INTRO TO QUANTUM COMPUTING
WEEK #2

QUANTUM COMPUTING

in abstract

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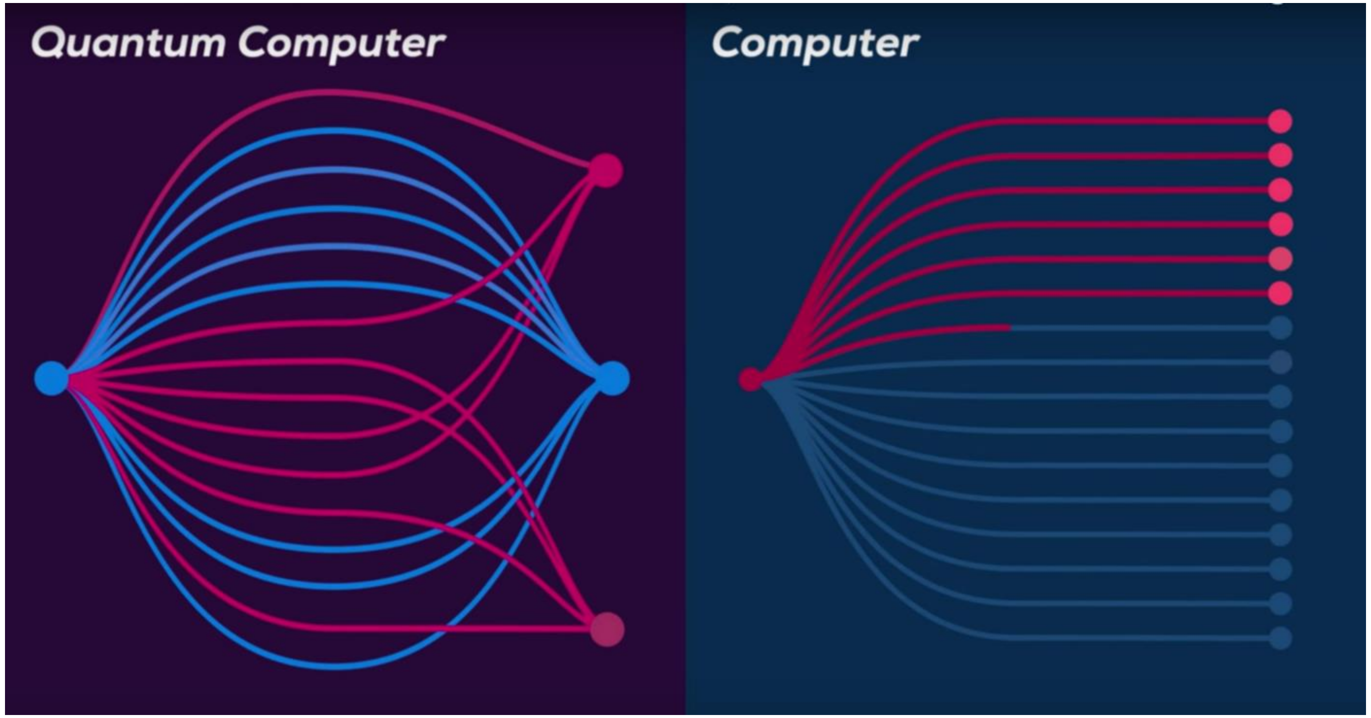
Classical Computing Recap

TOPICS COVERED

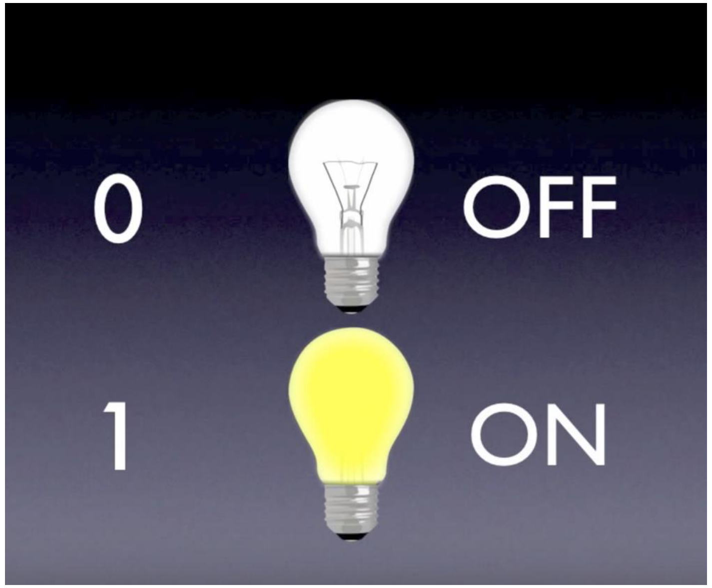
Classical Computing

- Binary Representation
- Bits
- Boolean Logic
- Universality
- Reversibility



BINARY

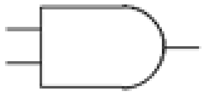
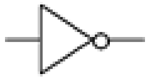
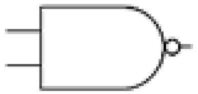
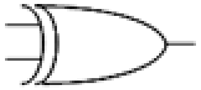
- **While it's common to use base-10 for counting, there is no mathematical reason to prefer one base over another.**
- **Base-2** is one of the most important bases for performing computation
- Base-2 is **binary**, meaning there are only two possible digits (0 and 1)
  - Also referred to as a **bit (binary digit)**



- **We can describe any number with a combination of bits**
- **All of the operations in a classical computer happen by manipulating bits**

LOGIC GATES

- **Logic gates:** Maps input bit(s) to output bit(s)

Gate	Symbol	Operator
and		$A \cdot B$
or		$A + B$
not		$\bar{A}$
nand		$\overline{A \cdot B}$
nor		$\overline{A + B}$
xor		$A \oplus B$

Truth Table

Input A	Input B	Output
0	0	0
1	0	1
0	1	1
1	1	1

UNIVERSALITY

Any computation operation can be made by using a combination of:

{NOT, AND, OR, FANOUT}

REVERSIBILITY

Given the output of a gate, we can determine what the inputs are.

- **Reversible gate:** preserves all the information
- **Non-reversible gate:** loses some information

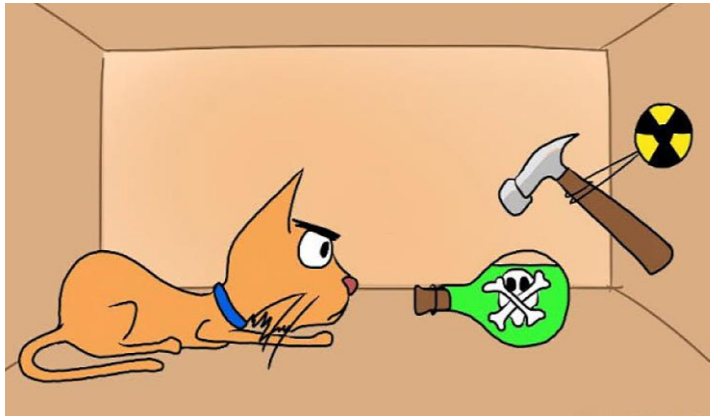
LECTURE OBJECTIVES

Why are we learning about *classical computing* when this course is about *quantum computing*?

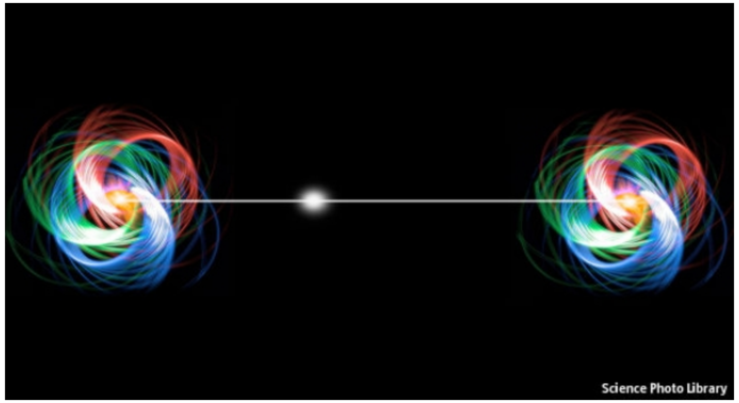
- Qubits
- Quantum superposition
- Quantum gates
- Quantum entanglement

QUANTUM RESOURCES for COMPUTING

SUPERPOSITION



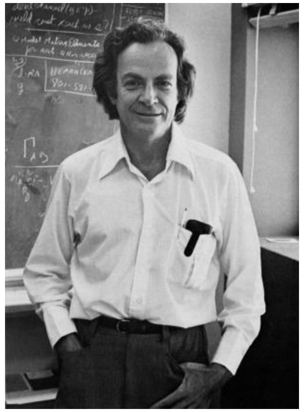
ENTANGLEMENT



QUANTUM INTERFERENCE

These three weird quantum properties enable the design of quantum algorithms which can compute in ways classical computers cannot, making quantum computers more powerful for solving certain types of problems.

[QU]BIT OF QUANTUM HISTORY



1981

Feynman proposes a framework for simulating the evolution of quantum systems.

1994

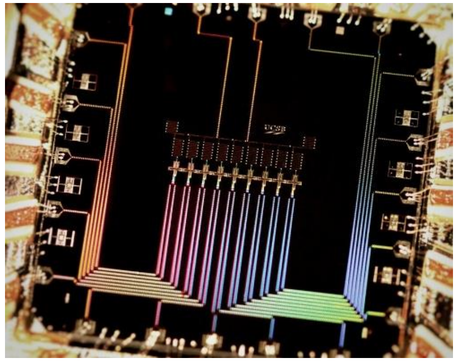
Peter Shor shows that quantum computers can factorize large integers efficiently.

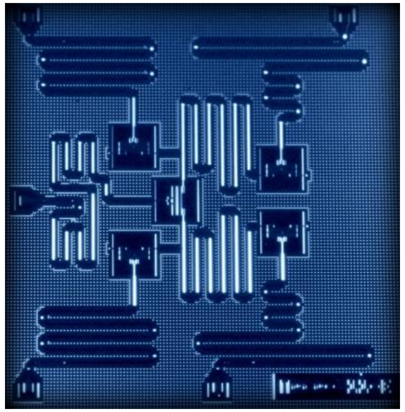
1998

First experimental demonstration of a quantum algorithm. A working 2-qubit NMR quantum computer.

2012

Few-qubit processors & error detection



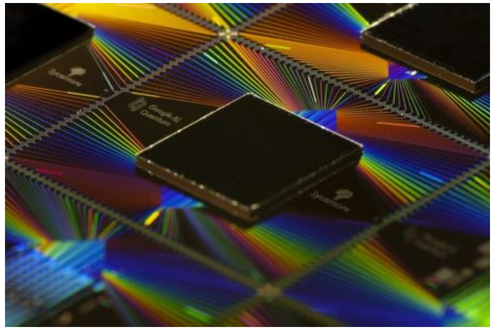


2017

Cloud-based Quantum Computing

2019

Quantum Supremacy



Quantum bits: Qubits

How quantum computers compute

Bit to Qubit

Bit	Qubit
0	$\vert 0\rangle$
1	$\vert 1\rangle$

$|\ \rangle$ is a ket and it indicates that we're talking about a quantum state.

example: QxQ $\mapsto$ $|$ QxQ $\rangle$

Quantum Superposition

Quantum object can be in two states at once!

Superposition

Superposition: a qubit can be $|0\rangle$ and $|1\rangle$ at the same time!

This is how we show it: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

measurement: collapses the quantum state of the qubit $|\psi\rangle$

to either $|0\rangle$ or $|1\rangle$

Measurement

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

measurement: collapses the quantum state of the qubit $|\psi\rangle$ to either $|0\rangle$ or $|1\rangle$

probability of measuring $|0\rangle$: $|\alpha|^2$

probability of measuring $|1\rangle$: $|\beta|^2$

example

50-50 superposition of 0 and 1: $|\psi\rangle = \sqrt{0.5}|0\rangle + \sqrt{0.5}|1\rangle$

90-10 superposition of 0 and 1: $|\psi\rangle = \sqrt{0.9}|0\rangle + \sqrt{0.1}|1\rangle$

practice

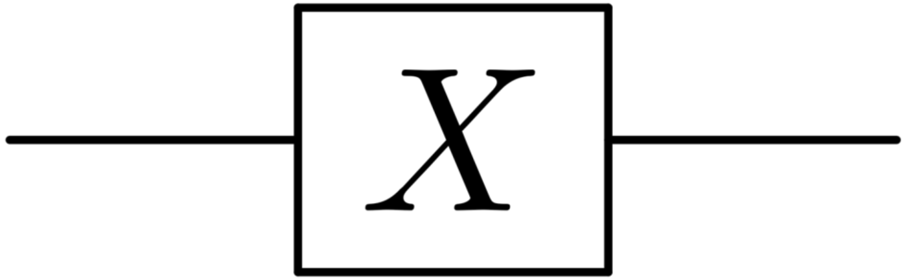
QUANTUM GATES

Quantum GATES: single-qubit

- X-gate
- Z-gate
- Hadamard gate

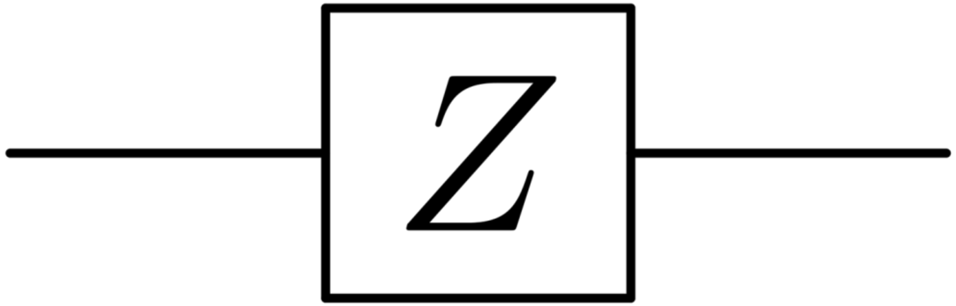
Quantum GATES: X-gate

X (or $\boldsymbol{\sigma}^x$): bit-flip



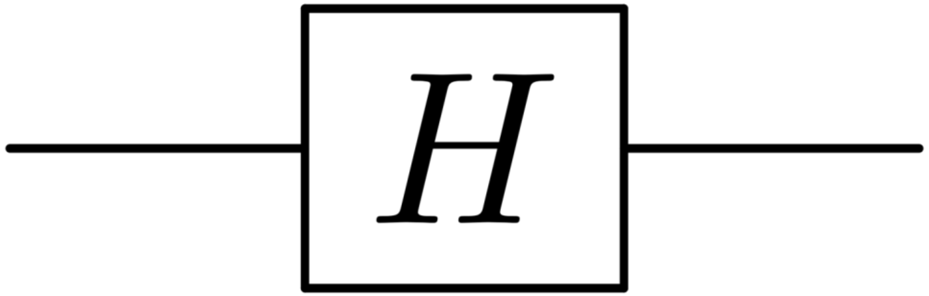
Quantum GATES: Z-gate

Z (or $\boldsymbol{\sigma}^z$): phase gate



Quantum GATES: Hadamard

Hadamard (H): creates a 50-50 superposition from $|0\rangle$ and $|1\rangle$



Quantum GATES applied to superposition

Quantum gates apply to each state of the superposition

- separately
- in parallel

$$X|\psi\rangle = X\,(\alpha|0\rangle + \beta|1\rangle)$$
$$= \alpha\,(X|0\rangle) + \beta\,(X|1\rangle)$$
$$= \alpha\,|1\rangle + \beta|0\rangle$$

practice

Quantum GATES applied to superposition

What is the difference between a coin flip and quantum superposition?

Coin flip:

Quantum GATES applied to superposition

What is the difference between a coin flip and quantum superposition?

Superposition:

Quantum Interference

Result of two classical coin flips: 50% 0, 50% 1

Result of two hadamard gates on $|0\rangle$: 100% $|0\rangle$

The states involved in quantum superposition can cancel or amplify

Why are quantum computers faster

# of qubits	# of superposition states
1	2 ($\|0\rangle, \|1\rangle$)
2	4 ($\|00\rangle, \|01\rangle, \|10\rangle, \|11\rangle$)
3	8 ($\|000\rangle, \|001\rangle, \|010\rangle, \|011\rangle,$ $\|100\rangle, \|101\rangle, \|110\rangle, \|111\rangle$)
4	16

n qubits → 2^n superposition states

Each operation acts on all the elements of the superposition!

Quantum Supremacy

A programmable quantum device can solve a problem that no classical computer can solve in any feasible amount of time

Two qubits

Let's say we have two qubits: qubit A and qubit B

qubit A

qubit B

$|00\rangle$ or $|0\rangle|0\rangle$: qubit A is $|0\rangle$ and qubit B is $|0\rangle$

$|01\rangle$ or $|0\rangle|1\rangle$: qubit A is $|0\rangle$ and qubit B is $|1\rangle$

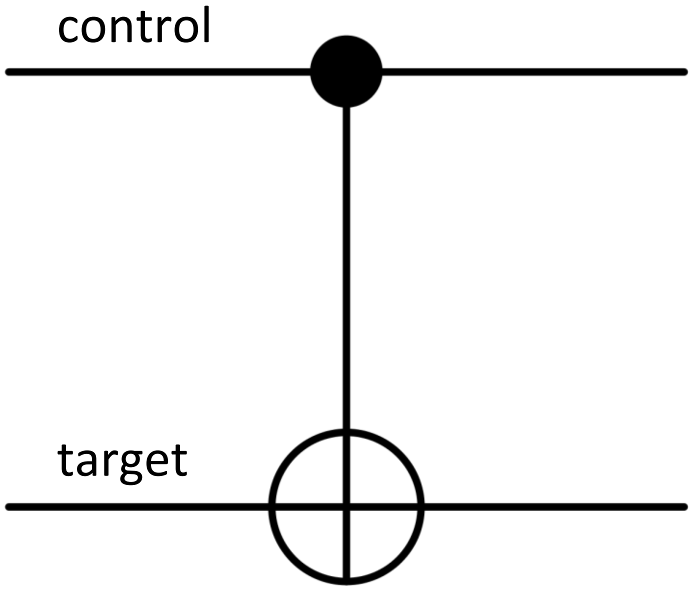
$|10\rangle$ or $|1\rangle|0\rangle$: qubit A is $|1\rangle$ and qubit B is $|0\rangle$

$|11\rangle$ or $|1\rangle|1\rangle$: qubit A is $|1\rangle$ and qubit B is $|1\rangle$

Quantum GATES: two-qubit

- CNOT gate

Quantum GATES: CNOT



CNOT (controlled not):

if the control qubit is 0, does nothing

if the control qubit is 1, flip the target qubit

Quantum Entanglement

Quantum correlation between two qubits where the state of one qubit depends on the other qubit

Entanglement

Entangled state: $|\psi\rangle = \sqrt{0.5}|00\rangle + \sqrt{0.5}|11\rangle$

if we measure $|\psi\rangle$:

- we get $|00\rangle$ with 50% probability
- we get $|11\rangle$ with 50% probability

Entanglement

Entangled state: $|\psi\rangle = \sqrt{0.5}|00\rangle + \sqrt{0.5}|11\rangle$

what if we measure only measure qubit A?

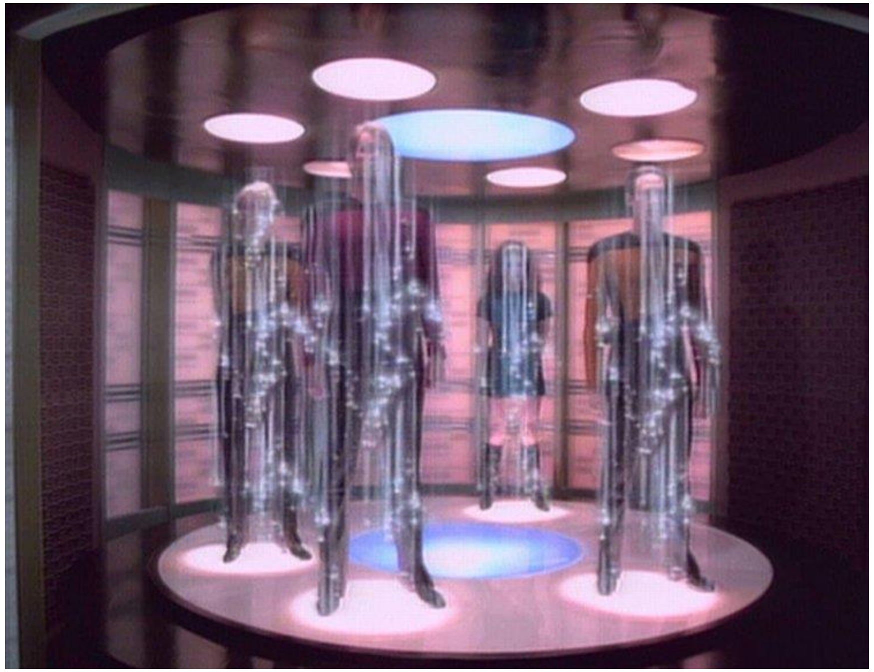
- If qubit A is 0 $\rightarrow$ the quantum state of qubit B is immediately set to $|0\rangle$
- If qubit A is 1 $\rightarrow$ the quantum state of qubit B is immediately set to $|1\rangle$

Applications of Entanglement

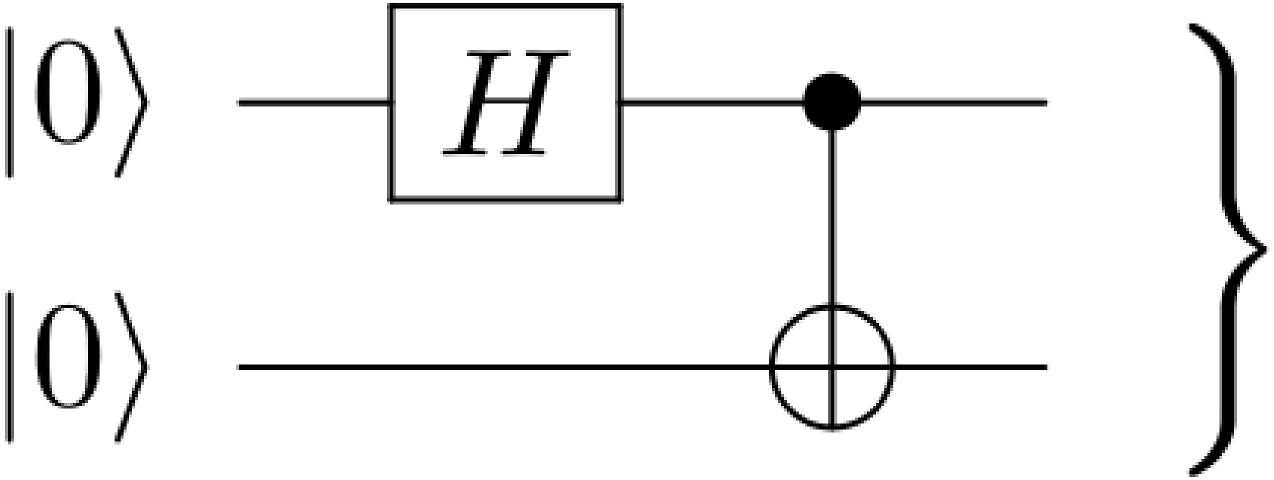
- Quantum Teleportation
- Quantum Cryptography
- Superdense Coding
- Quantum speedups

Quantum teleportation

Transferring information or matter from one point to another without physically moving things!



How to create entanglement?



$$\frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

THIS WEEK

Lab:

- In your lab section this week, you will cover: Math review

Homework:

- Will be available on Discord in #course-announcements
- Math review
- <u>You will submit your homework for weeks 1 and 2 this week. Homework is due October 31st at 11:59pm EST</u>
- Updates will be announced on Discord!!!

Important Notes:

- You will be sent an email with your Canvas login information.
- NO MORE LAB CHANGES WILL BE PERMITTED!!!
- DO NOT SEND INDIVIDUAL MESSAGES UNLESS INSTRUCTED TO DO SO
- Today at 6pm EST is the last chance to get verified on Discord

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END OF LECTURE 2