Tutorial 21: Introduction to Quantum Computing: From Algorithm to Hardware

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San Jose State University, CA, USA

13:00-16:30, Sept. 21, 2023

IEEE QUANTUM WEEK

SJSU SAN JOSÉ STATE UNIVERSITY

Agenda

Tutorial 21

- Self-introduction
- Part I: Overview of Quantum Computing (Lecture)
- Part II: Understanding Quantum Gates (Hands-on)
    - Write your own simulator in Google Co-Lab
- Parts III & IV: Deutsch Algorithm and Quantum Fourier Transform (Lecture + Hands-on)
    - Programming on IBM-Q
- Part V: Superconducting Qubit Hardware (Lecture)
- Part VI: Optimizing Qubit Readout Using Qiskit and HFSS (Demo)

Resources

- Download tutorial files and hands-on materials
- https://github.com/hywong2/QCE2023_Tutorial_21

Resources

Tutorial 21

- 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) (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

Tutorial 21

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.

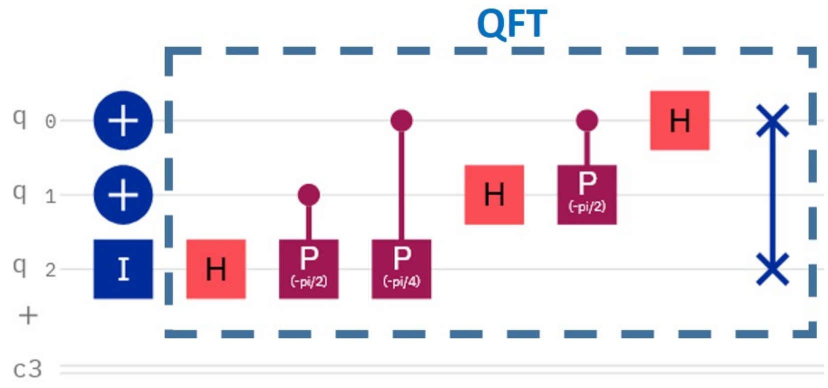
"Our top three are Cisco, Apple and Hewlett Packard," Newell said.

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

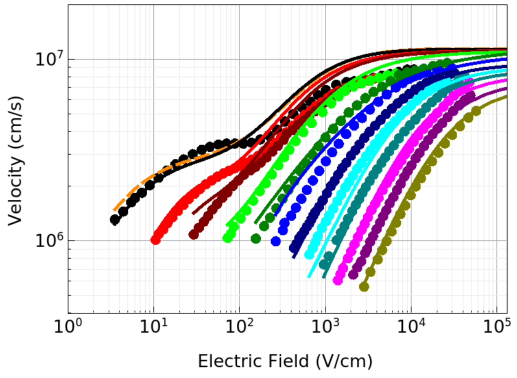
SJSU MSEE Specialization in *Quantum Information and Computing*

- 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)

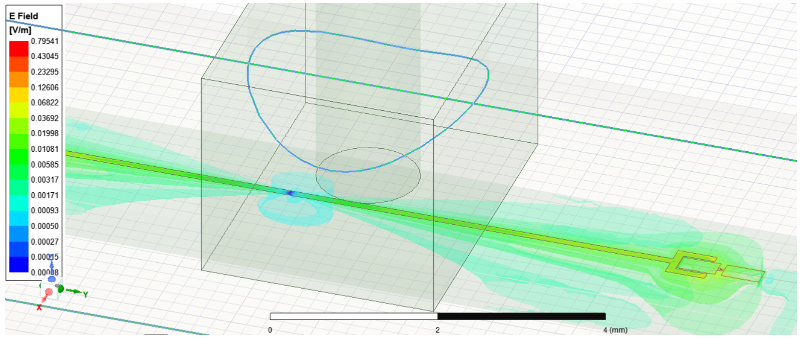
Python, Qiskit,



TCAD, Spectre



HFSS, Qiskit Metal

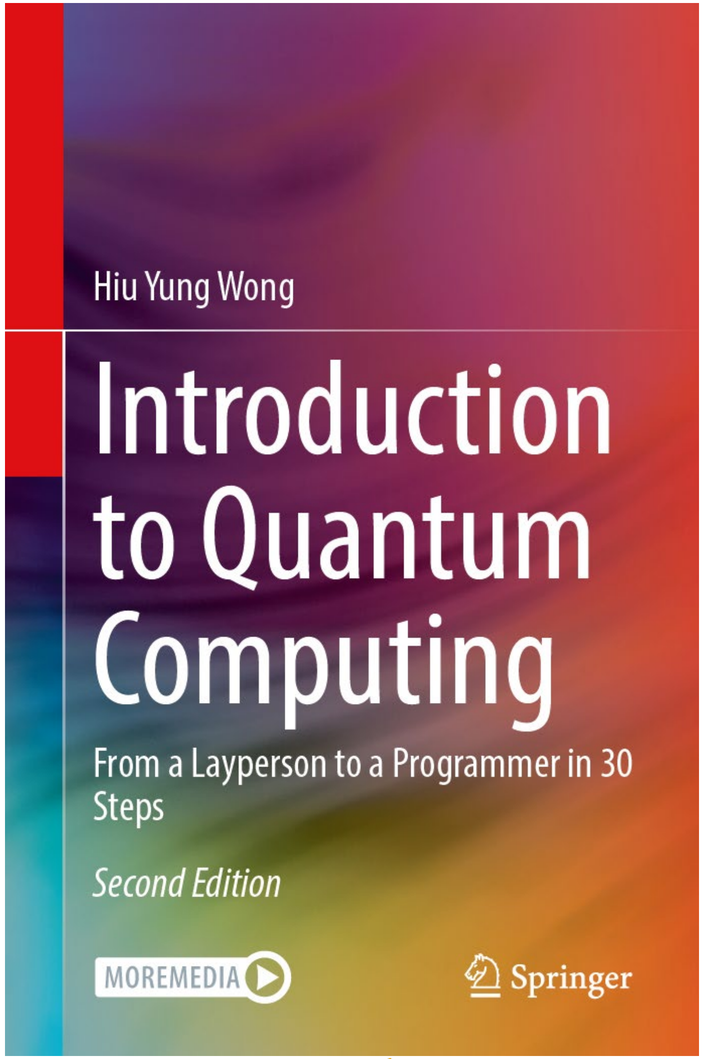


Quantum Technology, Master of Science

- 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
From a Layperson to a Programmer in 30 Steps



- Free download with institution subscription to SpringerLink
- Available in Amazon Kindle and Nook Book

Springer

amazon

Introduction to Quantum Computing (EE225)

Quantum Computing Hardware and Architectures (EE274)

YouTube

Part I: Overview of Quantum Computing (Lecture)

- Introduce the fundamental concepts in quantum computing: State, Superposition, Measurement, Entanglement, No-cloning Theorem, Error Correction

Learning Outcomes

- Understand the fundamental concepts
- Understand the power of quantum parallelism
- Understand the importance of superposition, entanglement, measurement, and error correction
- Understand that quantum computers cannot replace classical computers but are wonderful accelerators

Applications of Quantum Computing

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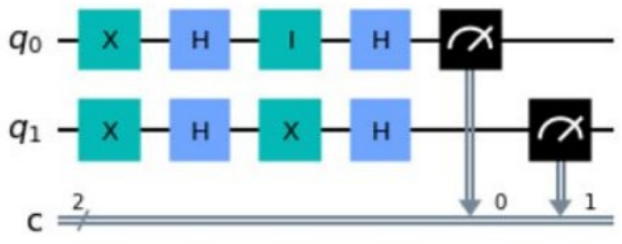
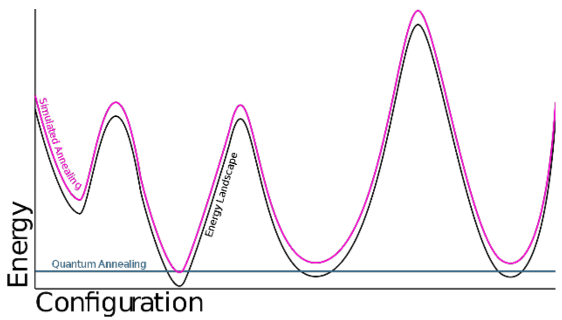
- Quantum computing uses two quantum phenomena
  - Superposition and entanglement and, also, *interference*
- Two major types of quantum computing
  - Gate-based (this talk)
  - Quantum annealing (optimization by minimizing energy)
- Applications
  - Material (battery) and drug (pharma) design
  - Computational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



Gate Model



Quantum Annealing

State and Superposition

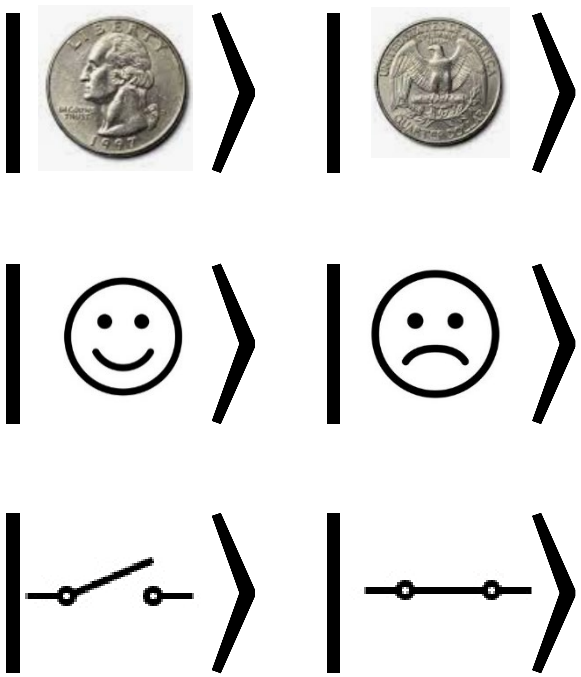
Classical Computing

0 $\qquad$ 1

Information represented by the **states**

Quantum Computing (basis states)

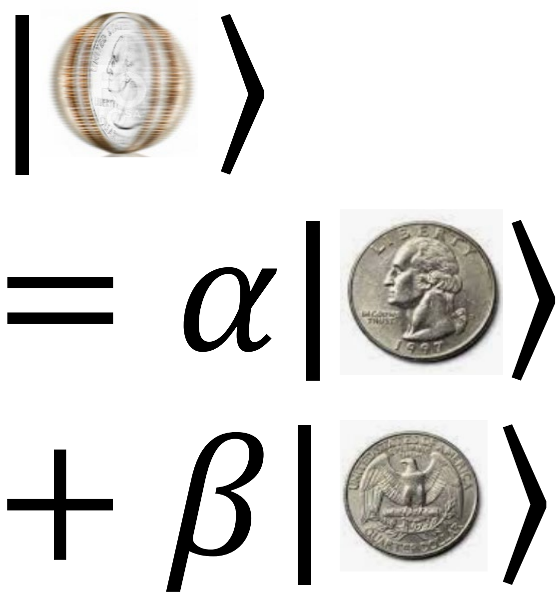
$|0\rangle$ $\qquad$ $|1\rangle$



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

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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

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

The Power of Superposition

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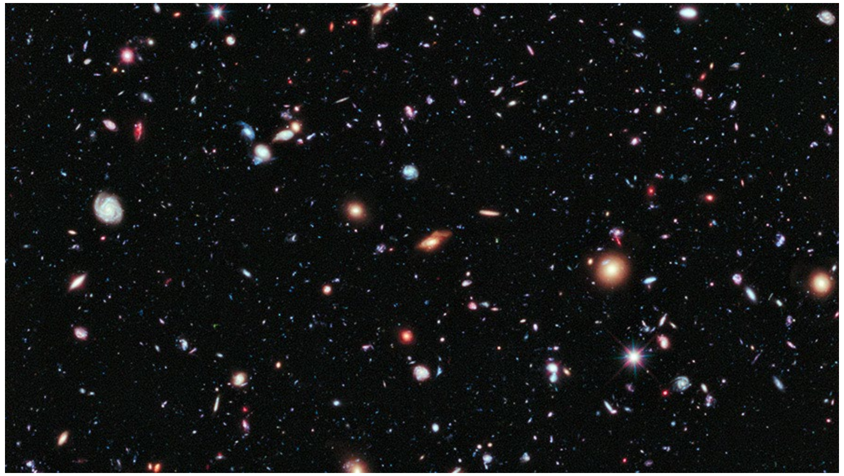
$$
\begin{aligned}
|\Psi\rangle &= a_0|00\cdots0\rangle + a_1|00\cdots1\rangle + \cdots + a_{2^n-1}|11\cdots1\rangle \\
&= a_0|0\rangle_{10} + a_1|1\rangle_{10} + \cdots + a_{2^n-1}|2^n-1\rangle_{10}
\end{aligned}
$$

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

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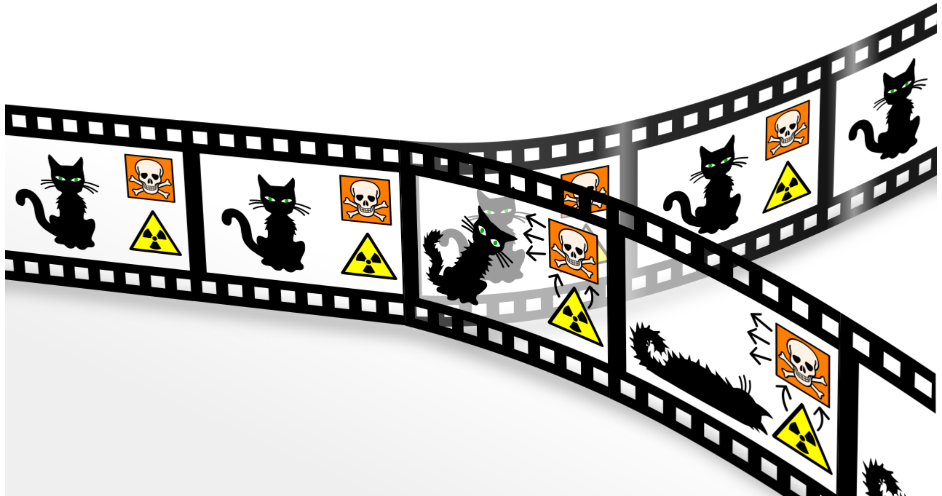
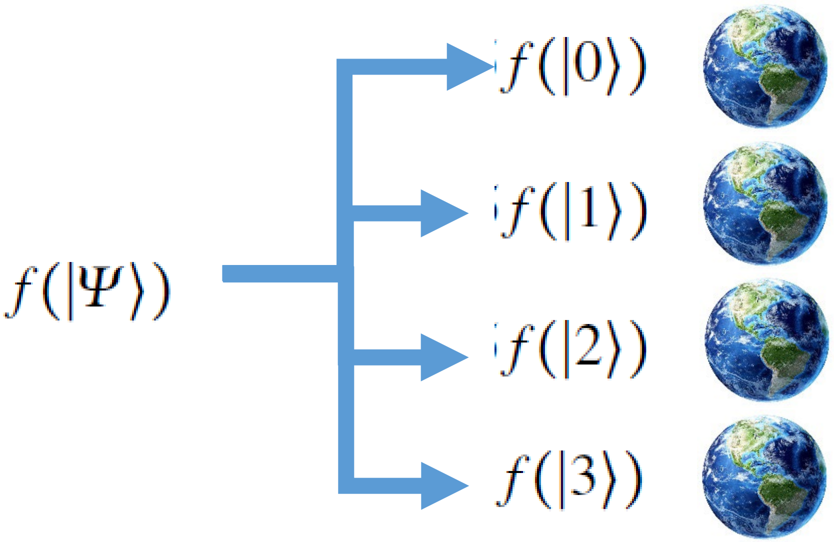
Linear Quantum mechanics

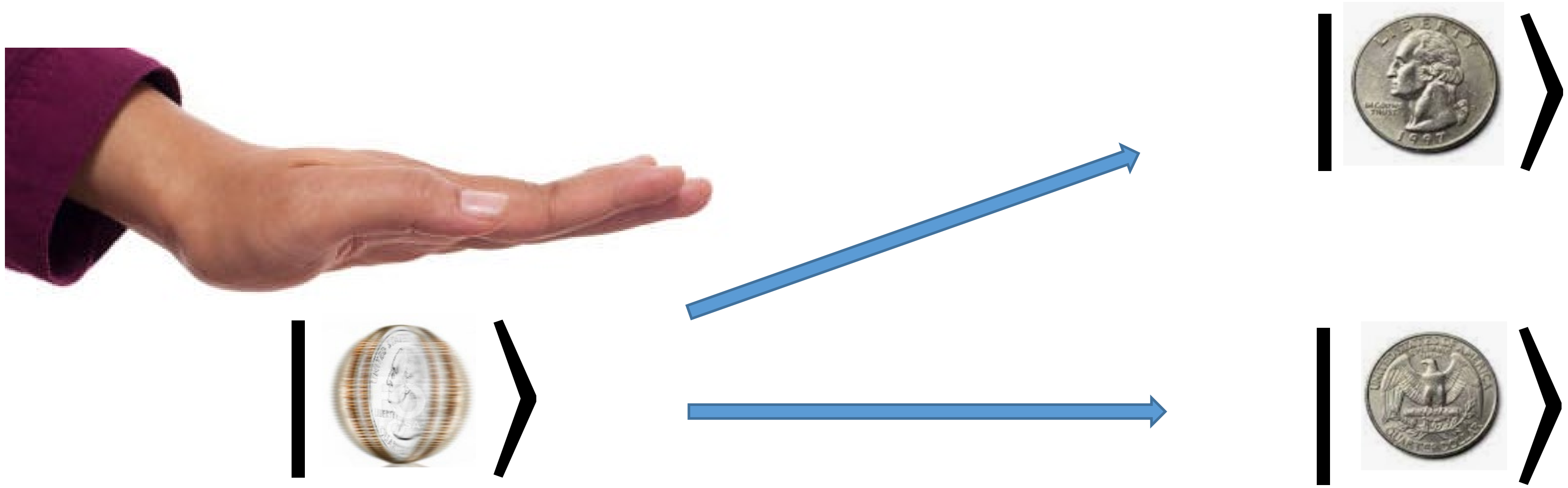
$$f(|\Psi\rangle) = f(0.5|0\rangle + 0.5|1\rangle + 0.5|2\rangle + 0.5|3\rangle)$$
$$= 0.5f(|0\rangle) + 0.5f(|1\rangle) + 0.5f(|2\rangle) + 0.5f(|3\rangle)$$



Wikipedia



Measurement



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

$|\alpha|^2$ $|0\rangle$

$|\beta|^2$ $|1\rangle$

Entangled States

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Unentangled State

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

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

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Step 1

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

e^1 e^2

Step 2

e^1 Earth

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

still entangled

100 light years away e^2

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

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

e^1 $|\uparrow\rangle$ Earth

100 light years away $|\uparrow\rangle$ e^2

Quantum Gates

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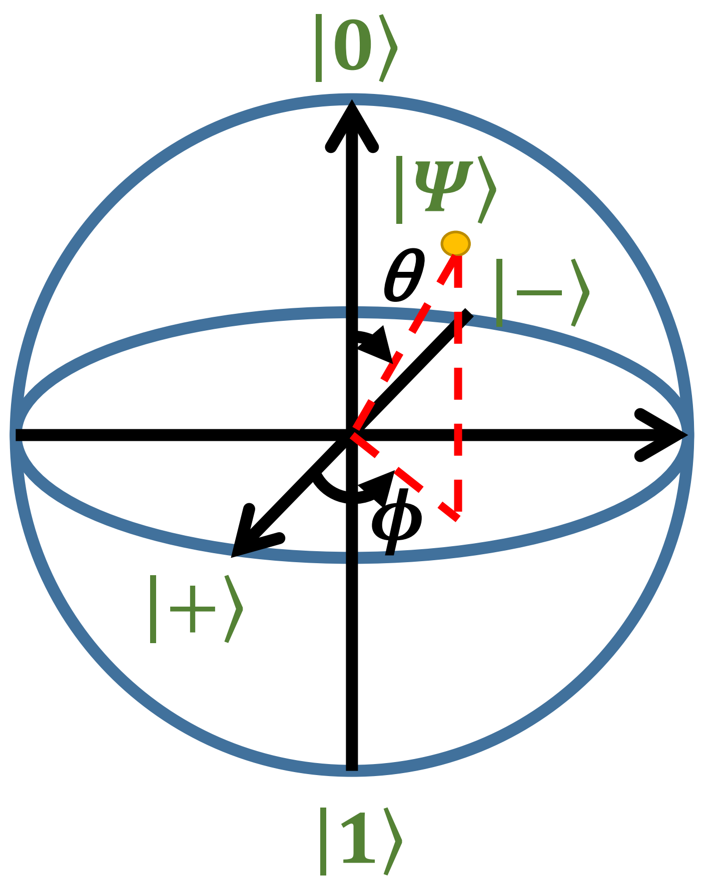
- Quantum gates rotate the vector (state) in the corresponding hyperspace
- *Very often, a gate is just a laser or microwave pulse*
- Some gates have classical counterparts
    - NOT (X) gate (1-qubit)
    - XOR (CNOT) gate (2-qubit) $U_{XOR}\,|ab\rangle = |a a \oplus b\rangle$
- Some gates have no classical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

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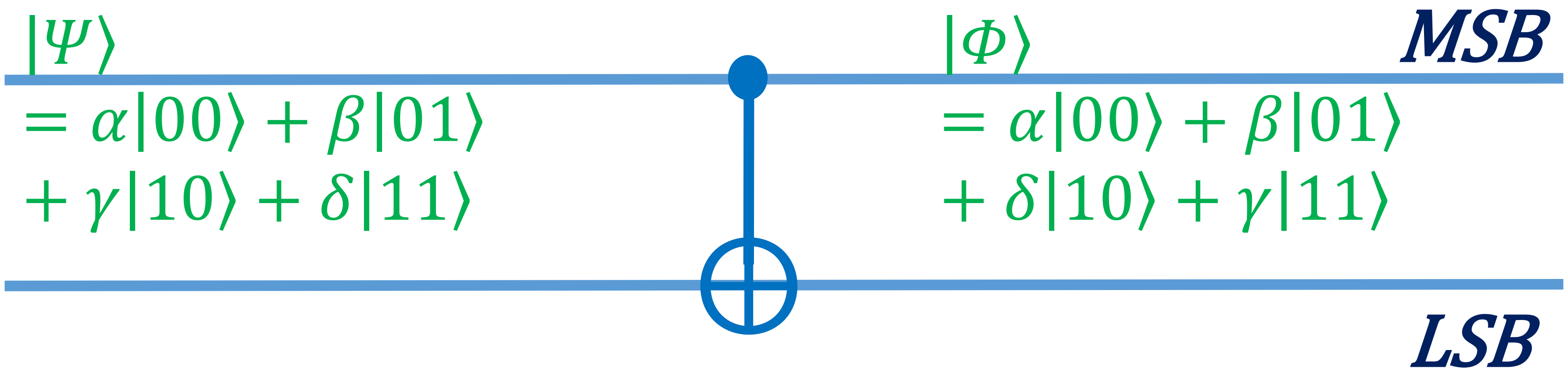
$$U_{XOR}|ab\rangle = |a a \oplus b\rangle$$

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

Control Qubit   Target Qubit



Entanglement Example

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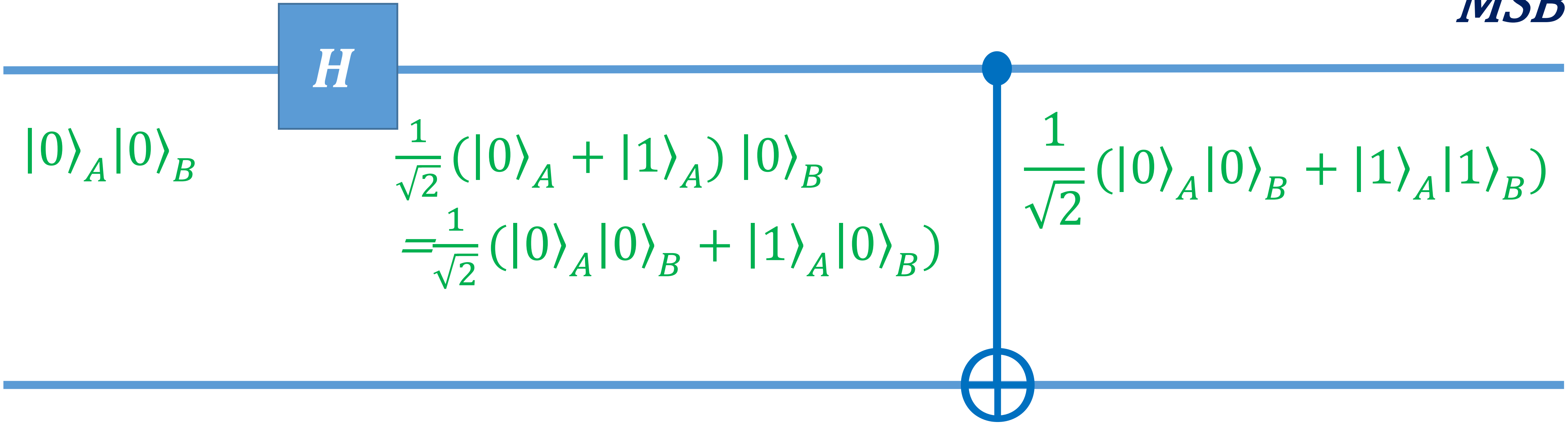
$|0\rangle_A$

$|0\rangle_B$



MSB

LSB

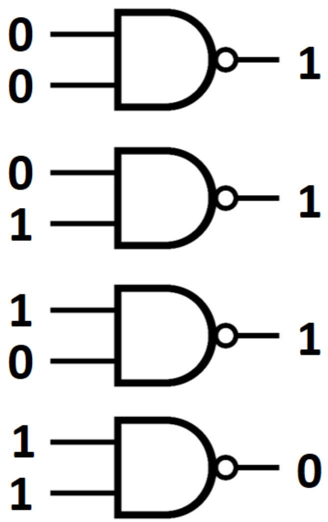
$|0\rangle_A|0\rangle_B$

$$\frac{1}{\sqrt{2}}(|0\rangle_A + |1\rangle_A)\,|0\rangle_B$$
$$=\frac{1}{\sqrt{2}}(|0\rangle_A|0\rangle_B + |1\rangle_A|0\rangle_B)$$

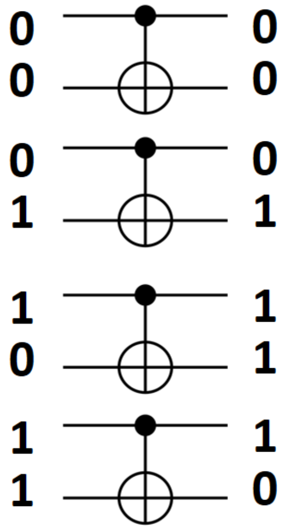
$$\frac{1}{\sqrt{2}}(|0\rangle_A|0\rangle_B + |1\rangle_A|1\rangle_B)$$

Quantum Gates and Circuits

Quantum gates must be reversible

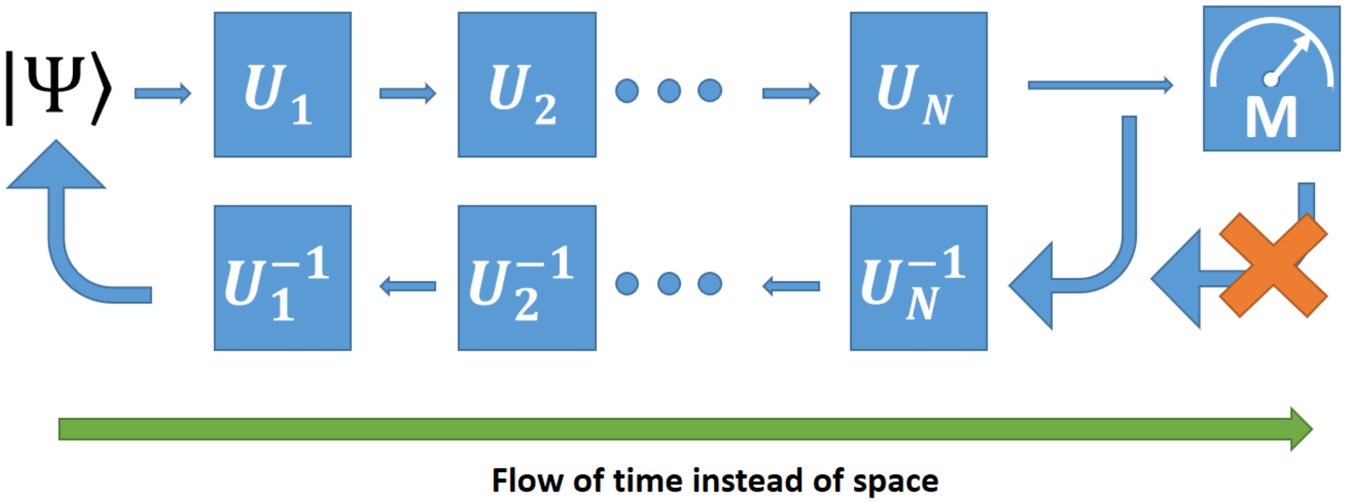


NAND Gate



CNOT Gate

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



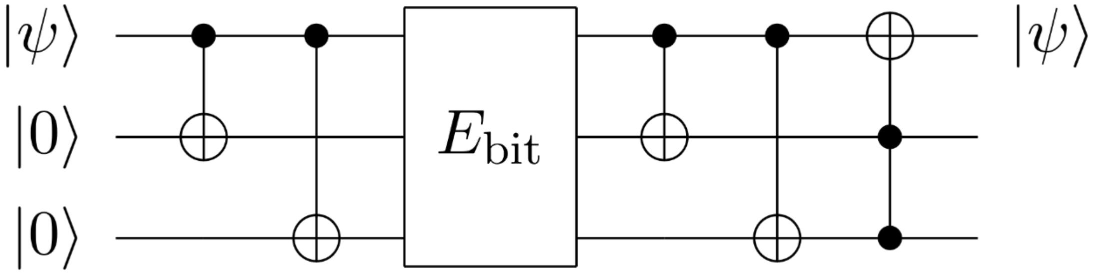
Error Correction

- **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

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

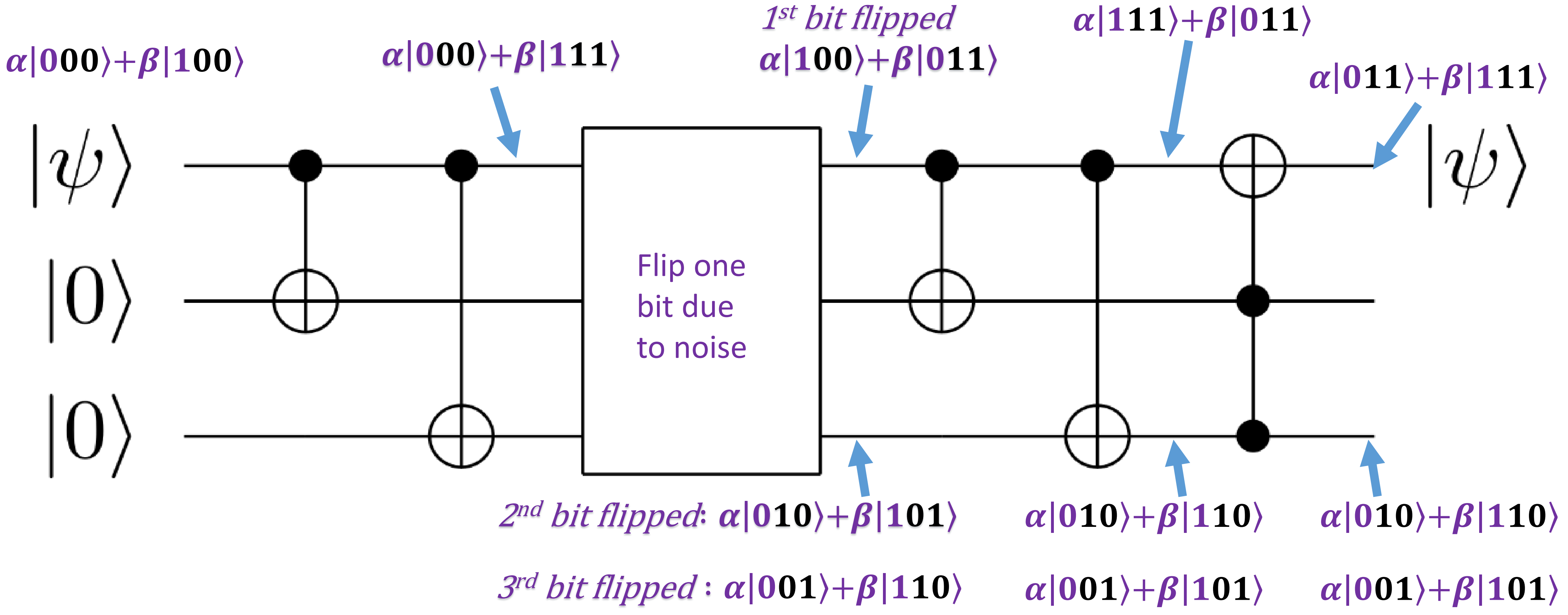
Quantum Error Correction



E.g. Through entanglement and syndrome measurement

Error Correction: Bit Flip Code Example

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



Part II: Understanding Quantum Gates (Hands-on)

- Use Google Co-lab to write a quantum gate simulator in python

Learning Outcomes

- Understand the operations of the following quantum gates
  - NOT
  - CNOT
  - Hadamard
  - Phase Shift
  - Z
  - iSwap
- Understand the importance of entanglement gates
- Able to code a simple quantum computer simulator based on the template
- Understand Tensor Product and Entanglement

NOT (X) Gate

A gate is defined by how it transforms the basis vectors

Definition →

$$U_{NOT}\,|0\rangle = |1\rangle \qquad U_{NOT}\,|1\rangle = |0\rangle$$

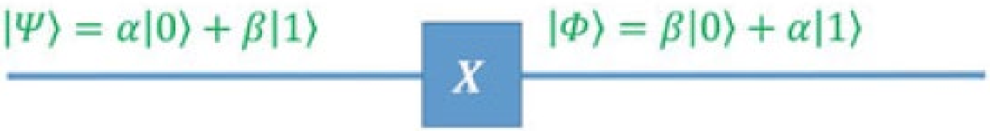
$$U_{NOT} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$U_{NOT}\,|0\rangle = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}|0\rangle \quad = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} = |1\rangle$$

General state $\quad |\Psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$

$$U_{NOT}\,|\Psi\rangle = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}|\Psi\rangle \quad = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \begin{pmatrix} \beta \\ \alpha \end{pmatrix} = \beta\,|0\rangle + \alpha\,|1\rangle$$

NOT gate is Unitary



$$UU^\dagger = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = \boldsymbol{I}$$

Construction of 2 qubit gate using Tensor Product

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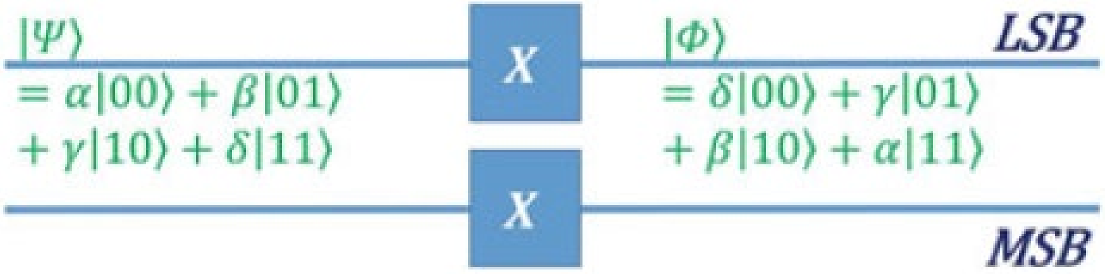
$$U_{NOT_2} = U_{NOT} \otimes U_{NOT} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \otimes \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$= \begin{pmatrix} 0\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} & 1\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \\ 1\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} & 0\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$$

$$U_{NOT_2}|\Psi\rangle = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \\ \gamma \\ \delta \end{pmatrix} = \begin{pmatrix} \delta \\ \gamma \\ \beta \\ \alpha \end{pmatrix}$$



NOT (X) Gate

- Let’s use Google Co-lab to construct 1-qubit and 2-qubit NOT gates
- Also create a 2-qubit NOT gate using tensor product

XOR (CNOT) Gate (2-qubit)

Definition

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

$$U_{XOR} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

$$U_{XOR}\,|\Psi\rangle = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \\ \gamma \\ \delta \end{pmatrix} = \begin{pmatrix} \alpha \\ \beta \\ \delta \\ \gamma \end{pmatrix}$$

$$= \alpha\,|00\rangle + \beta\,|01\rangle + \delta\,|10\rangle + \gamma\,|11\rangle$$

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

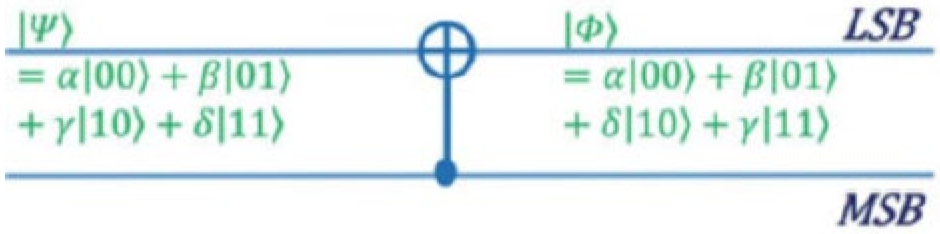
$$U_{XOR}\,|00\rangle = |0, 0 \oplus 0\rangle = |0, 0\rangle = |00\rangle$$

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

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

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

Control Qubit Target Qubit



XOR (CNOT) Gate (2-qubit)

- Let’s use Google Co-lab a CNOT Gate

Walsh-Hadamad (Hadamad) Gate

No classical Counter-Part – create super-position (previous gates only change one basis to another)

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

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

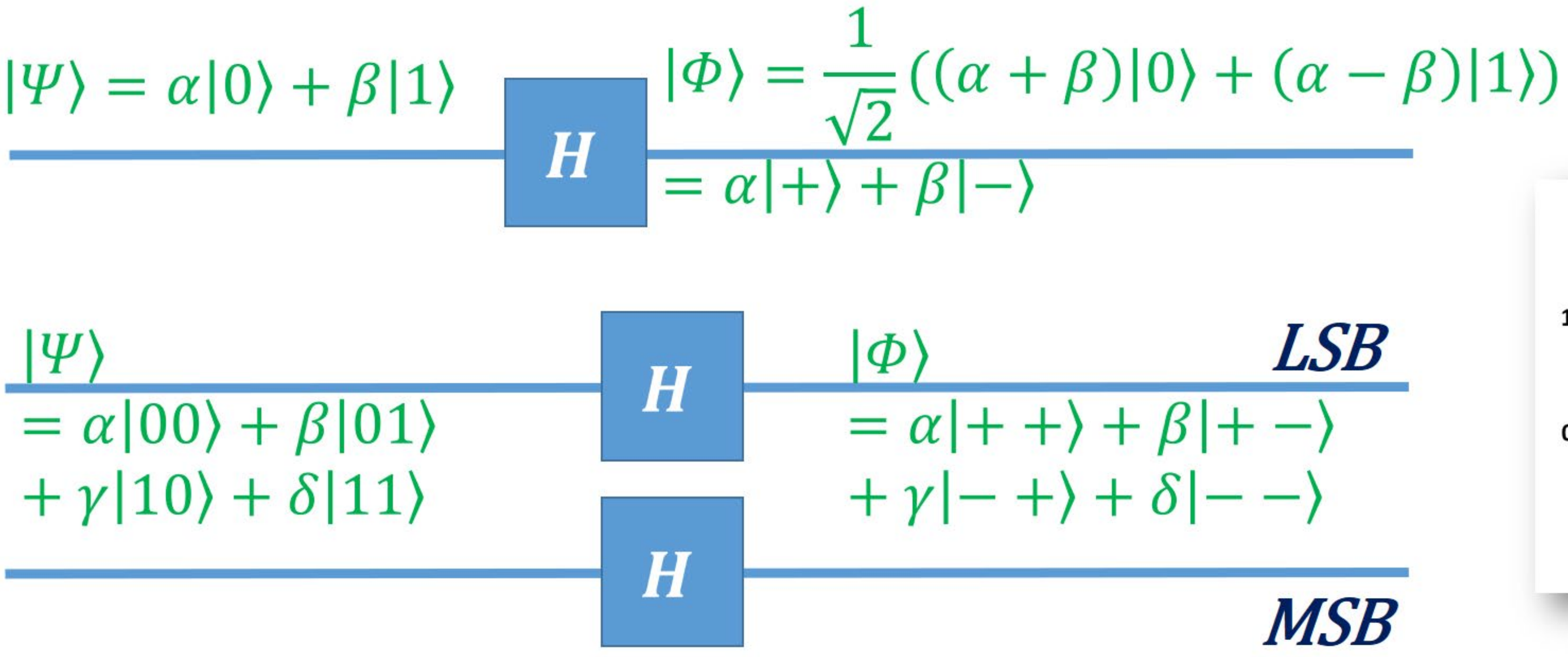
$$\longrightarrow \quad H = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

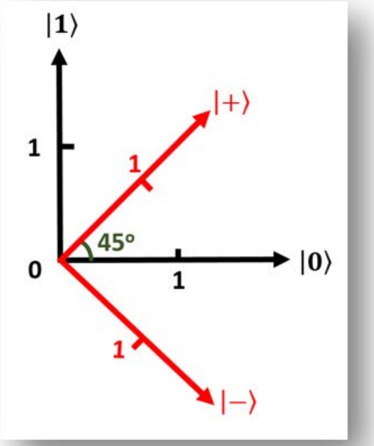
$$H\,|0\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}\begin{pmatrix} 1 \\ 0 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix} = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

$$H\,|1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}\begin{pmatrix} 0 \\ 1 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -1 \end{pmatrix} = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

Walsh-Hadamad (Hadamad) Gate

- Another view
- Let’s program on Google Co-lab





Create an Entanglement Circuit Using Your Simulator!

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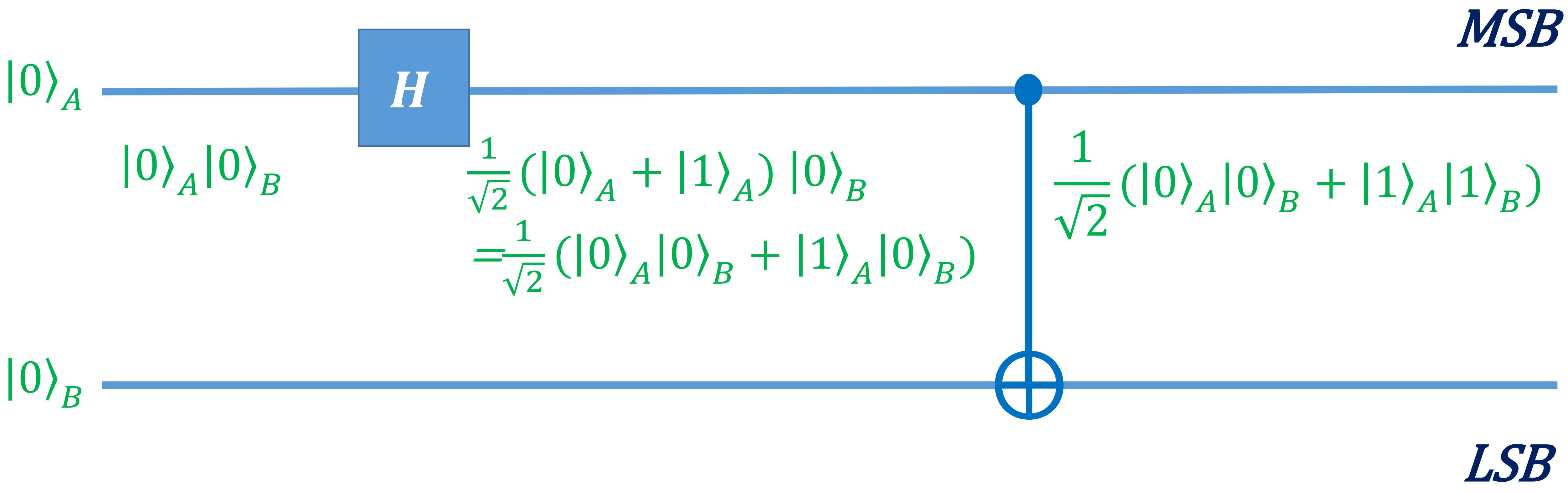


1-Bit Phase Shift Gate and Z-Gate

Definition

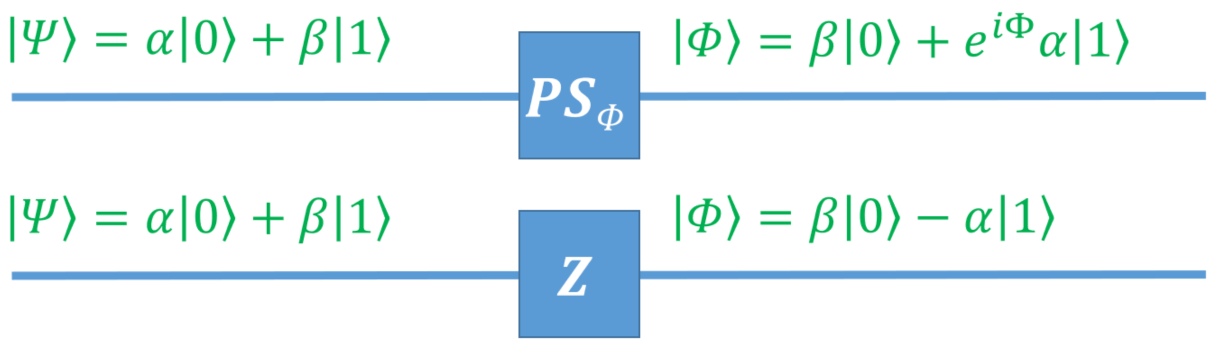
$$U_{PS,\Phi}\,|0\rangle = |0\rangle$$

$$U_{PS,\Phi}\,|1\rangle = e^{i\Phi}\,|1\rangle$$

$$U_{PS,\Phi} = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\Phi} \end{pmatrix}$$

When $\Phi = \pi$ $\quad \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ because $e^{i\pi} = \cos\pi + i\sin\pi = -1.$

And this is just the $\boldsymbol{\sigma_z}$ matrix, one of the important Pauli matrices. And it is also called the **Z-gate**.



Exchange (SWAP) Gate

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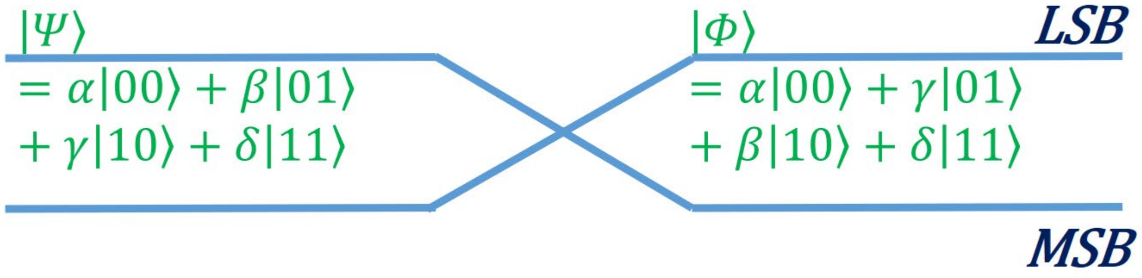
Definition $U_{SWAP}\,|ab\rangle = |ba\rangle$



$$U_{SWAP} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

In general, for a 2-qubit vector, $|\Psi\rangle = \alpha\,|00\rangle + \beta\,|01\rangle + \gamma\,|10\rangle + \delta\,|11\rangle$, we have

$$U_{XOR}\,|\Psi\rangle = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \\ \gamma \\ \delta \end{pmatrix} = \begin{pmatrix} \alpha \\ \gamma \\ \beta \\ \delta \end{pmatrix}$$

$$= \alpha\,|00\rangle + \gamma\,|01\rangle + \beta\,|10\rangle + \delta\,|11\rangle$$

Parts III: Deutsch Algorithm (Lecture + Hands-on)

- Deutsch Algorithm
- Use the Deutsch algorithm to demonstrate the important concepts in quantum computing with IBM quantum composer
- Use scripting (IBM Quantum Lab) to run quantum algorithms

Learning Outcomes

Tutorial 21

- Understand the concept of Quantum Oracle and its implementation
- Able to use IBM Composer
- Appreciate the meaning of quantum parallelism
- Able to program in IBM-Q Quantum Lab with the given circuit

Deutsch’s Problem

Tutorial 21

Finding if a Boolean function is balanced or constant.

Boolean function: f : {0, 1} → {0, 1}

$f_A(0) = 0 \quad \text{and} \quad f_A(1) = 0 \longrightarrow$ constant

$f_B(0) = 0 \quad \text{and} \quad f_B(1) = 1 \longrightarrow$ balanced

$f_C(0) = 1 \quad \text{and} \quad f_C(1) = 0 \longrightarrow$ balanced

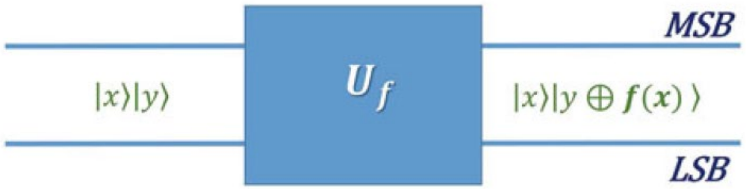
$f_D(0) = 1 \quad \text{and} \quad f_D(1) = 1 \longrightarrow$ constant

Classically, 2 computations, f(0) and f(1)
Quantum Computing: 1 computation

Learn the details

Quantum Oracle

Create a Quantum Oracle (Encode the Problem)



$$U_f\,|x\rangle\,|y\rangle = |x\rangle\,|y \oplus f(x)\rangle$$

Example:

If $f(x)$ is a constant function that always gives "0"

$$U_f\,|0\rangle\,|0\rangle = |0\rangle\,|0 \oplus f(0)\rangle = |0\rangle\,|0 \oplus 0\rangle = |0\rangle\,|0\rangle$$

$$U_f\,|0\rangle\,|1\rangle = |0\rangle\,|1 \oplus f(0)\rangle = |0\rangle\,|1 \oplus 0\rangle = |0\rangle\,|1\rangle$$

$$U_f\,|1\rangle\,|0\rangle = |1\rangle\,|0 \oplus f(1)\rangle = |1\rangle\,|0 \oplus 0\rangle = |1\rangle\,|0\rangle$$

$$U_f\,|1\rangle\,|1\rangle = |1\rangle\,|1 \oplus f(1)\rangle = |1\rangle\,|1 \oplus 0\rangle = |1\rangle\,|1\rangle$$

Deutsch Algorithm

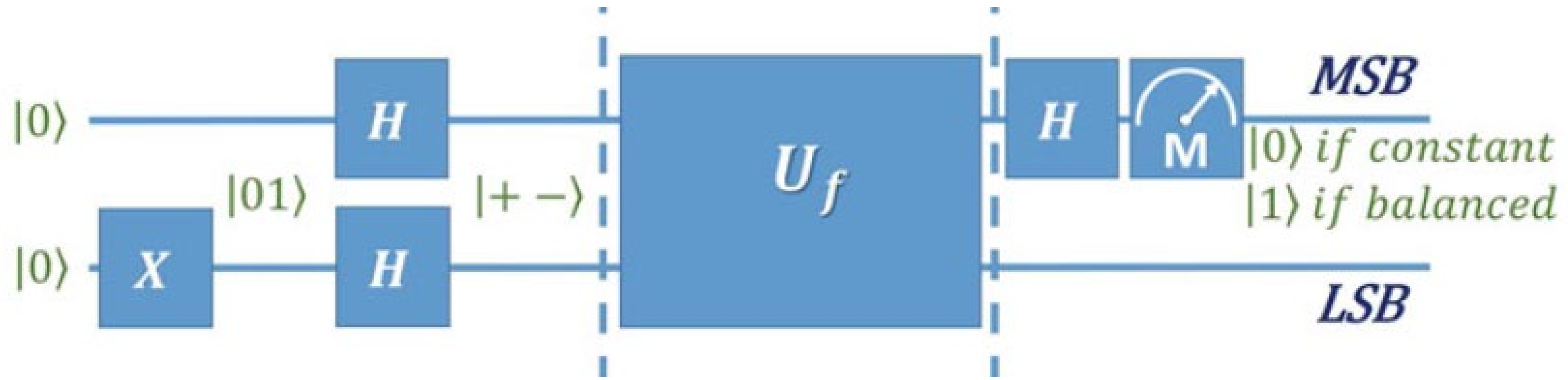
Quantum Oracle: $U_f(|x\rangle|y\rangle) = |x\rangle|y \oplus f(x)\rangle$

Prepare Initial State: $|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \otimes \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) = |+\rangle \otimes |-\rangle$

Operation (parallelism): $U_f|\psi\rangle$

Operation (prepare to measurement in $|+\rangle|-\rangle$Basis: $(H \otimes I_2)U_f|\psi\rangle$

Measurement 1st bit: If $|0\rangle$, constant; If $|1\rangle$, balanced;



Parallel Operation in Deutsch Algorithm

IEEE QUANTUM WEEK

Tutorial 21

$f(0)$ and $f(1)$ are evaluated at the same time!

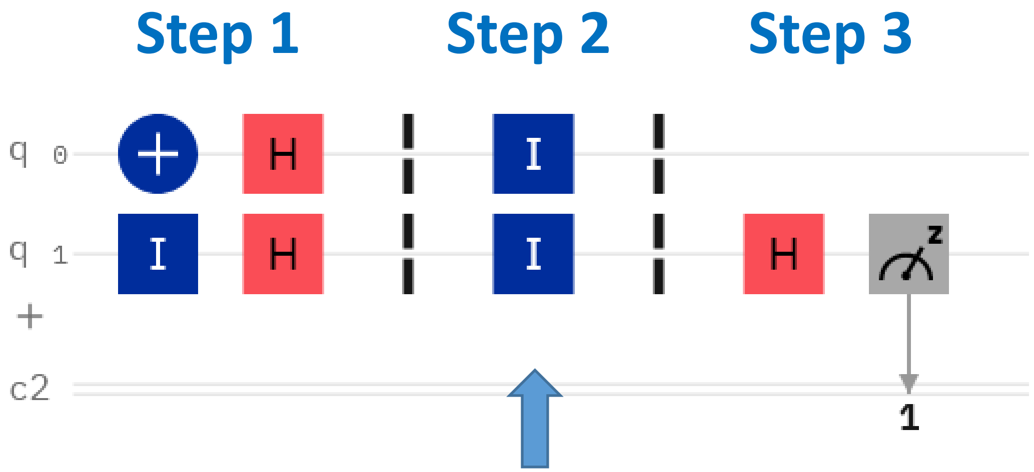
$$
\begin{aligned}
U_f|+\rangle|-\rangle &= \frac{1}{2}\left(|0, f(0)\rangle - \left|0, \overline{f(0)}\right\rangle + |1, f(1)\rangle - \left|1, \overline{f(1)}\right\rangle\right) \\
&= \frac{1}{2}\left(|0, f(0)\rangle - \left|0, \overline{f(0)}\right\rangle + |1, f(0)\rangle - \left|1, \overline{f(0)}\right\rangle\right) \\
&= \frac{1}{2}\left(|0\rangle|f(0)\rangle - |0\rangle\left|\overline{f(0)}\right\rangle + |1\rangle|f(0)\rangle - |1\rangle\left|\overline{f(0)}\right\rangle\right) \\
&= \frac{1}{2}\left((|0\rangle + |1\rangle)|f(0)\rangle - (|0\rangle + |1\rangle)\left|\overline{f(0)}\right\rangle\right) \\
&= \frac{1}{\sqrt{2}}\left(|+\rangle|f(0)\rangle - |+\rangle\left|\overline{f(0)}\right\rangle\right) \\
&= |+\rangle\frac{1}{\sqrt{2}}\left(|f(0)\rangle - \left|\overline{f(0)}\right\rangle\right)
\end{aligned}
$$

If constant, $|+\rangle$ is still $|+\rangle$ in MSB

$$
\begin{aligned}
U_f|+\rangle|-\rangle &= \frac{1}{2}\left(|0, f(0)\rangle - \left|0, \overline{f(0)}\right\rangle + |1, f(1)\rangle - \left|1, \overline{f(1)}\right\rangle\right) \\
&= \frac{1}{2}\left((|0\rangle - |1\rangle)|f(0)\rangle - (|0\rangle - |1\rangle)\left|\overline{f(0)}\right\rangle\right) \\
&= \frac{1}{\sqrt{2}}\left(|-\rangle|f(0)\rangle - |-\rangle\left|\overline{f(0)}\right\rangle\right) \\
&= |-\rangle\frac{1}{\sqrt{2}}\left(|f(0)\rangle - \left|\overline{f(0)}\right\rangle\right)
\end{aligned}
$$

If balanced, $|+\rangle$ becomes $|-\rangle$ in MSB

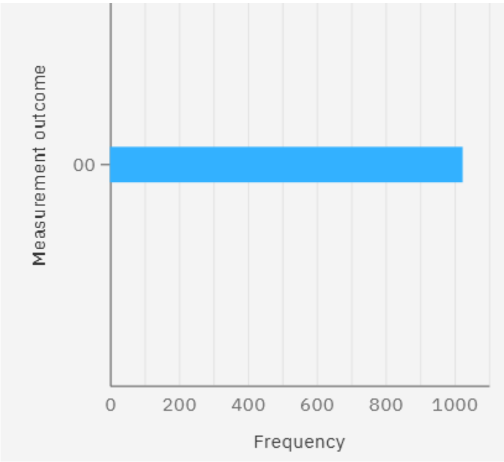
Live Demonstration on IBM-Q



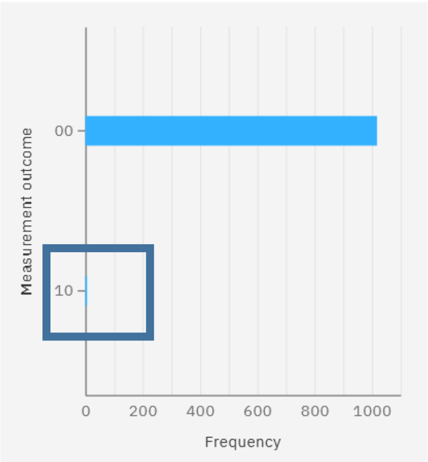
$$U_f(|x\rangle|y\rangle) = |x\rangle|y \oplus f(x)\rangle$$

$$f_A(0) = 0 \quad \text{and} \quad f_A(1) = 0$$

Simulation



Real Computer



https://youtu.be/owUnw9MwJlg?t=466

Run Deutsch Algorithm on IBM-Q using Scripting

- You can either run on
  - Quantum Lab
  - Or local Jupyter Notebook or Google Co-lab

Parts IV: Quantum Fourier Transform (Lecture + Hands-on)

- Have a deeper understand of destructive and constructive interferences to extract information

Learning Outcomes

Tutorial 21

- Appreciate the similarity between Fast Fourier Transform and QFT
- Appreciate the complexity of quantum circuits with many qubits
- Understand better the meaning of constructive and destructive interference

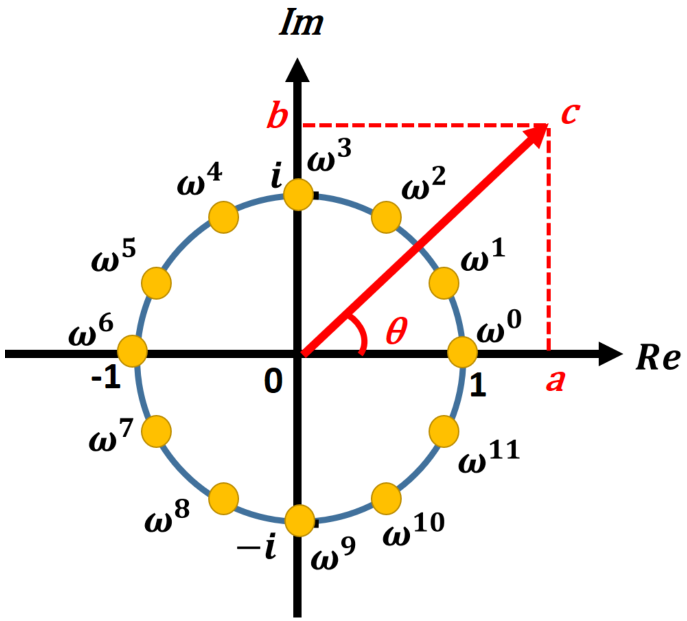
N-th Root of Unity

Tutorial 21

$$e^{i\theta} = (\cos\theta + i\sin\theta)$$

$$e^{i2\pi m} = \cos 2\pi m + i\sin 2\pi m$$

$$e^{i2\pi m/N} = \omega^m$$



Properties of the N-th Root of Unity

IEEE QUANTUM WEEK

Tutorial 21

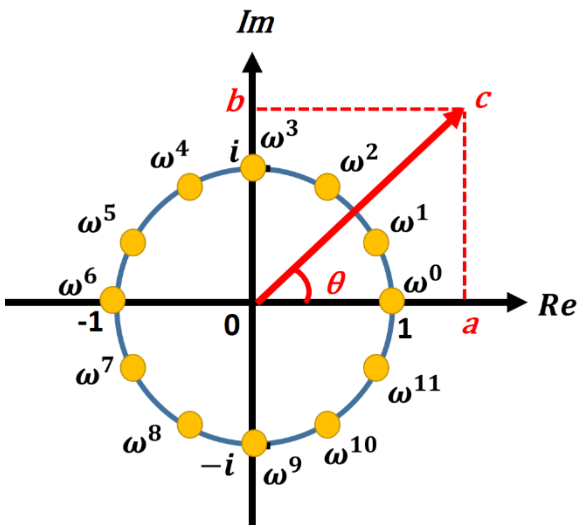
1) $$\sum_{m=0}^{N-1} \omega^m = \omega^0 + \omega^1 + \cdots + \omega^{N-1} \qquad = \frac{\omega^0 - \omega^N}{\omega^0 - \omega} = \frac{1-1}{1-\omega} = 0$$

destructive interference Similarly, for any integer $q \neq 0$,

2) $$\sum_{m=0}^{N-1} \omega^{mq} = \omega^{0q} + \omega^{1q} + \cdots + \omega^{(N-1)q} \qquad = \frac{\omega^{0q} - (\omega^q)^N}{\omega^{0q} - \omega^q} = \frac{1-1}{1-\omega^q} = 0$$

3) **constructive interference** if $q = 0$,

$$\sum_{m=0}^{N-1} \omega^{mq} = \sum_{m=0}^{N-1} \omega^0 = \sum_{m=0}^{N-1} 1 = N$$



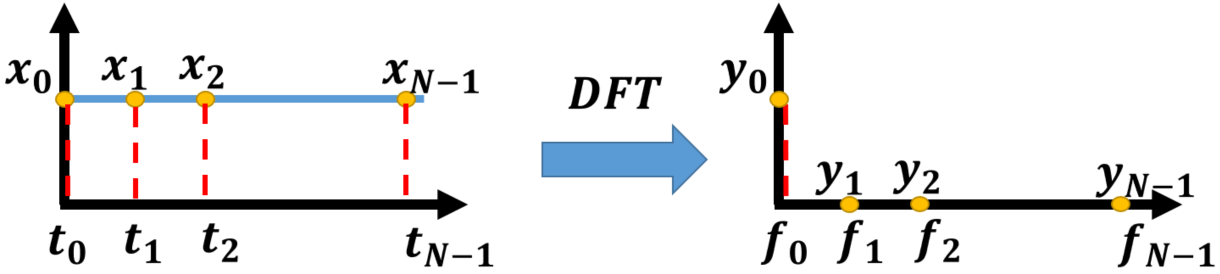
Many algorithms use this property to extract useful information through interferences (by using QFT).

Discrete Fourier Transform

Tutorial 21

$\vec{X} = \begin{pmatrix} x_0 \\ x_1 \\ \vdots \\ x_{N-1} \end{pmatrix}$ and $\vec{Y} = \begin{pmatrix} y_0 \\ y_1 \\ \vdots \\ y_{N-1} \end{pmatrix}$. The DFT is defined as

$$y_k = \frac{1}{\sqrt{N}} \sum_{j=0}^{N-1} \omega^{-kj} x_j = \frac{1}{\sqrt{N}} \sum_{j=0}^{N-1} e^{-i2\pi kj/N} x_j$$



$$\begin{pmatrix} y_0 \\ y_1 \\ \vdots \\ y_{N-1} \end{pmatrix} = \frac{1}{\sqrt{N}} \begin{pmatrix} \omega^{-0\cdot 0} & \omega^{-0\cdot 1} & \cdots & \omega^{-0\cdot(N-1)} \\ \omega^{-1\cdot 0} & \omega^{-1\cdot 1} & \cdots & \omega^{-1\cdot(N-1)} \\ \vdots & \vdots & \ddots & \vdots \\ \omega^{-(N-1)\cdot 0} & \omega^{-(N-1)\cdot 1} & \cdots & \omega^{-(N-1)\cdot(N-1)} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \\ \vdots \\ x_{N-1} \end{pmatrix}$$

Quantum Fourier Transform

IEEE QUANTUM WEEK

Tutorial 21

$$U_{QFT}\,|j\rangle = \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1}\omega^{-kj}\,|k\rangle$$

$$= \frac{1}{\sqrt{N}}\begin{pmatrix} \omega^{-0\cdot 0} & \omega^{-0\cdot 1} & \cdots & \omega^{-0\cdot(N-1)} \\ \omega^{-1\cdot 0} & \omega^{-1\cdot 1} & \cdots & \omega^{-1\cdot(N-1)} \\ \vdots & \vdots & \ddots & \vdots \\ \omega^{-(N-1)\cdot 0} & \omega^{-(N-1)\cdot 1} & \cdots & \omega^{-(N-1)\cdot(N-1)} \end{pmatrix}\begin{pmatrix} 0 \\ 1 \\ \vdots \\ 0 \end{pmatrix}$$

1. In some literature, this is called Inverse QFT.
2. Unlike in electrical engineering, we are not transforming between time and frequency basis. QFT is transforming within the same basis.

1-qubit and 2-qubit QFT

This is a 1-qubit U_{QFT}.

$$
\begin{aligned}
U_{QFT} &= \frac{1}{\sqrt{2}} \begin{pmatrix} \omega^{-0\cdot 0} & \omega^{-0\cdot 1} \\ \omega^{-(2-1)\cdot 0} & \omega^{-(2-1)\cdot 1} \end{pmatrix} \\
&= \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & \omega^{-1} \end{pmatrix} \\
&= \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & e^{-i2\pi/2} \end{pmatrix} \\
&= \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}
\end{aligned}
$$

This is just a 1-qubit Hadamard gate.

2-qubit matrix

$$
\begin{aligned}
U_{QFT} &= \frac{1}{\sqrt{4}} \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & i^{-1} & i^{-2} & i^{-3} \\ 1 & i^{-2} & i^{-4} & i^{-6} \\ 1 & i^{-3} & i^{-6} & i^{-9} \end{pmatrix} \\
&= \frac{1}{2} \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & -i & -1 & i \\ 1 & -1 & 1 & -1 \\ 1 & i & -1 & -i \end{pmatrix}
\end{aligned}
$$

Implementation of n-qubit QFT

- Let’s implement an n-qubit QFT in our quantum computer simulator

Part V: Superconducting Qubit Hardware (Lecture)

- Use superconducting qubits as an example to show how initialization, readout, 1-qubit, and 2-qubit gates are possible

Role of Engineers in QC – My perspective

Tutorial 21

Semiconductor:

Physicist | **Engineer**

$$\frac{\partial B_{n'\mathbf{K}'}(t)}{\partial t} = -\frac{\mathrm{i}}{\hbar}\left\{\sum_{n\mathbf{K}} M_{nn'}(\mathbf{K},\mathbf{K}')B_{n\mathbf{K}}(t) + E_{B,n'}(\mathbf{K}')\,B_{n'\mathbf{K}'}(t)\right\}$$

$$\rightarrow$$

$$\mu_{\mathrm{dop}} = \mu_{\mathrm{min1}}\exp\left(-\frac{P_{\mathrm{c}}}{N_{\mathrm{A,0}}+N_{\mathrm{D,0}}}\right)$$

Scattering based on Fermi Golden Rule and Bloch Function
(David Esseni, "Nanoscale MOS Transistors")

Priceless

TCAD Analytical Equation
(Synopsys, Silvaco)

$100M/year

Quantum Computer:

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

$$\rightarrow$$

$$$

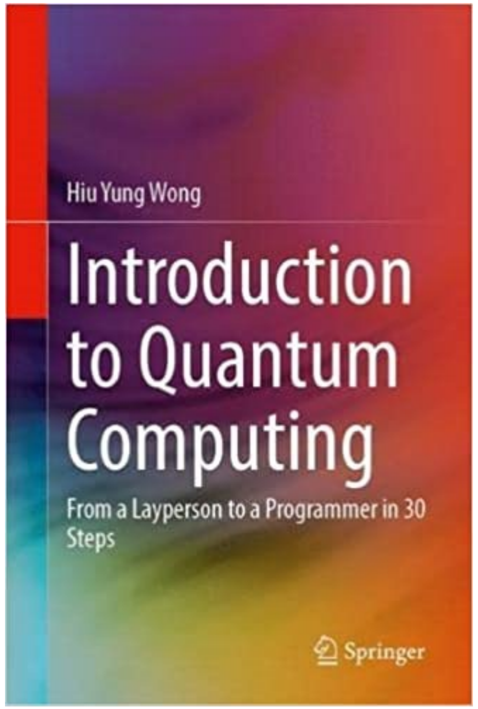
Jaynes-Cummings Hamiltonian
(Blais et al, PHYSICAL REVIEW A 69, 062320 (2004))

Analytical Equation (Your names, your companies)

There is plenty of room in the (eco-)System

Tutorial 21

Algorithm



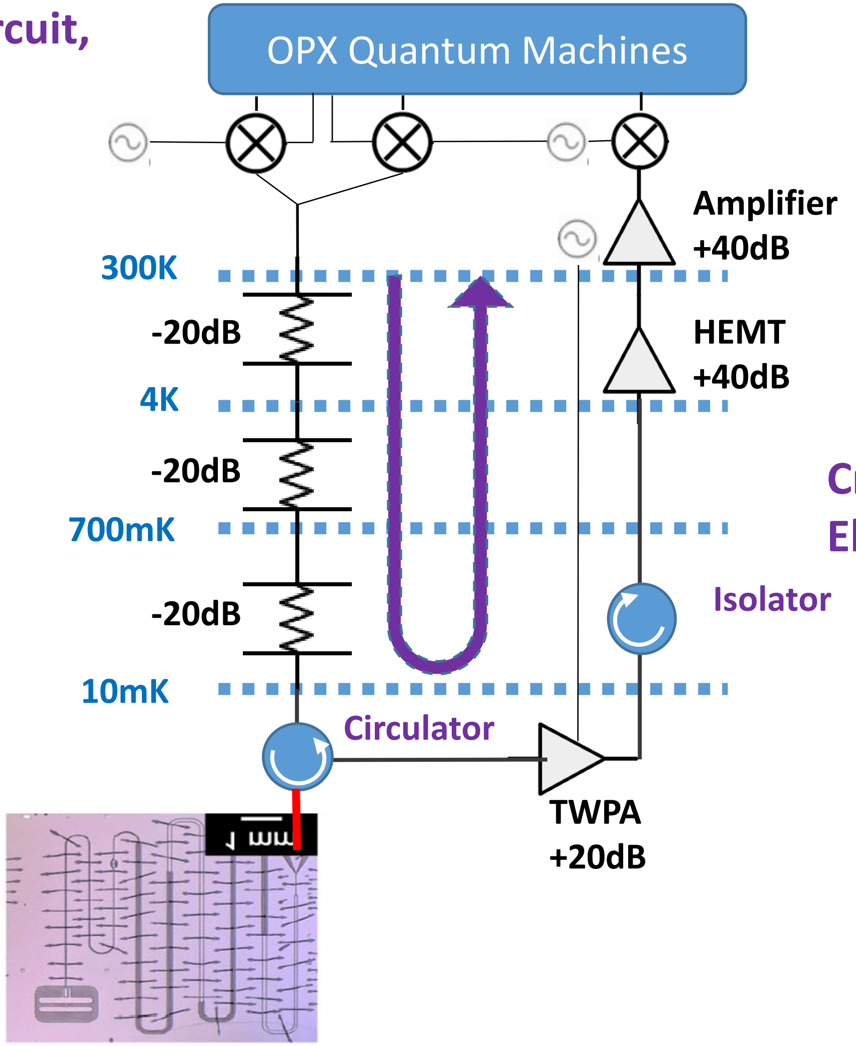
Education

High Speed Circuit, Programming

Microwave Engineering

Vacuum and cryogenic technologies

Qubit Physics



Cryogenic Electronics

DiVincenzo’s Criteria

- 5 Necessary Criteria for quantum computing:
  - A scalable physical system with well-characterized qubit (**system needs to remain in the 2-level subspace**)
  - 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 work 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 with one bit stationary and one bit flying**)
  - The ability to faithfully transmit flying qubits between specified locations (**without decoherence**)

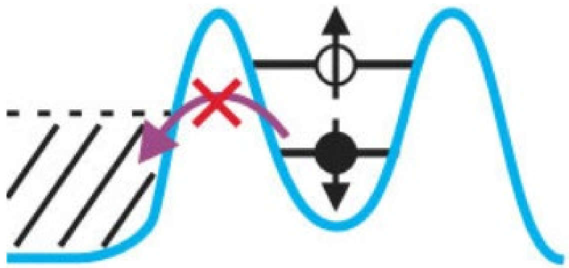
Implementations of Qubits

Tutorial 21

$$|Mood\rangle = \alpha|☺\rangle + \beta|☹\rangle$$

Not a reliable qubit

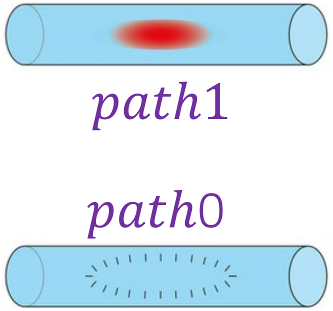
Electron Spin Qubit



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

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

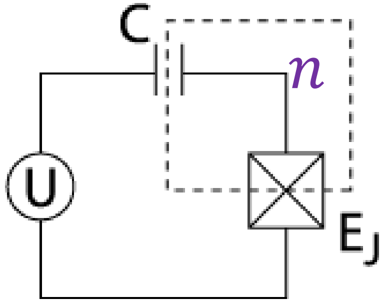
Photonic Qubit



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

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

Superconducting Charge Qubit



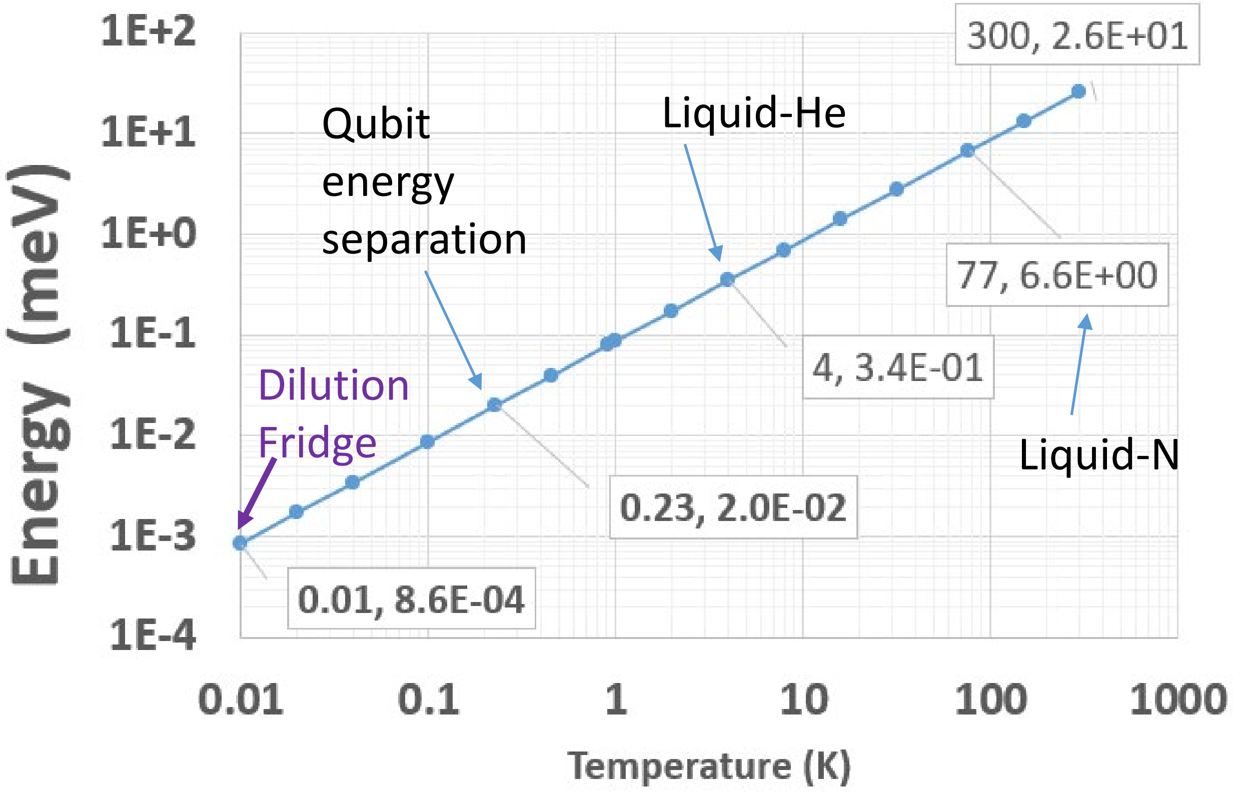
$$|\psi\rangle = \alpha|n = 0\rangle + \beta|n = 1\rangle$$

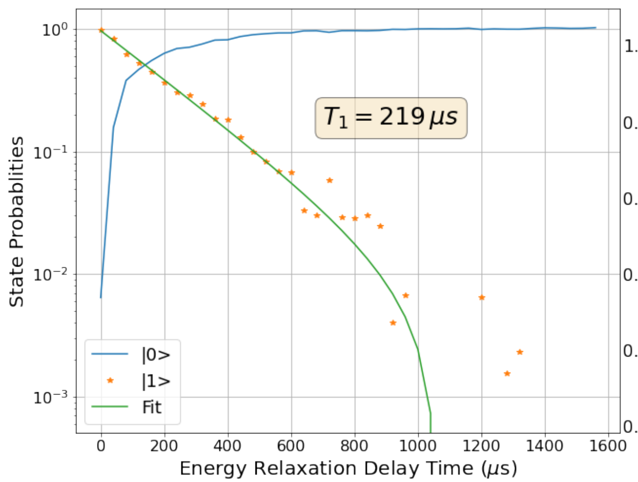
Wikipedia

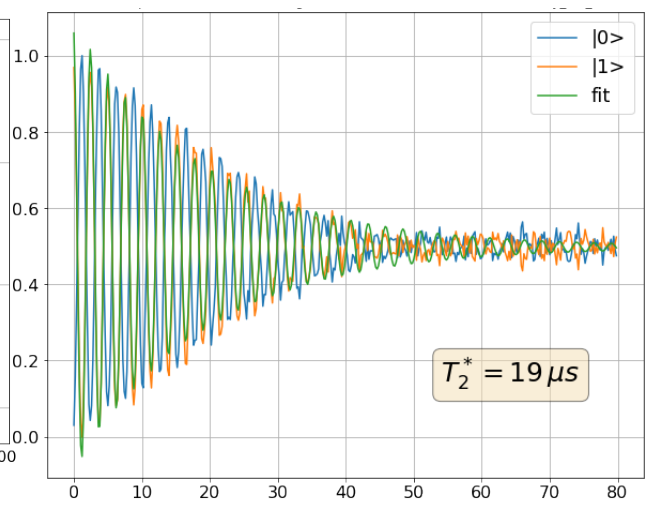
Noise, De-coherence Time and Energy Scale

Tutorial 21

- 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: $|0\rangle + |1\rangle \Rightarrow ? |0\rangle ? |1\rangle$



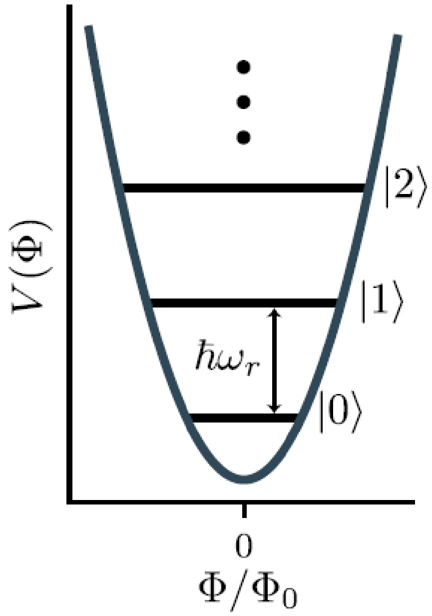


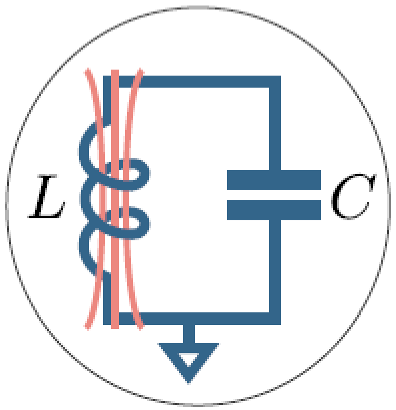


Why not LC Tank?

Blais et al, Review of Modern Physics (2021)

Tutorial 21

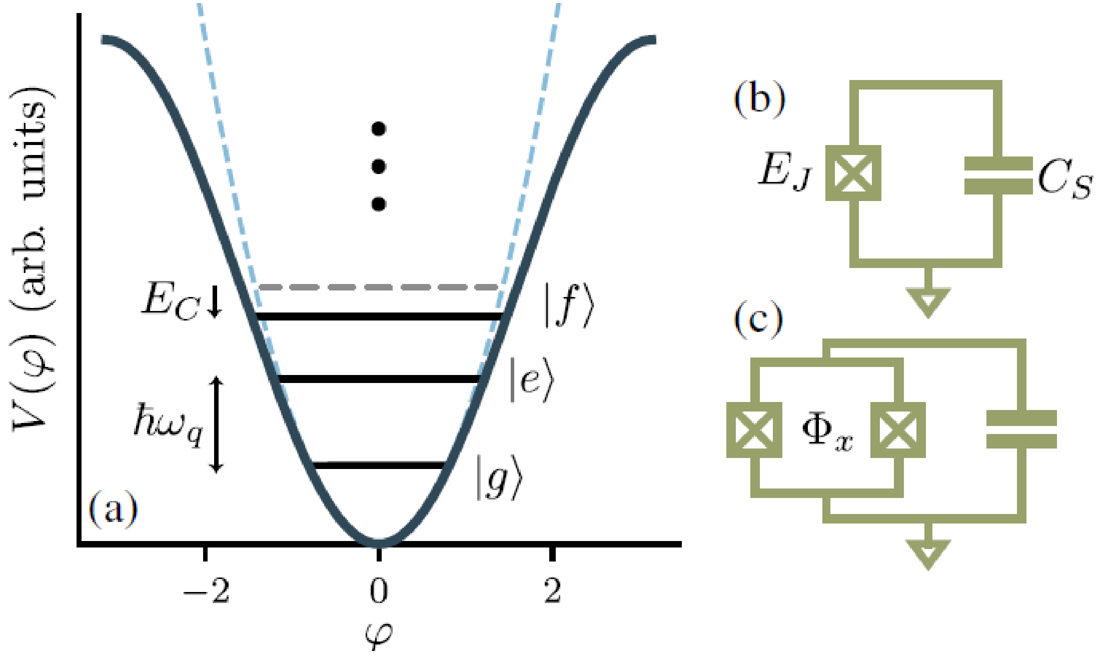




$$H_{LC} = \frac{Q^2}{2C} + \frac{1}{2}C\omega_r^2\Phi^2$$ Lack of anharmonicity

Generalized momentum: Q

Generalized Coordinate: Φ

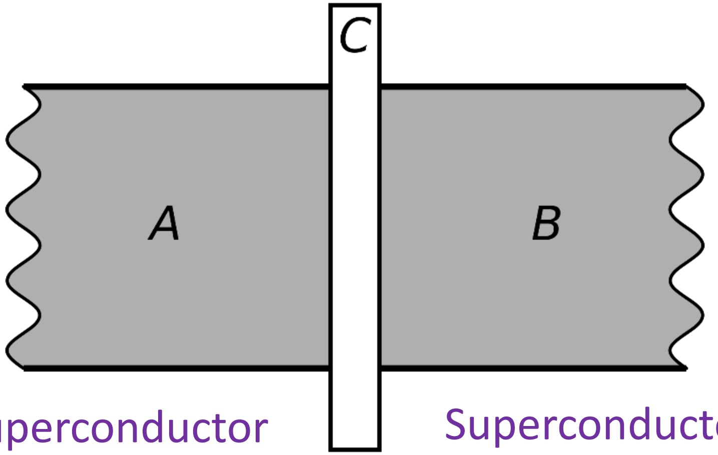


- Charge qubit
- Transmon qubit when E_C<<E_J (less sensitive to charge noise, n_g)

Josephson Junction

Wiki

Tutorial 21



Superconductor
Al

Superconductor
Al

Insulator
(Al_2O_3)

Josephson Equations

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

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

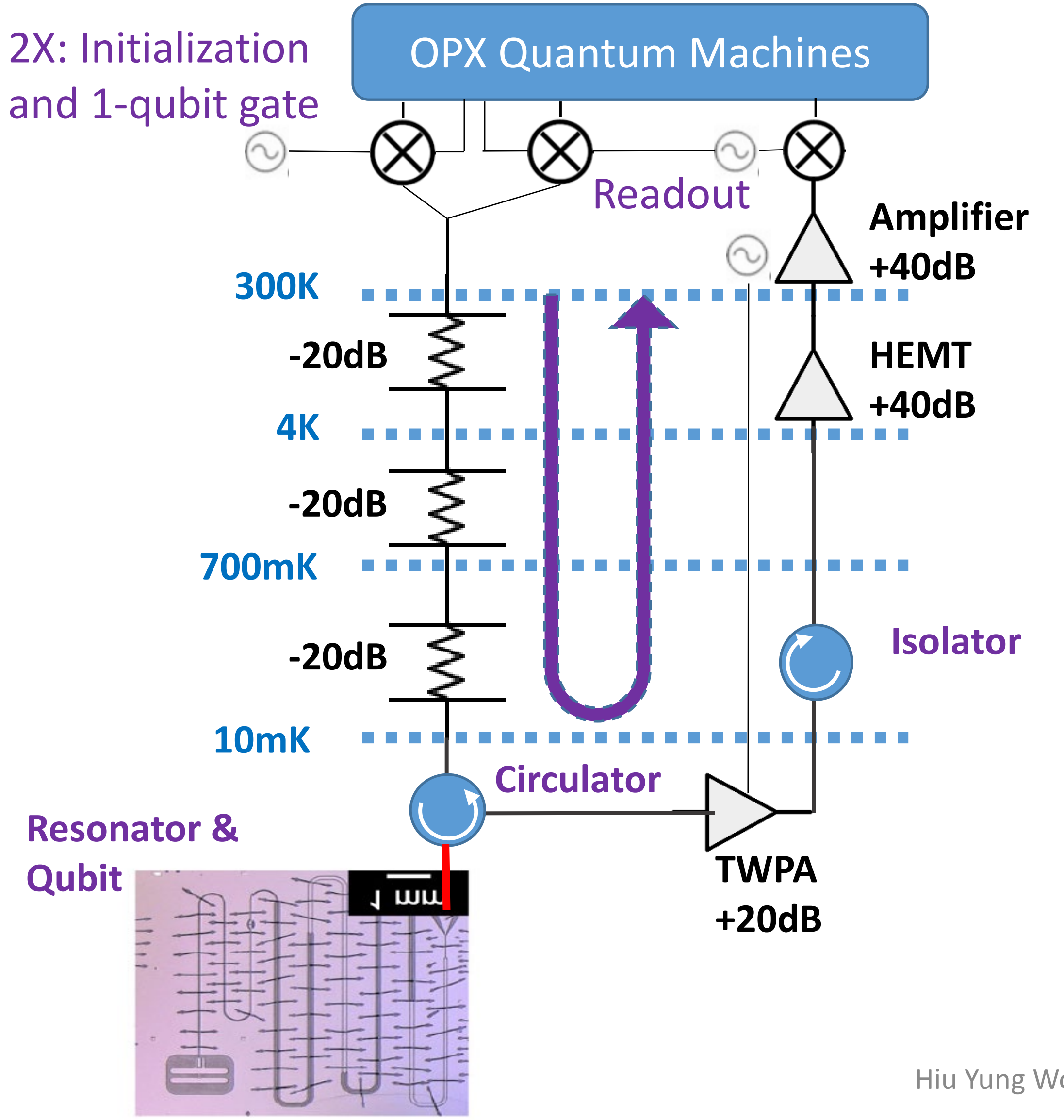
Nonlinear Inductance

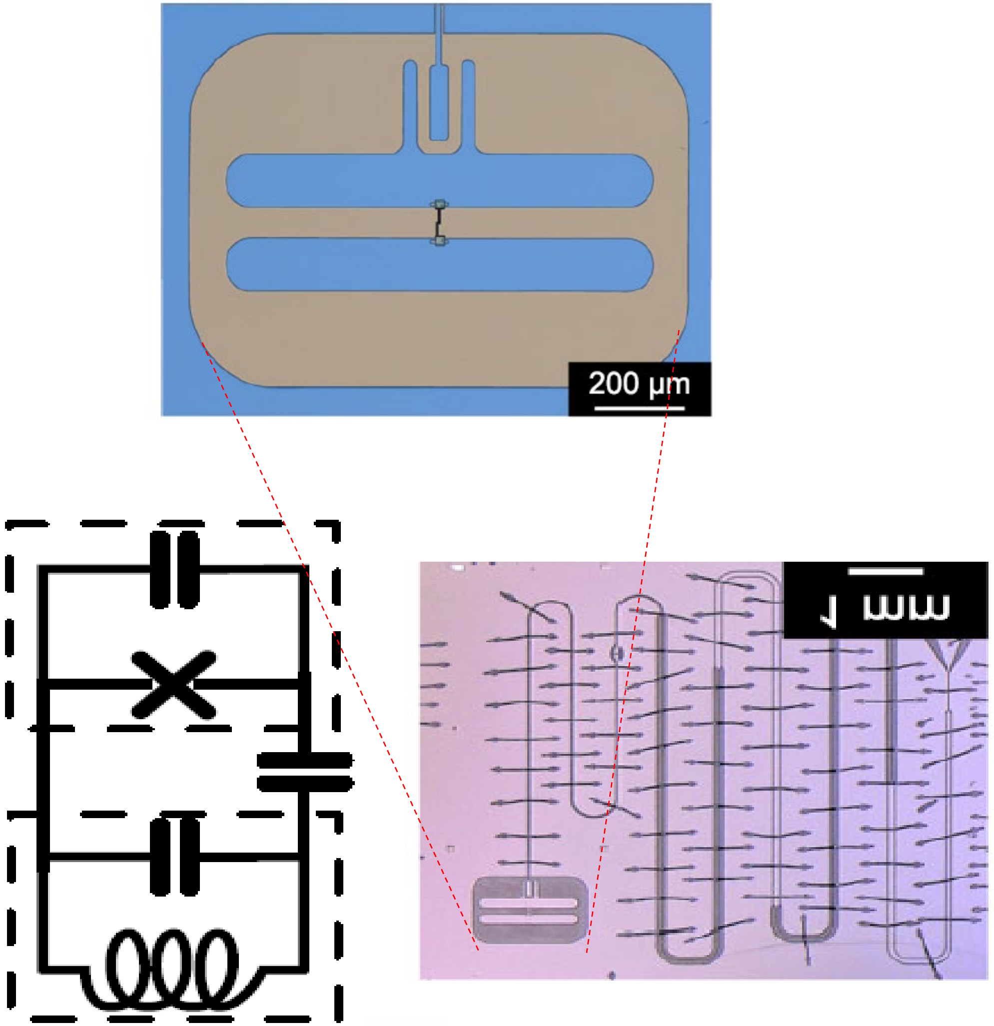
$$L(\varphi) = \frac{\Phi_0}{2\pi I_c \cos\varphi} = \frac{L_J}{\cos\varphi}.$$

Josephson Energy

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

System Overview

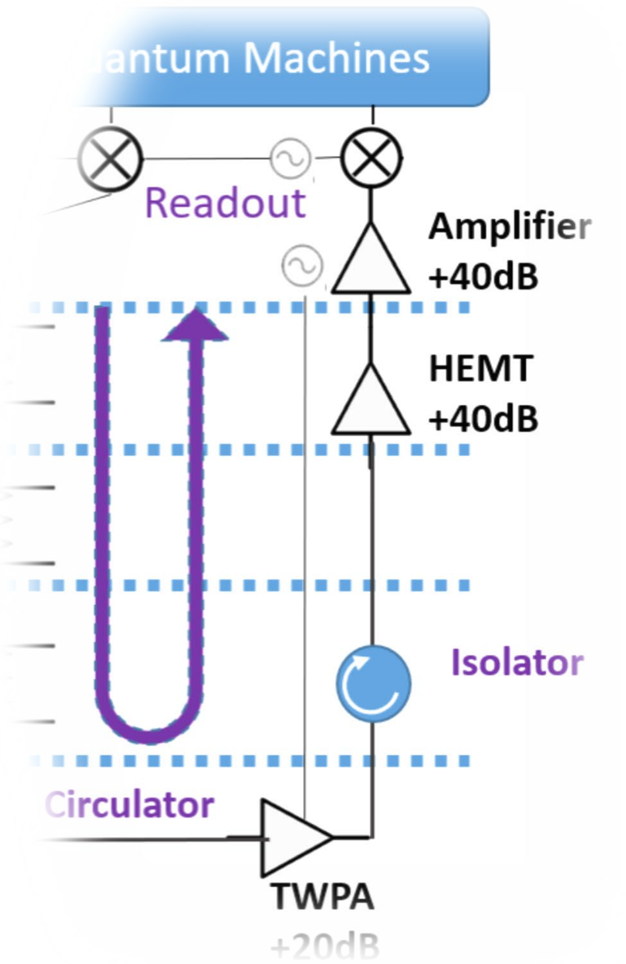




A. Place, et al., Nat. Comm 12, 1779 (2021)

SJSU SAN JOSÉ STATE UNIVERSITY

Signal Amplification and Noise



Friis' Equation

$$NF_{tot} = 1 + (NF_1 - 1) + \frac{NF_2 - 1}{A_{P1}} + \cdots + \frac{NF_m - 1}{A_{P1} \cdots A_{P(m-1)}}$$

Reminder:

$$\mathrm{NF}|_{\mathrm{dB}} = 10 \log \frac{SNR_{in}}{SNR_{out}}.$$

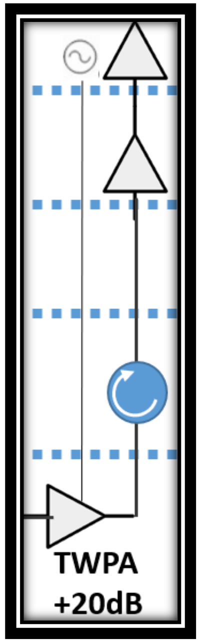
$$P(dB) = 10 \log_{10} \frac{P(W)}{1W} \qquad P(dBm) = 10 \log_{10} \frac{P(W)}{1mW}$$

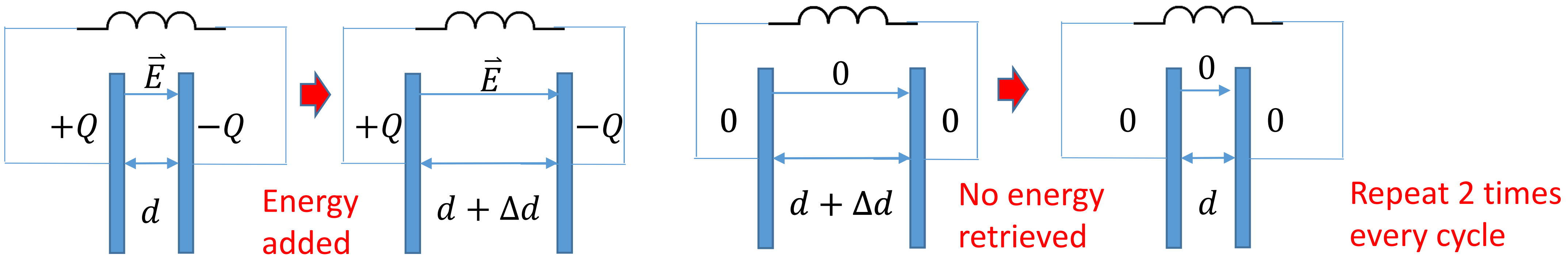
$$G(dB) = 20 \log_{10} G$$

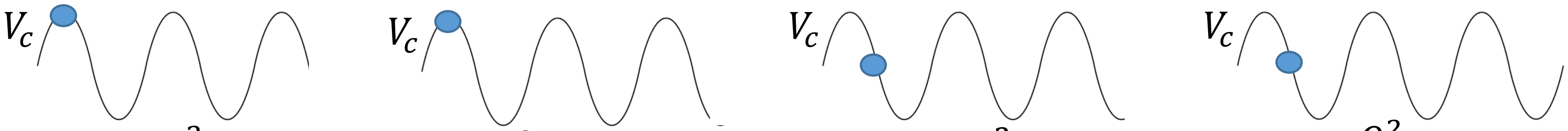
Numerical Example:

T	Signal (dBm)	Noise (dBm)	SNR (dB)
0.01	-9.28E+01	-1.03E+02	9.901334E+00
1.5	-5.28E+01	-6.27E+01	9.896553E+00
54	-1.28E+01	-2.27E+01	9.896535E+00

Parametric Amplifier







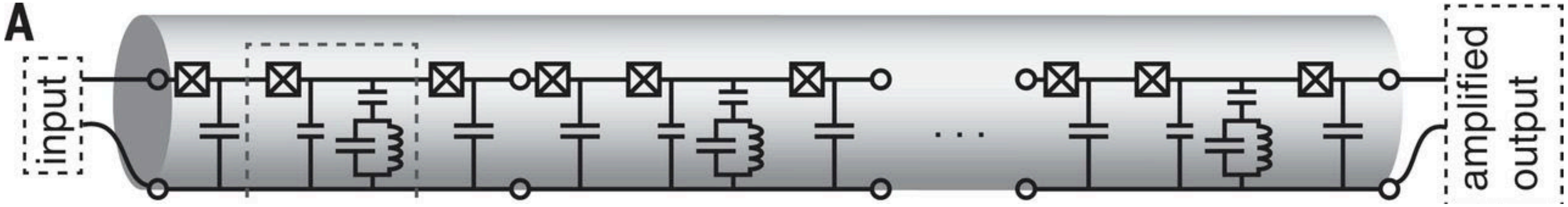
$$E = \frac{Q^2}{2C}, C = \frac{\varepsilon}{d}$$

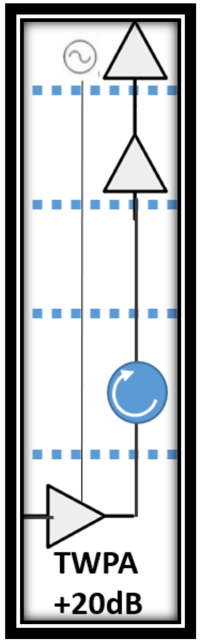
$$E = \frac{Q^2}{2C}, C = \frac{\varepsilon}{d + \Delta d}$$

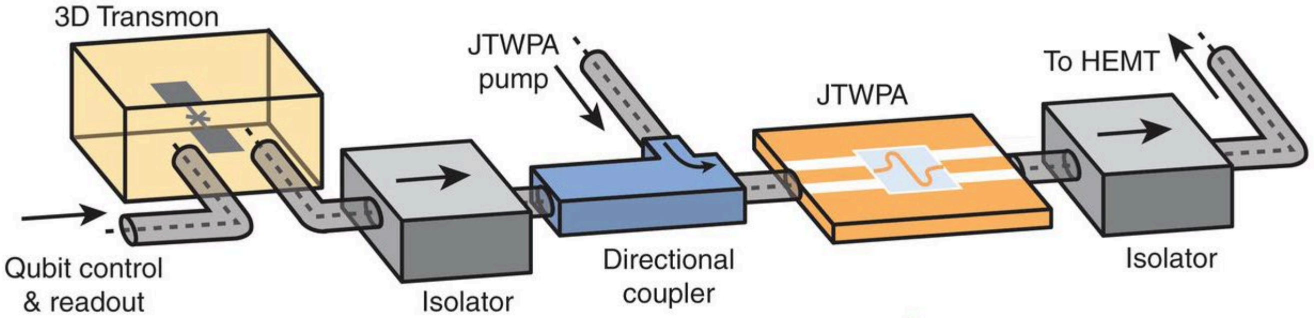
$$E = \frac{Q^2}{2C} = 0$$

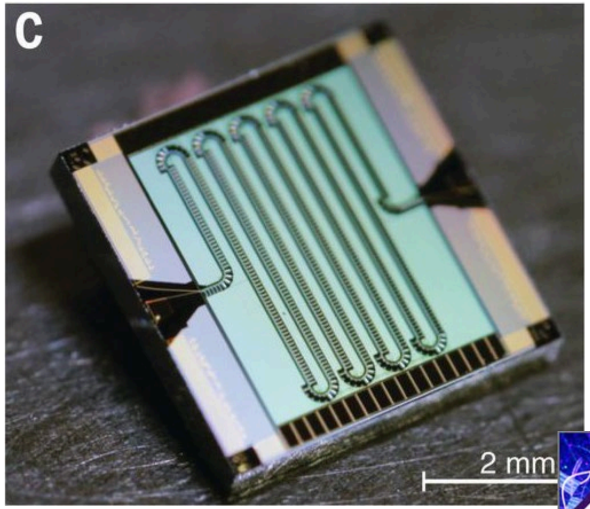
$$E = \frac{Q^2}{2C} = 0$$

Traveling Wave Parametric Amplifier









Add minimum noise to the signal (Quantum Limited Amplifier)
Noise source: Uncertainty Principle

C. Macklin et al., "A near–quantum-limited Josephson traveling-wave parametric amplifier", Science, 2015

Discrete Cryo HEMT LNA

1st stage: Input matching and low noise

3rd stage: Gain flatness and output match

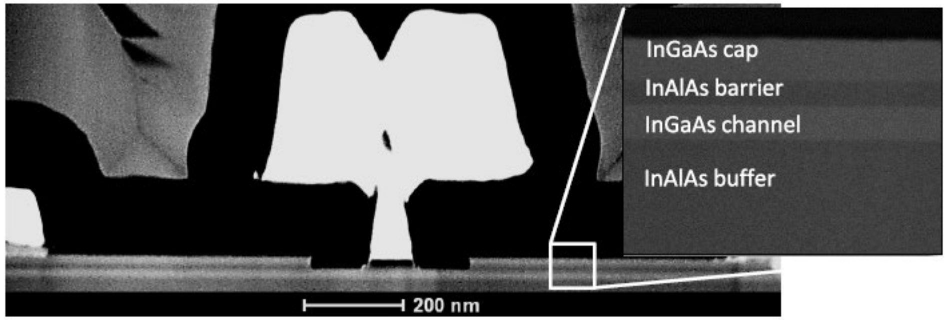


Fig. 1. Cross-sectional STEM HAADF image of 100 nm InP HEMT fabricated in this paper. Epitaxial layers consisted of, from the top to the bottom, an InGaAs cap layer, an InAlAs barrier including δ-doping and spacer,

4860 IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 66, NO. 11, NOVEMBER 2018

0.3–14 and 16–28 GHz Wide-Bandwidth Cryogenic MMIC Low-Noise Amplifiers

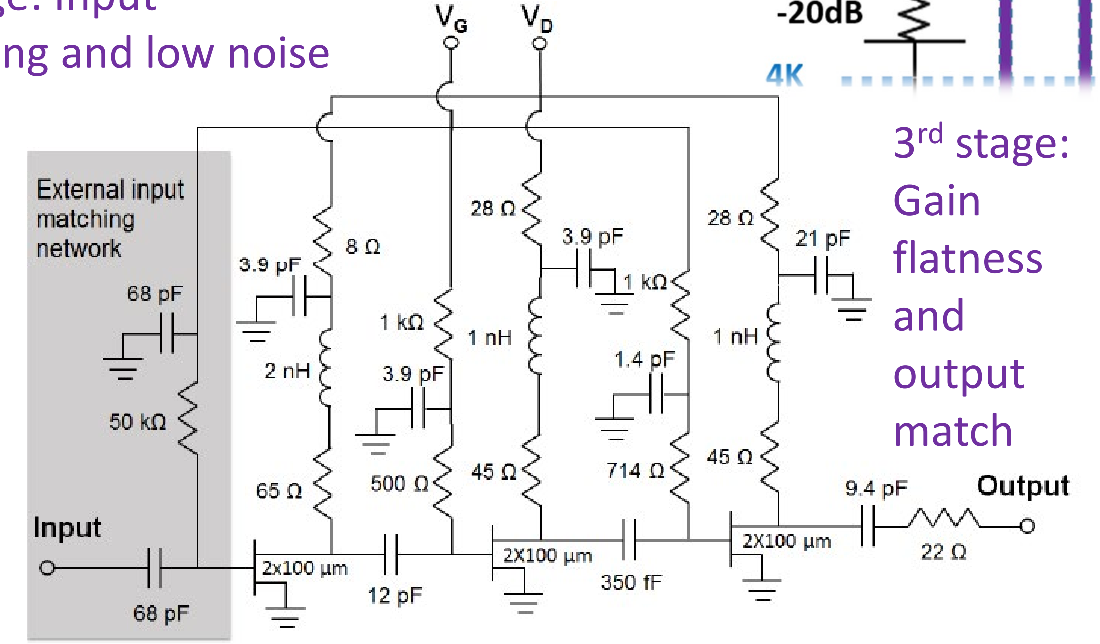


Fig. 8. Schematic of the 0.3–14 GHz MMIC LNA.

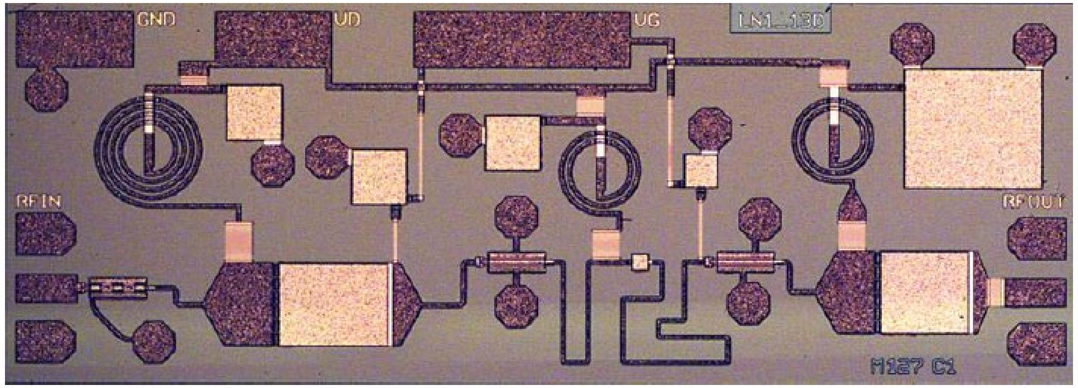
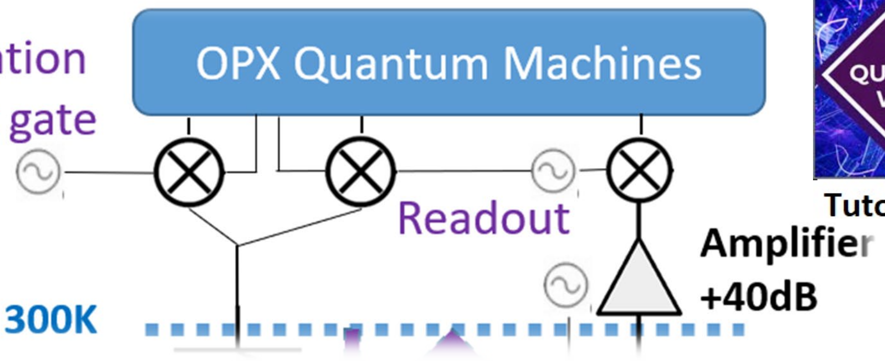


Fig. 9. 0.3–14 GHz LNA photograph. The chip size is 2×0.75 mm.

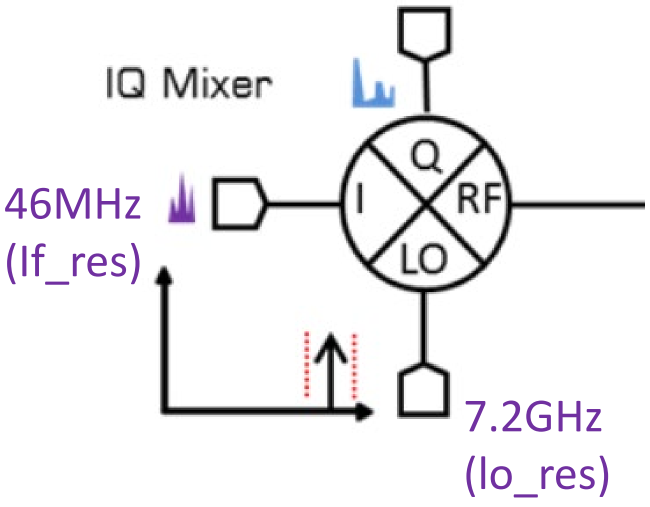
I-Q Mixers

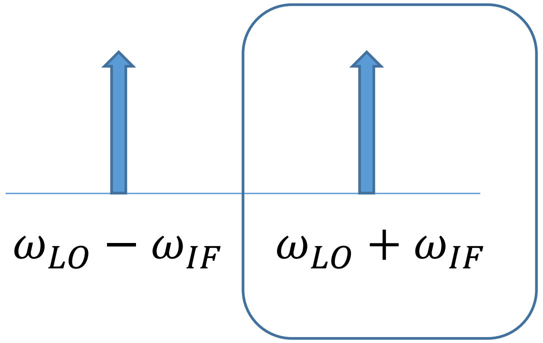
Tutorial 21

2X: Initialization and 1-qubit gate



$$A\cos(2\pi f t+\phi)$$
$$= A\cos(2\pi f t)\cos(\phi)\text{-}A\sin(2\pi f t)\sin(\phi)$$
$$= A\cos(\phi)\cos(2\pi f t)\text{-}A\sin(\phi)\sin(2\pi f t)$$
$$= I\cos(2\pi f t)\text{-}Q\sin(2\pi f t)$$





1 qubit gate: to be discussed later

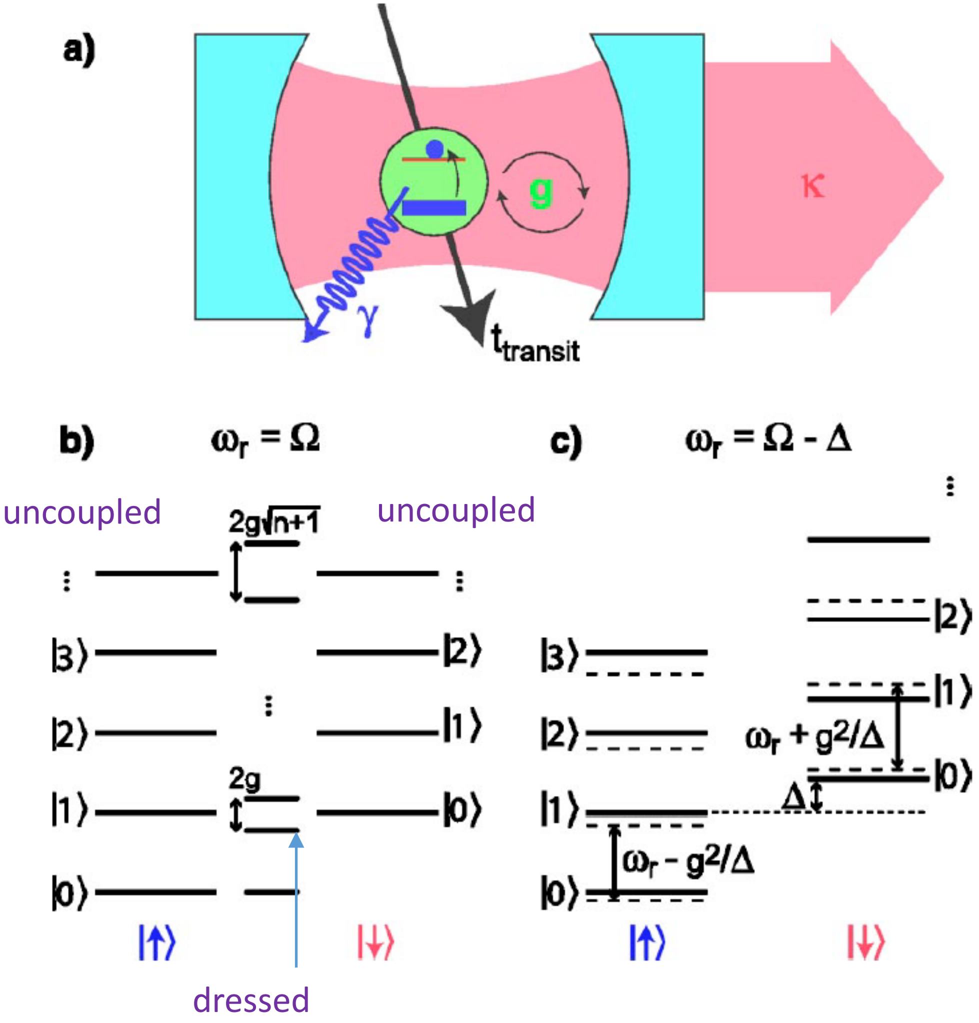
Single-side band mixer Enabled by proper engineering of the I/Q signal

$$H=-\frac{\boxed{\Delta}}{2}\sigma_z+\frac{\boxed{\Omega_R}}{2}(\cos\boxed{\phi}\,\sigma_x+\sin\boxed{\phi}\,\sigma_y)$$

$$\Delta=\omega_{01}-(\omega_{LO}+\omega_{IF})$$
$$\Omega_R\sim A$$

https://www.markimicrowave.com/blog/the-why-and-when-of-iq-mixers-for-beginners/

Cavity QED



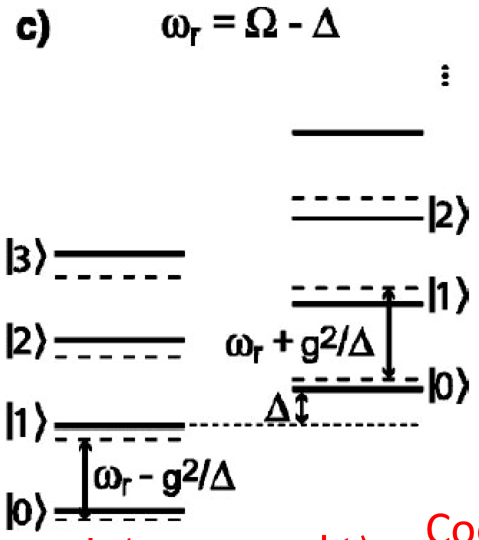
$$H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\Omega}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + \sigma^+ a) + H_\kappa + H_\gamma.$$

- ω_r: Cavity resonant frequency
- Ω: Atom transition frequency
- g: atom-photon coupling strength
- Δ: detuning (Ω-ω_r)

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

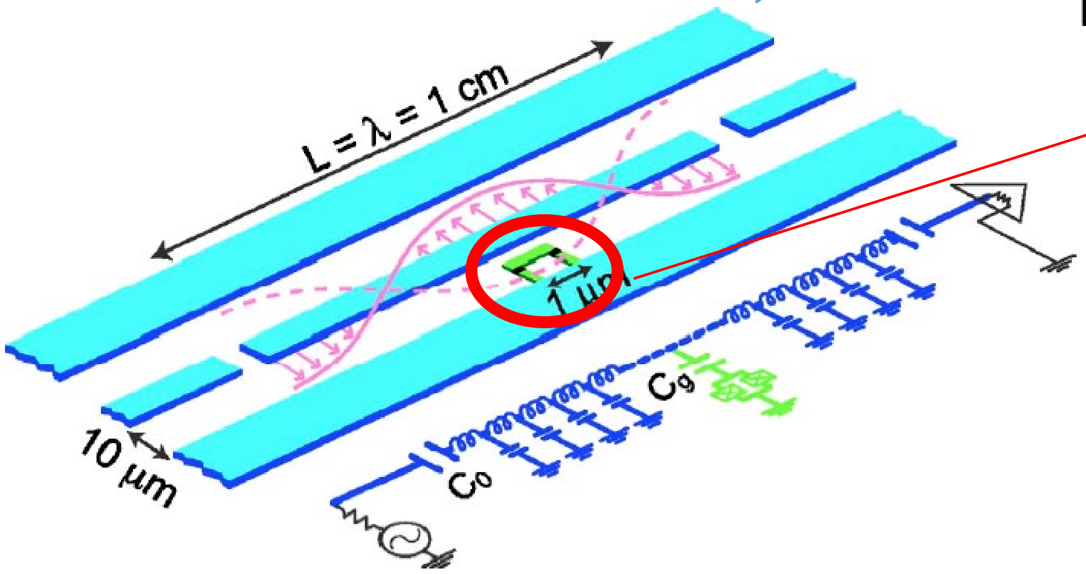
Circuit QED

Resonator as Cavity



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

Cooper Pair Box:
Artificial Atom



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

$|1\rangle_{ph}|0\rangle_{charge}$: $\omega_r - \dfrac{g^2}{\Delta}$

$|0\rangle_{ph}|1\rangle_{charge}$: $\Omega + \dfrac{2g^2}{\Delta}$ Suppressed

Apply a pulse

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

$|1\rangle_{ph}|2\rangle_{charge}$: $\omega_r - \Delta - \dfrac{3g^2}{\Delta}$ Suppressed

$|1\rangle_{ph}|1\rangle_{charge}$: $\omega_r + \dfrac{g^2}{\Delta}$

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

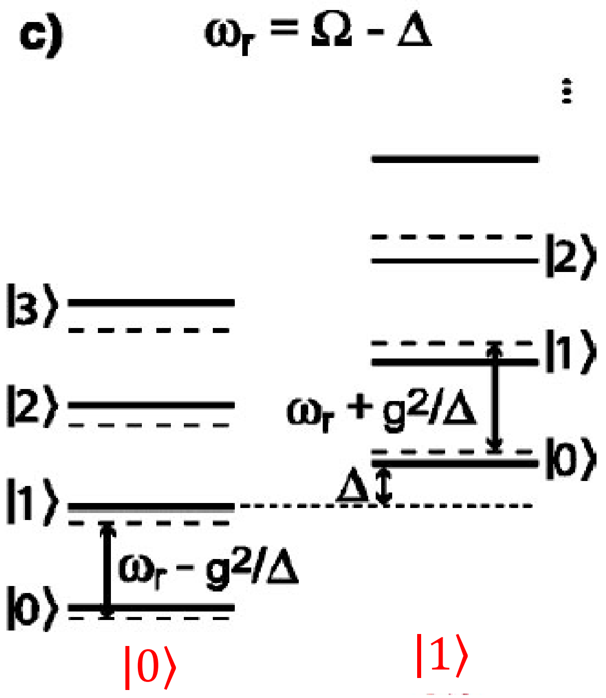
Tutorial 21

Cross Kerr

Cross-Kerr, $\chi = \frac{g^2}{\Delta}$, signifies how much the cavity resonant frequency is "pulled". This is only valid with large $E_C/\hbar >> \Delta$ (but charging energy usually is smaller than detuning).

More accurate one:

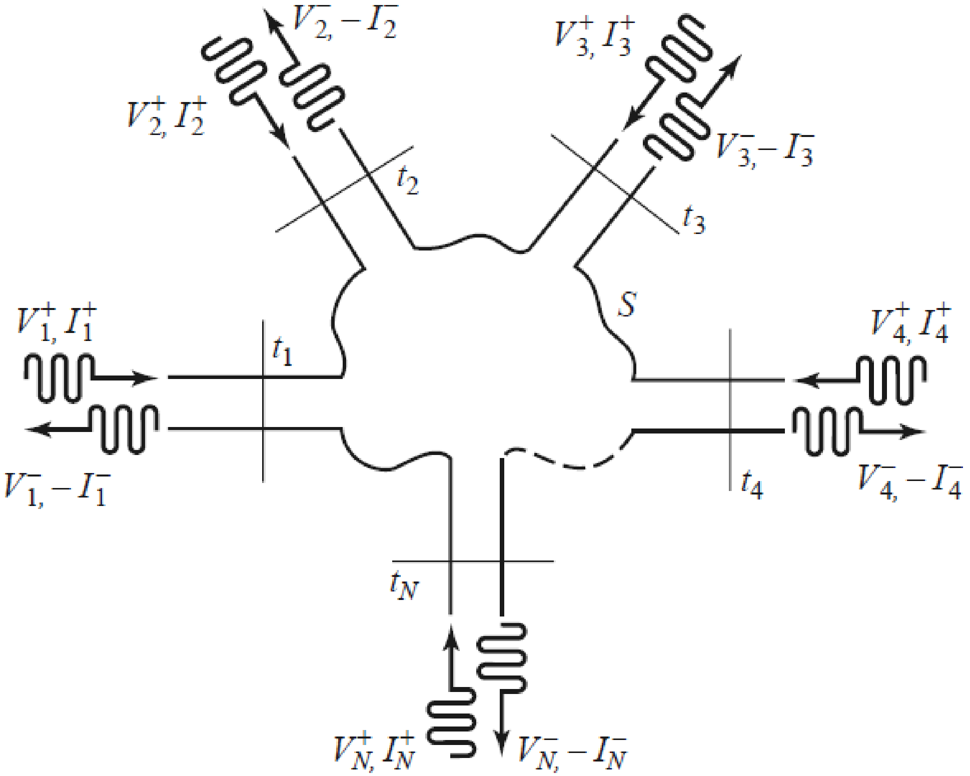
$$\chi = -\frac{g^2 E_C/\hbar}{\Delta(\Delta - E_C/\hbar)}$$



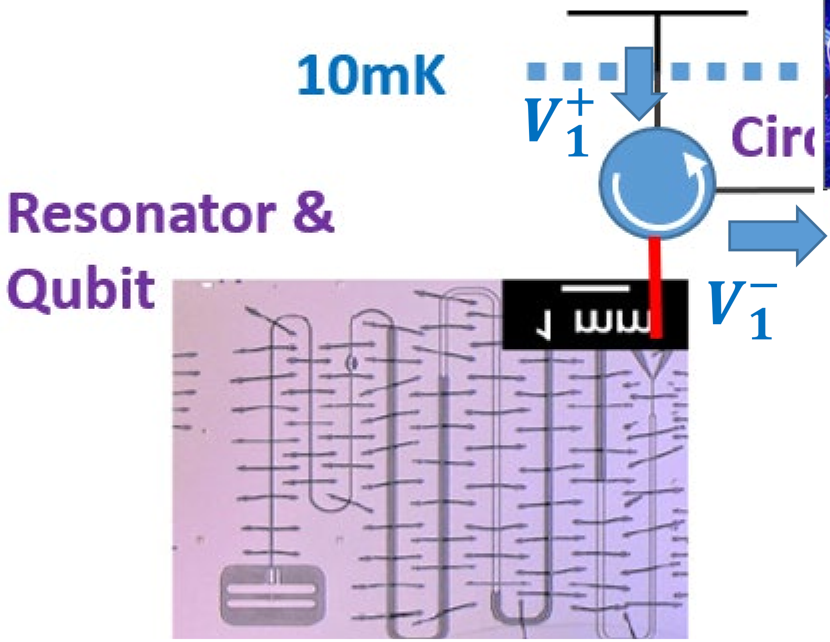
Rev. Mod. Phys., Vol. 93, No. 2, April–June 2021

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

Scattering Matrix



Pozar's Book



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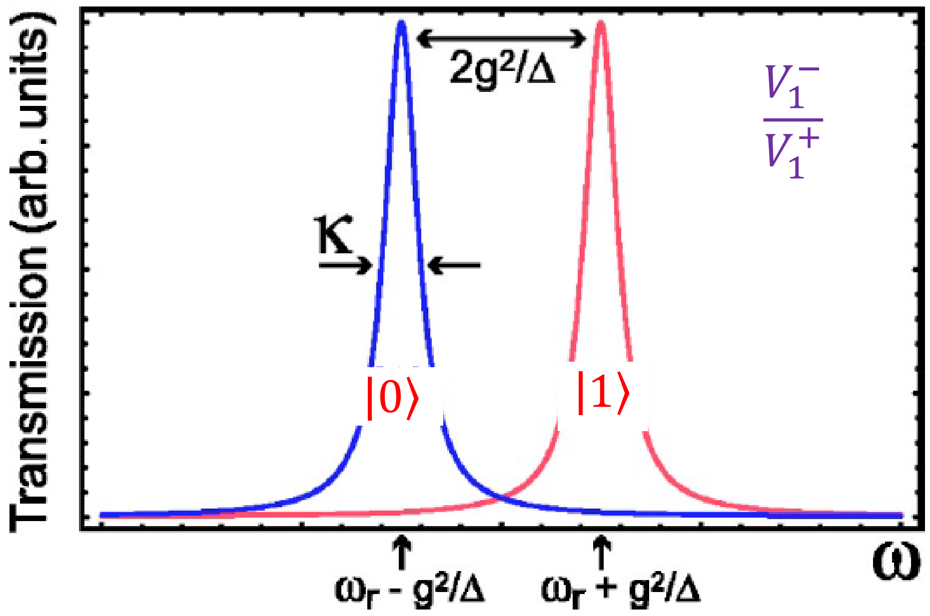
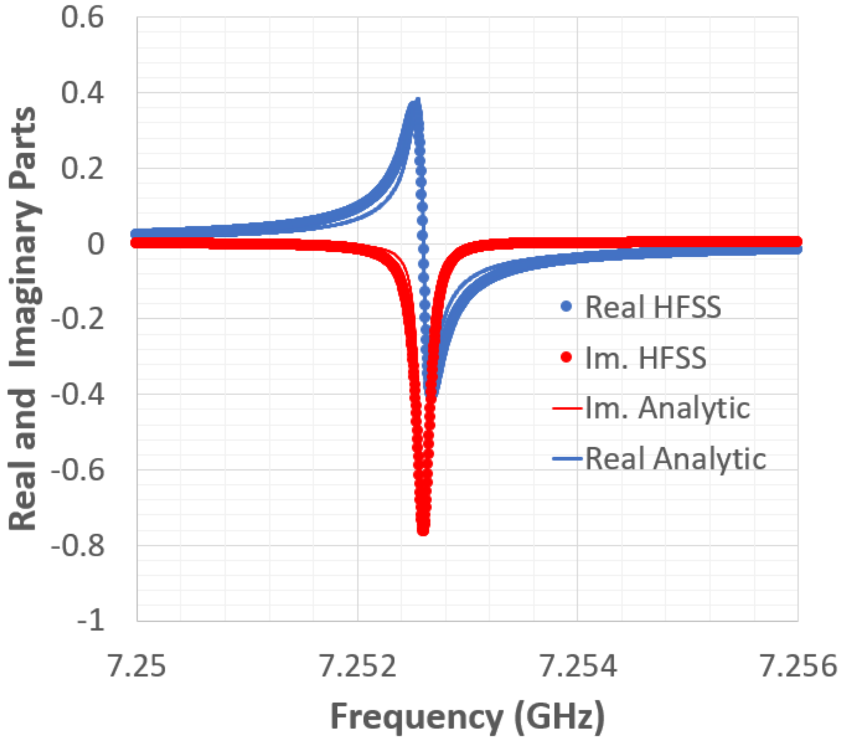
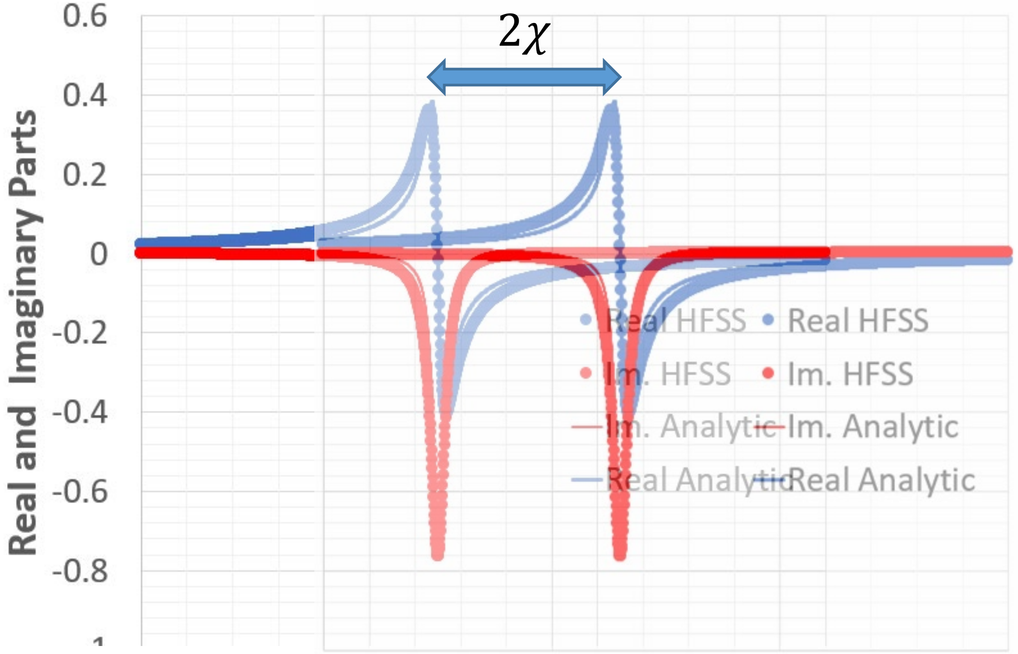


Phys. Rev. A 69, 062320 (2004)

Scattering Matrix





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

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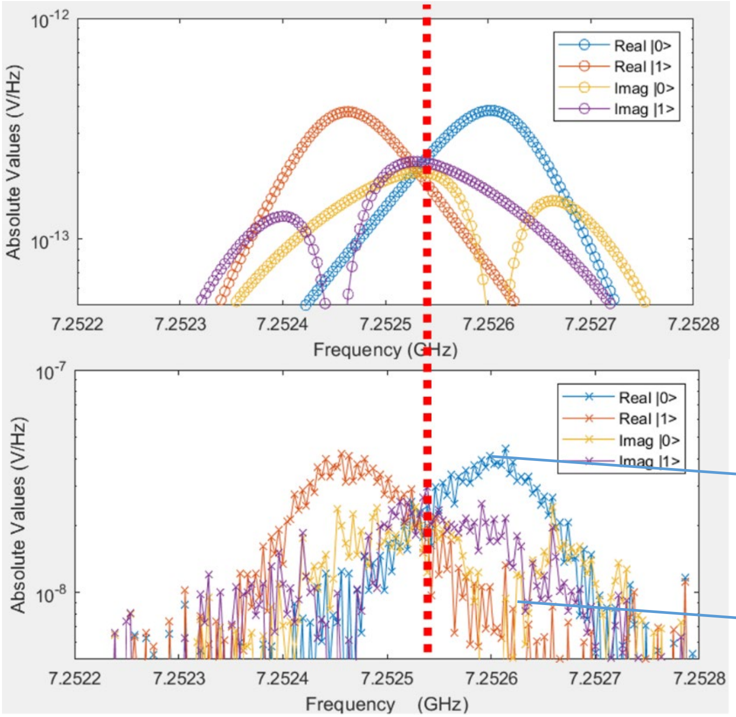
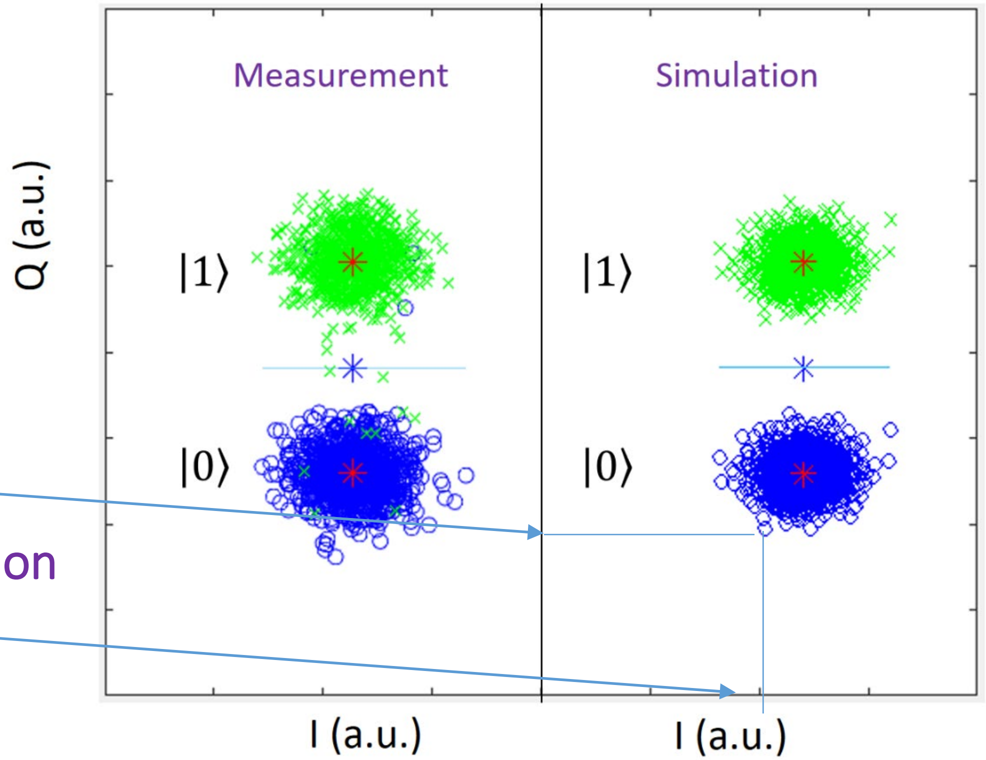


After transformation

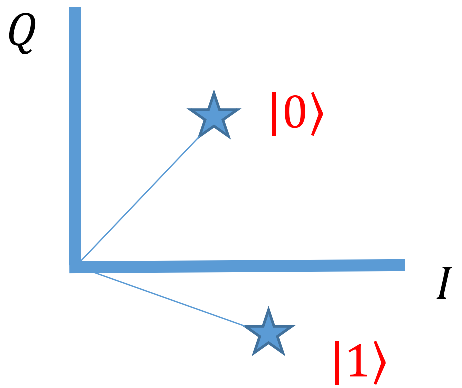


Hiu Yung Wong et al., "A Simulation Methodology for Superconducting Qubit Readout Fidelity," SSE, 2023.

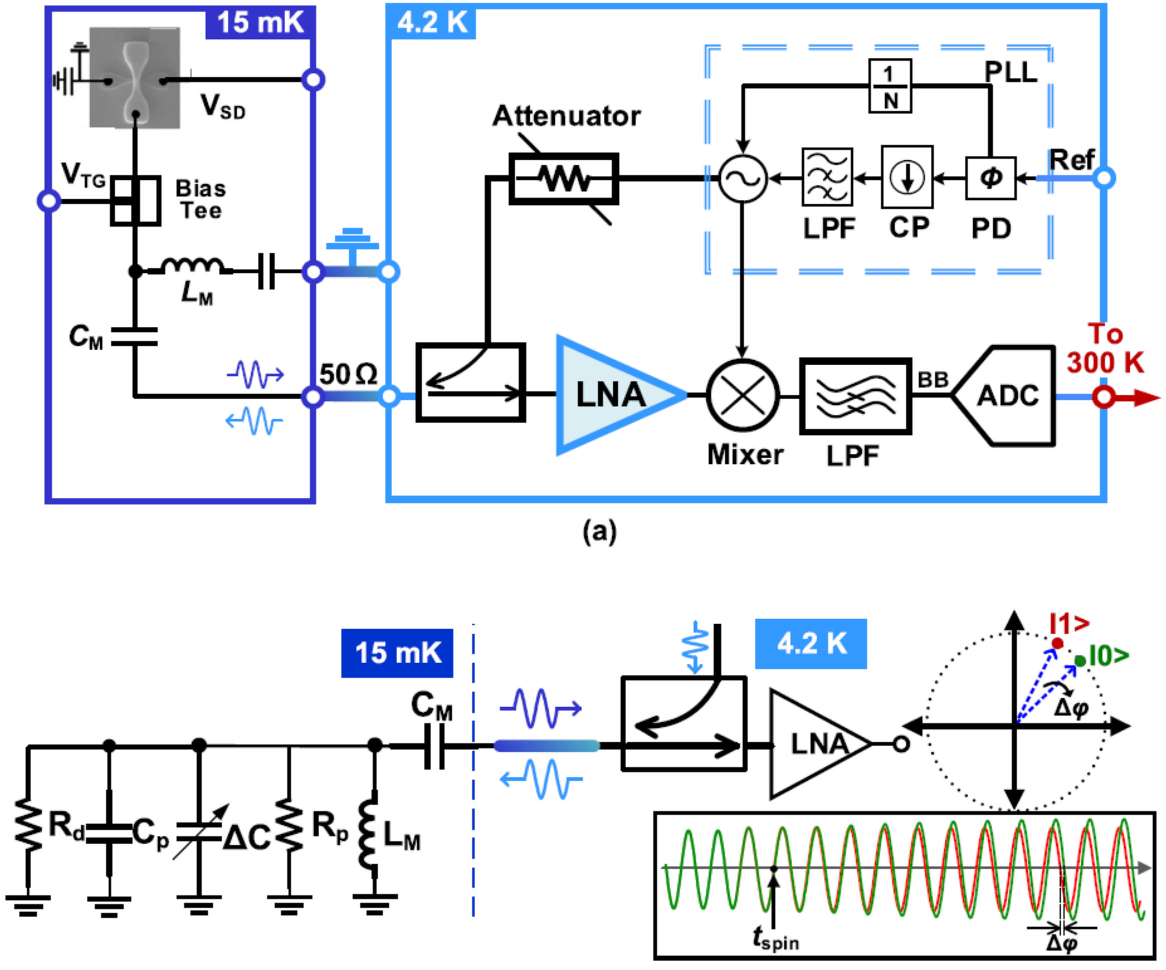
IQ Signal for Reading

$$
\begin{aligned}
&A\cos(2\pi f t+\phi)\\
&= A\cos(2\pi f t)\cos(\phi)\text{-}A\sin(2\pi f t)\sin(\phi)\\
&= A\cos(\phi)\cos(2\pi f t)\text{-}A\sin(\phi)\sin(2\pi f t)\\
&= I\cos(2\pi f t)\text{-}Q\sin(2\pi f t)
\end{aligned}
$$

$$\tan(\phi) = -\frac{Q}{I}$$



Si QDOT qubit reading



(a)

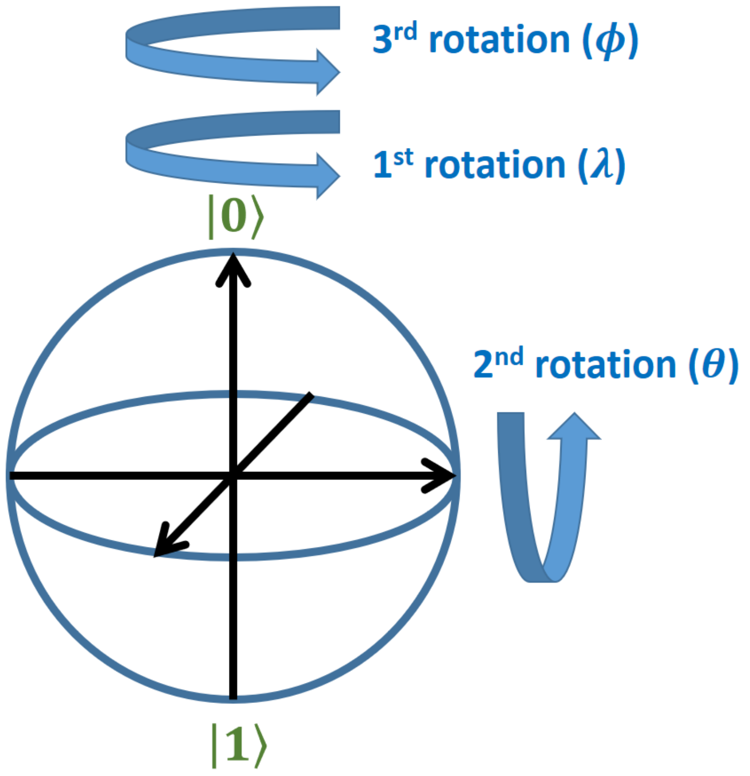
(b)

IEEE JSSC, vol. 56, no. 7, pp. 2040-2053, July 2021

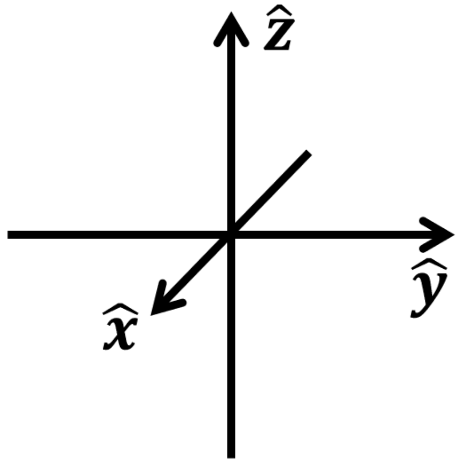
Single Qubit Gate

Tutorial 21

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

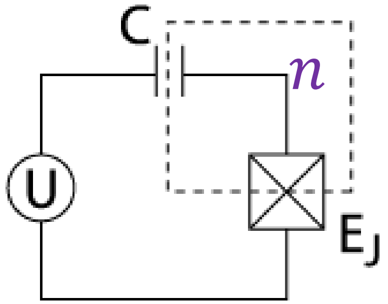


Real 3D Space Coordinate



Implementation of Single Qubit Gates

Superconducting Charge Qubit

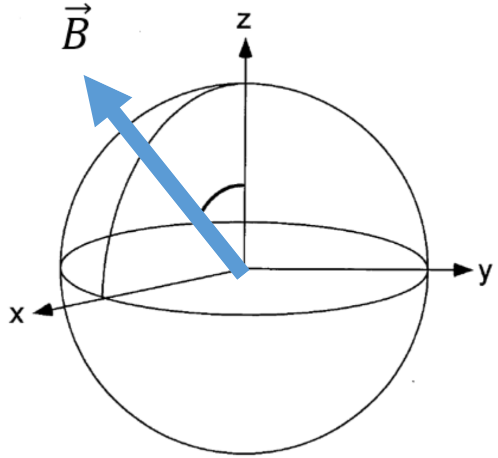


$$|\psi\rangle = \alpha|n=0\rangle + \beta|n=1\rangle$$

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)

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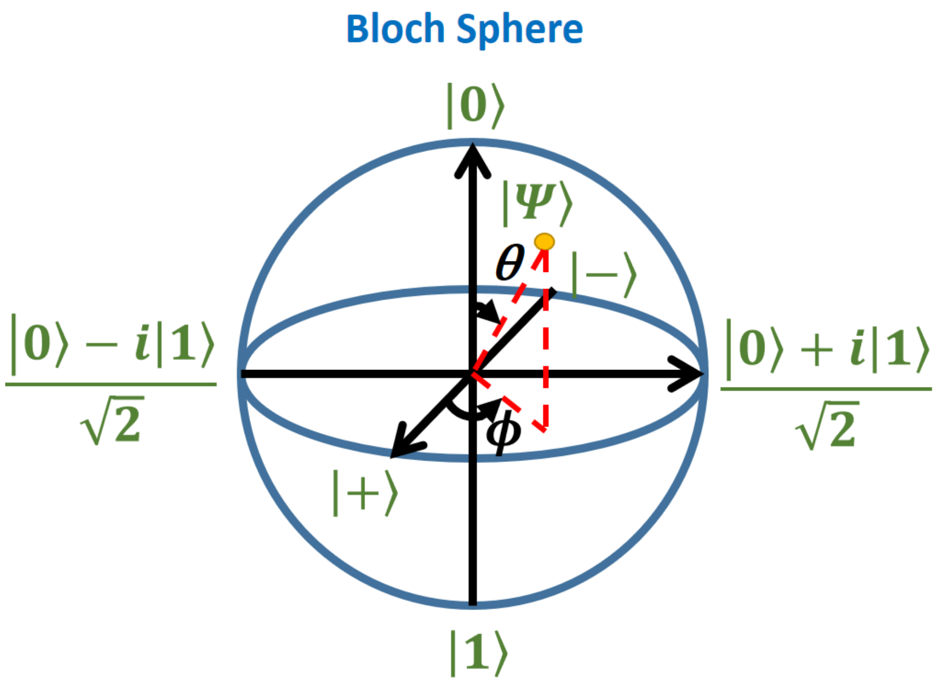
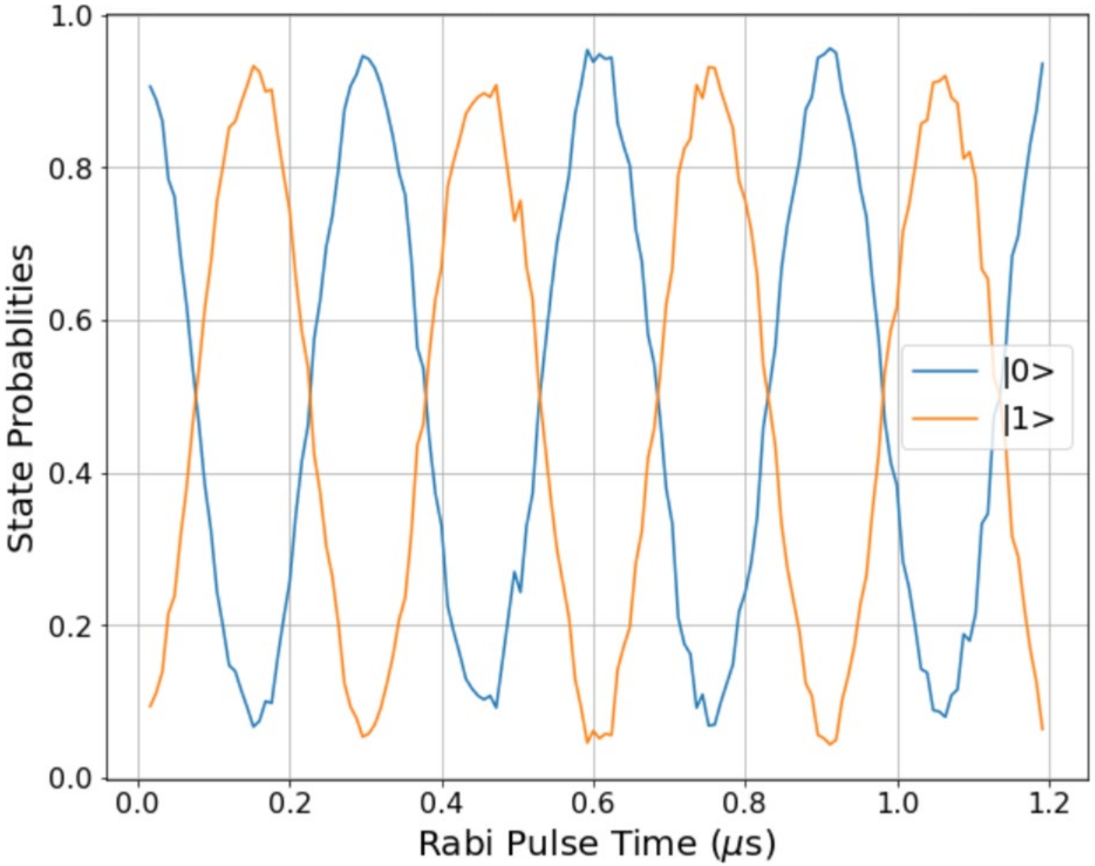
Different frequencies of the microwave pulse cause the rotation about different axes in the x-z plane.



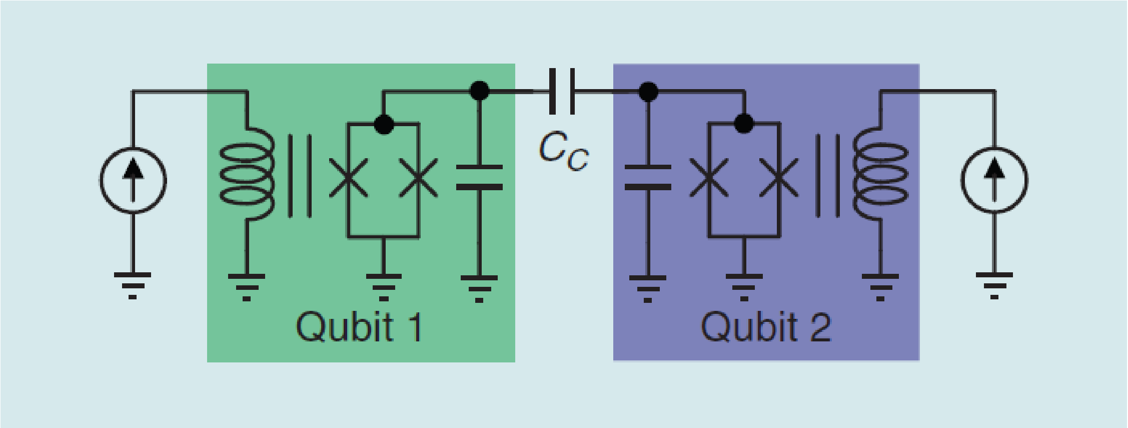


iSWAP Gate – 2-qubit gate

iSWAP Gate for entanglement operation

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

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



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?

Tutorial 21

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

$$|\Psi\rangle = a_0 |00\cdots 0\rangle + a_1 |00\cdots 1\rangle + \cdots + a_{2^n-1} |11\cdots 1\rangle$$

- 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 computers but can be a very powerful accelerator for difficult problems, e.g. optimization problems.

Part VI: Optimizing Qubit Readout Using HFSS with Qiskit Metal (Demo)

- Show how to combine Qiskit Metal and HFSS to design the circuit of a quantum qubit in terms of Energy Participation Ratio

Learning Outcomes and Materials

- Appreciate the role of high-speed electronics, microwave electronics, and cryogenic electronics in quantum computer

- See the last 10 videos (Lab 1 to Lab 10) for installation instructions
    - https://www.youtube.com/playlist?list=PLnK6MrIqGXsL1KShnocSdwNSiKnBodpie

Energy Participation Ratio

npj | Quantum Information

www.nature.com/npjqi

ARTICLE OPEN

Check for updates

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Tutorial 21

Energy-participation quantization of Josephson circuits

Zlatko K. Minev[1,4✉], Zaki Leghtas[1,2], Shantanu O. Mundhada[1,5], Lysander Christakis[1,6], Ioan M. Pop[1,3] and Michel H. Devoret[1]

- Reduced the quantization problem to "what fraction of the energy mode *m* is stored in element *j*?
- Energy participation ratio: p_{mj}
- Use eigenmode simulation in HFSS

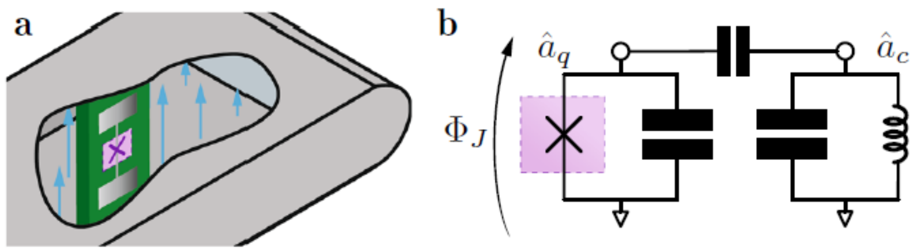

Fig. 2 Quantizing a simple circuit. a Illustration of a 3D cavity enclosing a transmon qubit chip. The cross symbol marks the location of a Josephson junction. Vertical blue arrows depict the electric field $\vec{E}_m(\vec{r})$ of the fundamental cavity mode, TE_{101}. **b** Equivalent two-mode lumped-element representation of the distributed circuit. Operators $\hat{a}_q$ and $\hat{a}_c$ denote the qubit and cavity mode operators, respectively.

$$\hat{H}_{\text{full}} = \hat{H}_{\text{lin}} + \hat{H}_{\text{nl}} ,$$

$$\hat{H}_{\text{lin}} = \hbar\omega_c \hat{a}_c^\dagger \hat{a}_c + \hbar\omega_q \hat{a}_q^\dagger \hat{a}_q ,$$

$$\hat{H}_{\text{nl}} = -E_J \left[\cos(\hat{\varphi}_J) + \hat{\varphi}_J^2/2\right] ,$$

$$\hat{\varphi}_J = \varphi_q\left(\hat{a}_q + \hat{a}_q^\dagger\right) + \varphi_c\left(\hat{a}_c + \hat{a}_c^\dagger\right) ,$$

- Goal:
  - Get ω_c, ω_q from eigenmode analysis
  - Get φ_c, φ_q (zero point fluctuations) from EPR

Energy Participation Ratio

npj | Quantum Information

www.nature.com/npjqi

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Tutorial 21

Energy-participation quantization of Josephson circuits

Zlatko K. Minev[1,4]✉, Zaki Leghtas[1,2], Shantanu O. Mundhada[1,5], Lysander Christakis[1,6], Ioan M. Pop[1,3] and Michel H. Devoret[1]

$$p_m := \frac{\text{Inductive energy stored in the junction}}{\text{Total inductive energy stored in mode } m},$$

- Can be computed from E and H field at mode m
- P_m is between 0 and 1

$$p_m = \frac{\langle \psi_m | \frac{1}{2} E_J \hat{\varphi}_J^2 | \psi_m \rangle}{\langle \psi_m | \frac{1}{2} \hat{H}_{\text{lin}} | \psi_m \rangle},$$

$$\varphi_c{}^2 = p_c \frac{\hbar\omega_c}{2E_J} \text{ and } \varphi_q{}^2 = p_q \frac{\hbar\omega_q}{2E_J},$$

$$\hat{H}_{\text{eff}} = (\omega_q - \Delta_q)\hat{n}_q + (\omega_c - \Delta_c)\hat{n}_c - \chi_{qc}\hat{n}_q\hat{n}_c - \tfrac{1}{2}\alpha_q\hat{n}_q(\hat{n}_q - \hat{1}) - \tfrac{1}{2}\alpha_c\hat{n}_c(\hat{n}_c - \hat{1}),$$

$$\alpha_q = \frac{1}{2}\chi_{qq} = p_q^2 \frac{\hbar\omega_q^2}{8E_J},$$

Get anharmonicity

$$\alpha_c = \frac{1}{2}\chi_{cc} = p_c^2 \frac{\hbar\omega_c^2}{8E_J},$$

$$\chi_{qc} = p_q p_c \frac{\hbar\omega_q\omega_c}{4E_J}.$$

χ_{qc} is the qubit–cavity dispersive shift (cross-Kerr coupling).

Steps to Install and Run Qiskit Metal

- **Lab 1) How to Install Ansys HFSS**
  - https://www.youtube.com/watch?v=eBUAmox45hk&list=PLnK6MrIqGXsL1KShnocSdwNSiKnBodpie&index=76
- **Lab 2) How to install Anaconda on Windows**
  - https://www.youtube.com/watch?v=ncftLDI8Mv8&list=PLnK6MrIqGXsL1KShnocSdwNSiKnBodpie&index=77
- **Lab 3) How to Install Qiskit Metal and Run a Simple Example**
  - https://www.youtube.com/watch?v=hs0tzZpH0xQ&list=PLnK6MrIqGXsL1KShnocSdwNSiKnBodpie&index=78
  - If you have error, see "Lab 4) Possible Errors when Installing Qiskit Metal"
    - https://www.youtube.com/watch?v=rLAH1RZHgtM&list=PLnK6MrIqGXsL1KShnocSdwNSiKnBodpie&index=79

Overview of Qiskit Metal (Hands-on)

Tutorial 21

- I called my environment “qmetal”
  - conda activate qmetal
  - jupyter notebook
  - http://localhost:8888/tree/Dropbox/SJSU/SJSU/Research/Presentations/QCE2023/Final%20Materials/Project_Test
- Copy from:
  - https://pypi.org/project/qiskit-metal/
  - See Lab 3 example

Interaction between Qiskit Metal and HFSS (Hands-on + Demo)

- Go to
  - https://qiskit.org/ecosystem/metal/tut/4-Analysis/4.02-Eigenmode-and-EPR.html
  - Or directly download:
  - https://github.com/qiskit-community/qiskit-metal/blob/main/docs/tut/4-Analysis/4.02-Eigenmode-and-EPR.ipynb
- Understand
  - JJ mode
  - Cavity mode
  - EPR
  - Cross-Kerr

Analysis of an Existing HFSS Structure

Tutorial 21

- If you do not want to create the structure through qiskit metal, or if it is not supported (e.g. a 3D structure), you can also control HFSS through the qiskit metal library.
- Lab 7) Creating a 3D Cavity with Ports using HFSS
  - https://www.youtube.com/watch?v=sxgso3MG7lU&list=PLnK6MrIqGXsL1KShnocSdwNSiKnBodpie&index=82
- Lab 8) Create Transmon Qubit on Sapphire substrate in the 3D Cavity using HFSS
  - https://www.youtube.com/watch?v=hRjvxroiQ-k&list=PLnK6MrIqGXsL1KShnocSdwNSiKnBodpie&index=83
- Lab 9) Finding the cross-Kerr of Transmon qubit in a 3D Cavity using pyEPR in Qiskit Metal
  - https://www.youtube.com/watch?v=vCCVgfFAFwo&list=PLnK6MrIqGXsL1KShnocSdwNSiKnBodpie&index=84

Recap

- Part I: Overview of Quantum Computing (Lecture)
- Part II: Understanding Quantum Gates (Hands-on)
    - Write your own simulator in Google Co-Lab
- Parts III & IV: Deutsch Algorithm and Quantum Fourier Transform (Lecture + Hands-on)
    - Programming on IBM-Q
- Part V: Superconducting Qubit Hardware (Lecture)
- Part VI: Optimizing Qubit Readout Using HFSS and Qiskit (Demo)

How to study in a short time?

N. David Mermin:
Shut up and Calculate!

N. David Mermin, "Could Feynman Have Said This?," Physics Today **57** (5), 10 (2004); doi: 10.1063/1.1768652

Introduction to Quantum Computing
From a Layperson to a Programmer in 30 Steps
(2nd Edition with 200+ questions and answers and links to teaching videos)

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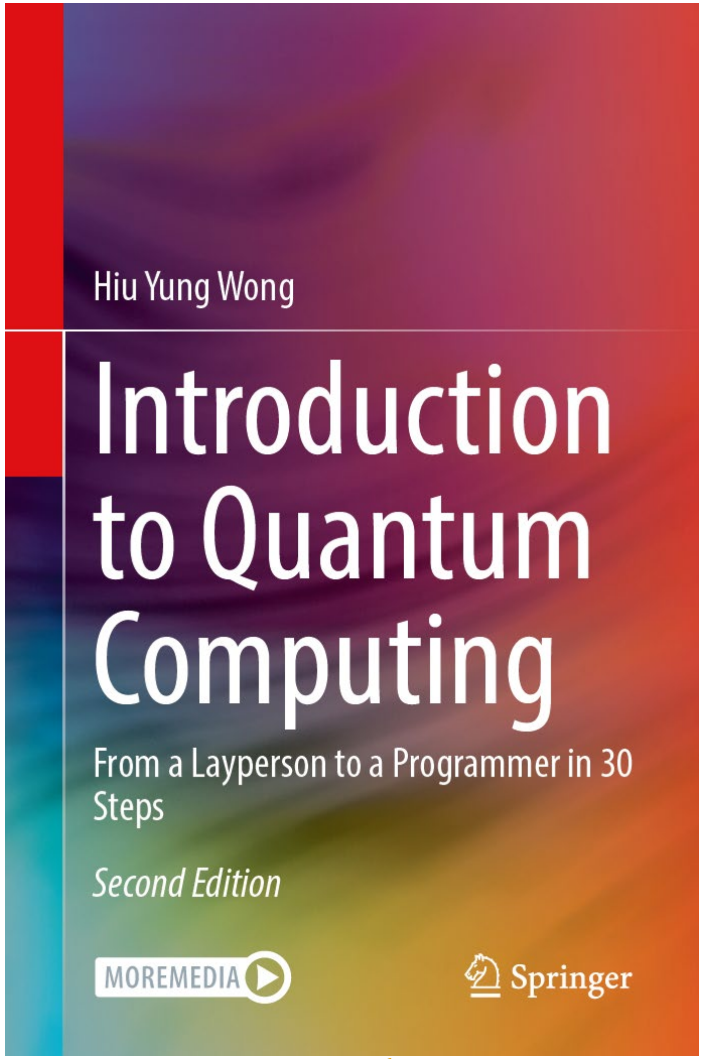

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Introduction to Quantum Computing (EE225)

Quantum Computing Hardware and Architectures (EE274)

YouTube