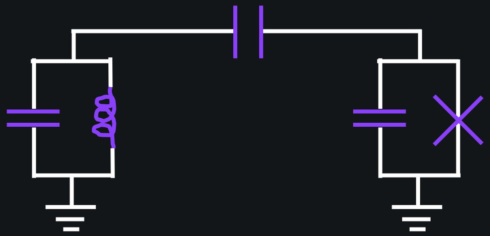




$$H = \hbar\omega_r\left(a^\dagger a + {}^1\!/_2\right)$$

$$H \sim \hbar\omega_q\sigma_Z$$

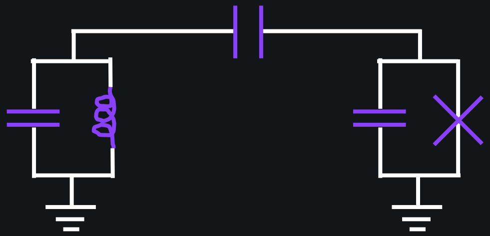
Circuit QED and Readout



Dispersive Jaynes Cummings Hamiltonian:

$$H^{JC} = \hbar(\omega_r + \chi\sigma_z)a^+a + \frac{\hbar}{2}(\omega_q + \chi)\sigma_z$$

Circuit QED and Readout



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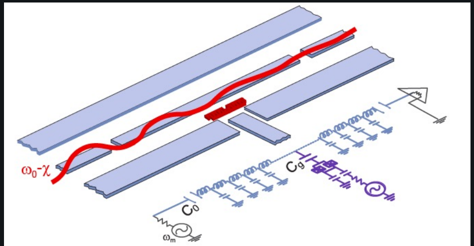

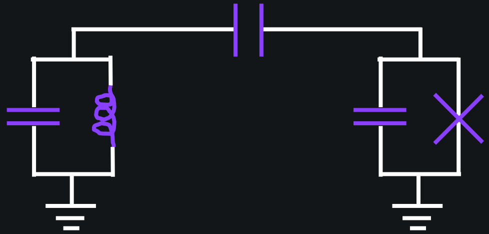

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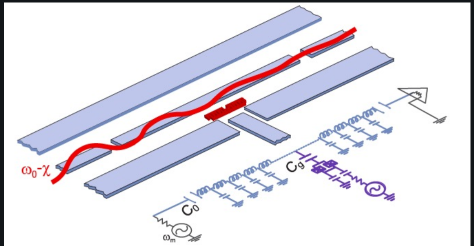

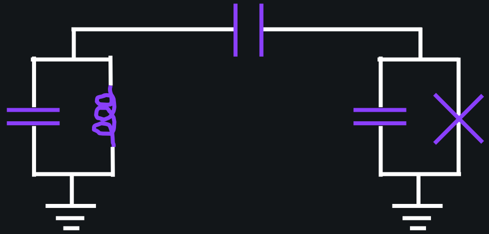

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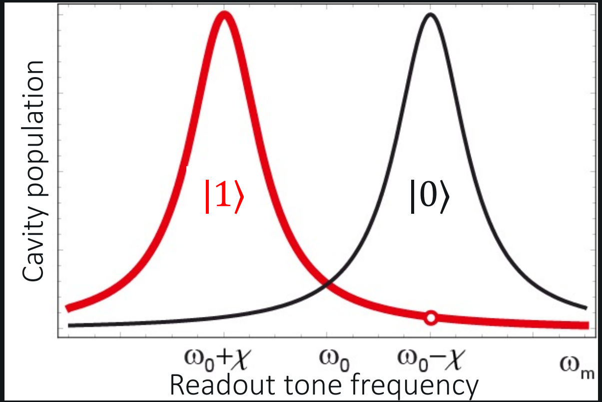

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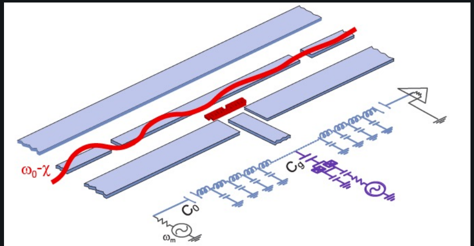

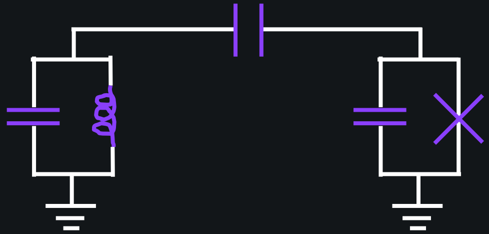

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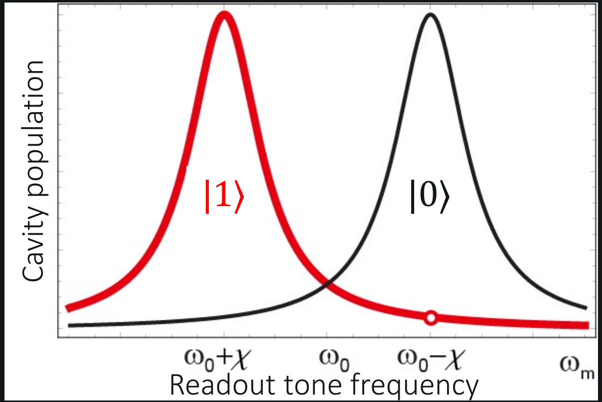
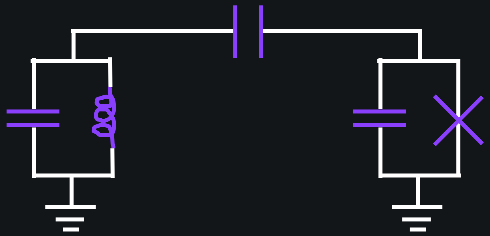
Superconducting Microwave Resonators:

- read-out of qubit states
- noise filter
- multi-qubit quantum bus



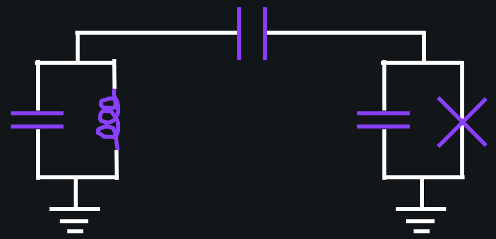
Circuit QED and Readout



Dispersive Jaynes Cummings Hamiltonian:

$$H^{JC} = \hbar\omega_r a^+ a + \frac{\hbar}{2}\left(\omega_q + 2\chi a^+ a + \chi\right)\sigma_z$$

Resonator Photons Will Shift the Qubit Frequency



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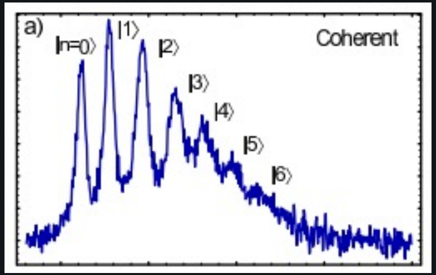
Can use the non-linear element to have coherent control of the linear cavity

Number Resolved Qubit Transitions



Schuster, D. I. et al "Resolving photon number states in a superconducting circuit." *Nature* 445, no. 7127 (2007): 515-518.

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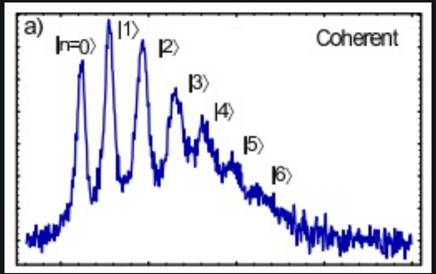
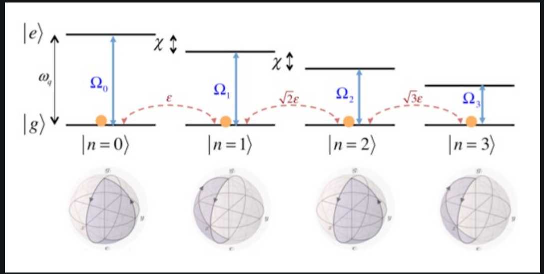


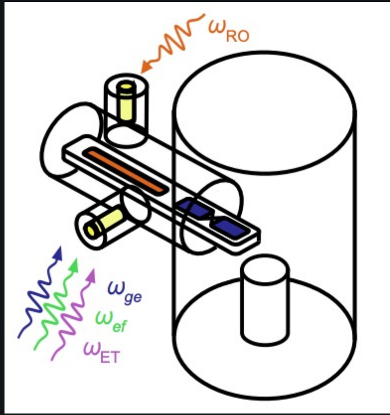
Schuster, D. I. et al "Resolving photon number states in a superconducting circuit." *Nature* 445, no. 7127 (2007): 515-518.

Selective Number-dependent Arbitrary Phase (SNAP) GATES



Krastanov, S. et al "Universal control of an oscillator with dispersive coupling to a qubit." *Physical Review A* 92, no. 4 (2015): 040303.

Bosonic Encoded Qubits with Linear Cavity



Reinhold, P. et al "Error-corrected gates on an encoded qubit." *Nature Physics* 16, no. 8 (2020): 822-826.

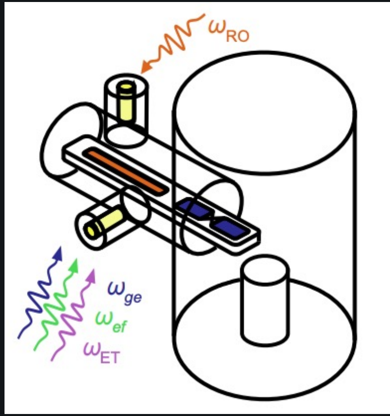
Can use the non-linear element to have coherent control of the linear cavity

"Repition Cat Qubits" | Seminar Series w/ Mazyar Mirrahimi

"Boson Sampling and Quantum Simulations in Circuit QED" | Seminar Series w/ Steve Girvin

"Surface Codes with Biased-Noise Qubits" | Seminar Series w/ Shruti Puri

Bosonic Encoded Qubits with Linear Cavity



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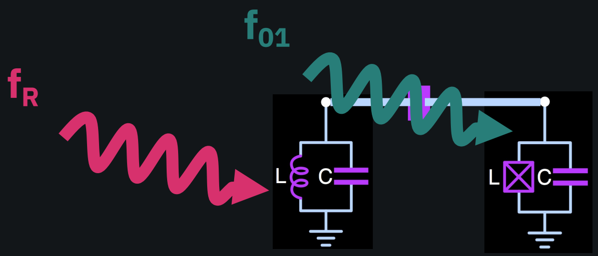
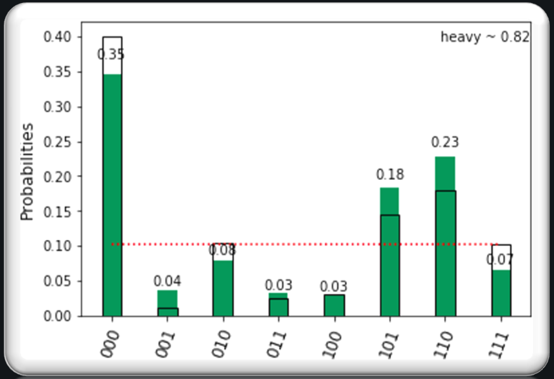
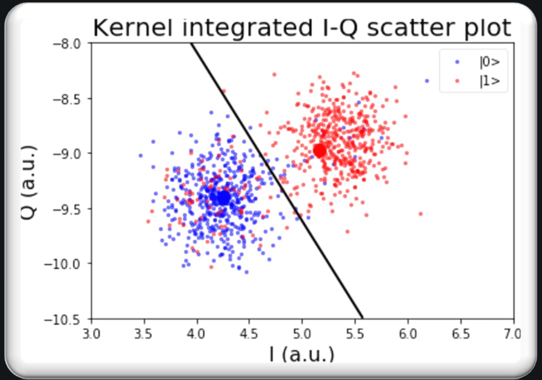
Measurement levels



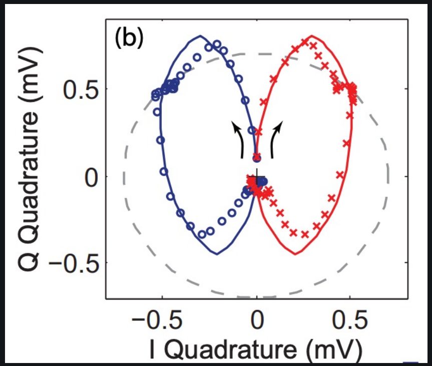
Measurement level 2



Measurement level 1



Measurement level 0



Overview

- Brief Review of superconducting qubits and circuit Quantum electrodynamics (cQED)
- Typical Device Errors and Error Mitigation Techniques
- Quantum Process Tomography

Typical Device Error Sources

1. T1/T2
2. Readout Errors
3. Gate Errors
4. Shots

Mitigation Strategies

1. Richardson Extrapolation
2. Methods:
   a. Excited State Promoted Readout
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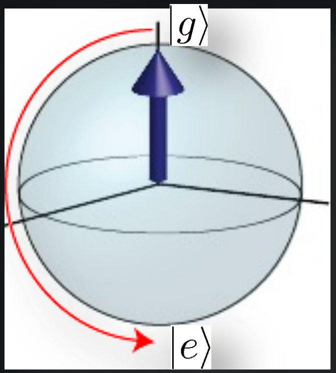
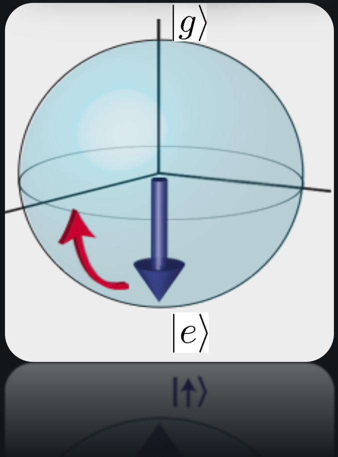
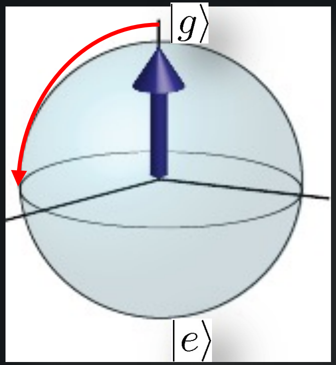
T_1 and T_2 are important traits in qubits

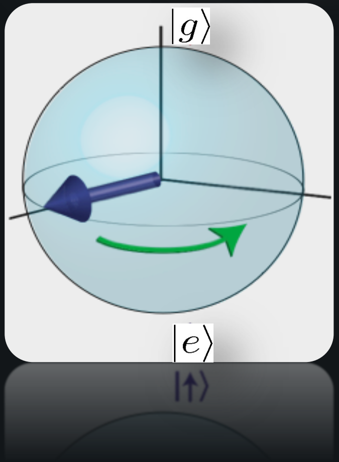
$T1: |1\rangle \rightarrow |0\rangle$





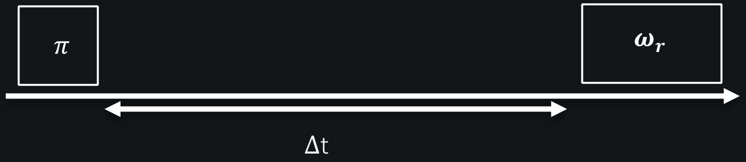
$T2: \alpha|0\rangle + \beta|1\rangle \rightarrow ?\,|0\rangle + ?\,|1\rangle$



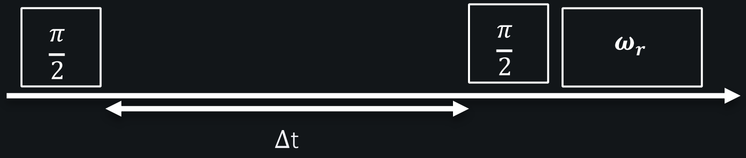


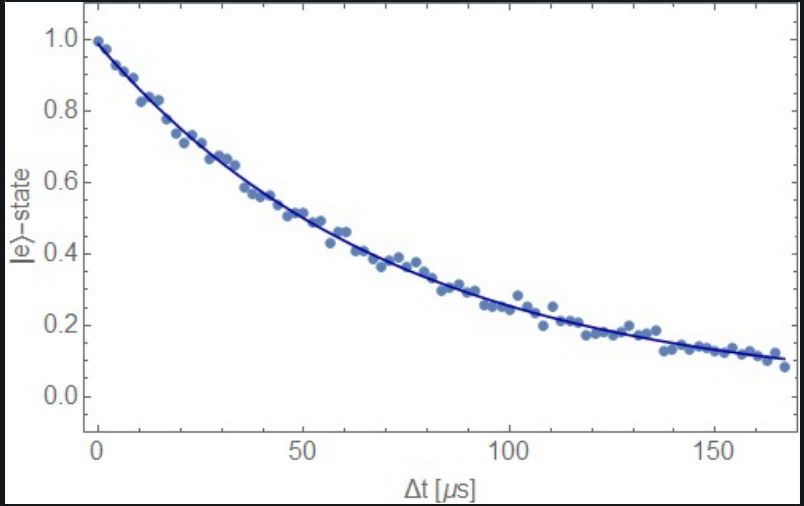
Measuring T_1 and T_2

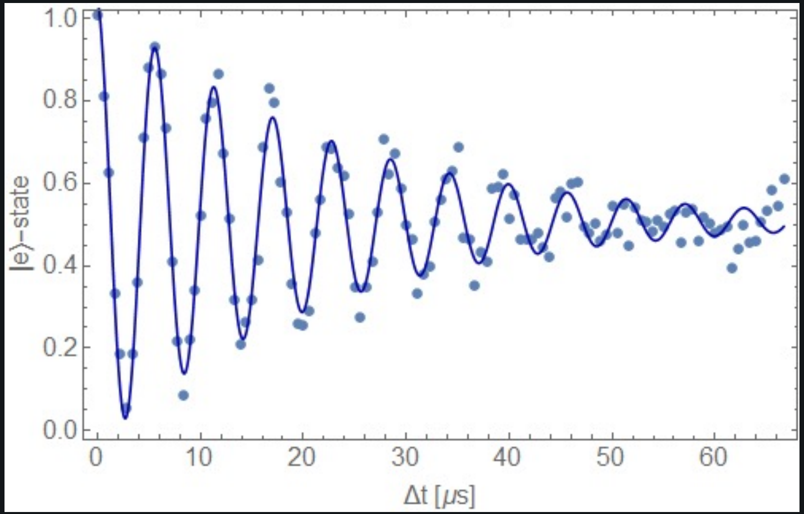
T1: $|1\rangle \rightarrow |0\rangle$



T2: $\alpha|0\rangle + \beta|1\rangle \rightarrow ?\,|0\rangle + ?\,|1\rangle$







Measuring T_1 and T_2

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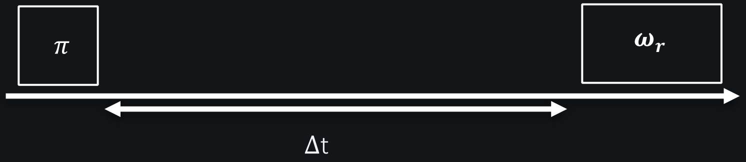

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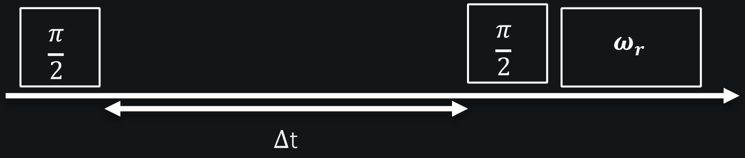
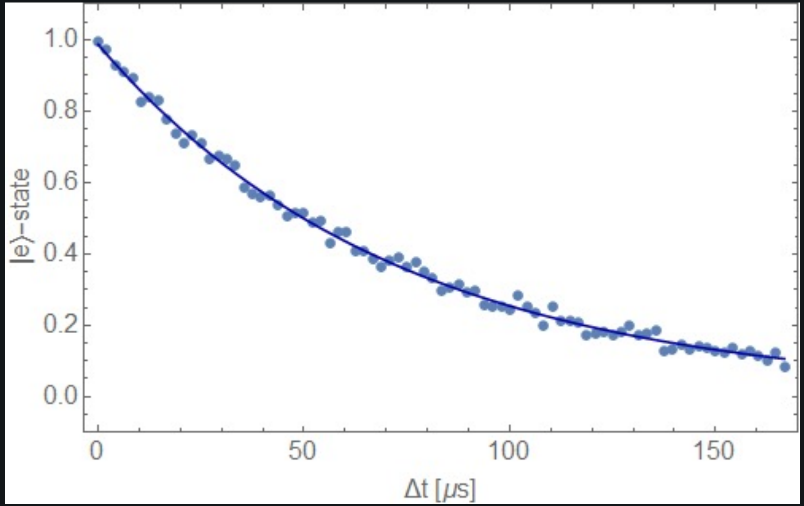
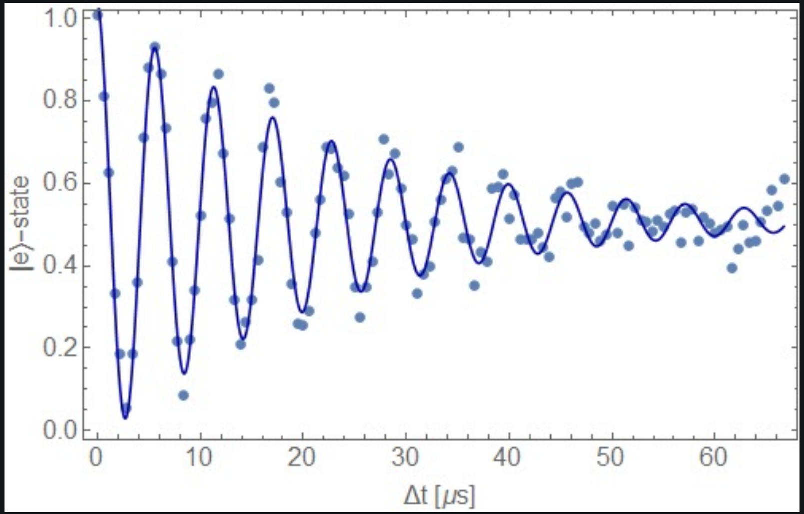


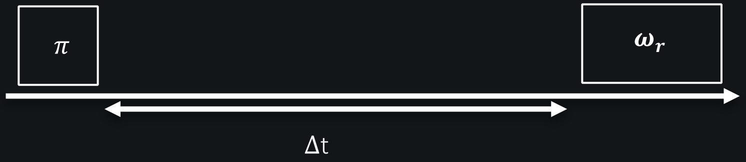




These are known Ramsey Oscillations

Measuring T_1 and T_2

$T1: |1\rangle \rightarrow |0\rangle$



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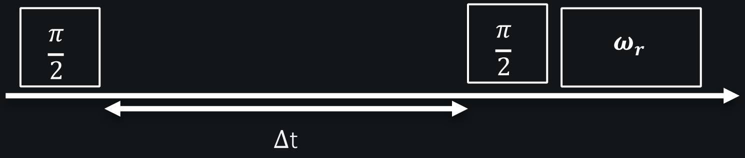
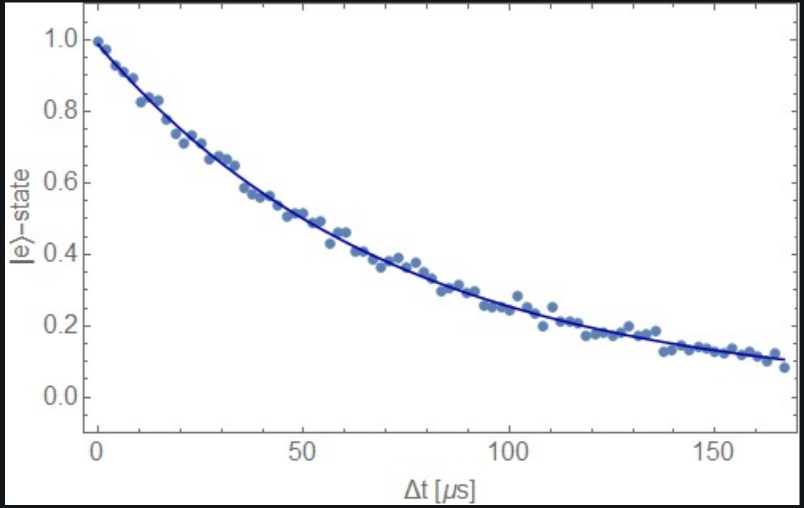
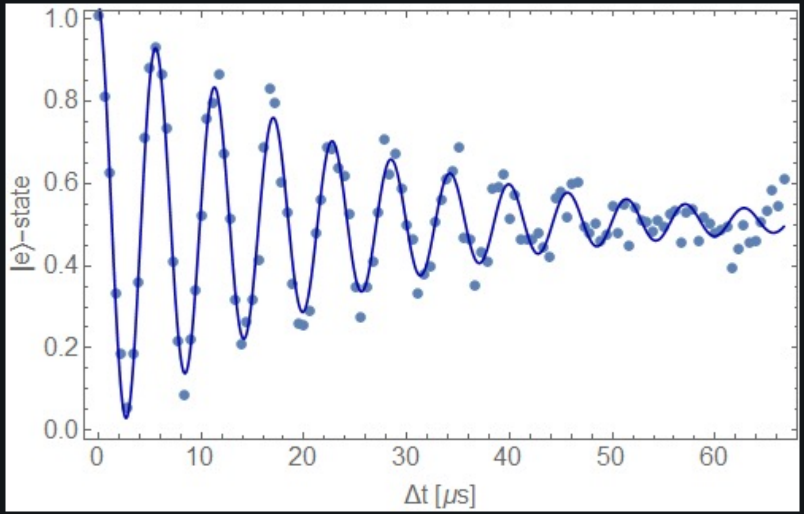


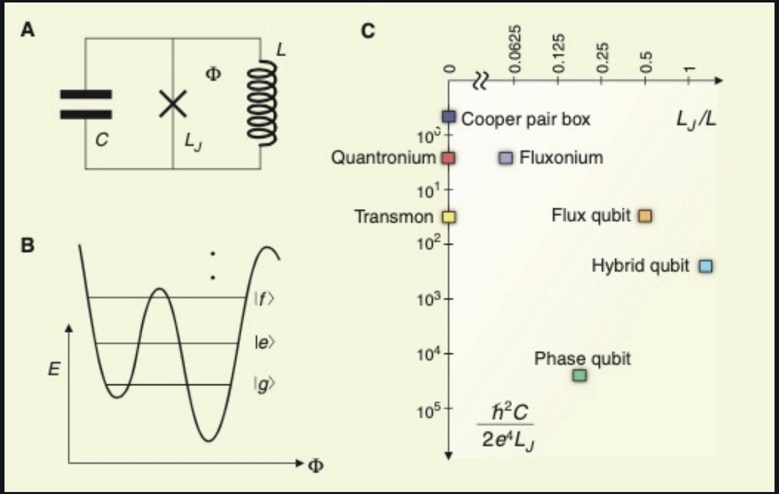




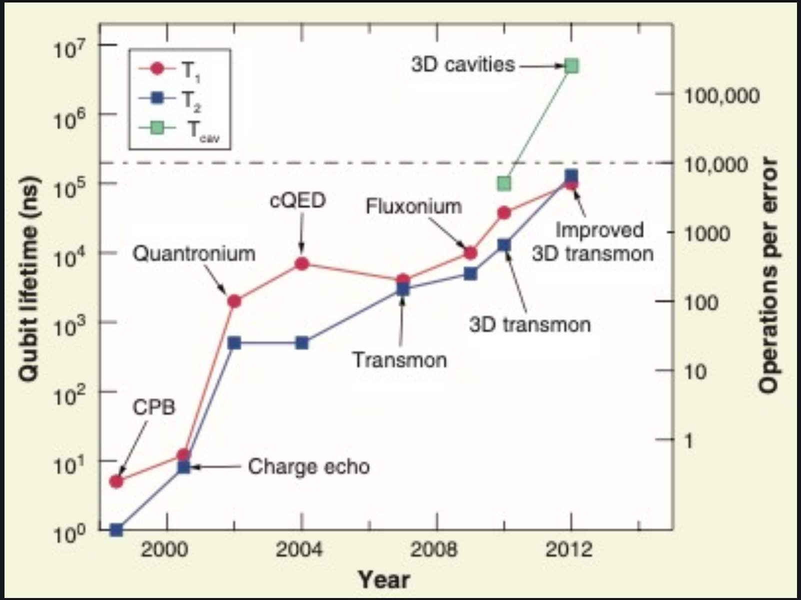
NEXT LECTURE WILL EXPLAIN HOW TO GET THE π AND $\frac{\pi}{2}$ PULSES

T_1 and T_2 Have Steadily Improved Since Inception

Qiskit



Devoret, Michel H., and Robert J. Schoelkopf. "Superconducting circuits for quantum information: an outlook." *Science* 339, no. 6124 (2013): 1169-1174.



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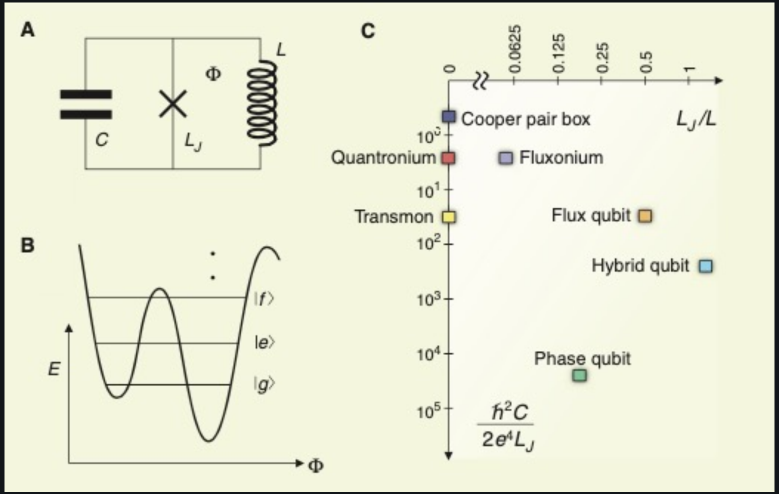

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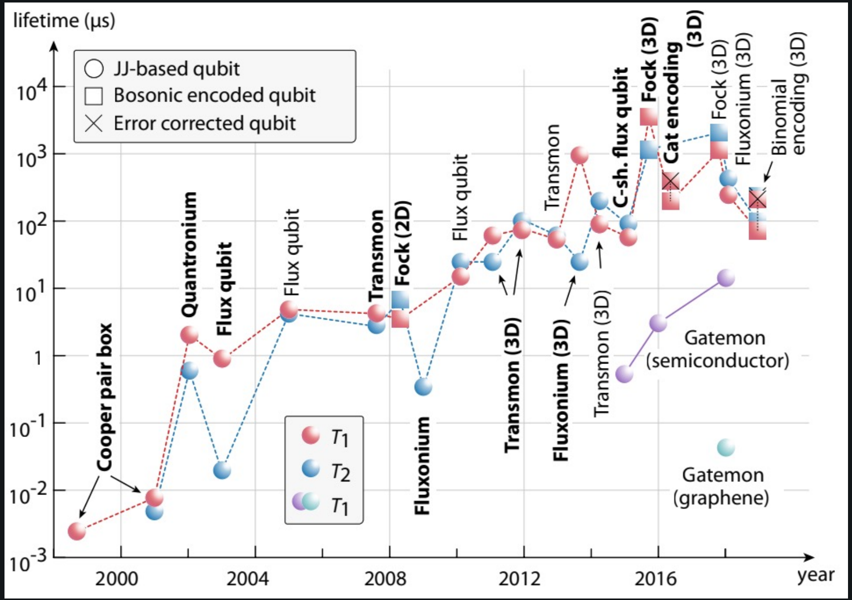
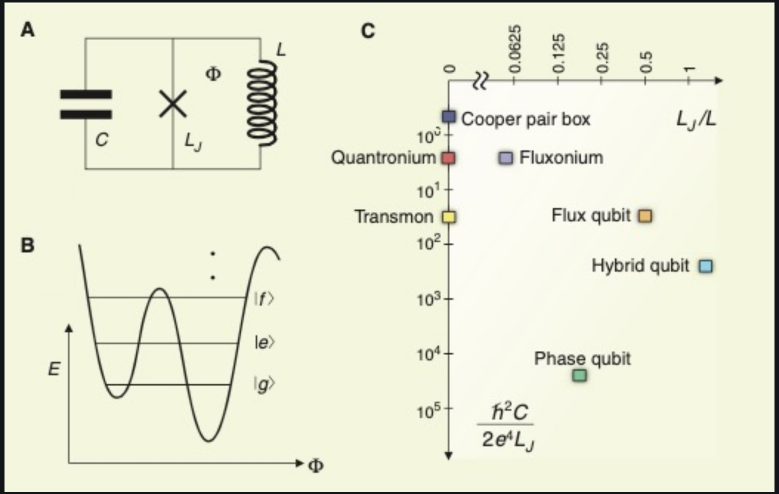


Kjaergaard, M. et al"Superconducting qubits: Current state of play." *Annual Review of Condensed Matter Physics* 11 (2020): 369-395.

We Have Not Yet Reached a Fundamental Limit on T_1 and T_2 Values



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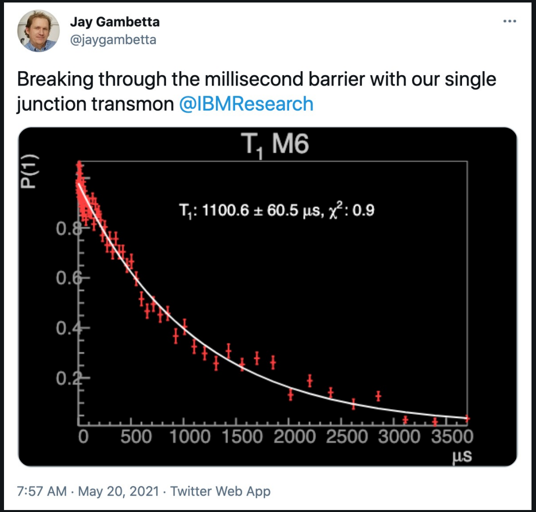

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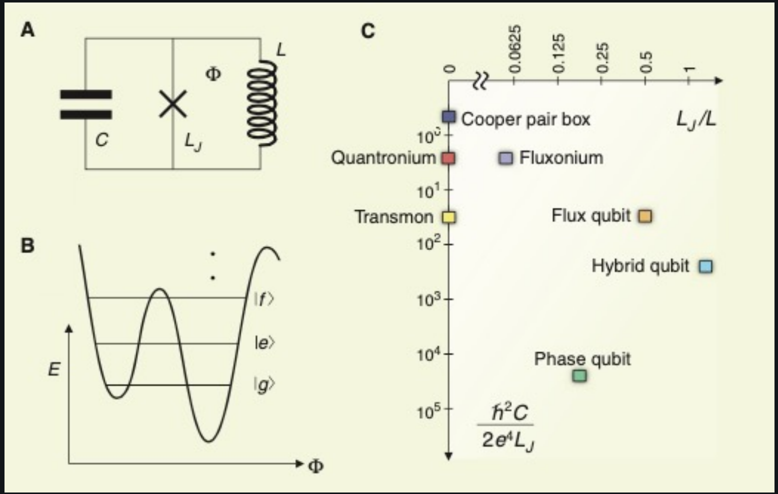

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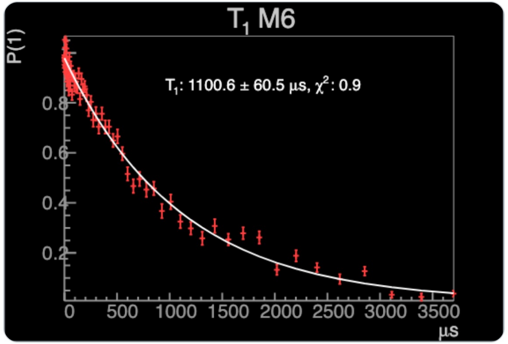
Jay Gambetta
@jaygambetta

Breaking through the millisecond barrier with our single junction transmon @IBMResearch



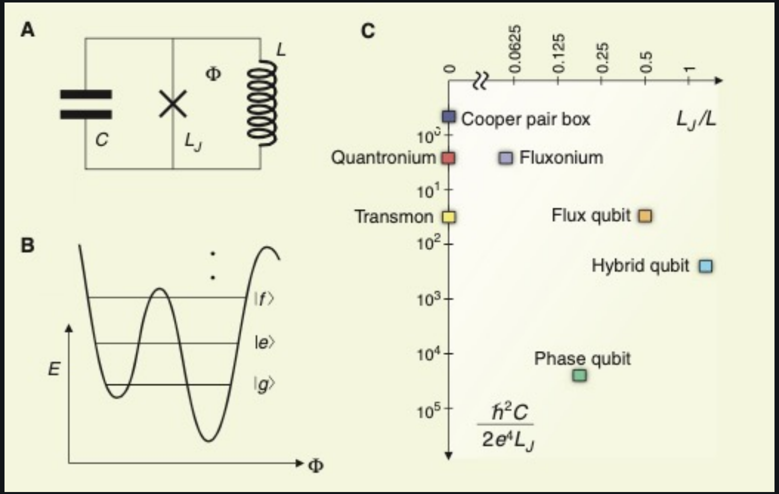
7:57 AM · May 20, 2021 · Twitter Web App

Blocking name out of consideration
Replying to @jaygambetta and @IBMResearch
What enabled this? Materials, filtering, geometry, voodoo?
1

Jay Gambetta @jaygambetta · May 20
all of the above.
1 10

T_1 and T_2 Are Not Constant – Fluctuations Cause Variations in Quantum Circuits

Qiskit



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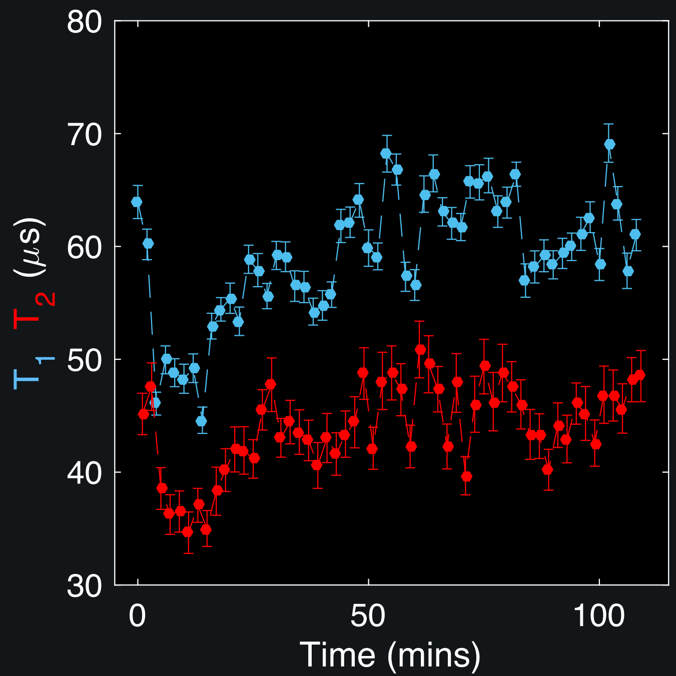

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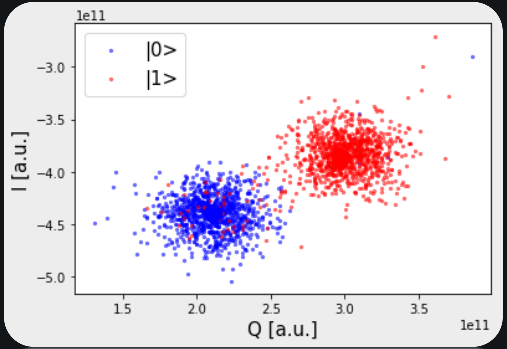
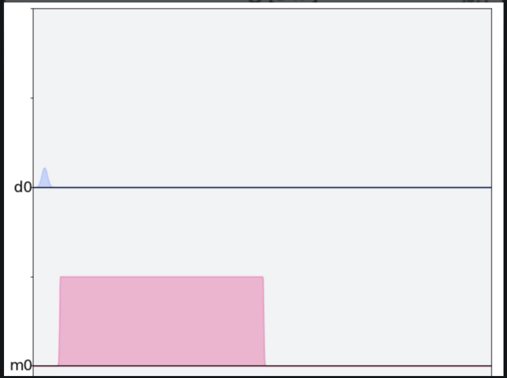
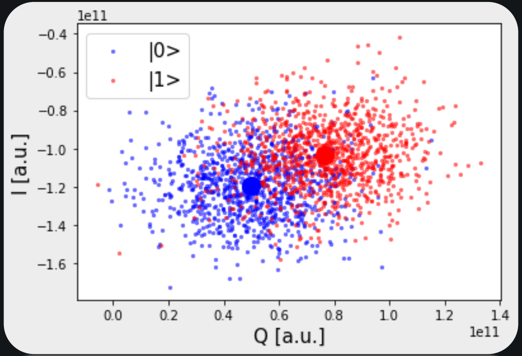
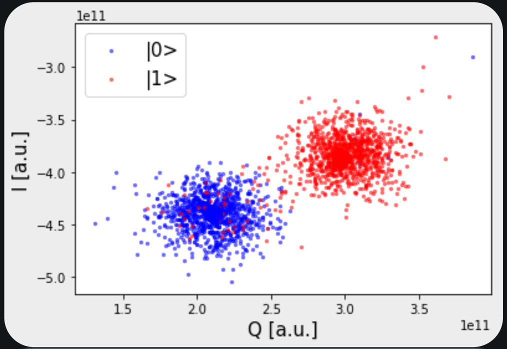
State Preparation and Measurement Errors

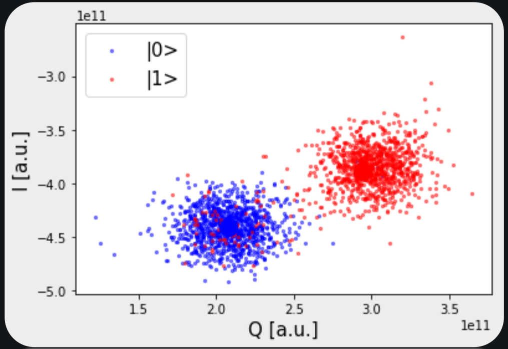


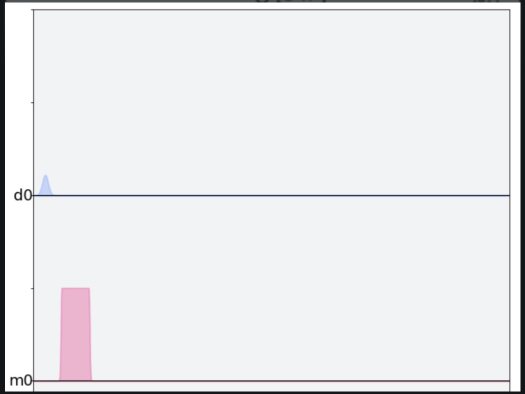


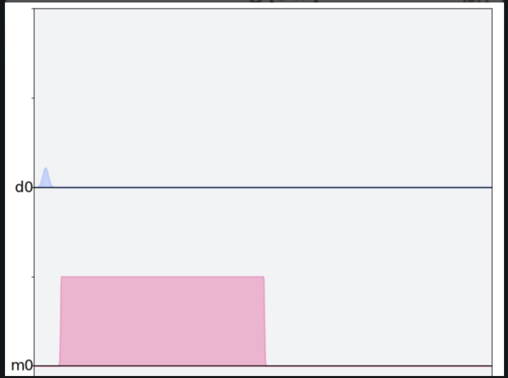
State Preparation and Measurement Errors

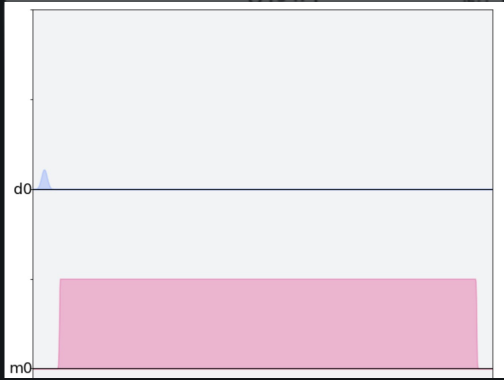












Readout Error mitigation techniques

Qiskit

Readout error mitigation: Correct for the probability to measure the wrong state

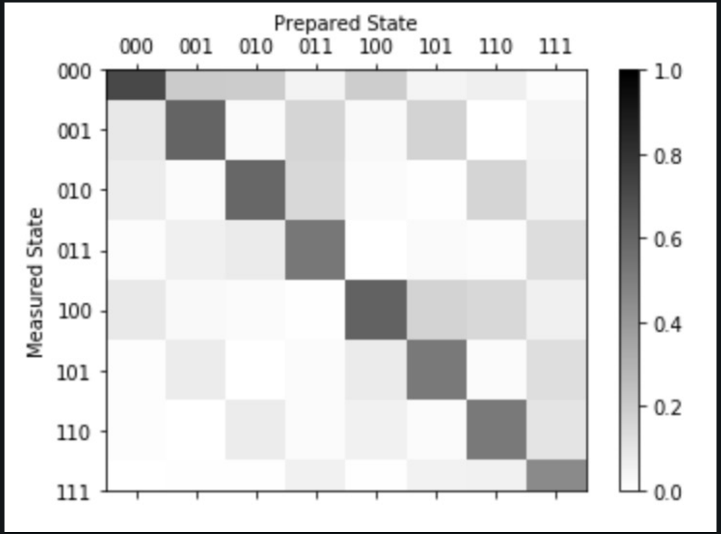
1. Prepare the 2^n states

For every prepared state:

2. Perform of m-shots

3. Find the probability to measure the expected state (diagonal elements) and the probability to measure any of the other $2^n - 1$ states (off diagonal elements)

4. Make the Calibration matrix

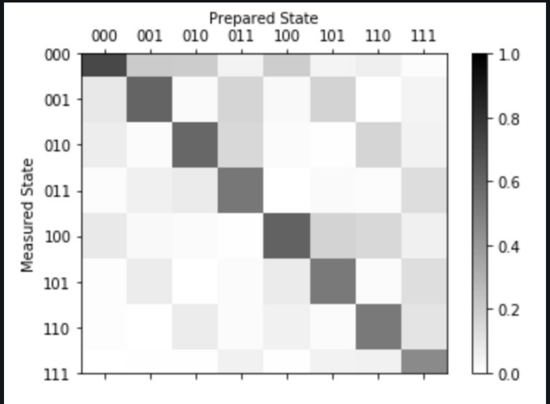


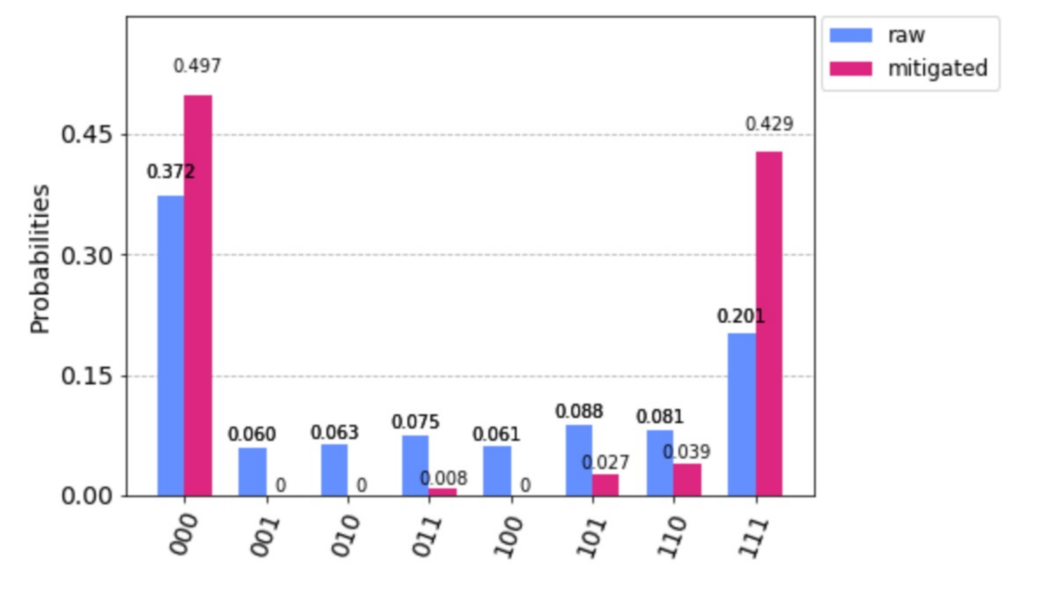
Calibration matrix for a 3 qubit system

Readout Error mitigation techniques

How does the readout error affect the measurement of a GHZ state?

5. Use the calibration matrix to post process any measurement output depending on the probabilities output





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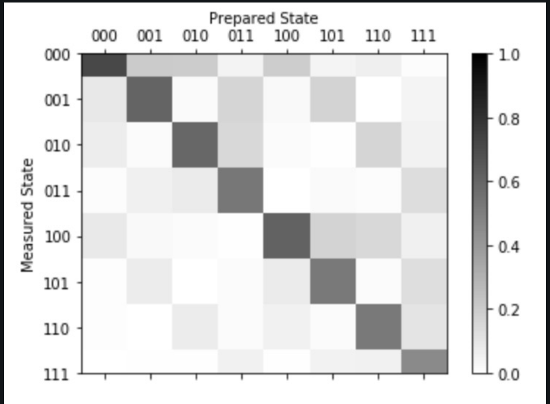

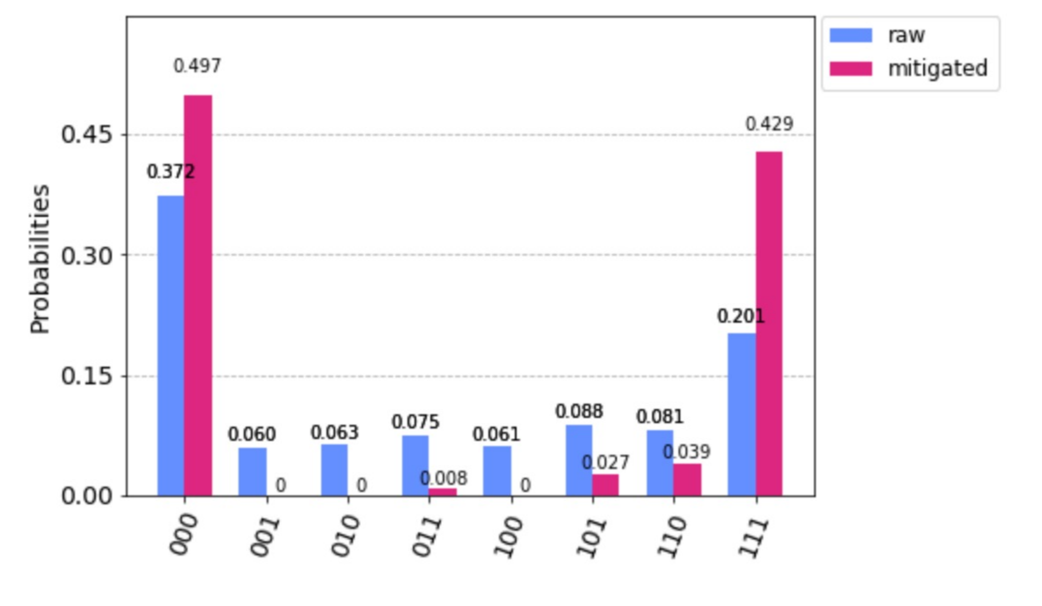

6. Beware of scaling. Taking subgroups of qubits helps

Typical Device Error Sources

1. T1/T2
2. Readout Errors
3. Gate Errors
4. Shots

Mitigation Strategies

1. Richardson Extrapolation
2. Methods:
   a. Excited State Promoted Readout
   b. A Matrix
3. Gate Design
4. Clever averaging techniques

Qubit and Coupling Design Impact Possible Native Gate sets

Qiskit

Table 1 State of the art high-fidelity two-qubit gates in superconducting qubits

Acronym[a]	Layout[b]	First demonstration [Year]	Highest fidelity [Year]	Gate time
CZ (ad.)	T–T	DiCarlo et al. (72) [2009]	99.4%† Barends et al. (3) [2014] 99.7%† Kjaergaard et al. (73) [2020]	40 ns 60 ns
$\sqrt{\text{iSWAP}}$	T–T	Neeley et al. (81)° [2010]	90%⋆ Dewes et al. (74) [2014]	31 ns
CR	F–F	Chow et al. (75) [2011]	99.1%† Sheldon et al. (5) [2016]	160 ns
$\sqrt{\text{bSWAP}}$	F–F	Poletto et al. (76) [2012]	86%⋆ ibid.	800 ns
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CZ (ad.)	T–(T)–T	Chen et al. (56) [2014]	99.0%† ibid.	30 ns
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Kjaergaard, M. et al "Superconducting qubits: Current state of play." *Annual Review of Condensed Matter Physics* 11 (2020): 369-395.

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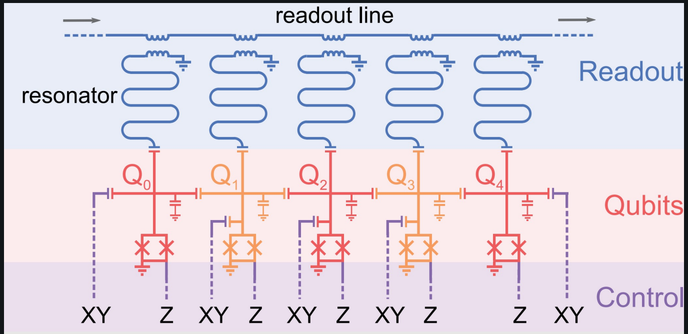

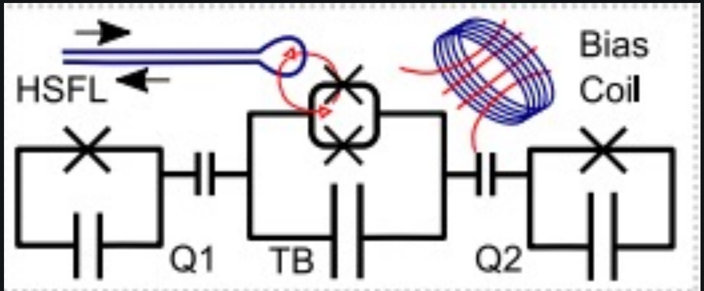

The Cross Resonance Gate is the 2Q gate used of IBM Quantum backends

Qiskit

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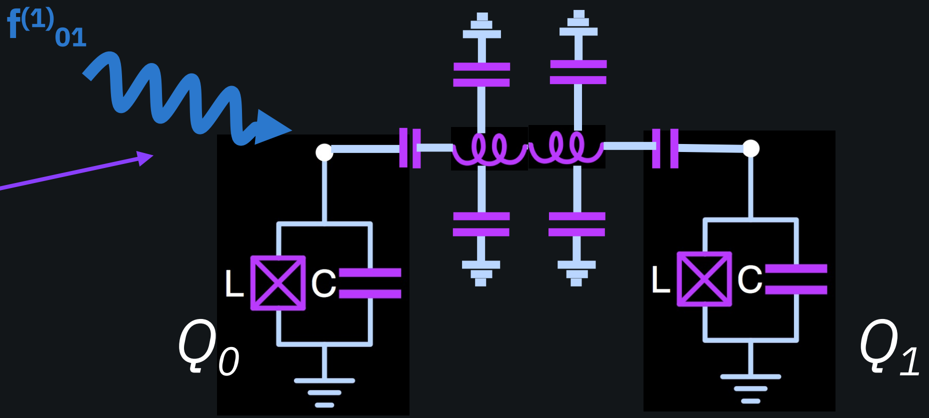
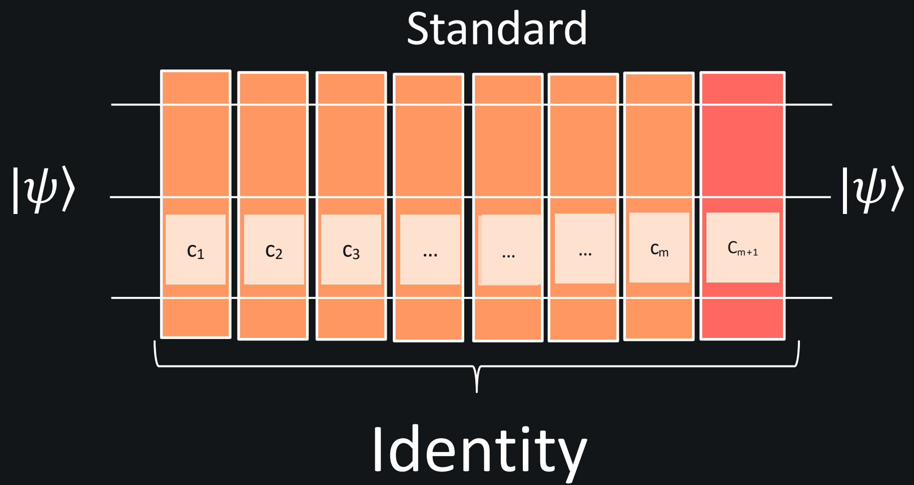


More Details in the Next Lecture

Gate Characterization – Randomized benchmarking



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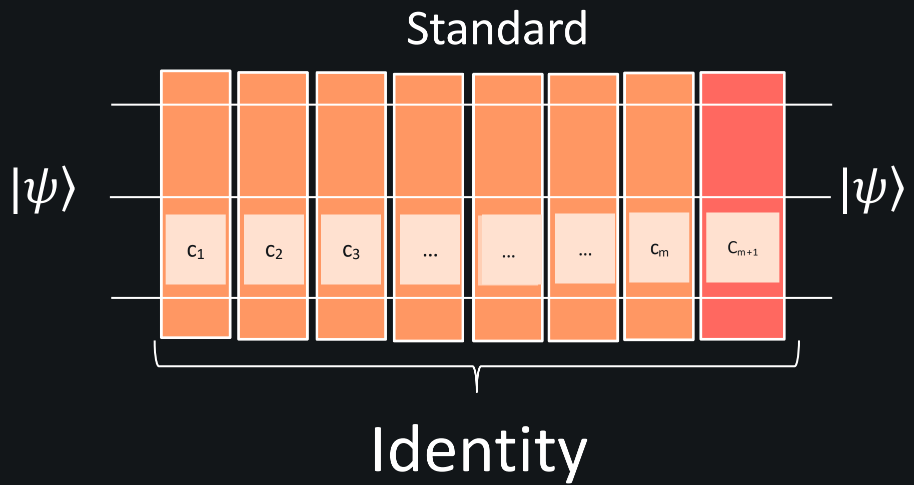

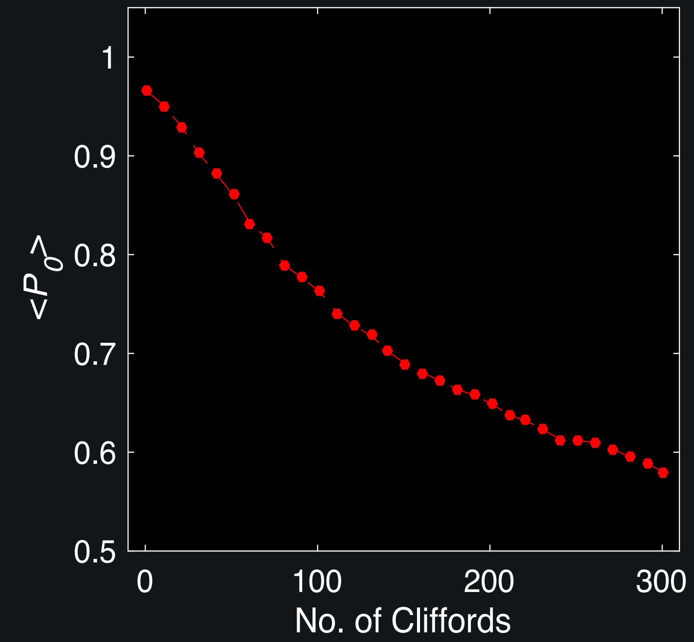

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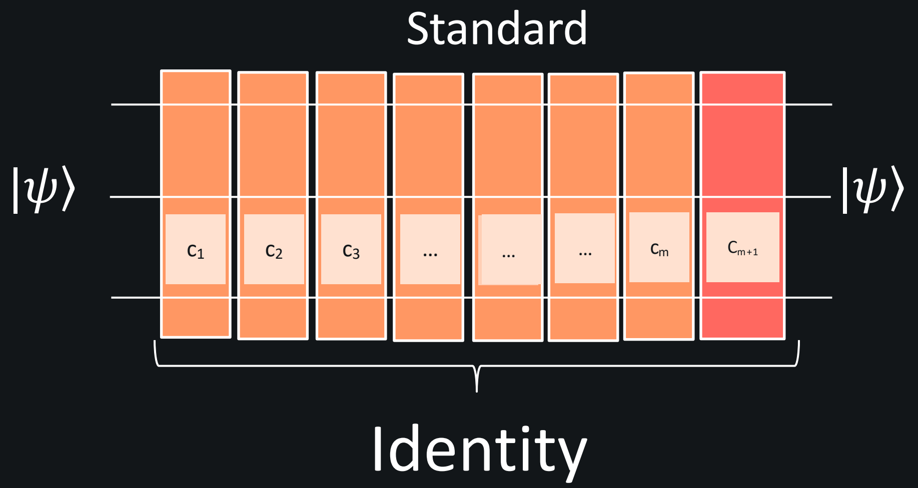
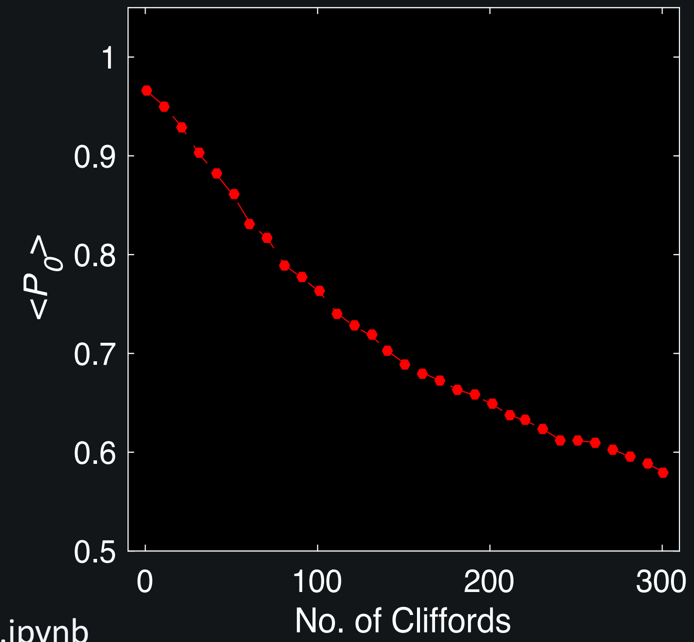
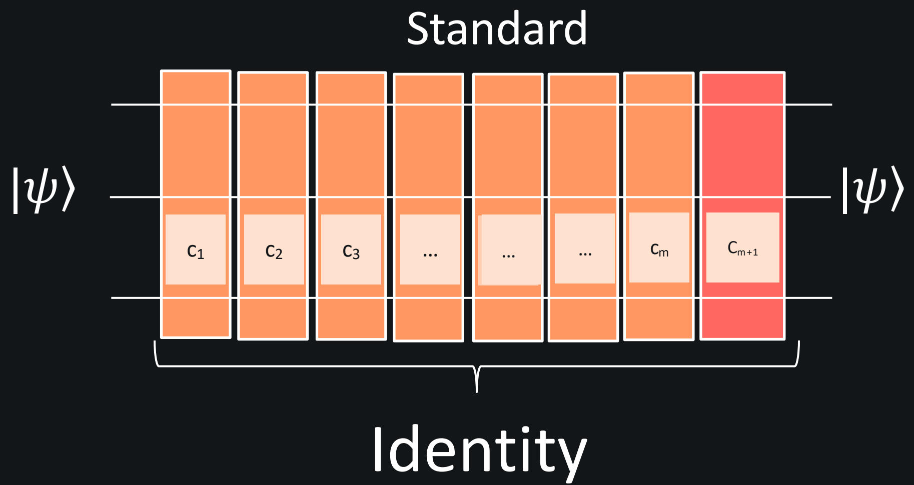




Qiskit Tutorial:

https://github.com/Qiskit/qiskit-tutorials/blob/master/tutorials/noise/4_randomized_benchmarking.ipynb

Gate Characterization – Randomized benchmarking



Different types of RB:

- Leakage RB
- Interleaved RB
- Many Others!

Qiskit Tutorial:

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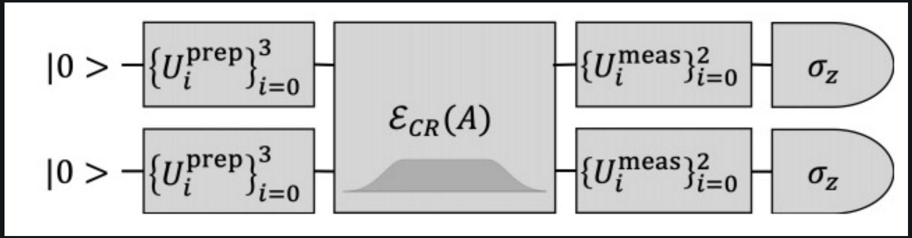
Circuit Characterization – Tomography

1. Quantum state tomography
   1. Given a state-preparation circuit that prepares a system in a state, reconstruct a description of the density matrix ρ of the actual state obtained in the system.

2. Quantum process tomography
   i. Given a circuit, reconstruct a description of the quantum channel $\mathcal{E}$ that describes the circuit's operator when running on the system.



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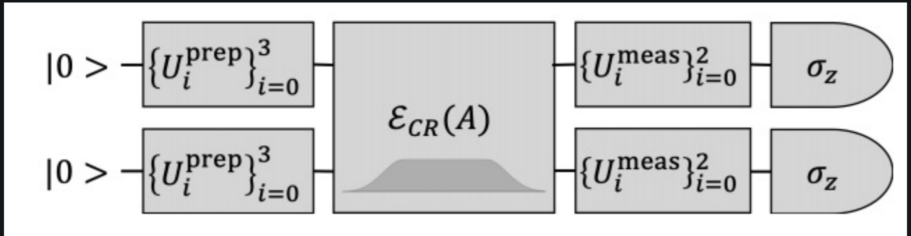

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1 Qubit Example:

Preparation States:

- $|0\rangle\langle 0|, |1\rangle\langle 1|, |+\rangle\langle +|, |-\rangle\langle -|$

Measurement Basis:

- $\sigma_X, \sigma_Y, \sigma_Z$

12 Circuits Needed

Circuit Characterization – Tomography

1. Quantum state tomography
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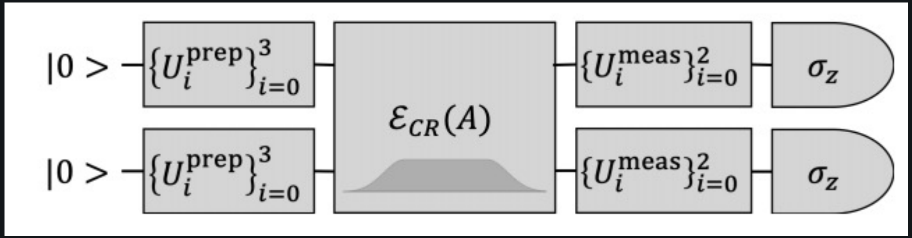

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$$Fidelity = \frac{Tr[S_U^{\dagger} S_{\mathcal{E}}]}{d^2}$$

Circuit Characterization – Tomography

Qiskit

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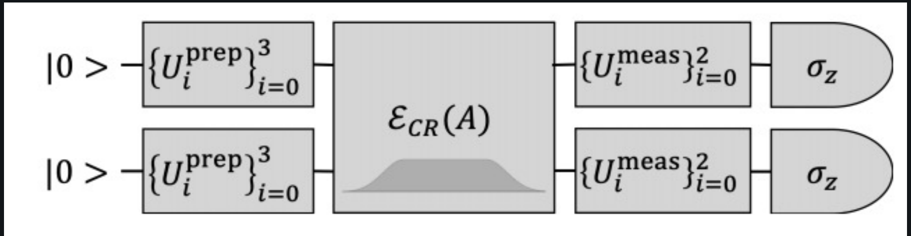

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Good Reference Papers:

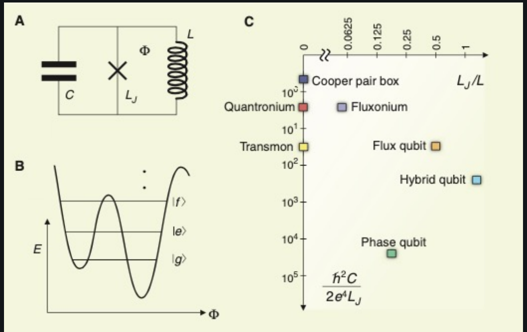
Alexander, T. et al. "Qiskit Pulse: Programming Quantum Computers Through the Cloud with Pulses." *arXiv preprint arXiv:2004.06755* (2020).

Chuang, Isaac L., and Michael A. Nielsen. "Prescription for experimental determination of the dynamics of a quantum black box." *Journal of Modern Optics* 44, no. 11-12 (1997): 2455-2467.

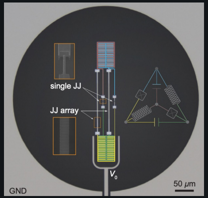
Thank you!

Qiskit

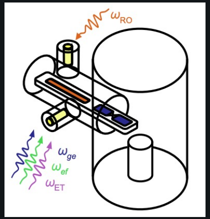
Different SC Qubit Architectures



Science 339, no. 6124 (2013): 1169-1174.

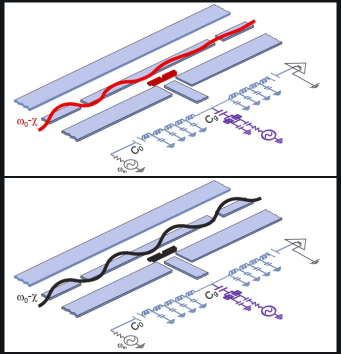


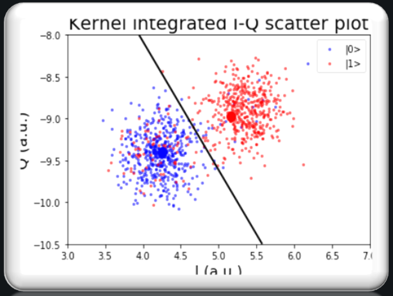
PRX Quantum 2, no. 1 (2021): 010339.



Nature Physics 16, no. 8 (2020): 822-826.

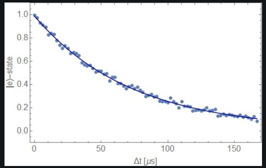
cQED and Qubit Readout



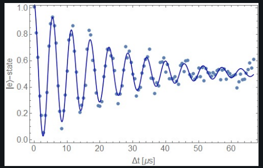


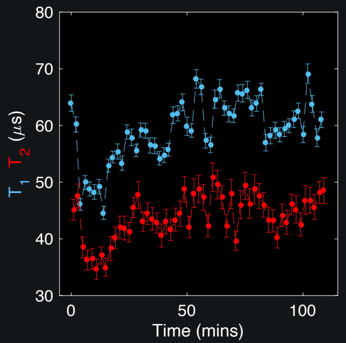
Common Errors and Some Error Mitigation Techniques

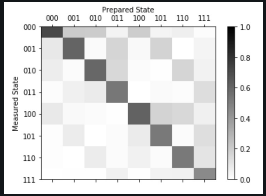
T_1



T_2







“A matrix” for readout errors