QUBIT X QUBIT



# Day 1 Summary of Key Concepts

## Lecture Part 1: Introduction to Quantum Computing

**What is quantum computing?**

- A quantum computer uses the properties of quantum mechanics to solve problems that classical computers cannot.
- Quantum Mechanics, also called Quantum Physics, describes how really small objects (atoms, electrons, and more) behave.
    - Many quantum mechanical phenomena we see are counterintuitive, and directly contradict laws of physics we see at larger scales.
- Three key quantum mechanical phenomena that are necessary for quantum computing: **superposition, interference, entanglement.**
- **Key Concept:** While quantum computers harness these properties to make computing faster and more powerful, it is crucial to understand that quantum computers are not simply faster versions of classical computers. Quantum computers solve problems in a **fundamentally different way.**

**Why do we need a different kind of computation?**

- Moore's Law: About 50 years ago, Gordon Moore (the co-founder of Intel) predicted that the power we could squeeze into a computer would double every year.
    - Squeezing more power into a computer means the smallest parts (called bits) are getting smaller! With this shrinking of bits, we begin to hit a physical limit where quantum mechanical properties begin to interfere with computation.
    - Quantum computing allows us to **leverage** the properties of quantum mechanics to our advantage.
- In addition to Moore's law, there are certain types of problems that classical computers have a hard time solving in a reasonable amount of time, especially when large datasets are involved. These problems include:
    - Problems that involve too much searching or testing for regular computers to do quickly (think: massive data sets)
    - Problems that involve simulating quantum mechanical systems
    - Optimization problems
    - Factoring and problems that require secure encryption

**Applications of quantum computing:**

- The problems listed above present across multiple different industries, including finance, biology, cybersecurity, chemistry, shipping & logistics, machine learning, and aerospace.
- Some notable applications:
  - Chemistry: Using quantum computers for molecular simulations, making tasks such as vaccine development quicker, cheaper, and more effective.
  - Cybersecurity: While quantum computers pose a cybersecurity threat because of their factoring abilities, they also have the ability to create virtually unhackable security networks (this is an area of study called post-quantum cryptography)
  - Combating climate change: Quantum computers can help us address climate change through a variety of ways! Some examples include helping us optimize clean energy infrastructure, materials science to develop carbon-capture technology or efficient solar panels, and quantum chemistry to create greener fertilizers.

**Understanding how we got here:**

While quantum computing is a relatively new technology, our understanding of quantum mechanics has influenced technological innovation for decades. We can understand this development through the lens of the First and Second Quantum Revolutions.

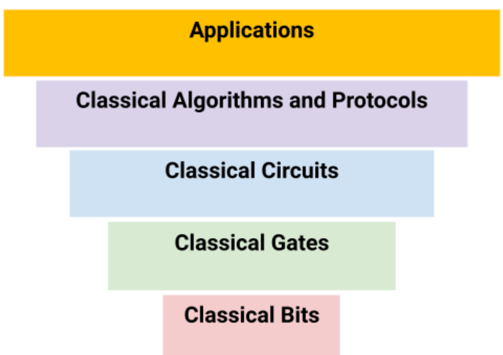
- The First Quantum Revolution: Build devices that tap into quantum physics naturally occurring. Examples include lasers, GPS, MRI machines, phones, and more.
- The Second Quantum Revolution: While the First Quantum Revolution *leveraged* the properties of quantum mechanics, the Second Quantum Revolution is focused on controlling individual quantum systems, and in turn, developing powerful new technologies.
  - Quantum computing is part of an even larger field called Quantum Information Science and Engineering (QISE), which studies the many different uses of quantum mechanics. Some other subfields include quantum sensing and quantum networking.

**Today's quantum ecosystem:**

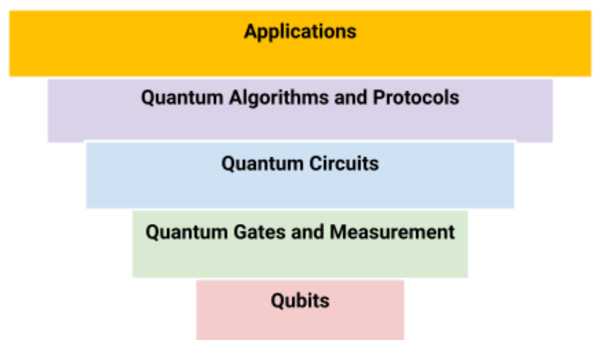
- Quantum computers are not scalable or viable for commercial use just yet. Scientists estimate it will be 10–15 years before we see wider-spread commercial adoption.
- On day 4, we will explore today's quantum ecosystem further, including hardware engineering challenges, near-term use cases, and next steps for researchers and industry.

**The Quantum Stack:**
We can conceptualize computation through the lens of the stack. This week, we will be exploring multiple layers of the **quantum stack.**

**The Classical Stack:**




**The Quantum Stack:**




Here is a quick review of the classical stack:

- Bits: Bits are how computers process information. Bits are electrical pulses represented as 0s and 1s.
- Gates: Gates are how circuits are made. Gates manipulate bits. (If you are familiar with logic gates, this is where those fall on the stack!)
- Circuits: Circuits are a collection of gates applied to bits. They are a conceptual framework, as well as how algorithms are physically implemented.
- Algorithms & Protocols: Algorithms and protocols are circuits or sets of instructions that tell computers how to perform their tasks.
- Applications: Applications are the layer we see in games, web browsers, and streaming services. They are the problems computers solve and the platforms they solve them on.

## Layers of the Quantum Stack

<u>Qubits</u>

A qubit is the fundamental unit of information in a quantum computer, just as a bit is the fundamental unit of information on a classical computer. While classical bits can only be a 0 or 1, qubits can be 0, 1, or a combination of these states.


Classical bits can be one of two states ONLY – 0 or 1

Qubits can be a 0, 1, or in a combination of these two states!

Qubits can physically be many different things! (Superconducting qubits, photons, trapped ions, topological qubits). Each of these physical implementations requires different hardware- not all quantum computers are built equal!

We can label quantum states using **Ket Notation:**

| **The 1 state:** | **The 0 state:** | Superposition |
|---|---|---|
| $\|1\rangle$ | $\|0\rangle$ | of $\|0\rangle$ and $\|1\rangle$ |

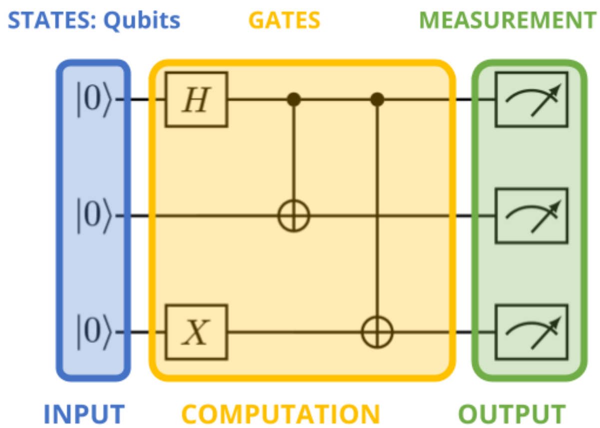
Any time you see something in |these brackets⟩, that means it is a quantum state.

<u>Quantum Gates & Measurement</u>

Like a classical gate changes a bit, quantum gates convert a qubit from one quantum state to another. We explored measurement in lecture part 2 today, and will learn about quantum gates during Day 2.

Quantum Circuits

A quantum circuit is a sequence of quantum gates. These gates work together to produce a target output state. We can examine a quantum circuit in three parts: states (qubits), gates, and measurement.




Quantum Algorithms & Protocols

- **Quantum algorithms:** A quantum algorithm is a circuit designed to solve a problem. Quantum algorithms are unique because they aim to achieve "quantum advantage," which is when quantum computers demonstrably solve a problem faster or more efficiently than a classical computer would.
- **Quantum protocols:** A set of standard rules that use the properties of quantum physics to allow electronic devices to communicate with each other/

Applications

We previously discussed applications: these are the problems quantum computers solve and the platforms we solve them on

**Next steps + things to consider:**

- QC is interdisciplinary. Math, physics, computer science. We will be exploring physics and computer science this week.
- Quantum computers will be relevant no matter which career you pursue. From policymaking to marketing/business strategy to scientist to engineering, you have a place in the quantum computing space.

## Lecture Part 2: Introduction to Quantum Mechanics

In this part of the lecture, we entered the **quantum world** and saw some of its counterintuitive properties. We discussed how the quantum world exists at **really small length scales**. At the end of the 19th century, technology had improved to the extent that we could start performing experiments on the scale of atoms and molecules. Scientists discovered that at this length scale, our everyday notions about how things move and interact with each other break down, and we need to use a new set of rules to understand the behavior of objects. This new set of rules is called **quantum mechanics**.

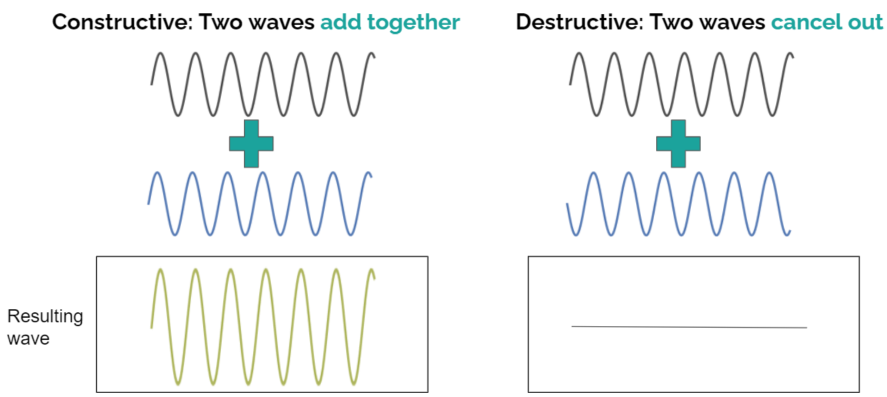
**Fundamentals of Quantum Mechanics:**

- **Quantum Mechanics** - The set of rules that govern the behavior of objects such as atoms, molecules, and light. Quantum computers use these rules to solve some problems that classical computers have a hard time with.
- **Quantum Objects:** Objects such as atoms, molecules, and light which follow the rules of quantum mechanics.
- **Wave-Particle Duality:** WPD is a core tenant of quantum mechanics. Dichotomy of waves and particles in classical physics, how that breaks down in quantum mechanics.

**Wave-Particle Duality**

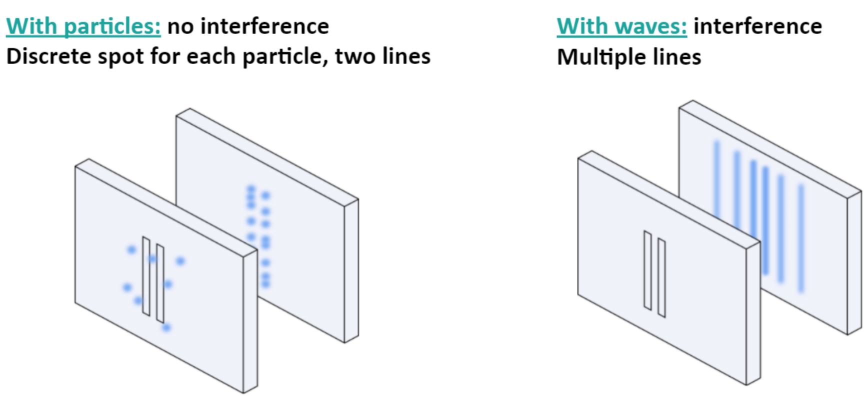
Quantum objects show both wave-like and particle-like properties. When quantum objects, such as electrons or photons (particles of light), are used in a double slit experiment, they create discrete spots (like particles) but the spots are arranged in an interference pattern (like waves). Because of wave-particle duality, we can think of qubits as both waves and particles.

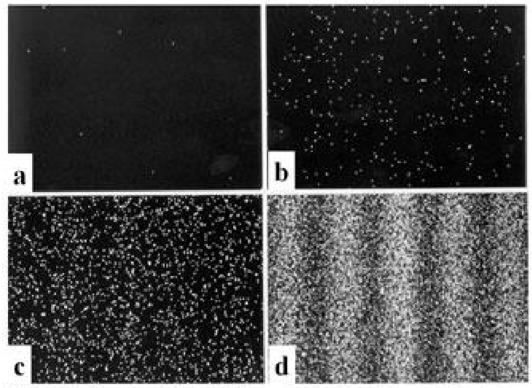
- **Wave properties:** Waves, such as sound waves and water waves, travel with a certain velocity. Further, waves interact with each other to form complex patterns in a process called **interference**. Sometimes waves can add onto each other to create a bigger wave **(constructive interference)**, and sometimes waves can cancel each other out **(destructive interference)**




- **Particle properties:** Particles, such as soccer balls, have mass, have a definite, discrete location, and also travel with a certain velocity.

- **Double-slit experiment:** The double-slit experiment helps differentiate between waves and particles. In this experiment, the wave or particle is aimed at two slits (two openings in an opaque barrier), behind which is a plain wall. Particles pass through either the left or the right slit, and create two lines of discrete spots on the wall. Waves passing through the slits interfere with each other and create a pattern of bright and dark lines on the wall.





Single-electron Build-up of Interference Pattern

**Quantum Properties:**

The counterintuitive behavior of atoms and molecules can be summarized into four quantum properties.

1. **Superposition -** Quantum objects can be in a combination of multiple possible states. For example, in an atom, electrons are in a superposition of many possible positions.

2. **Interference -** The possible states of quantum objects can add up or cancel out. An example of interference is noise cancelling headphones, which produce sound waves that cancel out external noise through interference. The fact that atoms and molecules show similar behavior hints at their wave-like nature.

3. **Entanglement -** Two quantum objects are entangled if the state of one object depends on the state of another. If you know the state of one quantum object, you know the state of the other. Entanglement does not depend on distance - entangled quantum particles remain entangled if they are separated by millions of miles. **Entanglement is a property of multiple (two or more) quantum objects**, unlike the earlier properties which can happen with one object.

4. **Measurement** - There are two ways in which measurement of quantum objects is different from measurement in our everyday experience

a. The **results of measurements** on quantum objects can be **random**, that is, we might not be able to predict the exact outcome of the measurement
b. The **state of the quantum object** being measured can **change** as a result of the measurement.

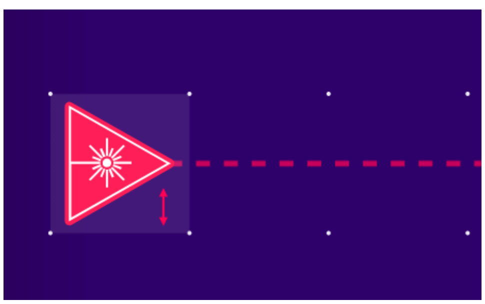
## Lab: Visualizing Quantum Mechanics Using Quantum Flytrap

In lab today, we used Quantum Flytrap, a virtual photonics lab simulator, to visualize some quantum mechanical properties in action.

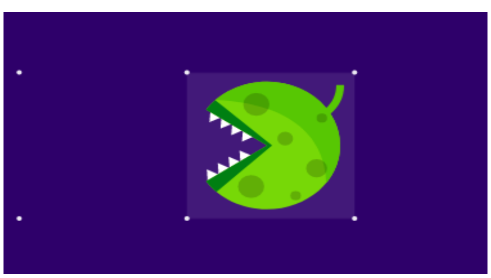
Quantum flytrap link: [https://lab.quantumflytrap.com/](https://lab.quantumflytrap.com/)

In the simulator, we used:

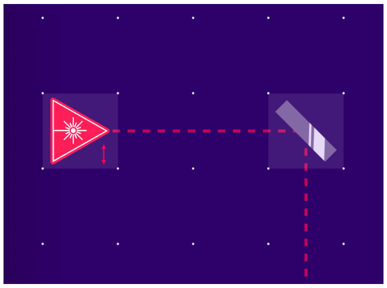
- Lasers- a source of light that does not spread out and has only one color.



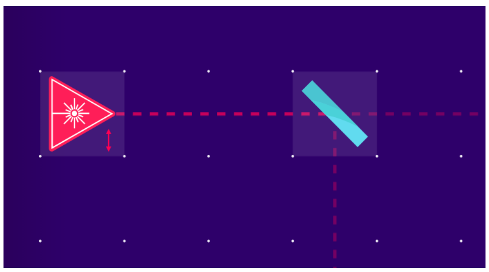
- Detectors- a sensor that tells us how much light is falling on it.



- Mirrors- used to change the direction of light.



- Beamsplitters- reflects half the light and lets the other half continue traveling in a straight line.



In lab, we used these resources to create superposition and interference.

**Creating Superposition:**

- Beamsplitters create superposition with photons. There are two possible paths the photon can take out of the beamsplitter. The photon is in a superposition of being reflected or transmitted.
- Quantum measurements can be random. When we detect a photon coming out of a beamsplitter, the photon gets detected randomly along one of the two possible paths. It is impossible to predict which path the photon will take.

**Creating Interference:**

- We can combine two beamsplitters and two mirrors to make a Mach-Zehnder interferometer.
- In the Mach-Zehnder interferometer, the first beamsplitter creates two possible paths for the photon. The photon is in a superposition of these two paths
- The mirrors reflect the two paths and make them overlap

- The second beamsplitter makes the two paths interfere. There is completely constructive interference along one path, and completely destructive interference along the other.
- 100% of the photons are detected at one of the detectors.