# Seminar 4

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# Quantum Mechanics II

Week 3 | October 9, 2022

**Lecture Overview:**

- Waves, particles, and the wave-particle duality
- How superposition, interference, and discretization arise form wave-particle duality?
- Open questions/interpretations in quantum mechanics?

## Waves vs. Particles

Classical physics says all objects are either particles or wave…what about quantum objects?

**What is a wave?**

Examples: Water, Light, Electromagnetic, Sound

Waves have an amplitude and a period. Waves travel at their own speed. For instance, the speed of light is ~300,000,000 m/s regardless of the color of the light. Speed of

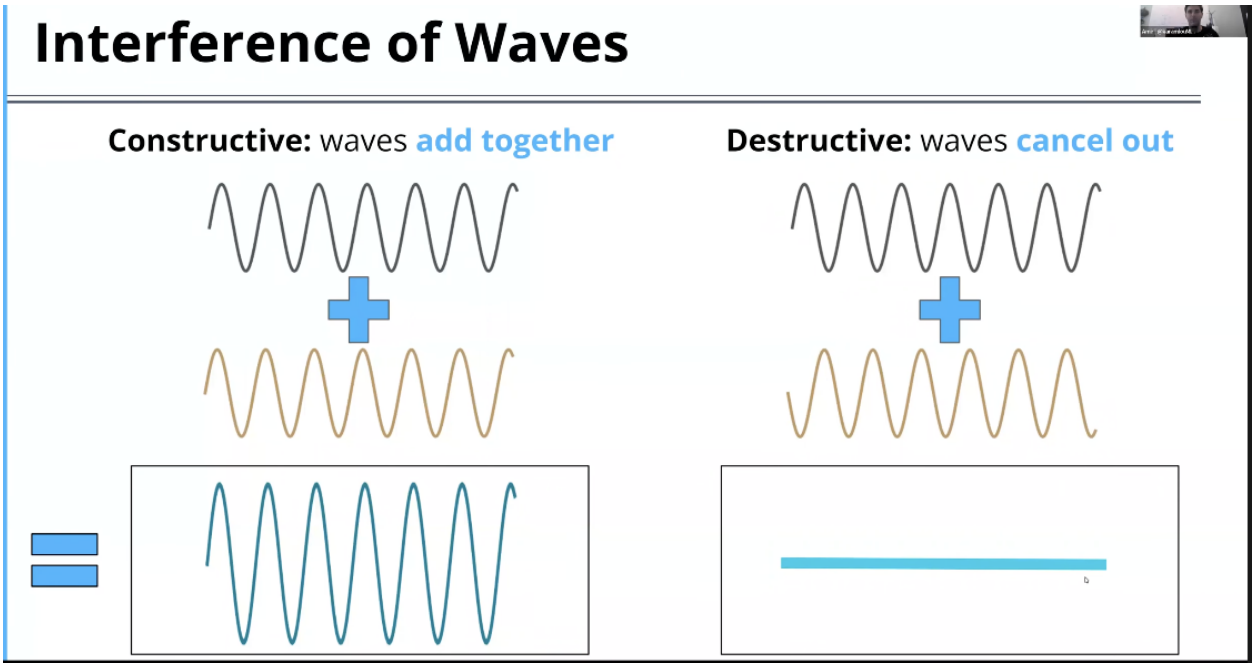
sound = 343 m/s regardless of how loud it is. This is why you see lightening (higher velocity) before you hear the associated thunder.

**Position of Waves:**

Waves do not have a discrete position but rather have a continuous spread of positions. This is why multiple people can hear the same sound or see the same thing.

**Interference of Waves:**

Given two waves when they come across each other, they cancel each other creating a 0 amplitude wave or grow into one single higher amplitude wave. Constructive interference results in waves being added together and destructive waves cancel each other.




**What is a Particle?**

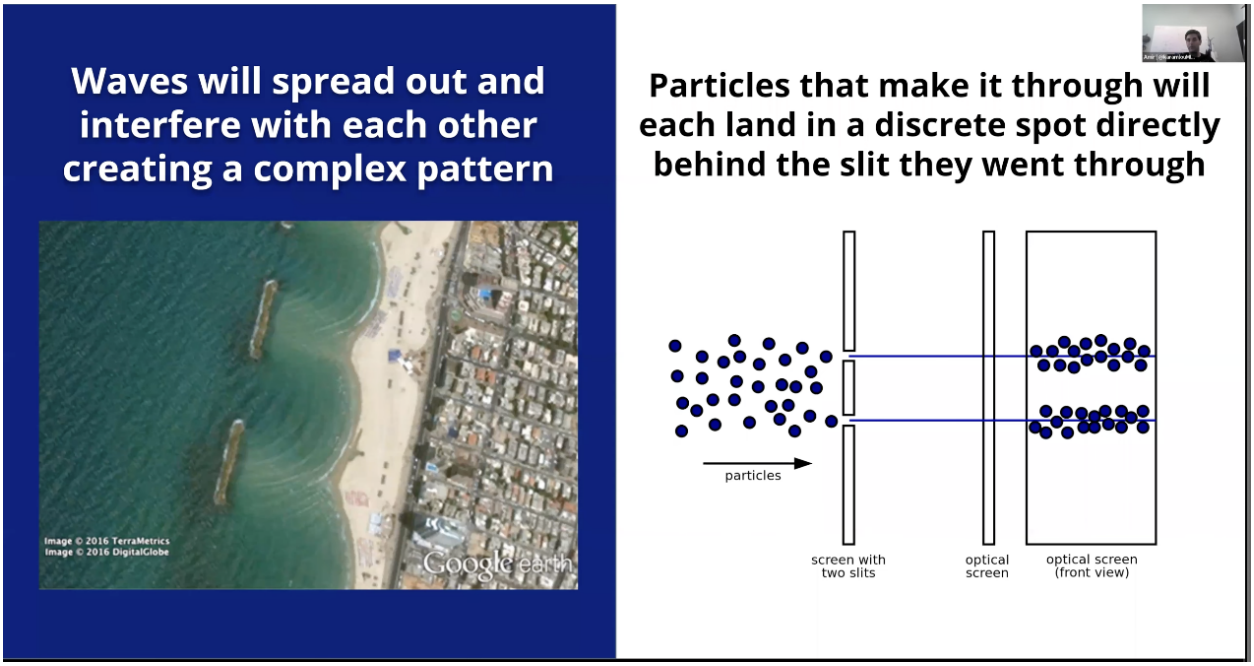
- Throwable Objects, Dust, Moving Objects (has a velocity), living things
- Particles contain: mass, location (well-defined, discrete), speed
- Particles exist in one discrete location and can interact but cannot interfere with each other

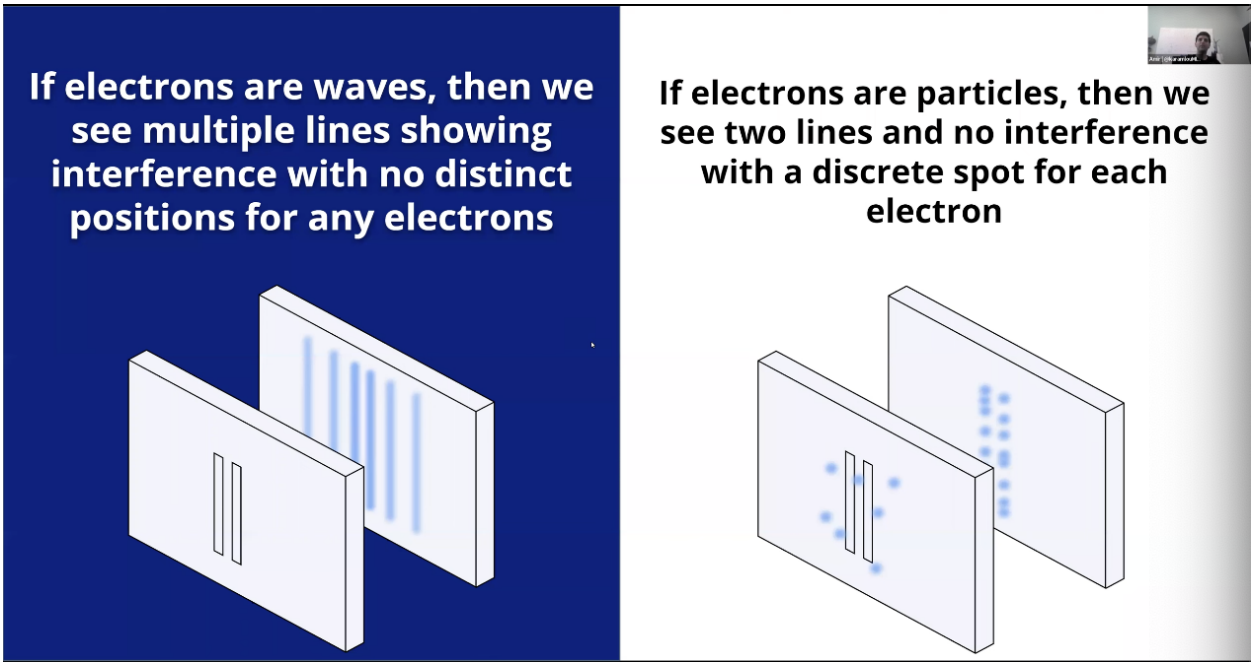
**Wave vs Particle: Quantum Edition**

The technical name for a particle of light is a photon. Light has to be thought of as travelling in small packets of waves called wave-packets.

***The Generalization***: All matter is both a wave and a particle, but that the wave nature becomes more apparent with smaller size.

**Double Slit Experiment:**



**Conclusion:** Electrons are waves *and* particles. Each electron is a discrete spot on the wall, but the discrete spots are arranged in an interference pattern…we call this the wave-particle duality.

**Key:** If we measure which slit each electron goes through we change the pattern to that of classical particles - observer effect. This will collapse the superposition and revert back to classical nature.

**Macroscopic Quantum Phenomenon** - There are even larger scale quantum effects known as macroscopic quantum phenomenon

- Levitation through superconductivity
- Large scale interference in Bose=Einstein Condensates
- Creeping liquid helium through superfluidity

Qubits are the fundamental units of quantum information - they can be in a combination of two state at the same time.

- **Key:** A q-state describes the probability that we find the object in one classical state versus another

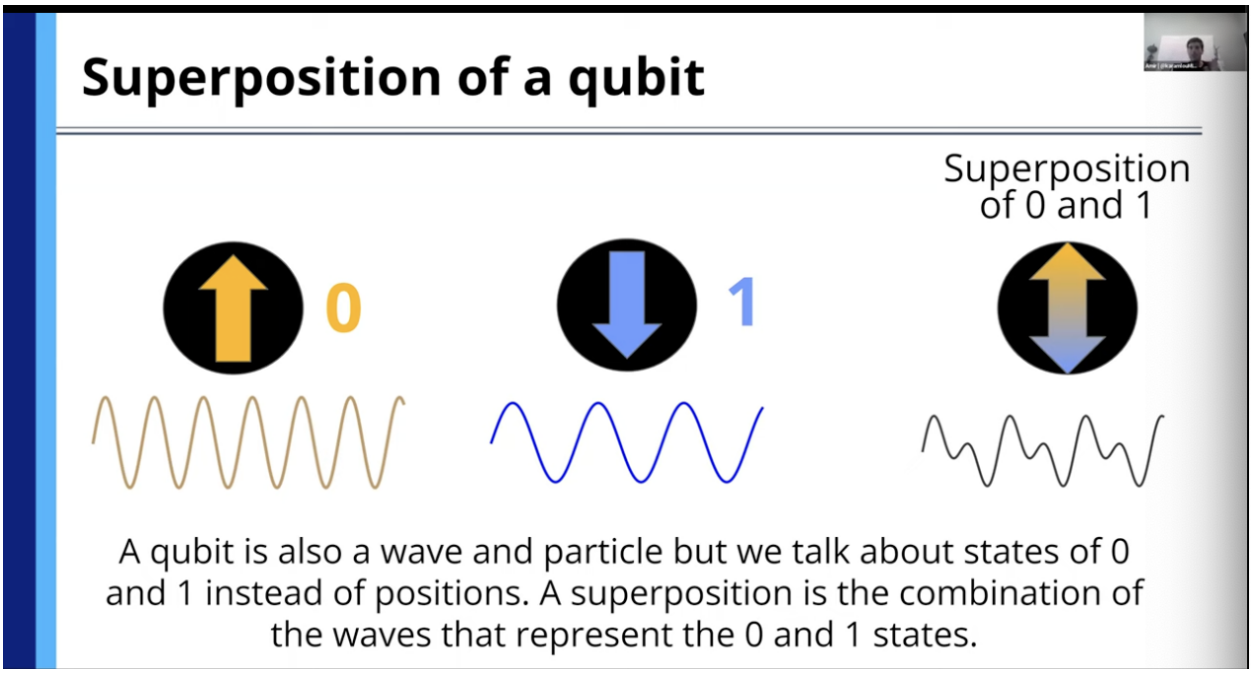
**Qubits can be a particle and a wave**

Example: Photonic Qubits. We can create qubits by sending photons through two possible paths. Since photons are q-mechanical, they can just choose a superposition of both paths. State s of qubits can be found by counting the number of photons that took one path versus another.

Measuring the brightness/darkness or number of photons (discrete). The state of qubits can interfere with each other bringing wave-like behavior.

## Quantum Properties Revisited:

The spreading of a quantum object’s wave is where superposition comes from. Waves of different shapes are superpositions of different positions.




A quantum object's wave interacting with itself is where interference comes from. The waves of multiple quantum objects can interfere too.

**Interference of a Qubit**

Different states of the qubit can interfere with each other: 0 state can constructively or destructively interfere with another 0 state depending on where the valleys/peaks interact.

**Discretization of quantum basketballs:**

But if the basketball is completely surrounded by like in a box, its wave will actually end up combining with itself to create one simple unmoving wave called a standing wave. More energy will create a standing wave with more ripples.

Because we confined the q-object to a portion in a space we force it to have discrete states. Compare this to string instruments in the classical state by creating waves on strings that are fixed on both ends (confined).

**Confinement of Quantum Objects:**

Some q-objects are confined by nature. For example, the attraction between the positive charged nucleus and the negative charged electrons confines the electron to the atom or molecule. These types of qubits are used in trapped ion Quantum Computers.

Another case is superconducting qubits where you can use electrified loops to create confinement - this idea is used in superconducting quantum computers.

## The UnKnown (?)

- Why do qubits show superposition?
- Why do qubits show interference?
- Why are qubit states discretized?
- Nature of Entanglement?
    - Not just mathematical description but more concerned about the “WHY?”
- Why is quantum measurement random?
- Is Q-mechanics the full story?

**Important: Superposition and interference are both caused by the wave nature of quantum objects. Discretization is caused by waves being confined (again due to wave-like nature of quantum objects)**