Week 4 Summary of Key Concepts

Lecture

Summary: In lecture this week, we applied the concepts of quantum mechanics we had learned in the past two weeks to qubits and quantum gates. We learned two new methods of representing qubits - the **ket notation** and the **Bloch sphere**. We also used this notation to learn how two fundamental gates in quantum computing, the **X and H gates**, apply to qubits. Here are the key concepts we discussed:

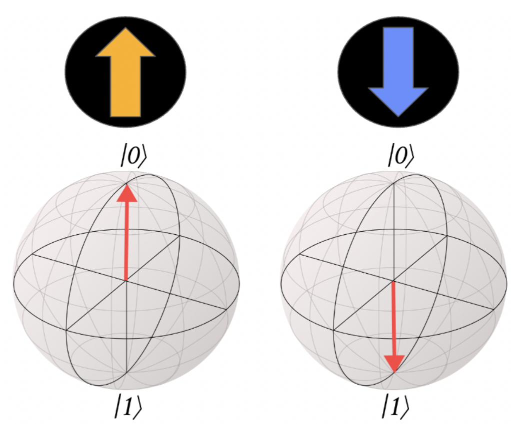
1. **Ket notation:** The ket notation is used to represent the state of qubits. Putting a “0” or a “1” inside a ket shows that it represents a quantum state

$|0\rangle$

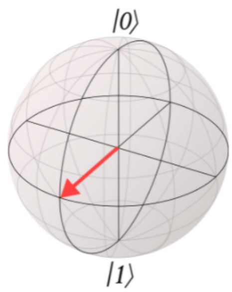
$|1\rangle$

Superposition of:
$|0\rangle \quad |1\rangle$

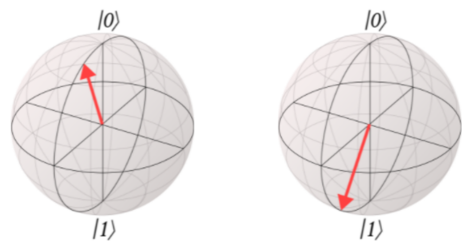
2. **Bloch sphere:** The Bloch sphere is a way to visually represent qubit states. It overcomes the limitations of the arrow notation that we’ve used so far to visualize qubit states, which is not very good for representing superposition states. **Any qubit state can be represented on the Bloch sphere.**
    a. The $|0\rangle$ state is located at the top of the Bloch sphere, and the $|1\rangle$ state at the bottom.



    b. **Any other state on the Bloch sphere represents a superposition of $|0\rangle$ and $|1\rangle$.** A superposition can be **equal**, meaning that $|0\rangle$ and $|1\rangle$ contribute equally to the state, or **unequal**, meaning that either $|0\rangle$ contributes more or $|1\rangle$ does. If the state is closer to $|0\rangle$, it has a greater contribution from $|0\rangle$. If it is closer to $|1\rangle$, it has a greater contribution from $|1\rangle$.

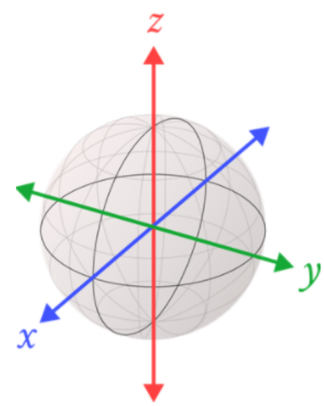


This is an equal superposition



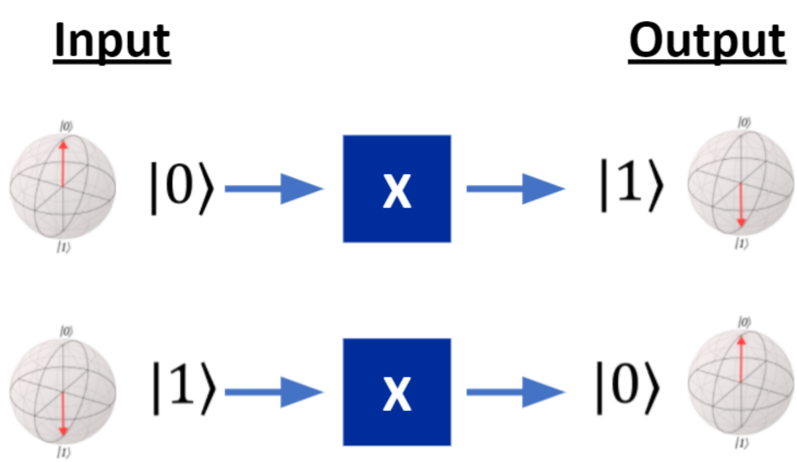
These are unequal superpositions!

3. **Quantum Gates:** Quantum gates manipulate or change the state of qubits. Gates are how we create superposition, interference, and entanglement! **The operation of gates on qubits can be visualized as rotations on the Bloch sphere.**
    a. To visualize these rotations, we need to associate a coordinate system with the Bloch sphere. Here is the conventional coordinate system:



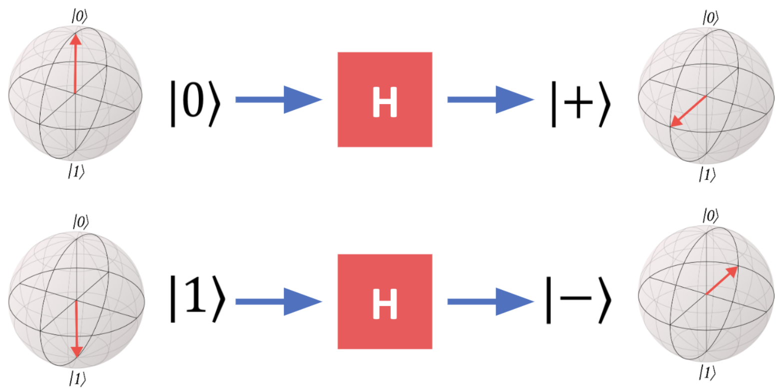
4. **The X gate:** The operation of the X gate can be summed up as follows:

Rule: Gives the opposite of the input



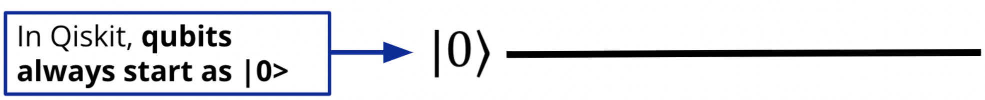
The X gate can be visualized as a 180 degree rotation about the X axis.

5. **The H gate:** The H gate creates **superposition**. It is a uniquely quantum gate!

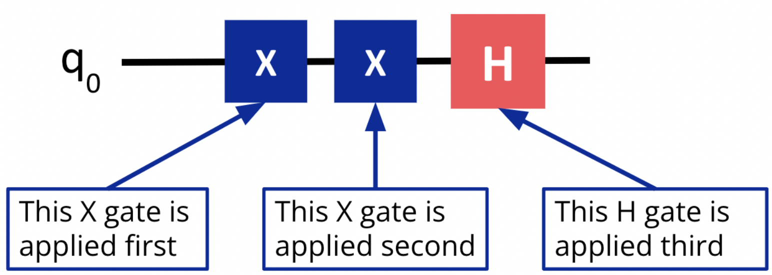


Here, $|+\rangle$ and $|-\rangle$ represent two superposition states. We will learn more about these states in the coming weeks!

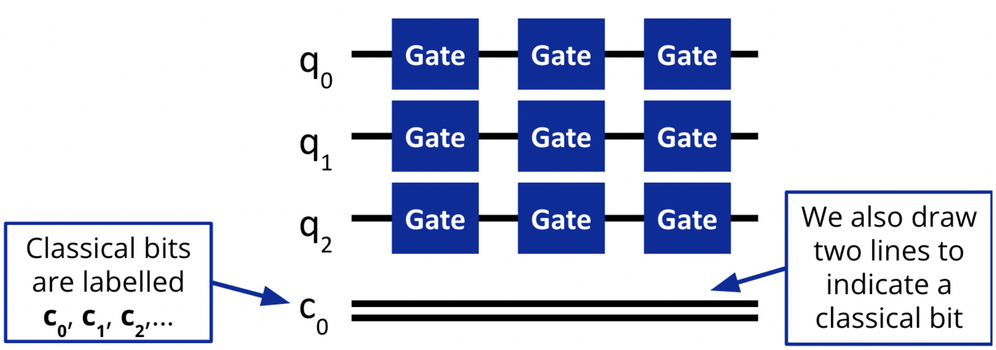
6. **Quantum circuits** are collections of quantum gates.
   a. We draw them as:



   b. We can add as many gates as we want to our circuit:



   c. We can have multiple qubits in our circuit or even classical bits, which are draw with double lines:



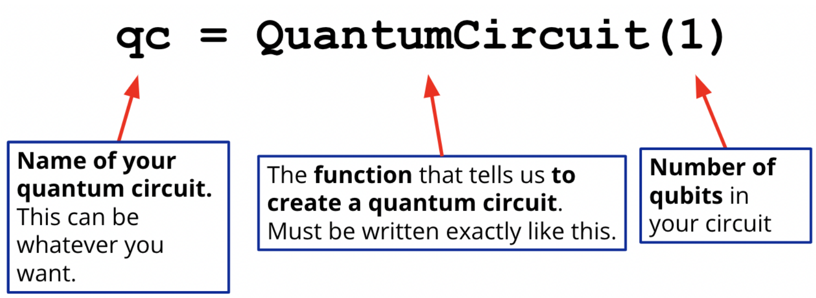
QUBIT X QUBIT

Lab

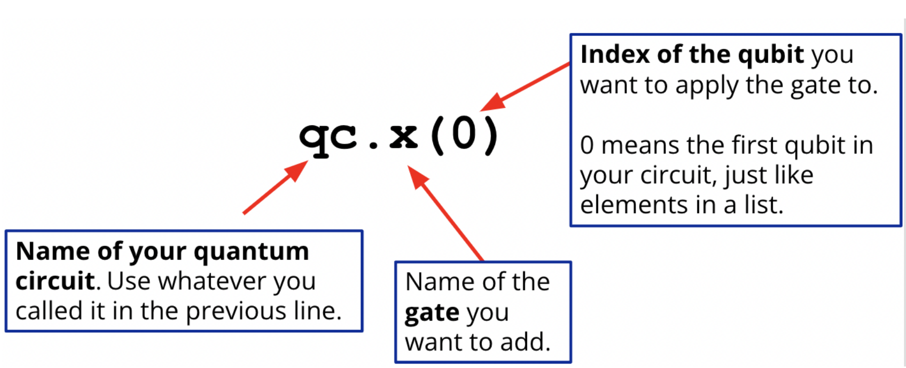
Summary: In lab this week, we started learning **Qiskit**! We took our first steps in quantum coding. We learned how to create quantum circuits, add gates to them, and run them on Qiskit. Here are the key concepts we discussed:

1. **Functions and Libraries:**
    a. Qiskit is a **library** of Python. A library in Python is a collection of prewritten functions that we can use. We just have to **import** the specific functions we want or the whole library.

2. **Circuits in Qiskit:** There are three steps for creating and running circuits in Qiskit:
    a. **Step 1: Create an empty circuit** - In this step we define the circuit. It is empty because we have not added any gates to it yet. We create quantum circuits using the **QuantumCircuit()** function. Here's what the code looks like

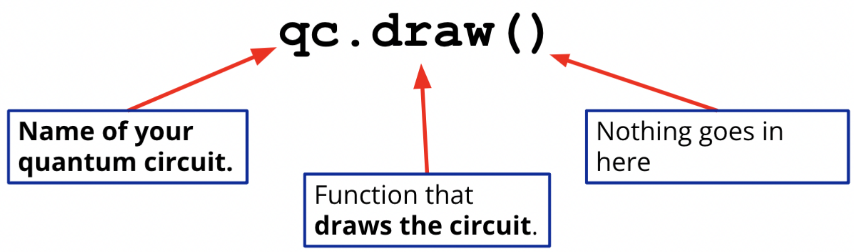


    b. **Step 2: Add gates to the circuit -** In this step we add whichever gates we want to the circuit. Here's the code for adding the X gate:

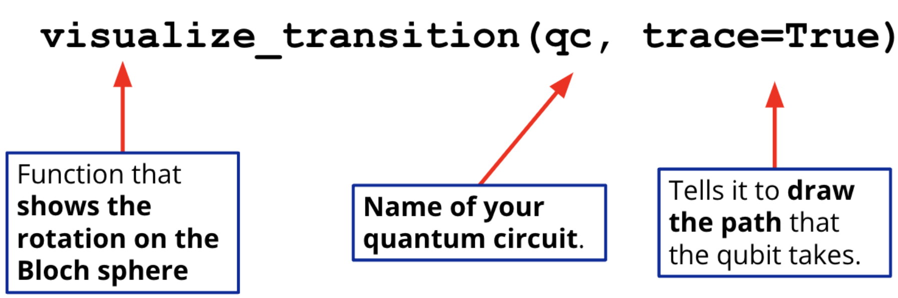


Similarly, the code for adding an H gate is *qc.h(0)*

c. **Step 3: Draw the circuit -** In this step we can draw a diagram of the circuit to see what it looks like and check that it is correct.



d. **Step 3: Run the circuit -** In this step we can also execute or run the circuit. There are many different ways that we will learn throughout this course to run circuits. In this lab, we used the visualize_transition() function:



Challenge questions

Based on discussions in lecture and lab this week, here are a few questions to think about. We will address these questions in the coming weeks!

- Knowing that the X gate performs a 180 degree rotation about the X-axis on the Bloch Sphere, what do you think the Z gate does?
- What would be the result of applying the X gate to a qubit in the $|+\rangle$ state? How about the $|-\rangle$ state?
- Does the order in which gates are applied matter? Is the final state the same if we first apply an X gate and then an H gate, and if we reverse the order of the gates?
- How can we relate $|0\rangle$ and $|1\rangle$ to $|+\rangle$ and $|-\rangle$?

Further readings and resources

- Qiskit textbook page on qubit representation - This page also covers statevectors, which we will discuss in the future!
- Qiskit textbook page on quantum gates - This page also covers the math of gates - matrices, which we will discuss in the future! It also discusses some gates that we will not cover in this course.
- ***Quantum Logic Gates Based on DNAtronics, RNAtronics, and Proteintronics*, Sheu, Hsu, and Yang (Scientific Paper)**
  - **URL:** https://onlinelibrary.wiley.com/doi/full/10.1002/aisy.202000273
  - **Summary:** This paper explores the use of specific amino acid and nucleotide base pairs as quantum logic gates. While it does include some perhaps unfamiliar gates and biology content, the CNOT and Pauli X-, Y-, and Z-gates should be recognizable!