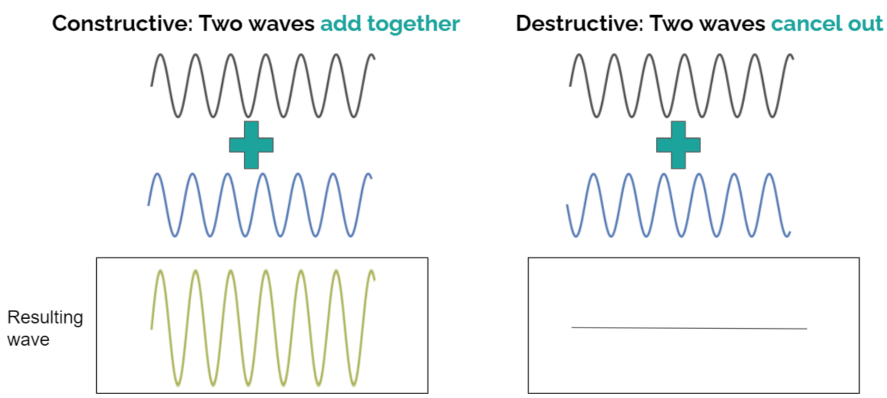
Week 3 Summary of Key Concepts

Lecture

This week in lecture, we discussed some of the **"why's" of quantum mechanics** - why do quantum objects show superposition? Why can their states interfere? Why are their states discretized? We discovered that quantum objects can show both wave and particle-like behavior, exemplified by the **double-slit experiment**. We used this **wave-particle duality** to explain superposition, interference, and discretization. We also discussed how there are still lots of **open questions** in quantum mechanics around measurement and entanglement.

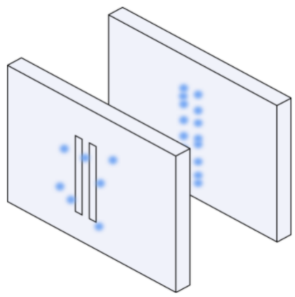
1. **Wave properties:** Waves, such as sound waves and water waves, travel with a certain velocity. Further, waves interact with each other to form complex patterns in a process called **interference**. Sometimes waves can add onto each other to create a bigger wave **(constructive interference)**, and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



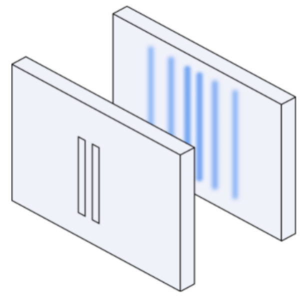
2. **Particle properties:** Particles, such as soccer balls, have mass, have a definite, discrete location, and also travel with a certain velocity.

3. **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.

With particles: no interference
Discrete spot for each particle, two lines

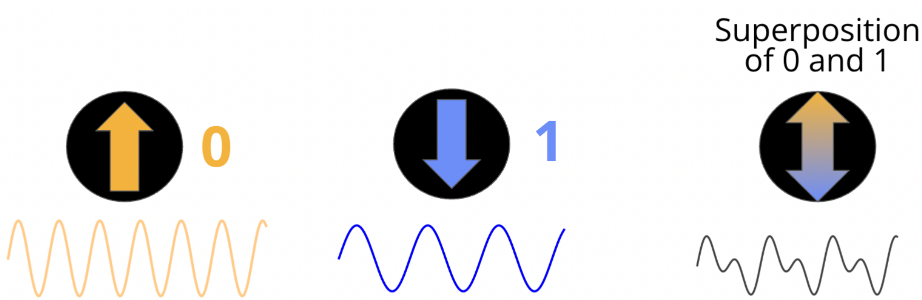


With waves: interference
Multiple lines



4. **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.

5. **Superposition with waves:** Superposition is a consequence of wave-particle duality. Using the wave nature of qubits, we can represent the two states of the qubit (0 and 1) with two waves. **To create a superposition state, we can combine these waves.**



6. **Interference with waves:** Interference is also a consequence of wave-particle duality, and can be described as the addition or subtraction of the waves representing qubit states. **Both superposition and interference involve overlap between waves.**

7. **Discretization with waves:** The discreteness of the quantum world arises when quantum objects are **confined.** Confinement of waves forces them to only take certain shapes or energies, much like the waves on the string of a musical

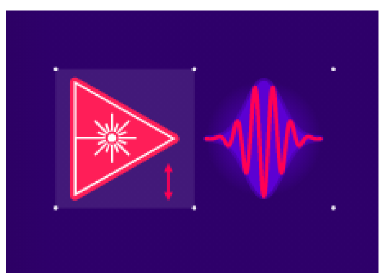
instrument fixed at two ends. In the quantum world, **confinement can exist naturally** (for example, in a trapped ion qubit, where the negatively charged electron is confined by the positively charged nucleus) **or be created artificially** (such as through electric circuits in superconducting qubits).

8. **Open questions:** There are lots of unresolved questions in quantum mechanics. We do not understand why the result of quantum measurement can be random, and we also do not know if there is an unexplained link between two entangled qubits. Attempts to answer such questions lead to different interpretations of quantum mechanics.

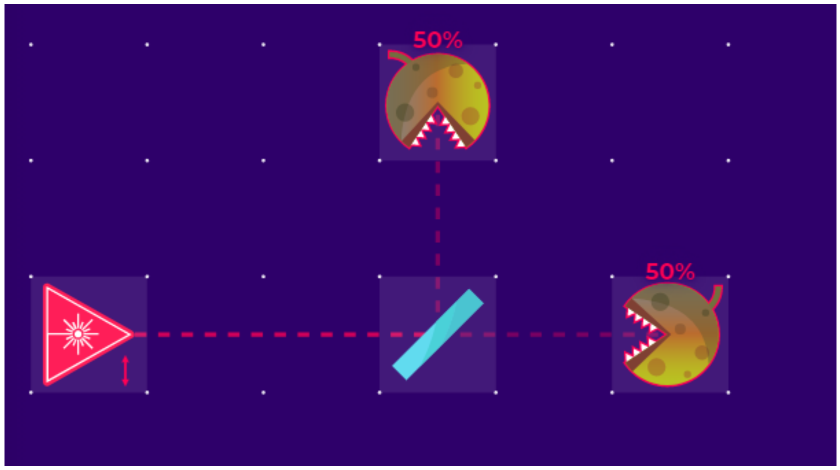
Lab

In this week's lab, we looked at [Quantum Flytrap], an online virtual lab to simulate quantum experiments with photons. In Flytrap, we learnt how to use lasers, mirrors, detectors, and beamsplitters. We used these tools to create **superposition** and **interference**, and **observe wave-particle duality** and the **randomness of quantum measurements**.

1. **Wave-particle duality:** We can visualize light as a wavepacket, as shown in the Flytrap screenshot below. **In this representation, the photon is shown as a wave, but the wave is localized like a particle.**

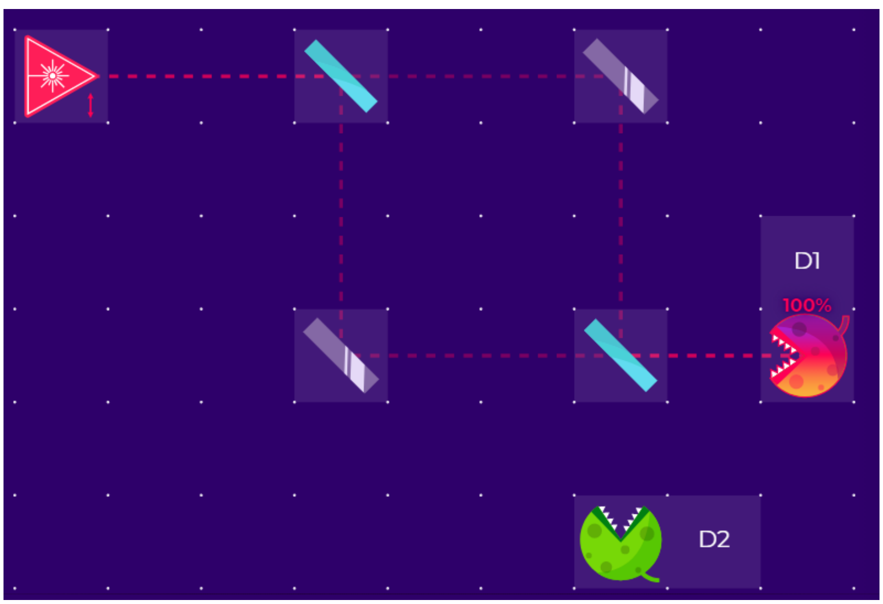


2. **Beamsplitter: A beamsplitter is used to split a beam of light.** It lets some light go through it, and reflects the rest of the light.
3. **Creating superposition**: We can create superposition by passing photons through a beamsplitter. There are two possible paths the photon can take out of the beamsplitter. **The photon is in a superposition of being reflected or transmitted.**



4. **Randomness of quantum measurement:** 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 detector the photon will hit.**

5. **Creating interference:** We can create interference in a Mach-Zehnder interferometer, as shown in the screenshot below:



In this setup, every photon from the laser gets detected on the detector D1. The second detector (D2) does not receive any photons. **The beamsplitter creates constructive interference along the path leading to D1 and destructive interference along the path leading to D2.**

Such interferometers are commonly used as high-precision detectors, because the perfectly constructive and destructive interference gets broken if there is any difference between the two paths that the photon can take in the interferometer.

Further readings and additional resources

1. MIT OCW lecture on Mach-Zehnder interferometer
2. Richard Feynman on the double-slit experiment
3. Dr. Quantum video on double-slit experiment
4. Paper demonstrating wave-particle duality in a Mach-Zehnder interferometer