Introduction to Quantum Computing: From Algorithm to Hardware

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Multi-Physics And Circuit

SJSU SAN JOSÉ STATE UNIVERSITY

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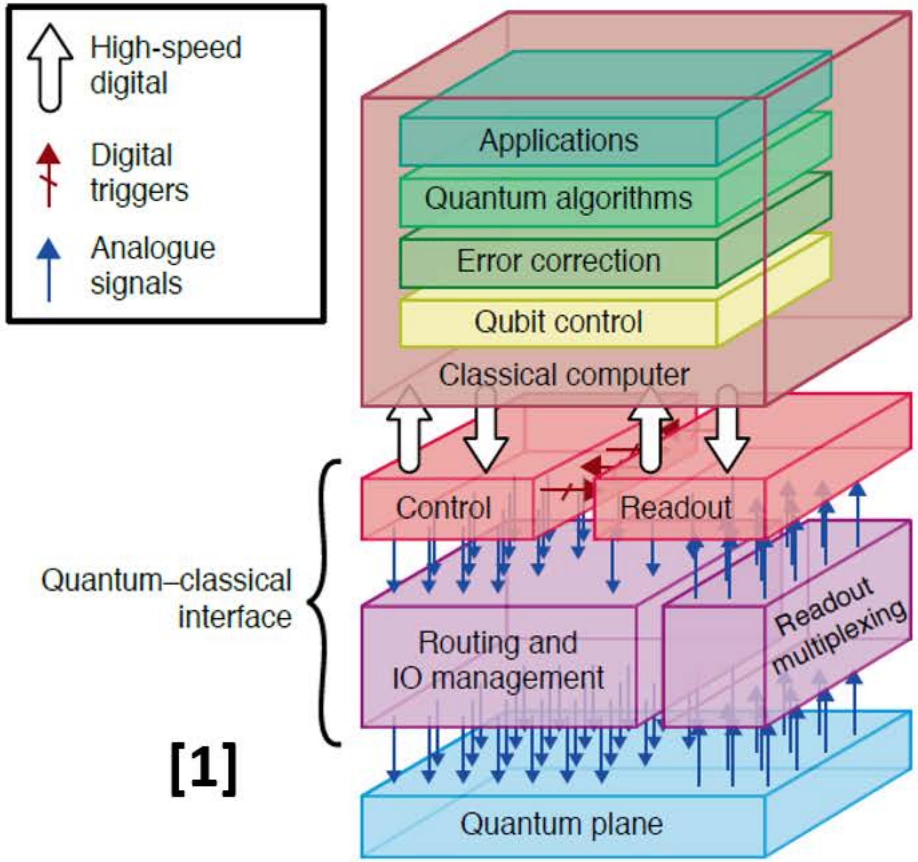
Quantum Computer Stack

By Dr. Imran Bashir



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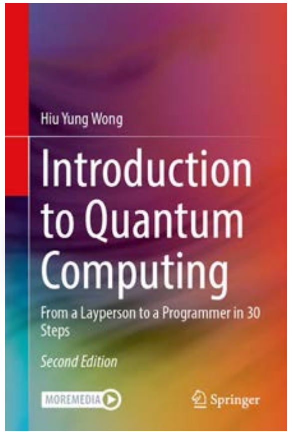
Innovations & Trends	This Workshop
Quantum + AI, Error Correction & Encoding, State Classifiers, Efficient Transpilers	Dr. Kundra, Dr. Kim, Dr. Spendier, Dr. Haidar
Low power & high fidelity qubit drive and read out architecture	This talk, Dr. Babie, Dr. Otten, Dr. Lee, Dr. Galicia, Castriotta
High density multiplexing at mK, 2.5D / 3D packaging	Dr. Schreckenberg, Dr. Das, Dr. Smith
Superconductor, semiconductor, photonics, trapped ions	Dr. Tennant, Dr. Zumbuhl, Dr. Baugh, Dr. Zalba, Dr. Tran, Dr. Steiner

Agenda

- Self-introduction
- Introduction to Quantum Computing
  - Basics and Algorithm
- Introduction to Quantum Computing
  - Hardware and Superconducting Qubit
- Conclusions

Resources

- Book: (**2nd Edition with 200+ questions and answers and links to teaching videos)**
  - **Introduction to Quantum Computing: From a Layperson to a Programmer in 30 Steps** | SpringerLink (https://link.springer.com/book/10.1007/978-3-030-98339-0) (Free if your school has a subscription, connect to VPN)
  - **Introduction to Quantum Computing: From a Layperson to a Programmer in 30 Steps**: Wong, Hiu Yung: 9783030983383: Amazon.com: Books (https://www.amazon.com/Introduction-Quantum-Computing-Layperson-Programmer/dp/3030983382)
- Videos (Youtube):
  - **Introduction to Quantum Computing From a Layperson to a Programmer in 30 Steps** – YouTube (https://www.youtube.com/playlist?list=PLnK6MrIqGXsJfcBdppW3CKJ858zR8P4eP)
  - **Quantum Computing Hardware and Architecture – YouTube** (https://www.youtube.com/playlist?list=PLnK6MrIqGXsL1KShnocSdwNSiKnBodpie)



Self-Introduction

- San Jose State University
- Quantum Technology Education
- “Introduction to Quantum Computing: from a Layperson to a Programmer in 30 Steps”

About San Jose State University

36,000 students
Minority Serving Institution (MSI)
Hispanic Serving Institution (HSI)
Electrical Engineering:
~300 master and ~500 undergraduate students

San Jose State tops Stanford and Cal for the most alums now working at Apple, according to LinkedIn's new education search utility.

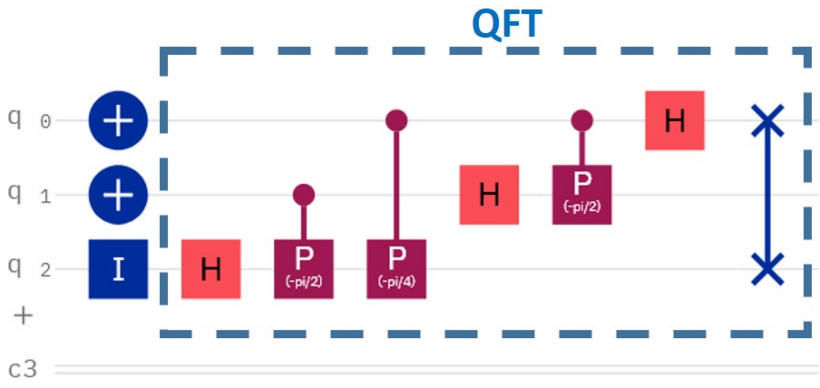
"Our top three are Cisco, Apple and Hewlett Packard," Newell said.

Jobvite, a recruiting platform, found Silicon Valley companies hire more San Jose State alums than any other college or university in the country.

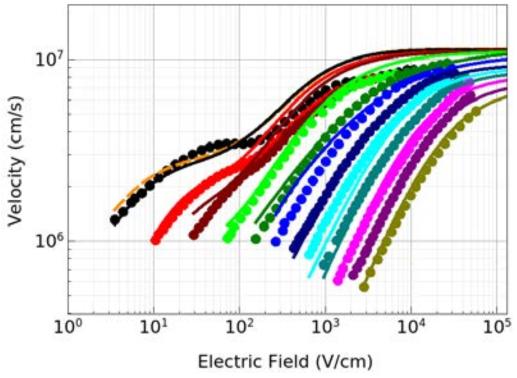
SJSU MSEE Specialization in
Quantum Information and Computing

- Electrical Engineering, Master of Science
  - EE225 Introduction to Quantum Computing (Every Fall)
  - EE226 Cryogenic Nanoelectronics (Spring 22, every 2 years)
  - EE274 Quantum Computing Architectures (Spring 23, every 2 years)

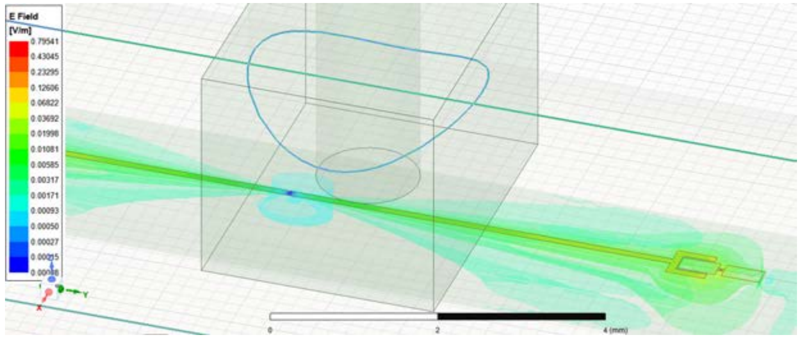
Python, Qiskit,



TCAD, Spectre



HFSS, Qiskit Metal



Quantum Technology, Master of Science

- MSQT@SJSU:
  - Started in 2023 Fall
  - Co-housed in Physics and EE
  - Core classes
    - Fundamentals of Quantum Information
    - Quantum Many-Body Physics
    - Quantum Computing Architectures
    - Quantum Programming
- NSF Research Traineeship Program (2125906)
  - Partner with Colorado School of Mines to develop *interdisciplinary* programs
  - Partner with LLNL and industry partners for hands-on experience
- To learn more: https://www.sjsu.edu/quantum/, Email: quantum@sjsu.edu

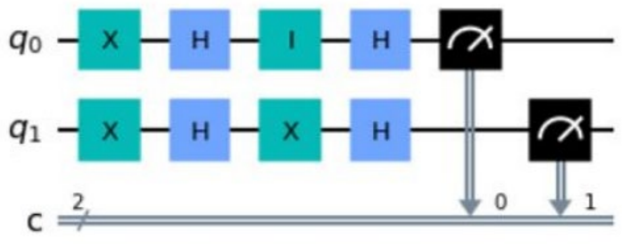
The degree promotes flexibility by offering a small set of core knowledge courses in quantum fundamentals along with a range of hardware and software focused electives ... partnerships with industry and national labs ... leveraging SJSU's unique position in Silicon Valley.

Introduction to Quantum Computing – Basics and Algorithm

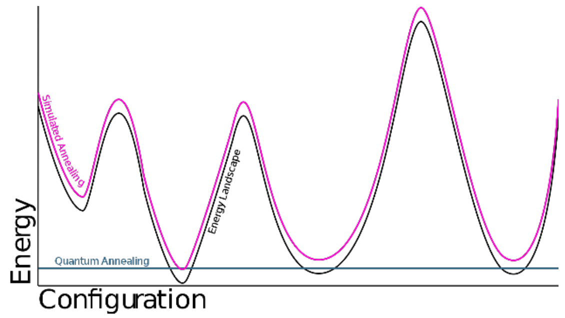
- State, Superposition, Measurement, Entanglement, Qubit Implementation, No-cloning Theorem, Error Correction, Caveats

Applications of Quantum Computing

- Quantum computing uses two quantum phenomena
  - Superposition and entanglement and, also, *interference*
- Two major types of quantum computing
  - Gate-based (this talk)
  - Quantum annealing (optimization by minimizing energy)
- Applications
  - Material (battery) and drug (pharma) design
  - Computational Fluid Dynamics
  - Secure communication
  - Quantum machine learning
  - Financial Services and Solutions (e.g. Black Swan Forecasting)



Gate Model



Quantum Annealing

State and Superposition

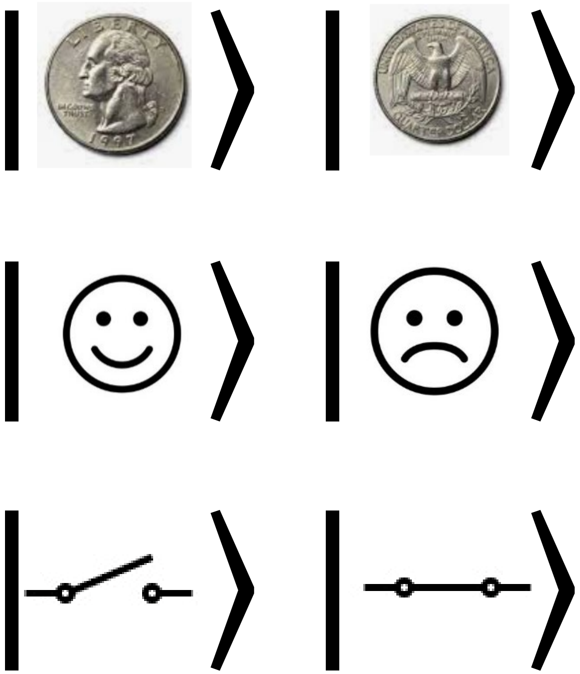
Classical Computing

$0 \qquad 1$

Information represented by the **states**

Quantum Computing (basis states)

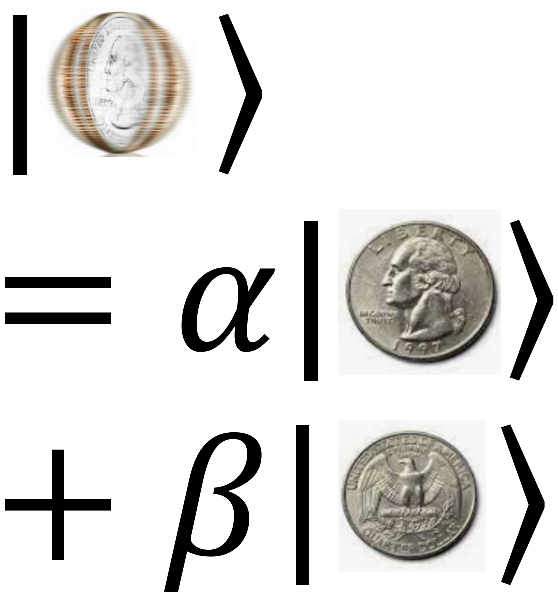
$|0\rangle \qquad |1\rangle$



No difference from classical computing

Quantum Computing with *superposition*

$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$



Quantum computing is powerful because it uses superposition

Quantum Registers

Value can be stored in a classical register	Basis states in a quantum register
$(0000)_2 = 0$	$\|0\rangle \otimes \|0\rangle \otimes \|0\rangle \otimes \|0\rangle = \|0\rangle\,\|0\rangle\,\|0\rangle\,\|0\rangle = \|0000\rangle = \|0\rangle_{10}$
$(0001)_2 = 1$	$\|0\rangle \otimes \|0\rangle \otimes \|0\rangle \otimes \|1\rangle = \|0\rangle\,\|0\rangle\,\|0\rangle\,\|1\rangle = \|0001\rangle = \|1\rangle_{10}$
$(0010)_2 = 2$	$\|0\rangle \otimes \|0\rangle \otimes \|1\rangle \otimes \|0\rangle = \|0\rangle\,\|0\rangle\,\|1\rangle\,\|0\rangle = \|0010\rangle = \|2\rangle_{10}$
$\vdots$	$\vdots$
$(1111)_2 = 15$	$\|1\rangle \otimes \|1\rangle \otimes \|1\rangle \otimes \|1\rangle = \|1\rangle\,\|1\rangle\,\|1\rangle\,\|1\rangle = \|1111\rangle = \|15\rangle_{10}$

Superposition of basis states of multiple qubits

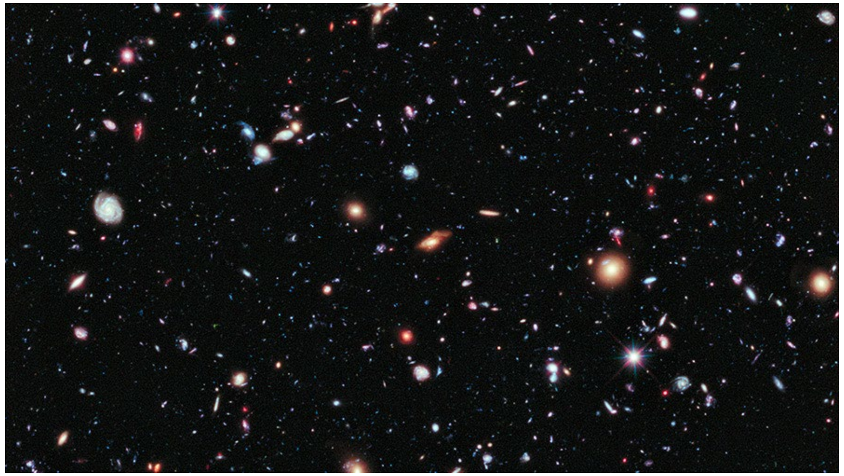
$$
\begin{aligned}
|\Psi\rangle &= a_0|00\cdots0\rangle + a_1|00\cdots1\rangle + \cdots + a_{2^n-1}|11\cdots1\rangle \\
&= a_0|0\rangle_{10} + a_1|1\rangle_{10} + \cdots + a_{2^n-1}|2^n-1\rangle_{10}
\end{aligned}
$$

The Power of Superposition

$$
\begin{aligned}
|\Psi\rangle &= a_0|00\cdots0\rangle + a_1|00\cdots1\rangle + \cdots + a_{2^n-1}|11\cdots1\rangle \\
&= a_0|0\rangle_{10} + a_1|1\rangle_{10} + \cdots + a_{2^n-1}|2^n-1\rangle_{10}
\end{aligned}
$$

n = 300 (e.g. electrons)
$2^{300} = 10^{90}$ complex coefficients, a_i

Number of atoms in the universe < 10^{82}

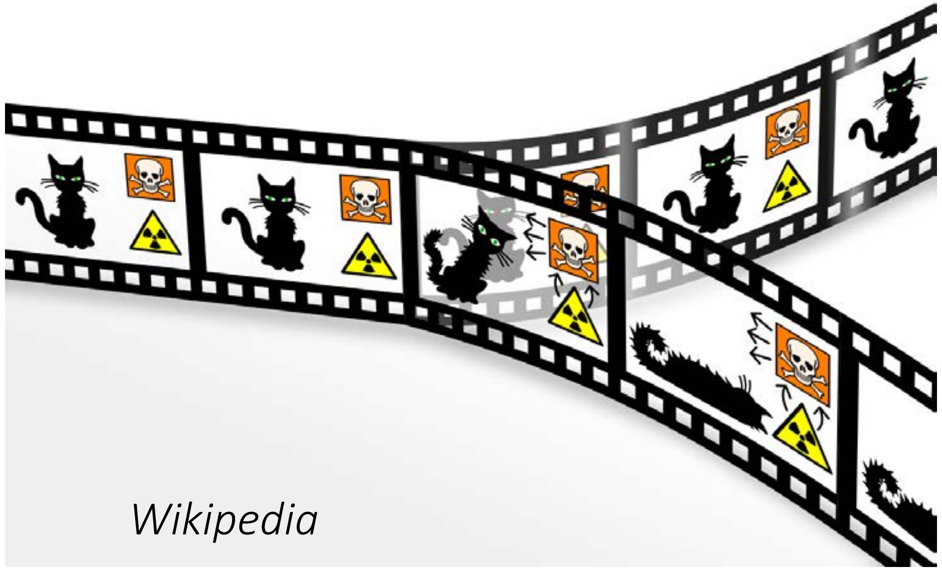


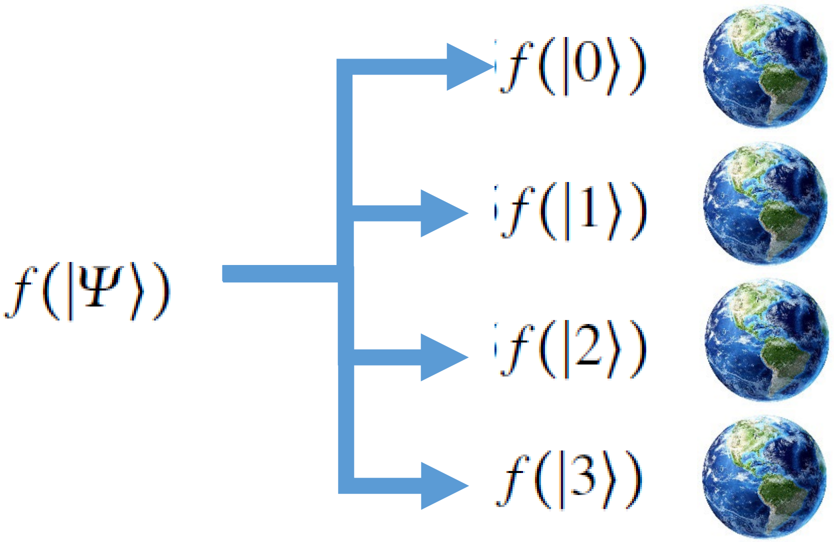
Total number of storage in the world < 10^{21} bytes

Quantum Parallelism

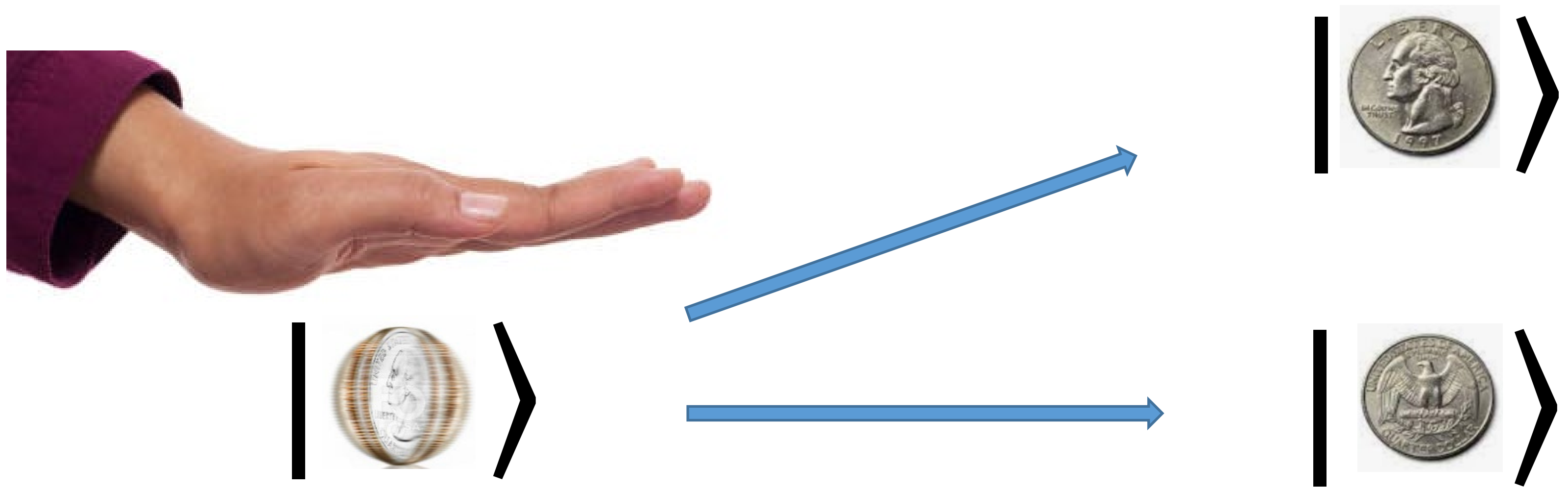
Linear Quantum mechanics

$$f(|\Psi\rangle) = f(0.5|0\rangle + 0.5|1\rangle + 0.5|2\rangle + 0.5|3\rangle)$$
$$= 0.5f(|0\rangle) + 0.5f(|1\rangle) + 0.5f(|2\rangle) + 0.5f(|3\rangle)$$

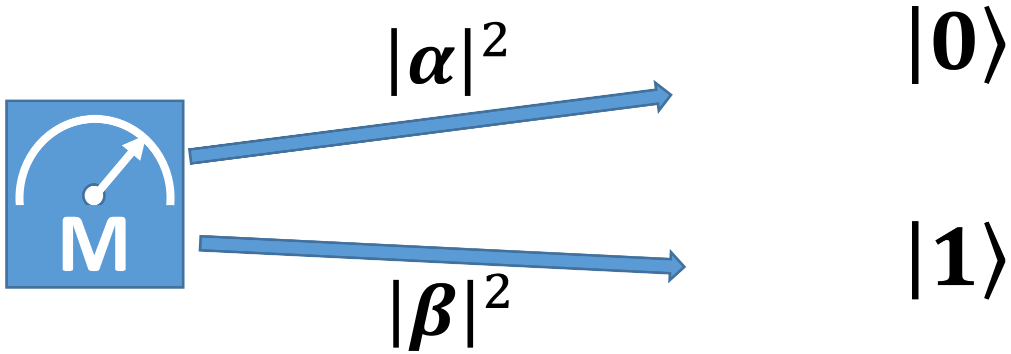

Wikipedia



Measurement



$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$



Entangled States

Unentangled State

$$\frac{1}{2}(|00\rangle - |01\rangle + |10\rangle - |11\rangle) = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \otimes \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

Electron 1 Electron 2

Entangled State: Used in quantum computing algorithms and also quantum communications

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \neq |Electron\ 1\rangle \otimes |Electron\ 2\rangle$$

Quantum Entanglement – Spooky Action

Step 1

e¹ e²

$$\Phi^+ = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle)$$

Step 2

e¹ Earth

$$\Phi^+ = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle)$$

still entangled

100 light years away e²

Step 3 measure e^1: 50% to get $|\uparrow\rangle$, assume obtained $|\uparrow\rangle$ for e^1

$$\Phi^+ \xrightarrow{\text{collapse}} |\uparrow\uparrow\rangle$$

e¹ $|\uparrow\rangle$ Earth

100 light years away $|\uparrow\rangle$ e²

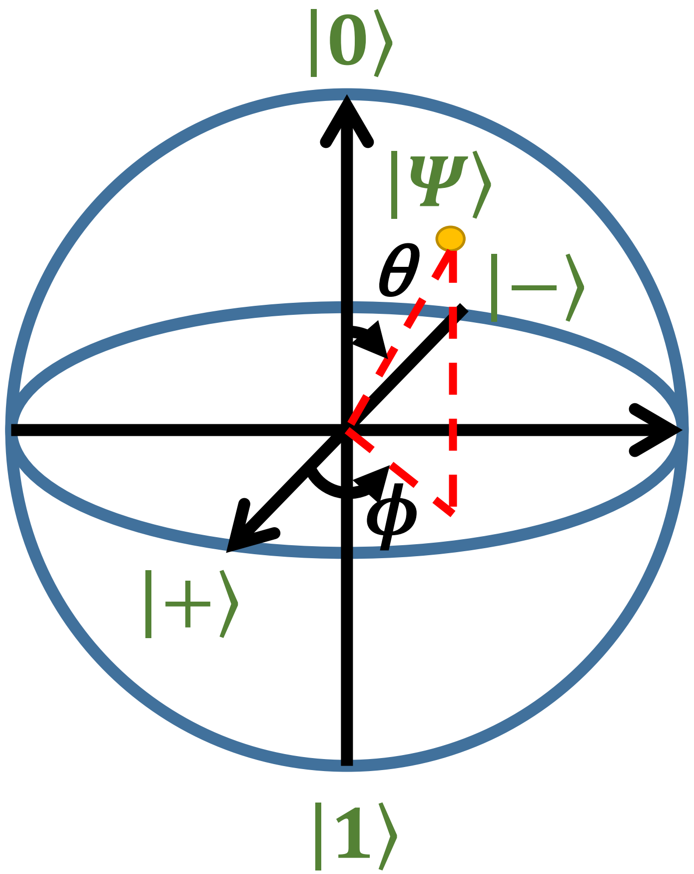
Quantum Gates

- Quantum gates rotate the vector (state) in the corresponding hyperspace
- *Very often, a gate is just a laser or microwave pulse*
- Some gates have classical counterparts
  - NOT (X) gate (1-qubit)
  - XOR (CNOT) gate (2-qubit) $\boldsymbol{U_{XOR}}|a,b\rangle = |a, a\oplus b\rangle$
- Some gates have no classical counterparts
  - Hadamard gate (for *Superposition*)

$$\boldsymbol{H}\,|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

$$\boldsymbol{H}\,|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

Bloch Sphere



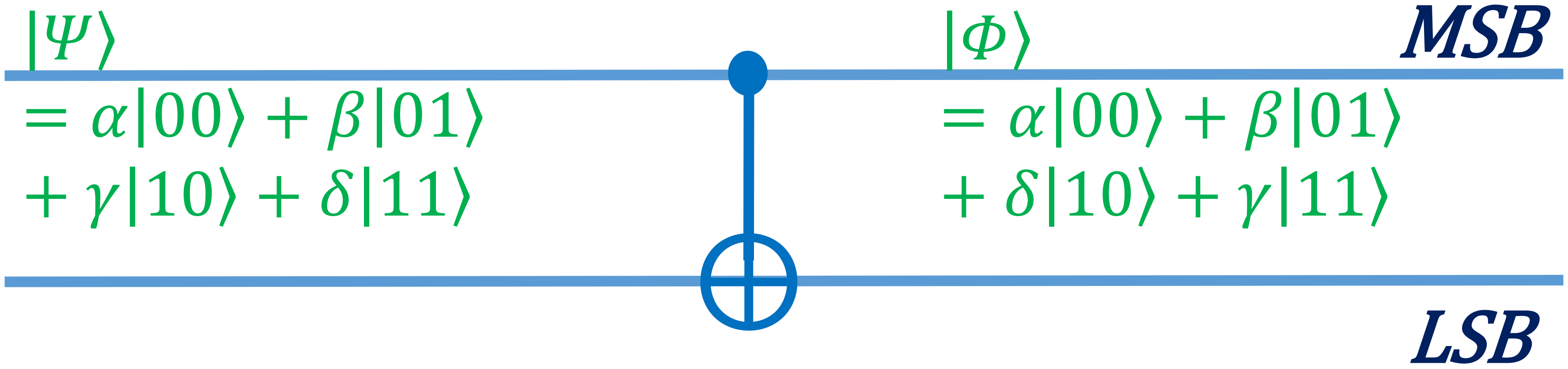
We embed the hyperspace of a qubit in our real 3D space

CNOT (XOR) Gate for Entanglement

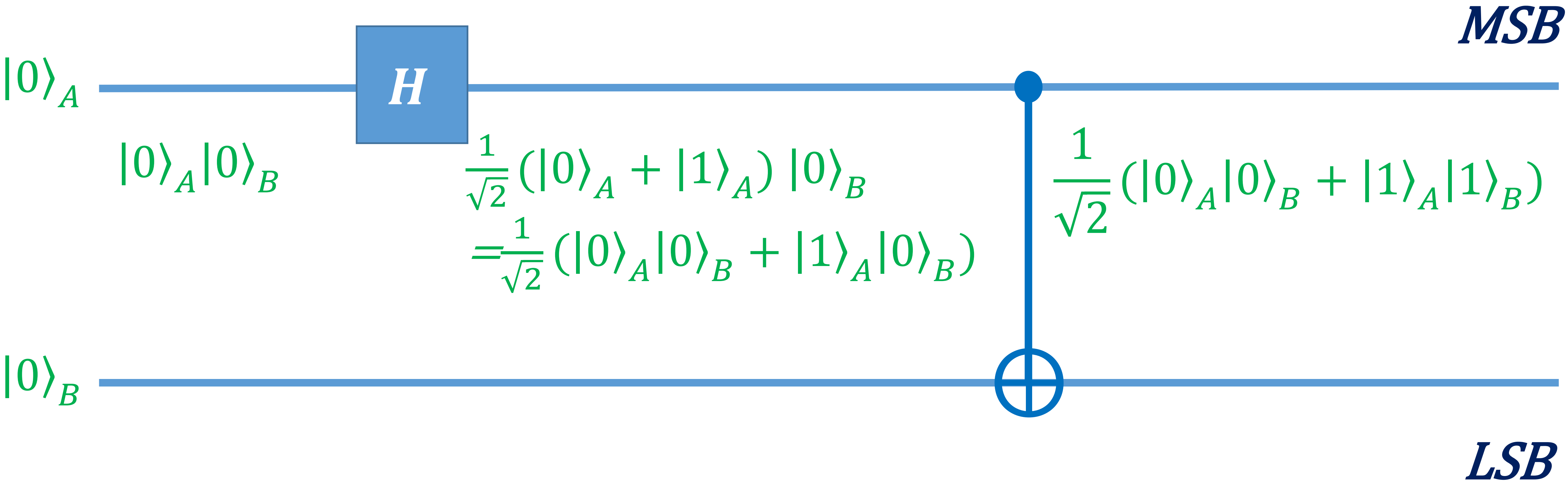
$$U_{XOR}|a,b\rangle = |a, a \oplus b\rangle$$

$$U_{XOR}|00\rangle = |0, 0 \oplus 0\rangle = |0, 0\rangle = |00\rangle$$
$$U_{XOR}|01\rangle = |0, 0 \oplus 1\rangle = |0, 1\rangle = |01\rangle$$
$$U_{XOR}|10\rangle = |1, 1 \oplus 0\rangle = |1, 1\rangle = |11\rangle$$
$$U_{XOR}|11\rangle = |1, 1 \oplus 1\rangle = |1, 1\rangle = |10\rangle$$

Control Qubit Target Qubit



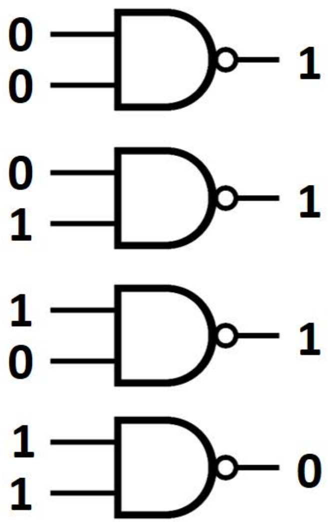
Entanglement Example



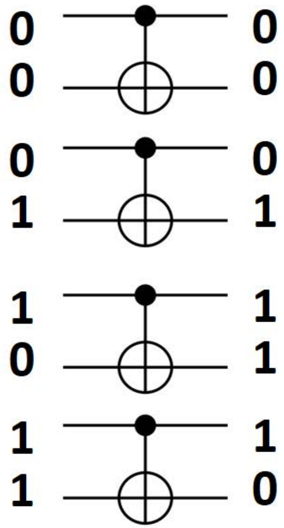
Quantum Gates and Circuits

Quantum gates must be reversible

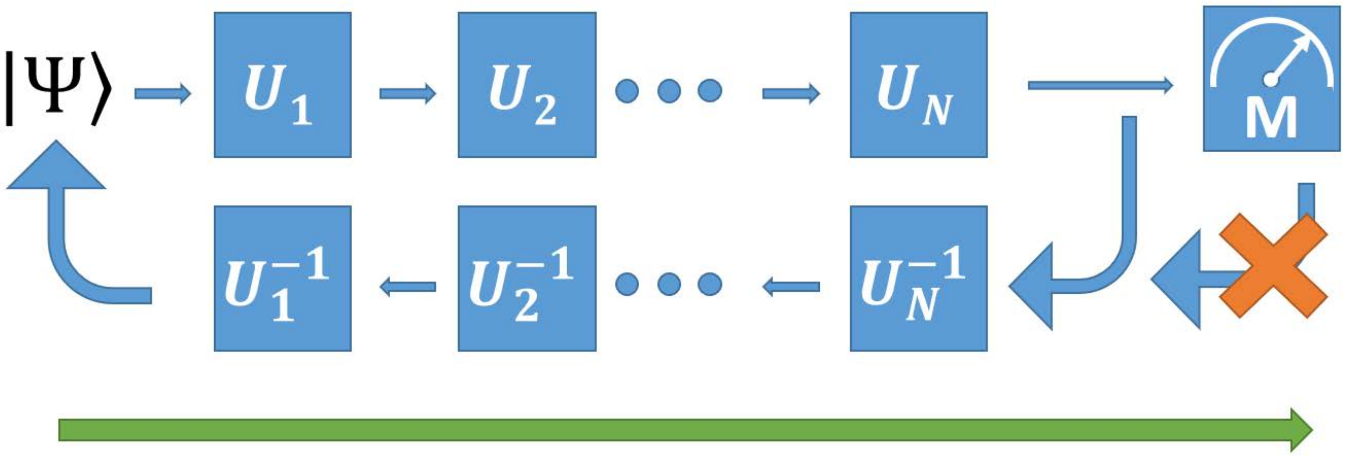
Quantum circuit is the application of operations (microwave/laser pulses) to usually stationary qubit carriers.



NAND Gate



CNOT Gate



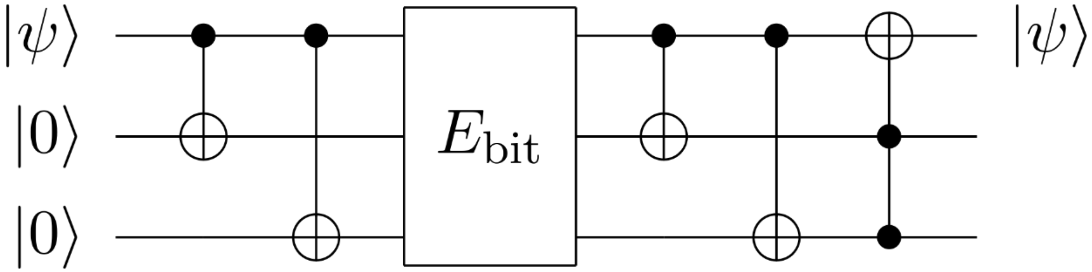
Error Correction

- **No-Cloning Theorem**: It is not allowed to copy an arbitrary state in quantum mechanics
- Syndrome measurement is used for error correction

Classical Error Correction

$$0 \Rightarrow 000$$
$$1 \Rightarrow 111$$

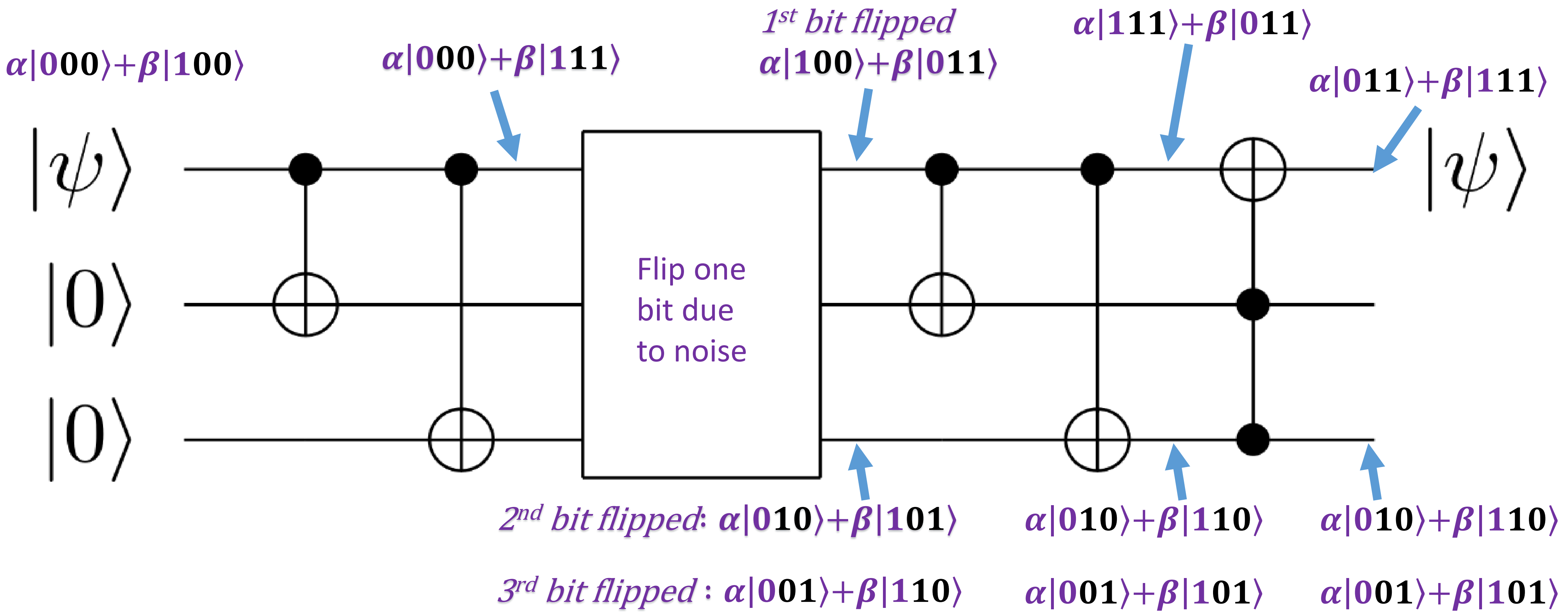
Quantum Error Correction



E.g. Through entanglement and syndrome measurement

Error Correction: Bit Flip Code Example

Qubit to transmit: $|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$



Introduction to Quantum Computing – Hardware and Superconducting Qubit

- Overview
- Reading
- Manipulations (Single Qubit and Multiple Qubits)

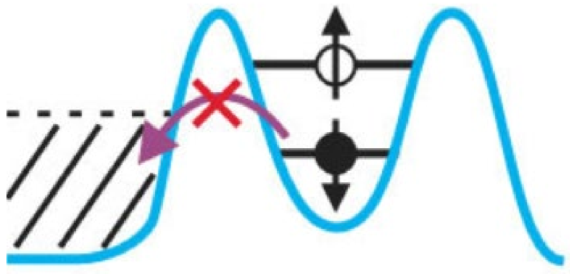
DiVincenzo’s Criteria

- 5 Necessary Criteria for quantum computing:
    - A scalable physical system with well characterized qubit (**system needs to remain in the subspace of 2 level**)
    - The ability to initialize the state of the qubits to a simple fiducial state (**initialization time is important**)
    - Long relevant decoherence times (**much longer than gate time)**
    - A "universal" set of quantum gates (1 qubit gates + entanglement gate)
    - A qubit-specific measurement capability (**Some algorithms only works without measuring all qubits at the same time e.g. teleportation)**
- 2 Necessary Criteria for quantum communication:
    - The ability to interconvert stationary and flying qubits (**even one bit stationary and one bit flying**)
    - The ability to faithfully transmit flying qubits between specified locations (**without decoherence**)

Implementations of Qubits

$|Mood\rangle = \alpha|☺\rangle + \beta|☹\rangle$ Not a reliable qubit

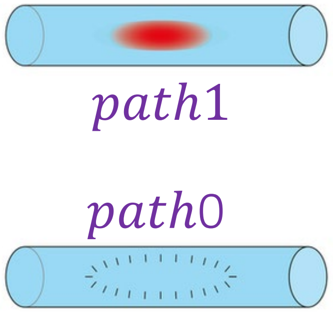
Electron Spin Qubit



$|\nearrow\rangle = \alpha|\downarrow\rangle + \beta|\uparrow\rangle$

Physics Today ***72***, 8, 38 (2019)

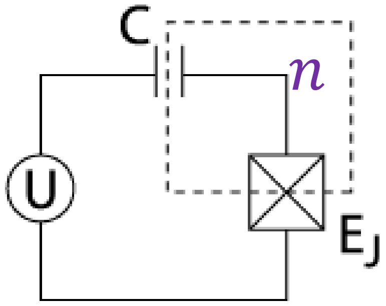
Photonic Qubit



$|\psi\rangle = \alpha|path0\rangle + \beta|path1\rangle$

Scientific Reports ***3***, 1394 (2013)

Superconducting Charge Qubit

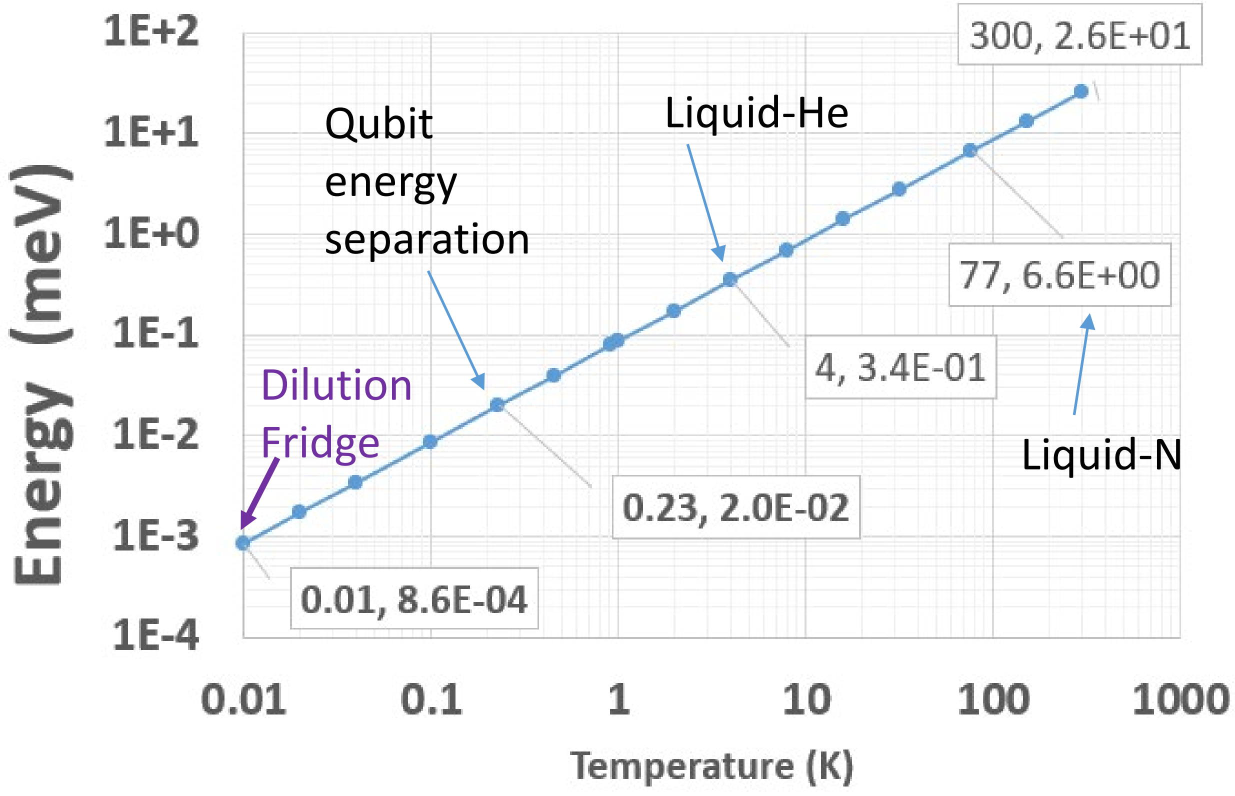


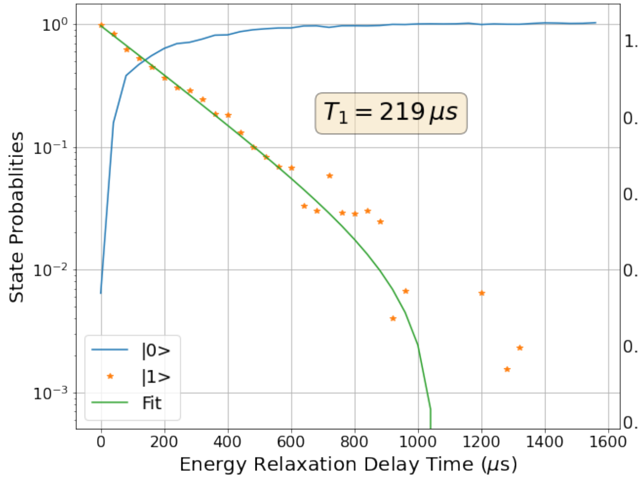
$|\psi\rangle = \alpha|n = 0\rangle + \beta|n = 1\rangle$

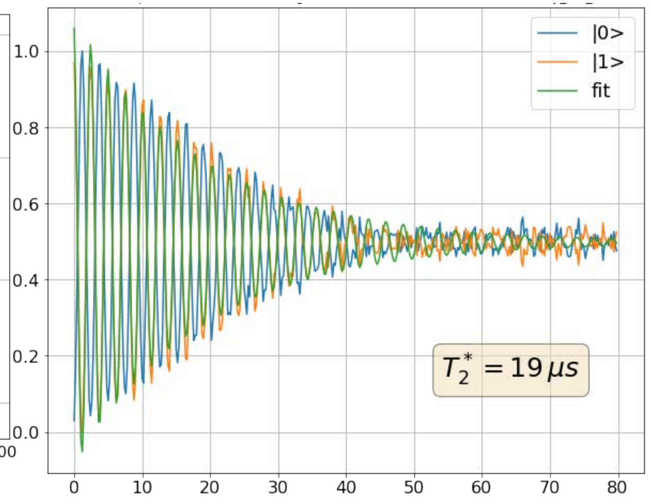
Wikipedia

Noise, De-coherence Time and Energy Scale

- Qubit loses its state due to noise
- Need ultra-low temperature to avoid thermal noise (DR, laser cooling)
- Decoherence time:
  - $T_1 : |1\rangle \Rightarrow |0\rangle$
  - $T_2 : |0\rangle + |1\rangle \Rightarrow ?\ |0\rangle ?\ |1\rangle$

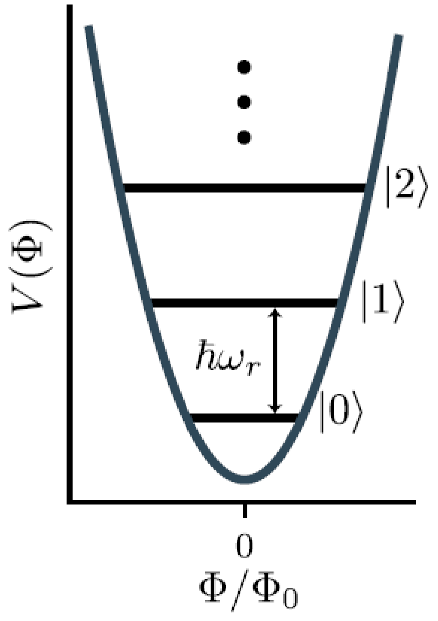


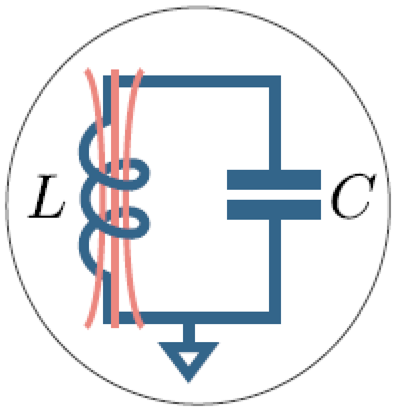




Why not LC Tank?

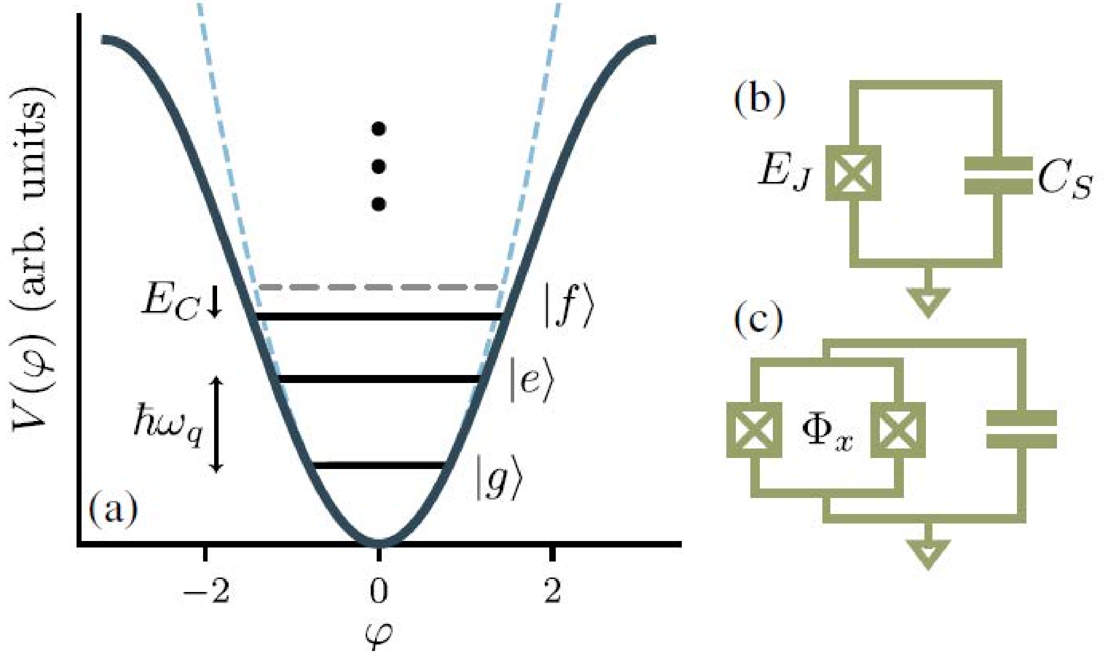
Blais et al, Review of Modern Physics (2021)





$$H_{LC} = \frac{Q^2}{2C} + \frac{1}{2}C\omega_r^2\Phi^2$$ Lack of anharmonicity

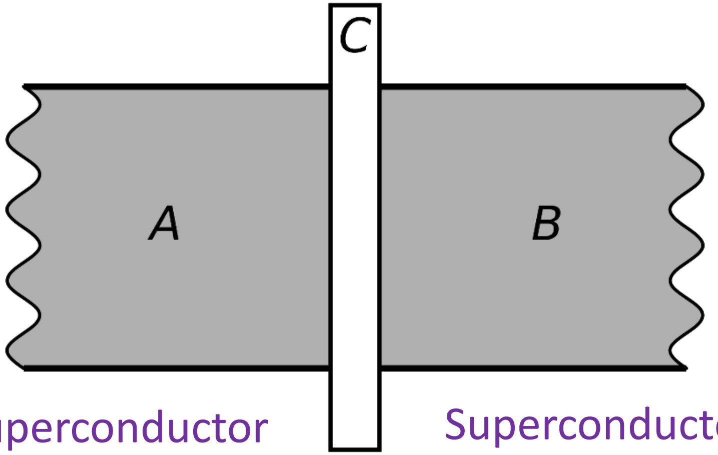
Generalized momentum: Q
Generalized Coordinate: Φ



- Charge qubit
- Transmon qubit when $E_C << E_J$ (less sensitive to charge noise, $\boldsymbol{n_g}$)

Josephson Junction

Wiki



Superconductor
Al

Insulator
(Al_2O_3)

Superconductor
Al

Josephson Equations

$$I(t) = I_c \sin(\varphi(t))$$

$$\frac{\partial \varphi}{\partial t} = \frac{2eV(t)}{\hbar}$$

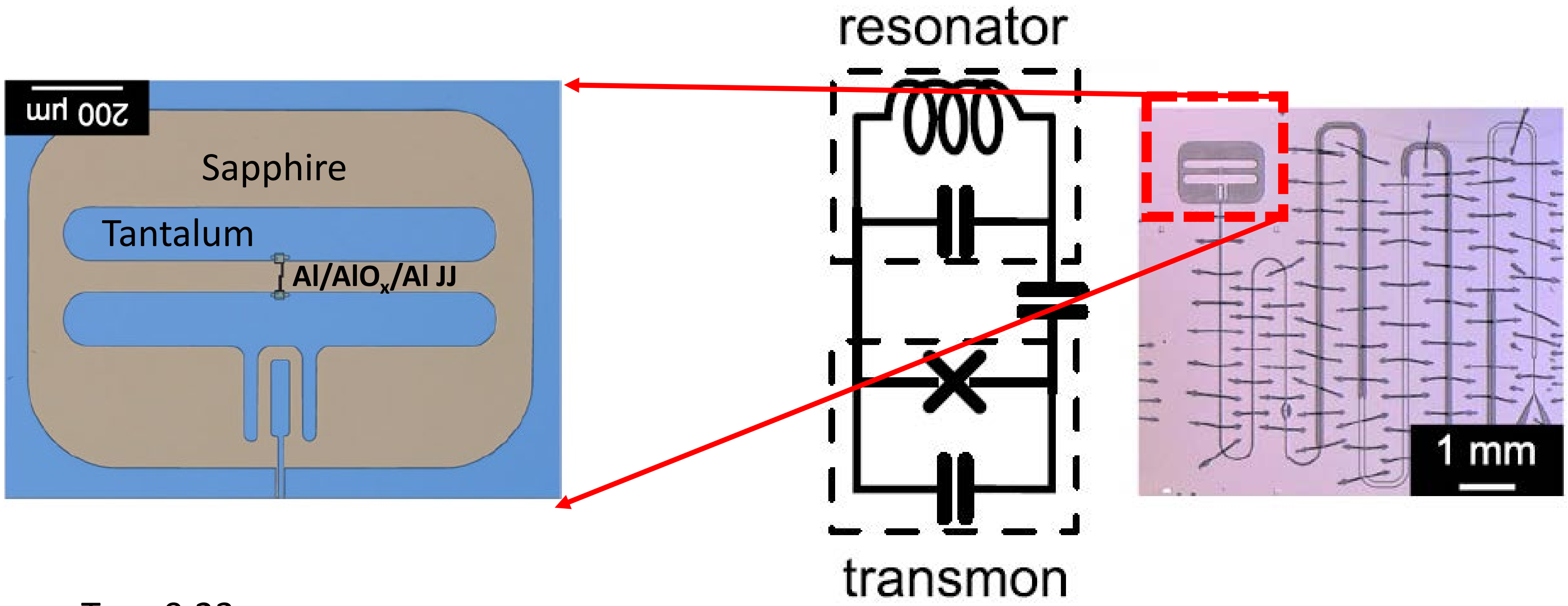
Nonlinear Inductance

$$L(\varphi) = \frac{\Phi_0}{2\pi I_c \cos\varphi} = \frac{L_J}{\cos\varphi}.$$

Josephson Energy

$$E(\varphi) = -\frac{\Phi_0 I_c}{2\pi}\cos\varphi = -E_J \cos\varphi.$$

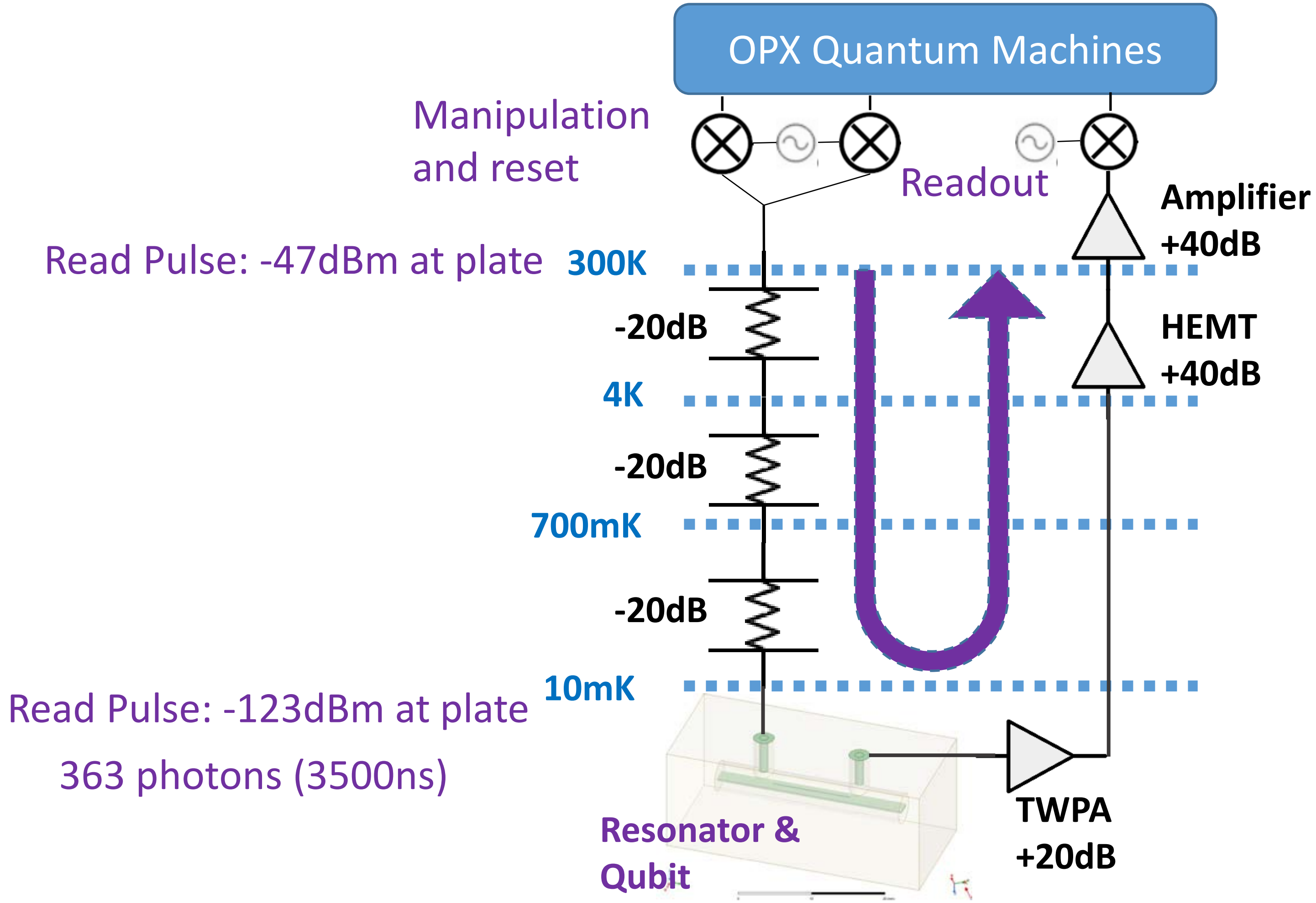
Transmon Qubit – Tantalum based



T_1 = 0.23ms

A. Place, et al., Nat. Comm 12, 1779 (2021)

A Superconducting Quantum Computer

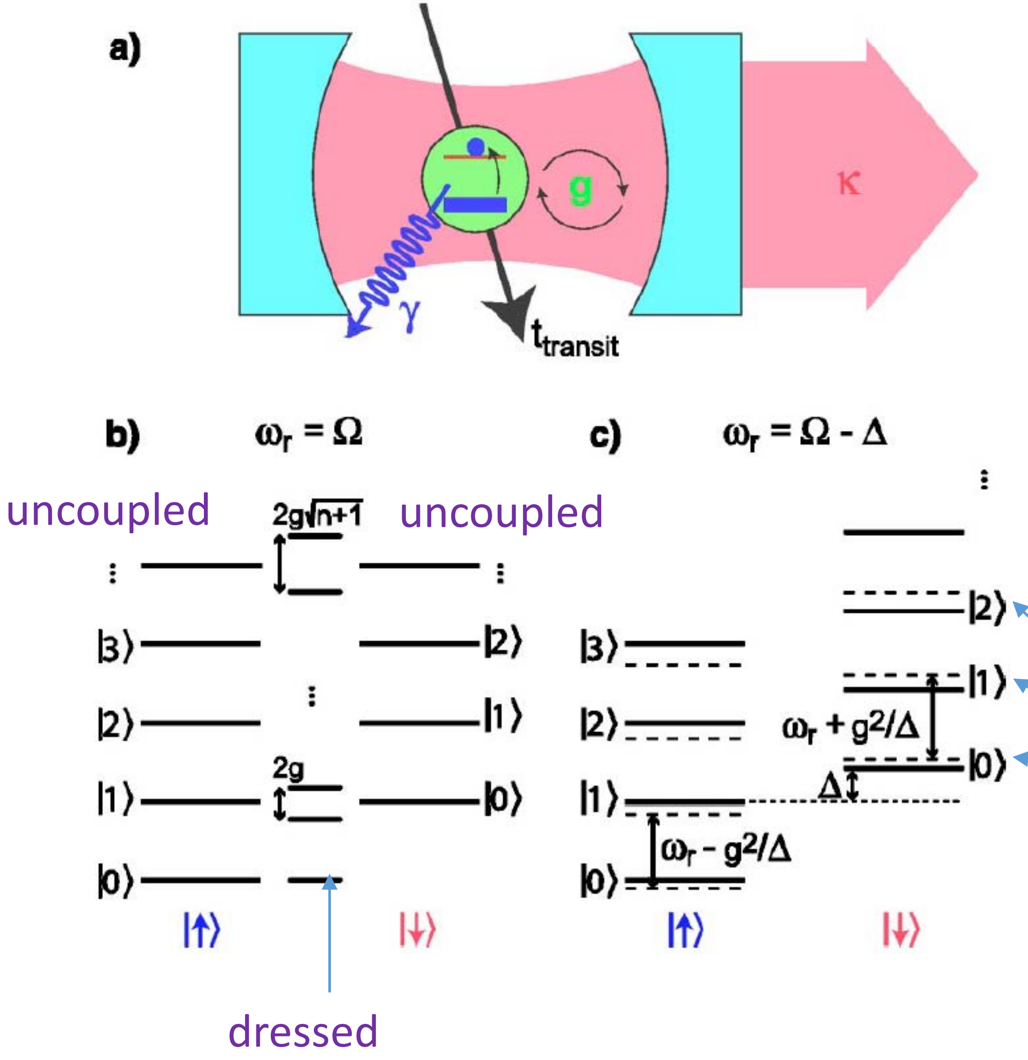


- Readout quality depends on
  - Readout Pulse Width (t_p)
  - Readout Pulse Energy (E_p)
  - Resonator quality factor
  - Noise

Hiu Yung Wong et al., "A Simulation Methodology for Superconducting Qubit Readout Fidelity," SSE, 2023.

Cavity QED

$$H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\Omega}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + \sigma^+ a) + H_\kappa + H_\gamma.$$

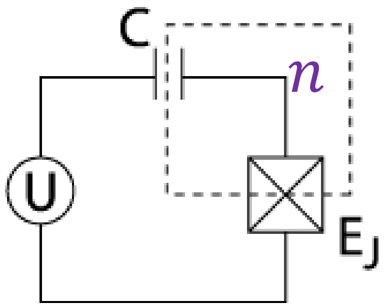


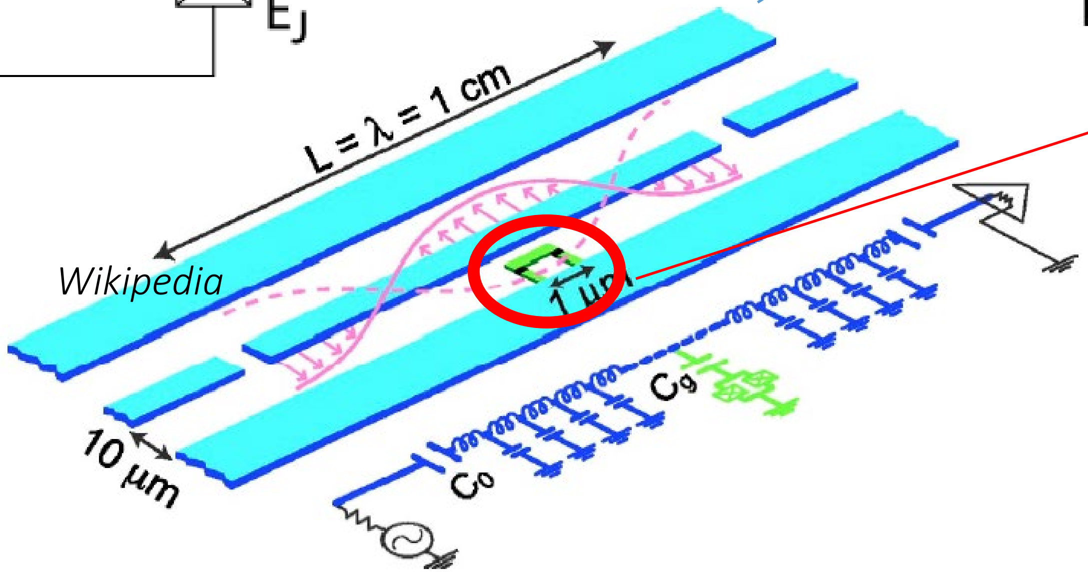
- ω_r: Cavity resonant frequency
- Ω: Atom transition frequency
- g: atom-photon coupling strength
- Δ: detuning (Ω-ω_r) – Different energy between |↑0⟩/ |↑1⟩ and |↓0⟩/ |↓1⟩ transitions

Each by $(n+1)\frac{g^2}{\Delta}$

(Blais et al, PHYSICAL REVIEW A 69, 062320 (2004))

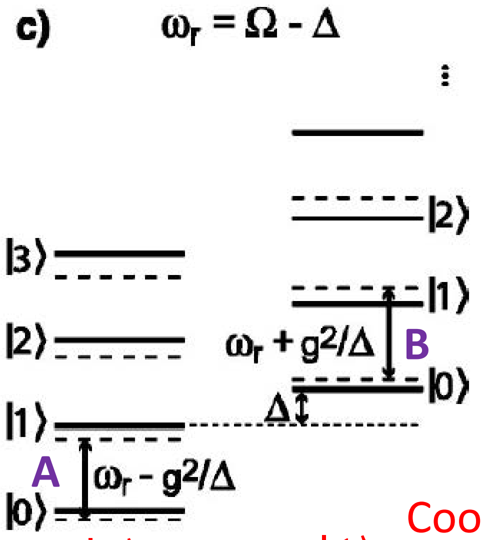
Circuit QED





Wikipedia

Resonator as Cavity



$|0\rangle$ $|1\rangle$

Cooper Pair Box: Artificial Atom

$|0\rangle_{ph}|0\rangle_{charge}$

A

$\omega_r - \frac{g^2}{\Delta}$

$|1\rangle_{ph}|0\rangle_{charge}$

Apply a pulse

$|0\rangle_{ph}|1\rangle_{charge}$

B

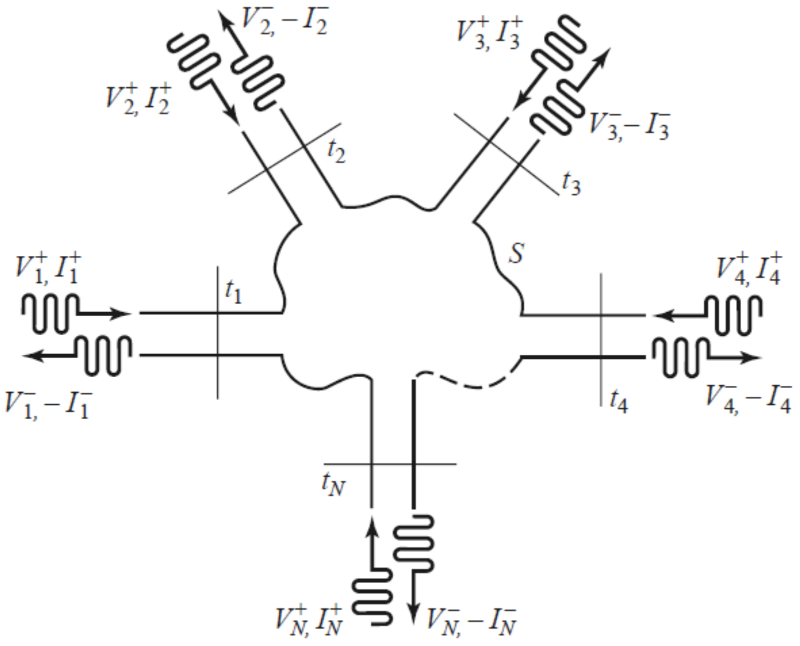
$\omega_r + \frac{g^2}{\Delta}$

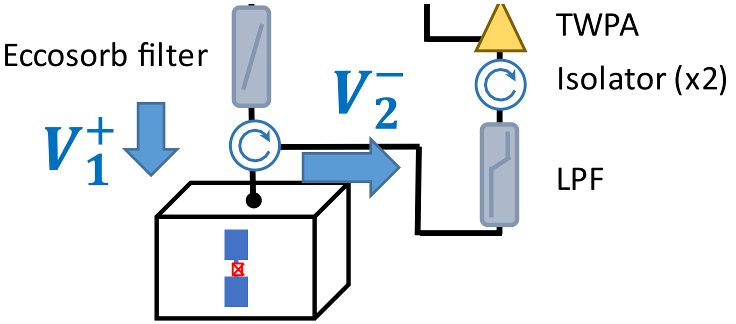
$|1\rangle_{ph}|1\rangle_{charge}$

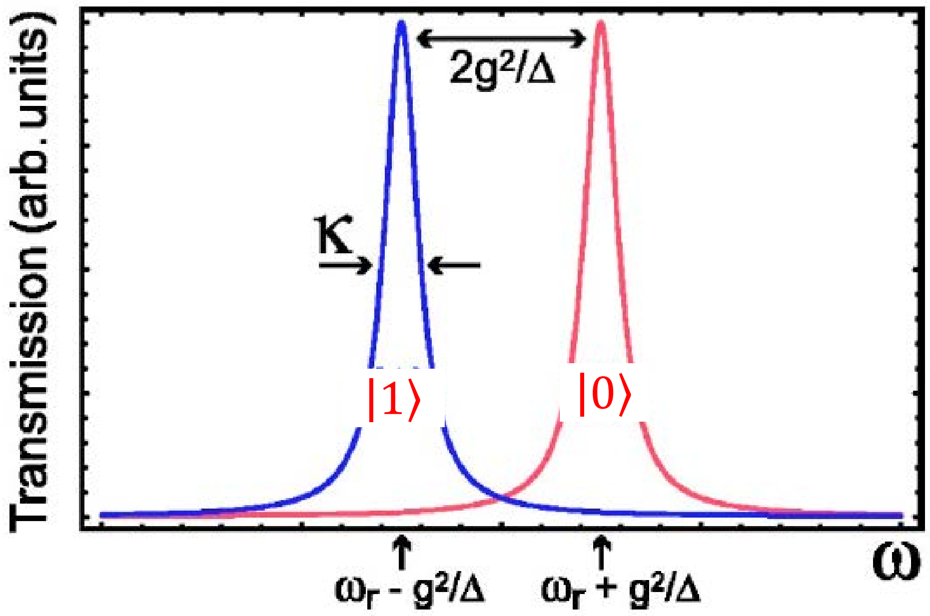
(Blais et al, PHYSICAL REVIEW A 69, 062320 (2004))

Scattering Matrix

Photon is entangled with the qubit





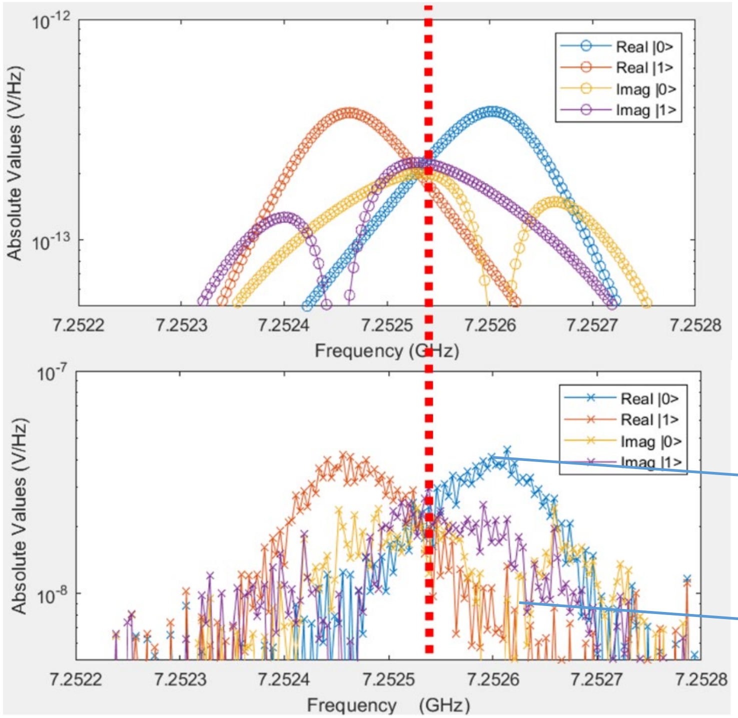


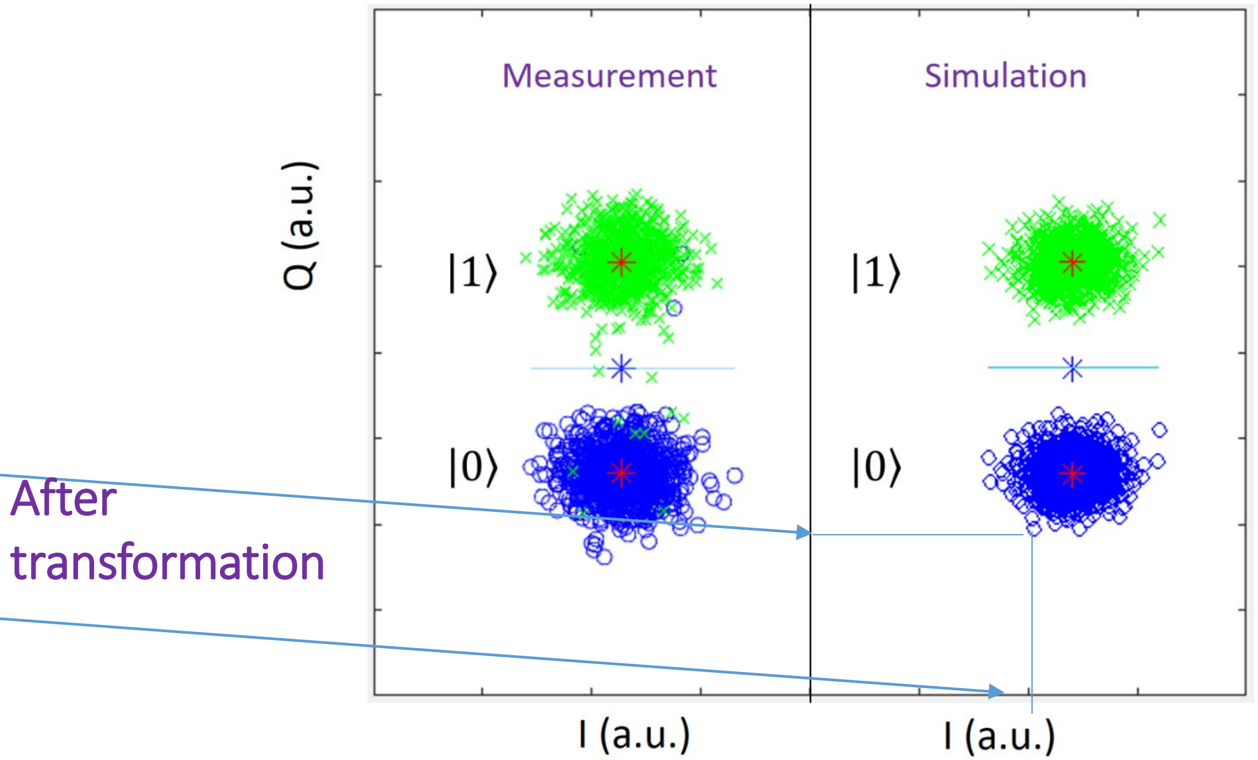
$$S_{21} = \left. \frac{V_2^-}{V_1^+} \right|_{V_2^+=0}$$

Pozar's Book

Phys. Rev. A 69, 062320 (2004)

Distinguishing $|0\rangle$ and $|1\rangle$

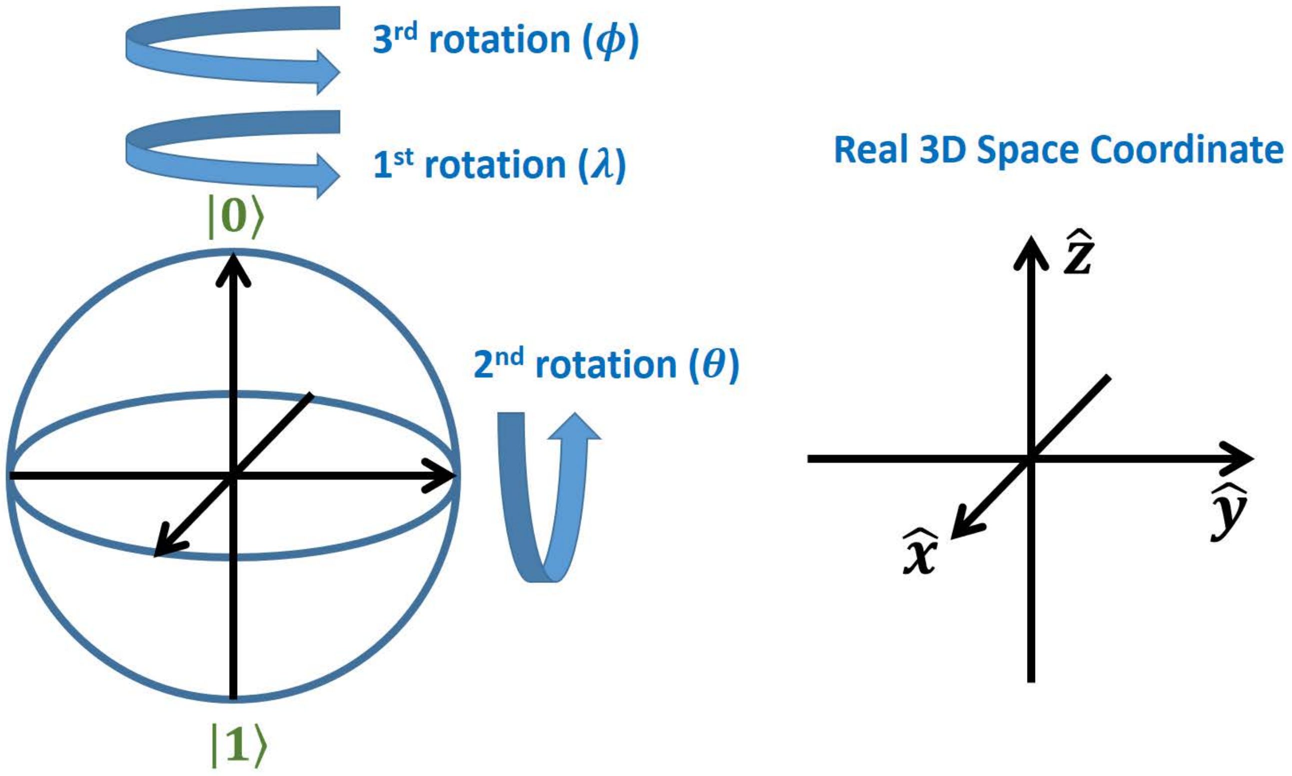




Hiu Yung Wong et al., "A Simulation Methodology for Superconducting Qubit Readout Fidelity," SSE, 2023.

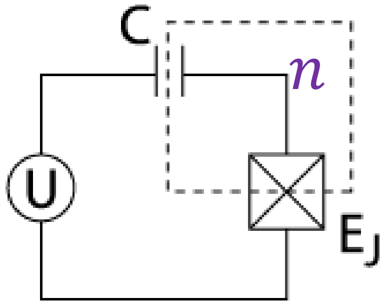
Single Qubit Gate

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



Implementation of Single Qubit Gates

Superconducting Charge Qubit

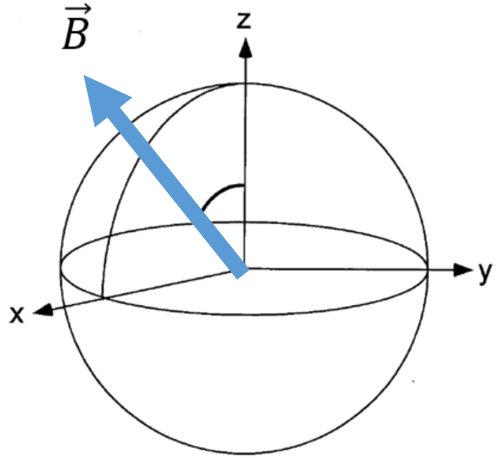


$|\psi\rangle = \alpha|n = 0\rangle + \beta|n = 1\rangle$

Wikipedia

$$H = \frac{1}{2}\begin{pmatrix} -E & -E_J \\ -E_J & E \end{pmatrix} = -\frac{1}{2}\vec{\sigma}\cdot\vec{B}$$

$$\vec{B} = \begin{pmatrix} E_J \\ 0 \\ E \end{pmatrix} \quad E = E_c(1 - 2n_g)$$



Make U time varying so that $n_g = \frac{1}{2} - \eta\cos(\omega_1 t + \varphi)$

Rotating frame approximation (set $\hbar = 1$)

$$H = -\frac{\Delta}{2}\sigma_z + \frac{\Omega}{2}(\cos(\varphi)\,\sigma_x + \sin(\varphi)\,\sigma_y)$$

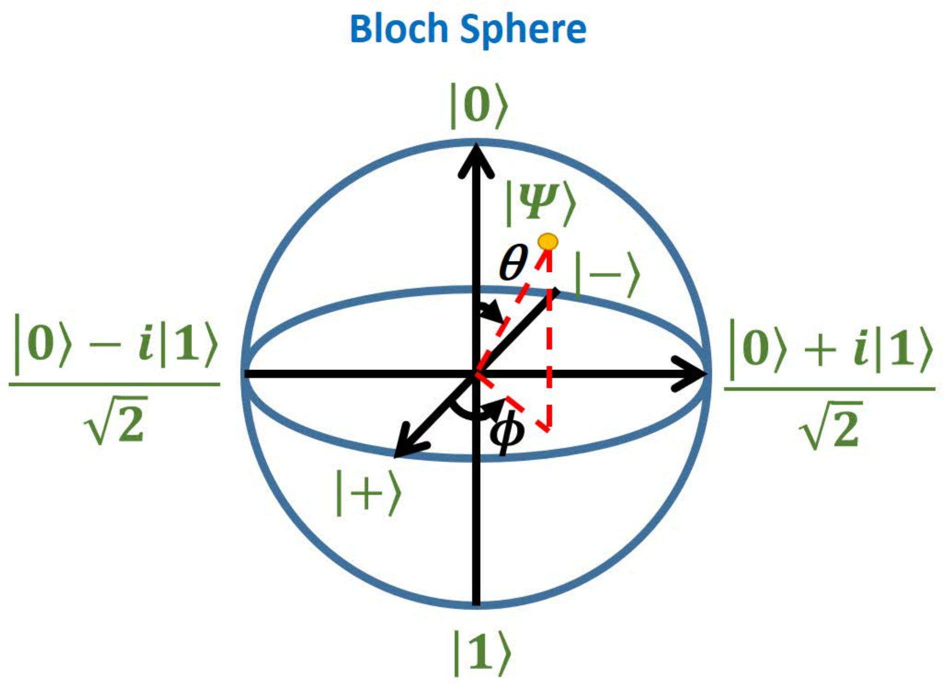
Depends on ω_1, E_J and E_C

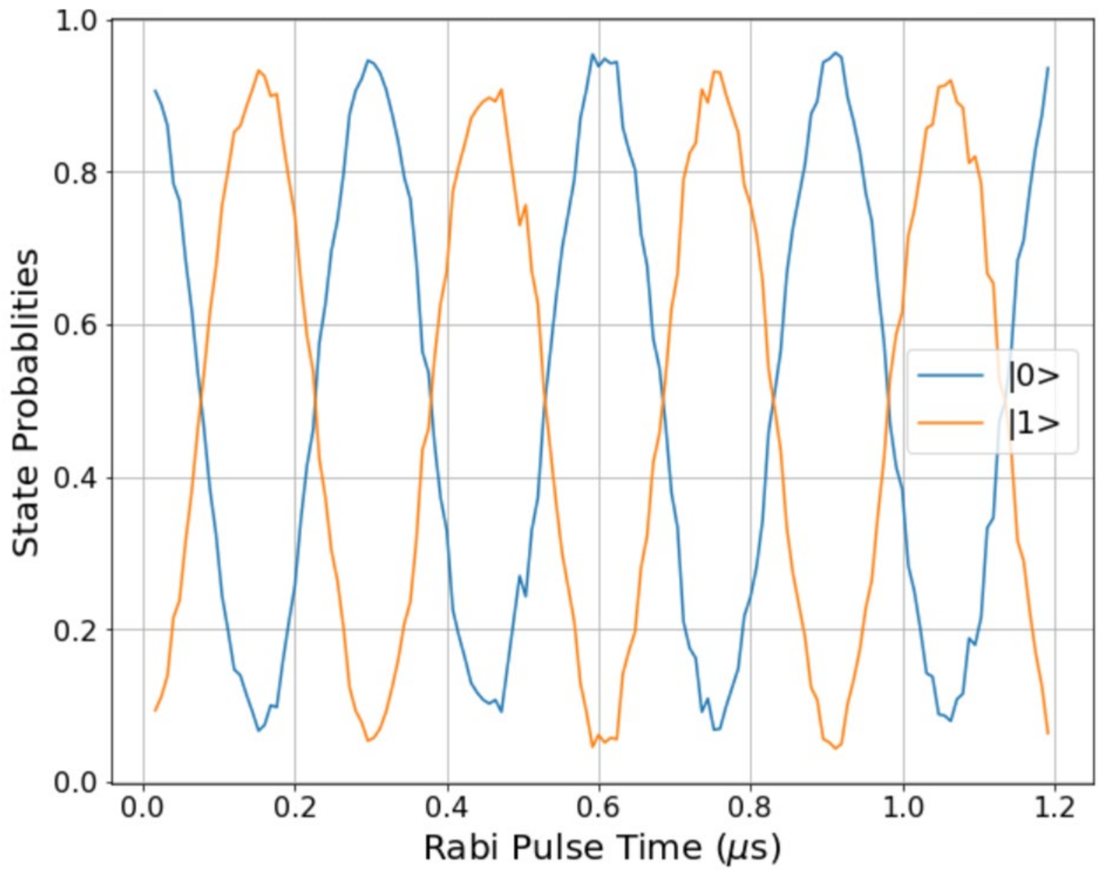
Depends on η and E_C

Phase of the driving pulse

Single Qubit Gate (e.g. X and H Gates)

Different frequencies of the microwave pulse causing the rotation about different axis in the x-z plane.



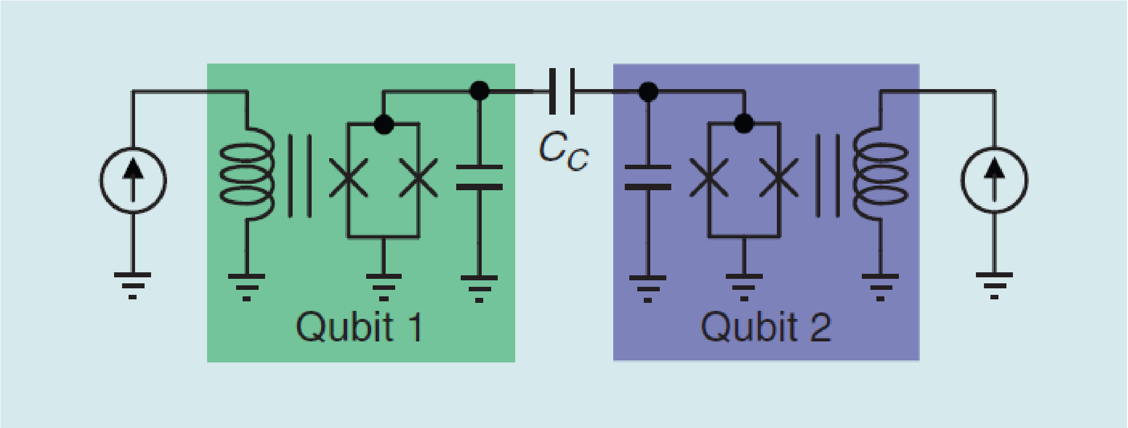


iSWAP Gate – 2-qubit gate

iSWAP Gate for entanglement operation

$$\hat{U}_{iSWAP}(\omega_s \Delta t) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\omega_s \Delta t/2) & -j\sin(\omega_s \Delta t/2) & 0 \\ 0 & -j\sin(\omega_s \Delta t/2) & \cos(\omega_s \Delta t/2) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$\hat{U}_{iSWAP}(\pi) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -j & 0 \\ 0 & -j & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



J. C. Bardin, D. Sank, O. Naaman and E. Jeffrey, "Quantum Computing: An Introduction for Microwave Engineers," in IEEE Microwave Magazine, vol. 21, no. 8, pp. 24-44, Aug. 2020.

Is Quantum Computing Omnipotent?

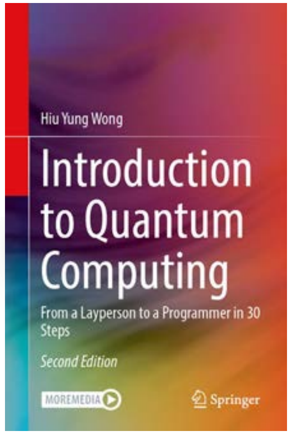
- Each state contains profound amount of information, but we cannot extract them with reasonable resources. How do we get the *a*'s?

$$|\Psi\rangle = a_0 |00\cdots0\rangle + a_1 |00\cdots1\rangle + \cdots + a_{2^n-1} |11\cdots1\rangle$$

- QC is suitable for answering questions that classical computers cannot answer well. Often, *destructive and constructive* interferences are used to obtain the answers.
  - E.g. Is the function balanced? What is the period of the function?
- QC cannot replace classical computer but can be a very powerful accelerator for difficult problems, e.g. optimization problems.

Resources

- Book: (**2nd Edition with 200+ questions and answers and links to teaching videos)**
  - **Introduction to Quantum Computing: From a Layperson to a Programmer in 30 Steps** | SpringerLink (https://link.springer.com/book/10.1007/978-3-030-98339-0) (Free if your school has a subscription, connect to VPN)
  - **Introduction to Quantum Computing: From a Layperson to a Programmer in 30 Steps**: Wong, Hiu Yung: 9783030983383: Amazon.com: Books (https://www.amazon.com/Introduction-Quantum-Computing-Layperson-Programmer/dp/3030983382)
- Videos (Youtube):
  - **Introduction to Quantum Computing From a Layperson to a Programmer in 30 Steps** – YouTube (https://www.youtube.com/playlist?list=PLnK6MrIqGXsJfcBdppW3CKJ858zR8P4eP)
  - **Quantum Computing Hardware and Architecture – YouTube** (https://www.youtube.com/playlist?list=PLnK6MrIqGXsL1KShnocSdwNSiKnBodpie)



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Lawrence Livermore National Laboratory

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NSF

Quantum Classrooms

SJSU-IBM Acceleration: Quantum Classrooms