Seminar 11

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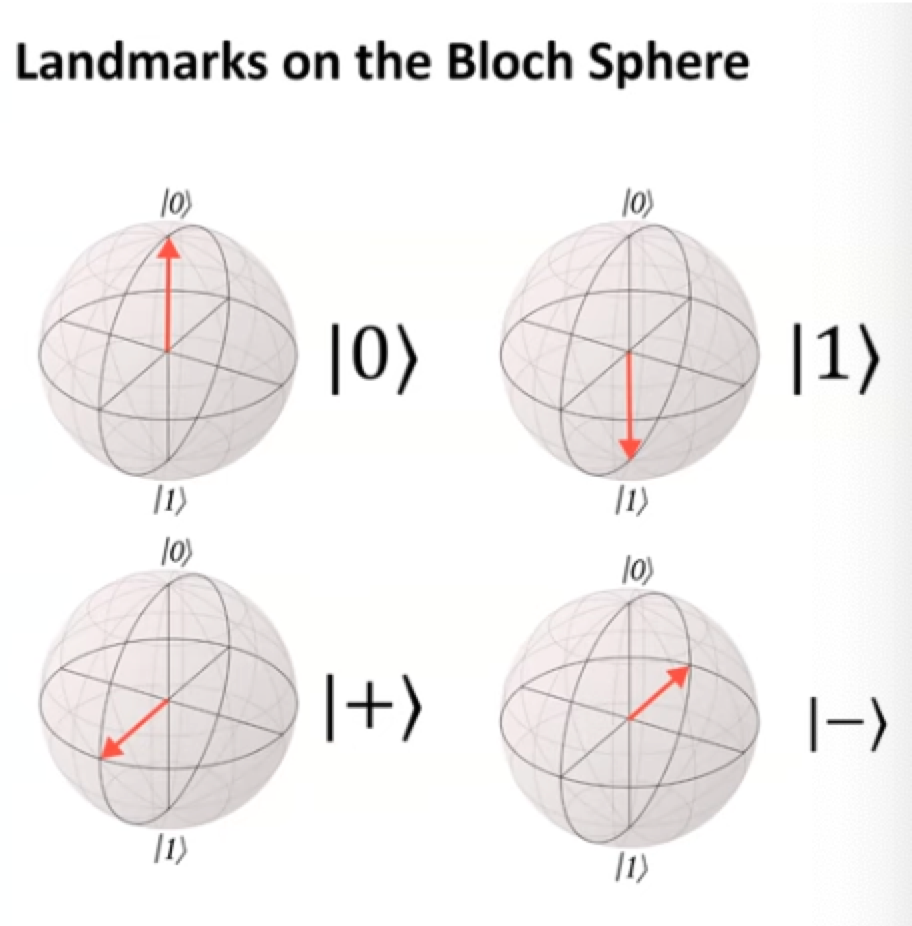
Materials	

Lens through the Quantum Stack

Qubits:

- Classical bits can be in two states only: 0 or 1
- Qubits can be in a combination of these two states
- Qubits (fundamental unit of information) can store quantum superposition and entanglement

Ket Notation is used to represent quantum states. These “brackets” signal a quantum state. The Bloch Sphere is a 3D visual representation of all possible quantum states; visual representation of gate transformations (for a single qubit).



*Usually, the “0” and “1” states are possible measurable outcomes, and the “+” and “-” states are superpositions. This can vary depending on what we choose our measurement basis to be.

What are qubits, physically?

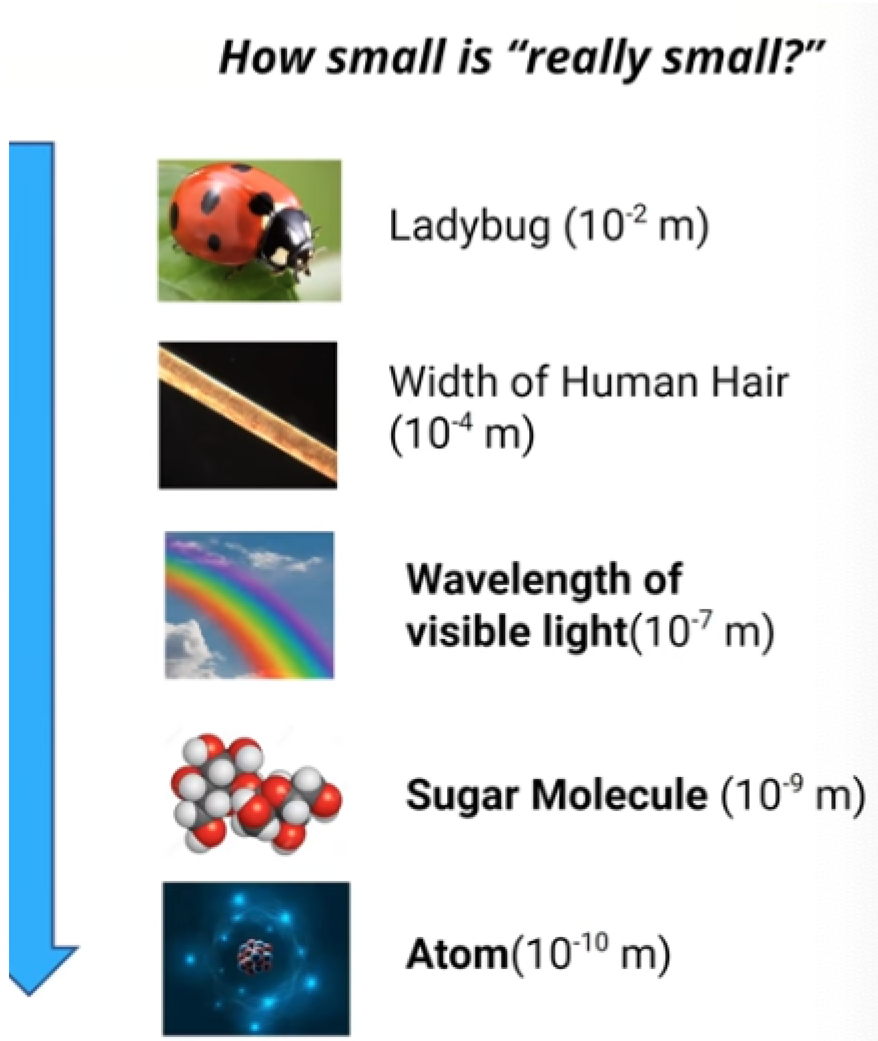
The choice of qubits largely defines what the quantum computer looks like and how it is built. Different types of qubits give us differing levels of errors and potential for scalability.

- Most widely used qubit - superconducting
  - Electronic circuit made with superconductors show q-properties making them good for quantum computing
  - gates are applied through microwave pulses
- Trapped-ion Qubits - use an electromagnetic field to trap ions (charged atoms) into place

    - Electromagnetic field (trap and suspend an ion in free space), and lasers (used to implement the gates
- Photonic Qubits
    - Properties allow photons to behave like a qubit
    - Linear Optics Quantum Computation (LOQC) - demonstrated quantum advantage
    - Use Case; quantum Communication
    - Requires uses of: mirrors, bema splitters, and phase shifters
- Topological Qubits
    - Proposed in theory but have not yet been demonstrated in practice. This practice is in stark contrast to more traditional qubits (very difficult to engineer)

Quantum Mechanics

A quantum computer uses the properties of mechanics to solve problems that classical computers cannot. The laws of mechanics begin to govern over classical physical laws at certain, very small length scales.



Quantum Mechanics become dominant smaller than "wavelength of visible light".

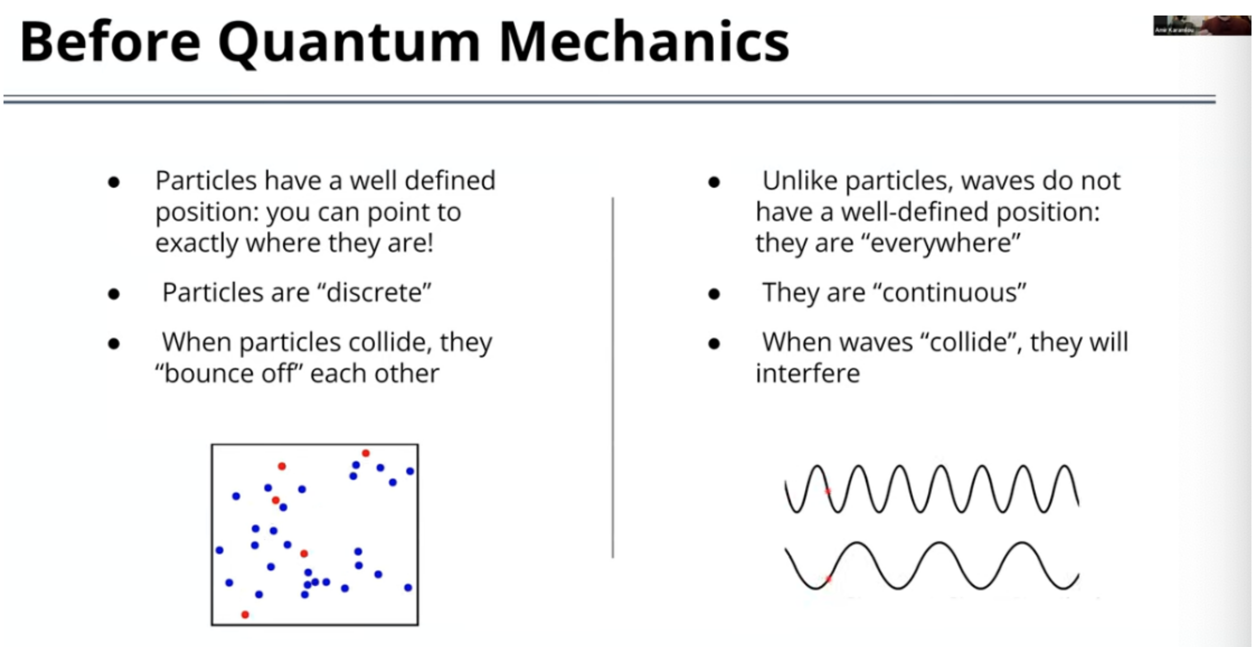
We say that a classical object has a state, which describes where it is and what it is doing at a certain time. Quantum Object also have states, but cannot be predicted with certainty where the object will be in. The Quantum state describes a probability of finding the object in one classical state versus another. Therefore, we describe quantum states to be probabilistic.

- Discreteness
    - Energy can only take certain values; objects operate between separate, discrete energy levels (ex: no acceleration between speeding up form 20 mph to 40 mph)
- Superposition

- Qubits can be in a combination of states at the same time; Objects being in multiple states at once (all states are possible at the same time)

- Interference
    - State of objects can add up or cancel each other (wave-like behavior of quantum systems)
    - Constructive interference: States add up to amplify the altitude (example radio and radio stations)
    - Destructive interference States cancel out to decrease or zero out the altitude (example: Noise-cancelling headphones)
- Entanglement:
    - One objects states depends on another objects state; The state of one object can't be described without describing the other state; dependent relation between two objects

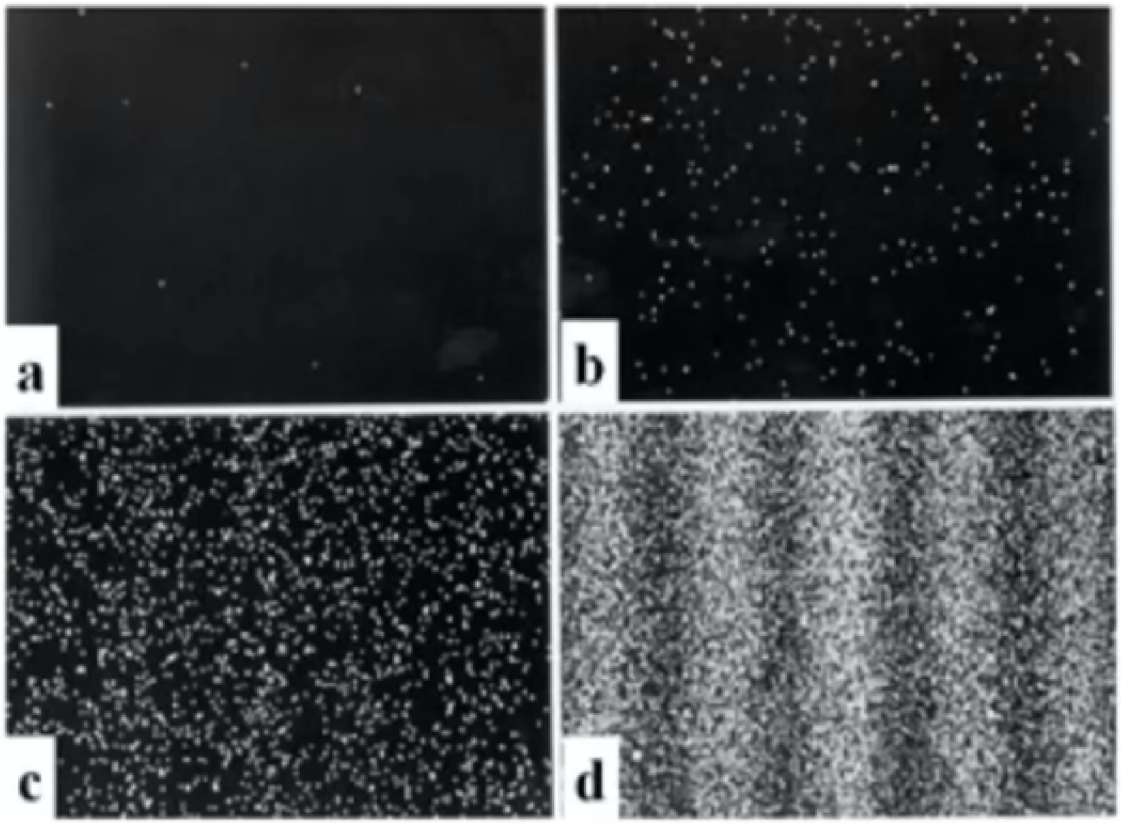
Why do these properties exist? - Wave Particle Duality



Light is both a particle and a wave.

- Light as a Particle: the photoelectric effect. For every one particle of light, only one electron can be kicked out of the metal

- Light as a Wave: the double slit experiment. Wave like interference pattern emerge during experiment.



Single-electron Build-up of Interference Pattern

We need to use wave equations to describe the position of quantum objects. We describe them in terms of probabilistic functions about the status of an object in space and time. These wave functions describe the motion of a quantum object - but they also have amplitudes, and so on…

Quantum Gates

Every one changes qubit states differently (different kind of rotation on the Bloch Sphere).

X Gate:

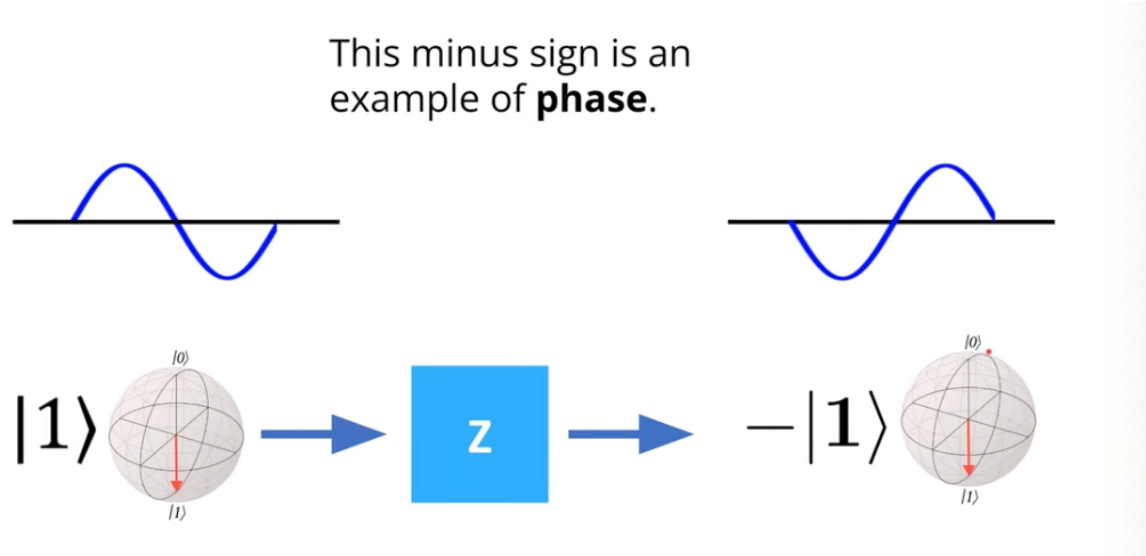
- Provides the opposite of the input. The X gate rotates the Bloch sphere 180 degrees around the X axis.

Hadamard Gate:

- The H-Gate creates a superposition. This is a uniquely quantum gates that create states we cannot replicate with classical gates

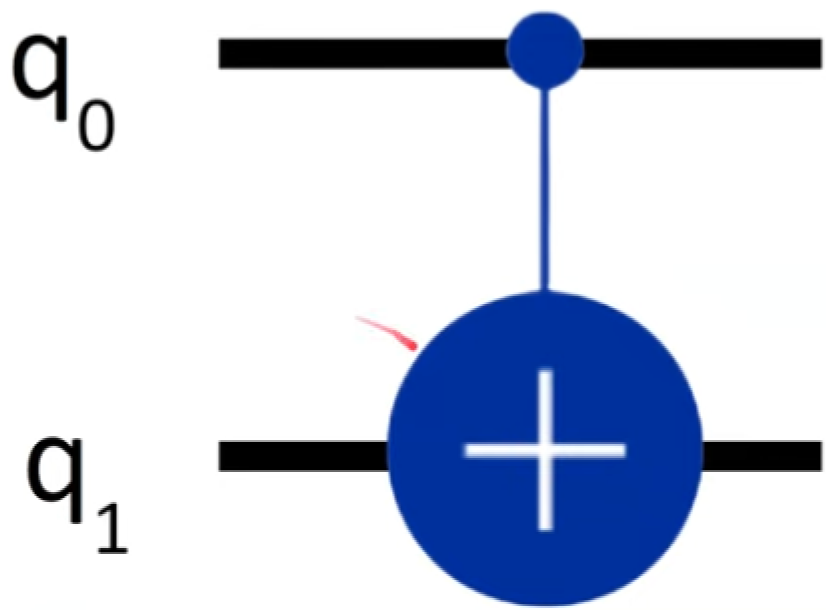
Z Gate:

- The Z Gate is a 180 degree rotation around the z-axis. This gives us no change in the “0” state, and phase shift in the “1” state. Adds a phase to the “1”. This also means that the “+” and “-” states switch with each other.



The CX (CNOT) Gate

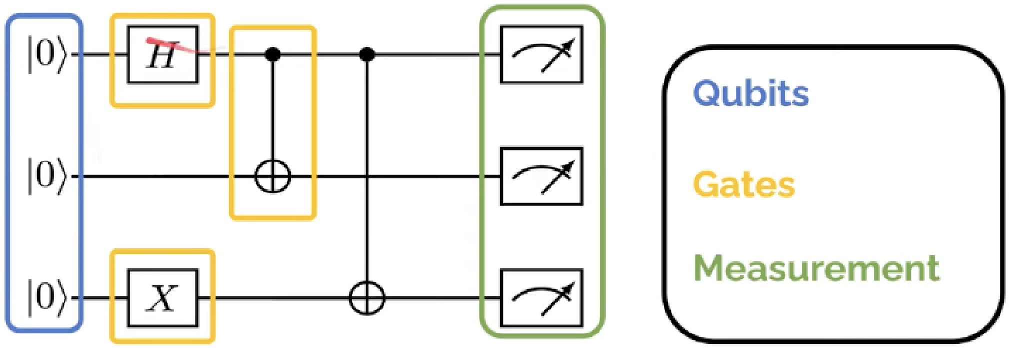
- The CX Gate is a 2 qubit gate:



- The CX Gate is a controlled gate. A controlled gate changes the target qubit based on the state of the control qubit. If the control is “0”, nothing happens to target. If control is “1”, a gate gets applied to the target.
- If the gate applied is an X Gate, the gate is called a controlled X gate. Similar rules apply for a controlled Z gate.

Quantum Circuits

A quantum circuit is a sequence of quantum gates. The following is a conventional way to draw a quantum circuit.



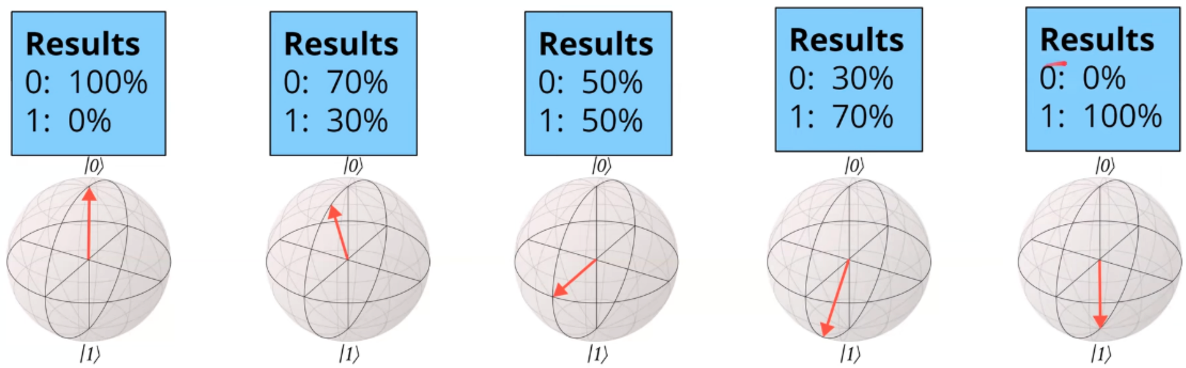
Quantum circuits can be single circuits with multiple gates or we can have as many qubits as we want, by adding more qubits with their own lines (a multi0qubit circuit). A quantum circuit model can be used to understand the components of a quantum circuit.

Quantum states are the qubits we use for computation. Gates are the changes we apply to qubits. Measurement is the final step in which we determine the value of our our outputs.

Quantum Measurement:

Measurement is how we learn information about our qubit states. It answers the question: “is the state a 0 or 1?”

1. The outcome of a q-measurement is often random.
    a. Measurement is random for any superposition states
    b. Can be more likely or not for one particular state depending on the probabilities



2. By observing or measuring a q-state, we can change it

   a. If we happen to measure a particular state, the qubit will end up in that state.

Z Basis

The Z basis describes states with the z axis pointed up. This is commonly called the computational basis and it is the standard basis to talk about qubits in

Basis States

The states corresponding to the up and down directions in a given basis are called the basis states

Quantum Algorithm and Protocols:

Protocol: A set of standard rules that allow e-devices to communicate with each other. Similar to contracts that multiple parties are bound to.

Quantum Algorithms:

1. Deutsch-Jozsa Algorithm
2. Shor's Factoring Algorithm
3. Grover's Algorithm
4. Near-Term Algorithms
   a. Attempts to use current quantum computers in conjunction to do something useful. These tend to be classical-quantum hybrid approaches. We are currently in the Noise Intermediate Scale Quantum Era

Quantum Protocols:

Three quantum protocols that we know have a significant advantage over any classical alternative.

1. **Quantum teleportation**: sending a quantum state to someone far away using entangled qubits and classical bits
2. **Superdense Coding:** Send the equivalent of multiple classical bits with just one quantum bit
3. **Quantum Key Distribution:** Establishing a secure communication channel, even with a presence of an eavesdropper

Quantum Applications, Industry and Future Outlook

Steps to “run” when coding on quantum hardware:

1. Transpilation
2. Gates as Pulses
3. Readout
4. Display

The aim of engineering useful, scalable quantum computers can be captured with 5 points:

1. Well-characterized and scalable qubits
2. Initialize Qubits
3. Long Coherence times
4. Universal set of gates
5. Efficiently measurable

How do we get there?

- More Qubits (Scalability)
    - Physical Qubits: the actual, physical materials that we use to process quantum information
    - Logical qubits are representations of qubits we use for programmings
    - To correct for errors, we need to implement multiple physical qubits per logical qubit in a quantum algorithm
- Better Quality Qubits (Less Noise)
    - All of this noise can be disturb the qubits’ state and cause errors in the quantum computer
    - Our goal is to design fault-tolerant quantum hardware

Quantum Error Correction:

- Is a field that is devoted to reducing the effects of noise in quantum computation
- Error correction is a general set of techniques of making computation work correctly even if there are errors

- QEC is about protecting q-computers from errors, often relying on q-properties since classical approaches don’t tend to work