Quantum Kraken Device - Introduction

The badge you hold is no ordinary piece of technology—it houses miniaturized quantum computer technology! This quantum device is the heart of your mission, enabling quantum communication and cryptographic operations. Smuggled aboard under the guise of ordinary electronics, your badge holds the key to establishing a secure quantum communication link with a supercomputer onboard the target ship.

The heist is as high-tech as it gets. Your mission involves leveraging the quantum capabilities of this device to bypass conventional security measures and gain access to the ship's critical systems. However, the journey begins with calibration. Being smuggled onboard has destabilized the device, and you must go through a series of steps to realign and understand its quantum operations. Along the way, you'll receive a crash course in quantum computing, preparing you for the tasks ahead.

To get started, connect through serial to your badge and look at the `help` menu! You can use several tools to connected, such as Putty, minicom, picocom, etc... and will be dependent on your setup.

Calibration 1 - Qubits and Quantum Information

To begin your calibration process, you start with the basics: qubits and their role in quantum information. While the calibrations will need to be performed delicately, the badge also includes a full simulator for you to play around with.

```
>  quantum 1
Initialized 1-qubit state: |0>
Quantum interactive mode. Type 'exit' to quit, 'help' for commands, or 'list' to show applied gates.

q>: help
Commands available:
  g <X|Y|Z|H> <qubit>
  g CNOT <control_qubit> <target_qubit>
  list (to see applied gates)
  sv (to view the qubit statevector)
  measure (collapses the state and automatically reinitializes)
  exit (to quit)

q>: 
```

By the end of the calibrations you will know more how these commands interact, but feel free to play around and familiarize yourself with how it operates.

Qubits and Mathematical Representation

A qubit is the fundamental unit of quantum information, analogous to a classical bit but with exponentially greater power. Unlike classical bits, which are strictly 0 or 1, qubits exist in a superposition of both states. Mathematically, a qubit is represented as:

$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

Where the states 0 and 1 are represented with linear algebra:

$$|0\rangle = \begin{bmatrix}1\\0\end{bmatrix} \quad |1\rangle = \begin{bmatrix}0\\1\end{bmatrix}$$

α and β are complex numbers that define the statevector of the qubit. These numbers satisfy the normalization condition $|\alpha|^2 + |\beta|^2 = 1$. Another way to think of this is that α and β are the probability chances of the qubit being 0 or 1.

- If $\alpha = 1$ and $\beta = 0$, the qubit is in state $|0\rangle$.
- If $\alpha = 0$ and $\beta = 1$, the qubit is in state $|1\rangle$.

Statevectors

A **statevector** is a mathematical representation of a quantum system's overall configuration. Each entry in the vector corresponds to one of the possible "basis states" the system can be in. For a single qubit, those basis states are $|0\rangle$ and $|1\rangle$. On the Quantum Kraken Device, statevectors are printed with amplitudes (complex numbers) next to each basis state, telling you how the qubit is distributed across $|0\rangle$ and $|1\rangle$. A value of 1+0i for $|0\rangle$ means the qubit is entirely in state $|0\rangle$, and 1+0i for $|1\rangle$ means it is entirely in state $|1\rangle$.

```
Statevector:
|0> : (1.000000 + 0.000000i)
|1> : (0.000000 + 0.000000i)
```

When you have more qubits, the statevector grows exponentially. Two qubits have four possible basis states ($|00\rangle$,$|01\rangle$,$|10\rangle$,$|11\rangle$), three qubits have eight basis states, and so on. Each basis state has an amplitude which is generally complex; the probability of measuring that basis state is the square of the amplitude's magnitude. Keeping track of the statevector is crucial for understanding how gates and operations affect your qubits - and why a qubit can be "in more than just $|0\rangle$ or $|1\rangle$ at once".

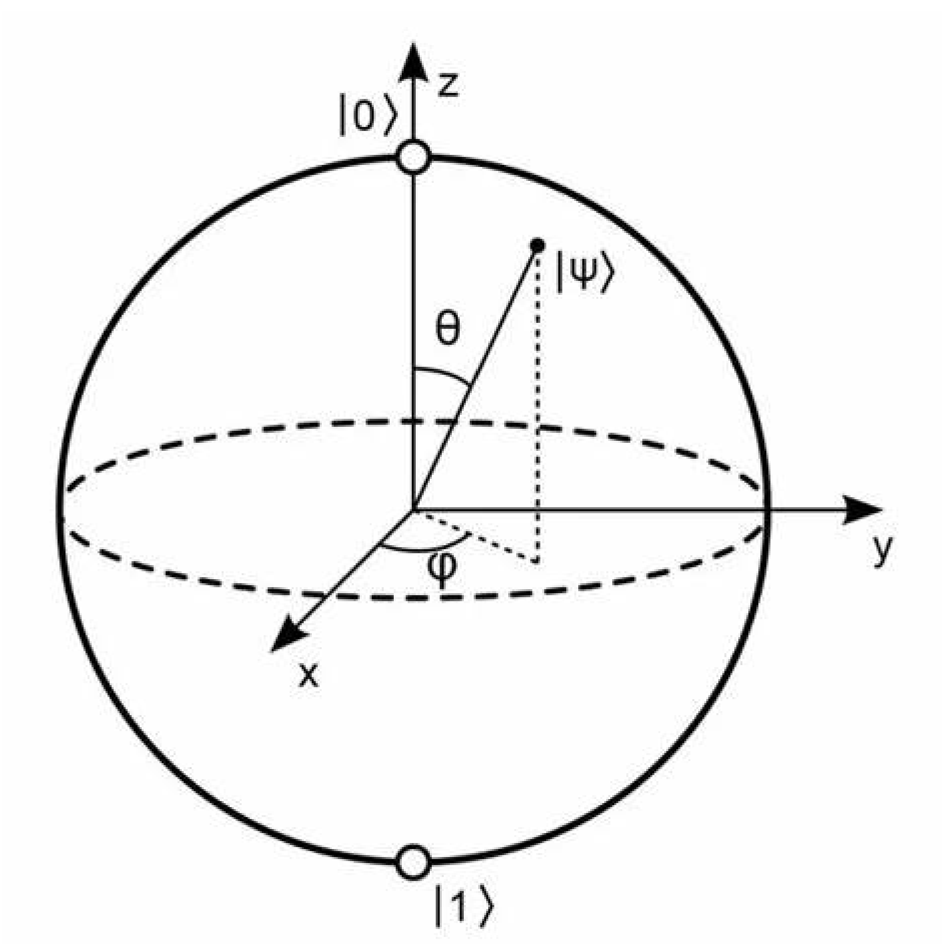
```
Statevector:
|00> : (1.000000 + 0.000000i)
|01> : (0.000000 + 0.000000i)
|10> : (0.000000 + 0.000000i)
|11> : (0.000000 + 0.000000i)
```

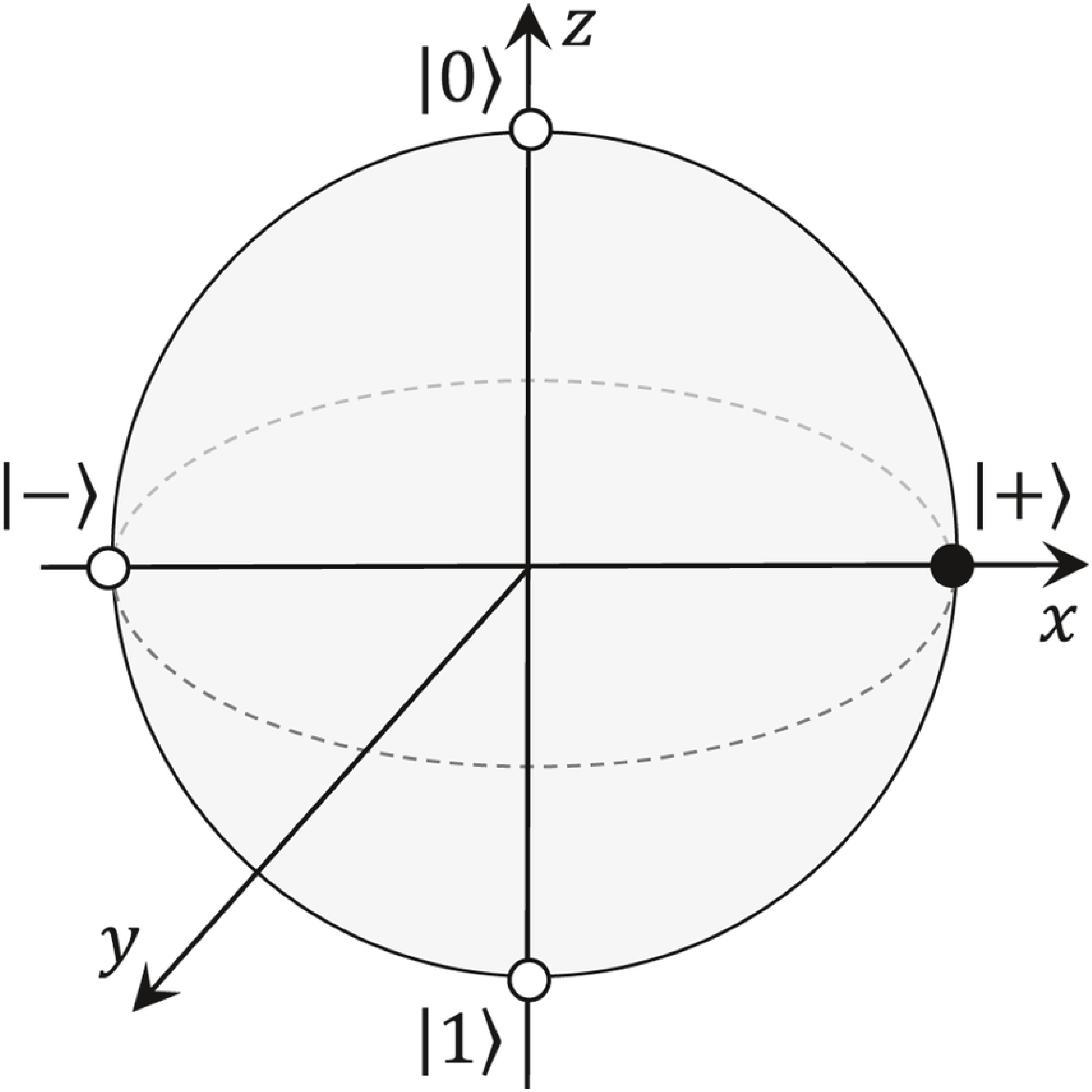
Bloch Spheres

We can illustrate this graphically on a qubit sphere, called a Bloch sphere. The qubit’s state can be visualized as a point in three-dimensional space, where the coefficients determine its position.

Notice on the below diagrams three things to ground you:

1. |0⟩ and |1⟩ are opposite ends of the Z axis
2. |+⟩ and |-⟩ are opposite ends of the X axis
3. |ψ⟩ is an arbitrary point on the Bloch sphere





Gate-Based Rotations

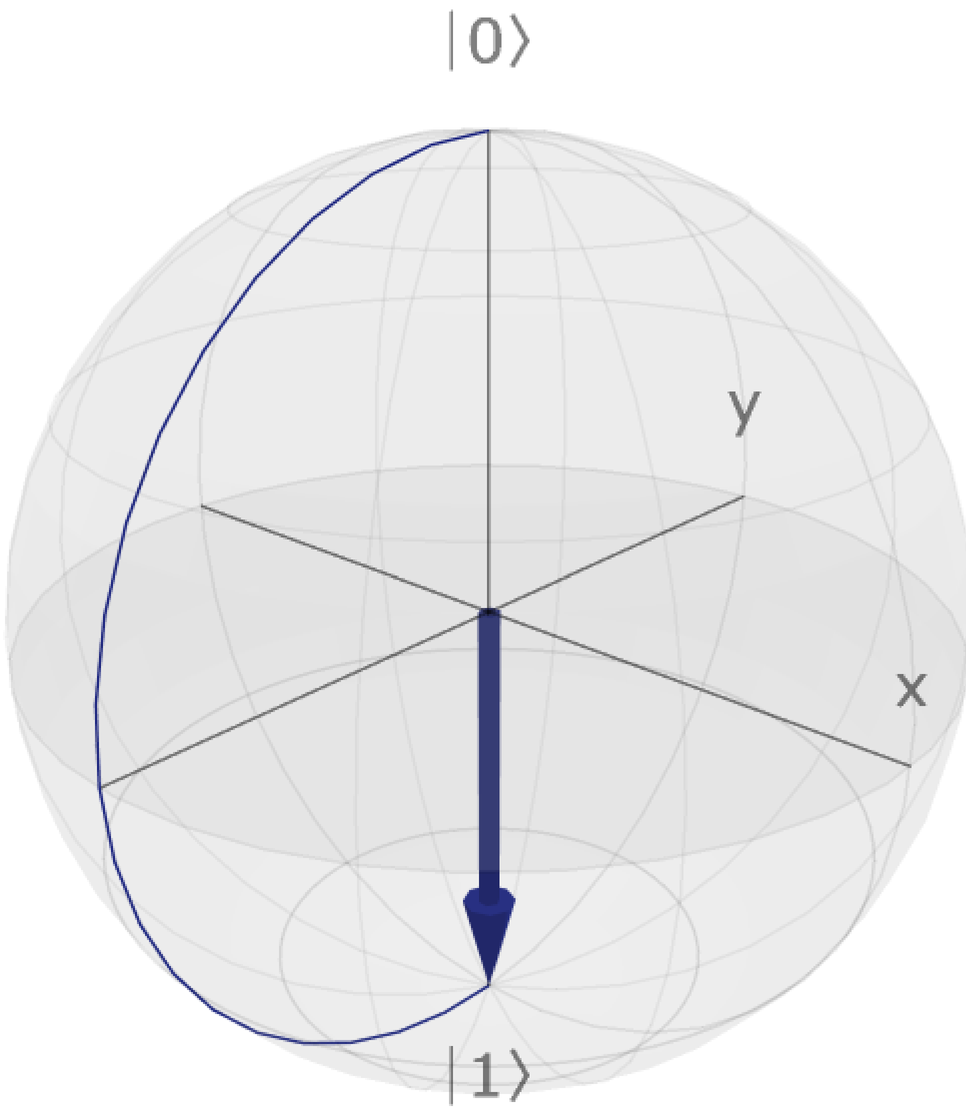
Quantum gates change qubits, altering their statevector and the point on the Bloch sphere by rotating around the qubit. Fundamental gates are the X gate (quantum NOT gate), Hadamard gate (H) which underpins superposition, and the Z gate (phase flip gate).

- **X Gate**: Flips the state of the qubit, analogous to a classical NOT operation. For instance, applying X to $|0\rangle$ results in $|1\rangle$, and applying X to $|1\rangle$ results in $|0\rangle$. Mathematically:

$$\mathbb{X}|0\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} |0\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} = |1\rangle$$

$$\mathbb{X}|1\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} |1\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} = |0\rangle$$

And demonstrating the rotation directly on the Bloch sphere:



```
>  quantum 1
Initialized 1-qubit state: |0>
Quantum interactive mode. Type 'exit' to quit, 'help' for commands, or 'list' to show applied gates.

q>: sv
Statevector:
|0> : (1.000000 + 0.000000i)
|1> : (0.000000 + 0.000000i)

q>: g X 0
Applying gate X to qubit 0...

q>: sv
Statevector:
|0> : (0.000000 + 0.000000i)
|1> : (1.000000 + 0.000000i)
```

- **H Gate**: can create a *uniform superposition* of the two states |0⟩ and |1⟩.

  Superposition allows a qubit to represent both |0⟩ and |1⟩ states simultaneously. The Hadamard gate (H gate) is a key tool to create superposition. When applied to |0⟩, it transforms the state into |+⟩:

$$|+\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right) \longleftrightarrow \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix},$$

$$|-\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle - |1\rangle\right) \longleftrightarrow \begin{bmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{bmatrix}.$$

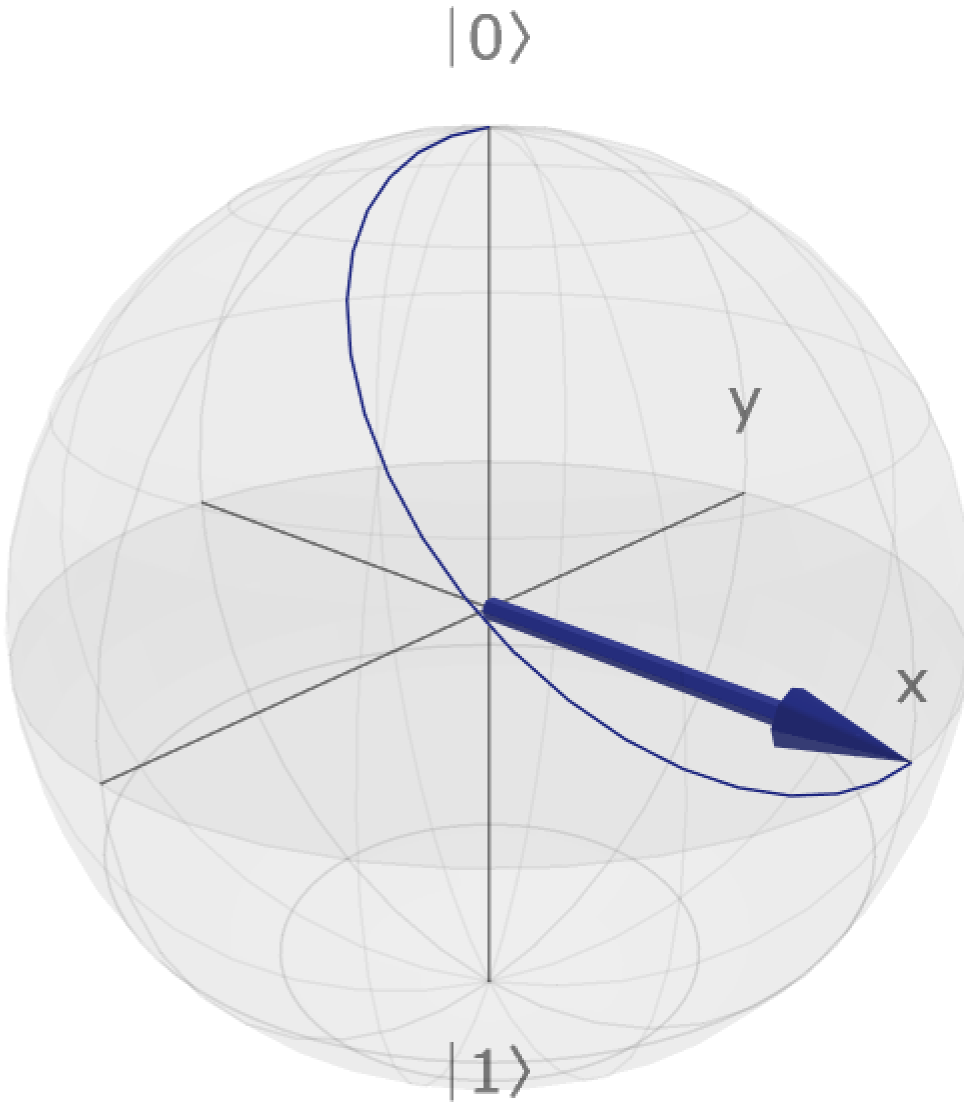
```
>  quantum 1
Initialized 1-qubit state: |0>
Quantum interactive mode. Type 'exit' to quit, 'help' for commands, or 'list' to show applied gates.

q>: sv
Statevector:
|0> : (1.000000 + 0.000000i)
|1> : (0.000000 + 0.000000i)

q>: g H 0
Applying gate H to qubit 0...

q>: sv
Statevector:
|0> : (0.707107 + 0.000000i)
|1> : (0.707107 + 0.000000i)
```

  Where both α and β coefficients are 1/√2. Mathematically this can make sense based on $|\alpha|^2 + |\beta|^2 = 1$, where a statevector of 0.707107 means $|0.707107|^2$, or 50% probability! And being normalized, it means that both probabilities are 50% of either being measured as a 0 or a 1. It should be clear from the statevector representation above that the qubit is not itself "simultaneously 0 and 1", but the point where it is on the qubit can be measured as either 0 or 1.



- **Z Gate**: Introduces a phase flip, leaving |0⟩ unchanged but flipping the phase of |1⟩.

  A **phase flip** is an operation that introduces a relative negative sign to one component of a qubit's superposition, leaving the other unchanged. In practice, this corresponds to the **Z gate**, which multiplies the amplitude of |1⟩ by –1 while leaving |0⟩ alone.

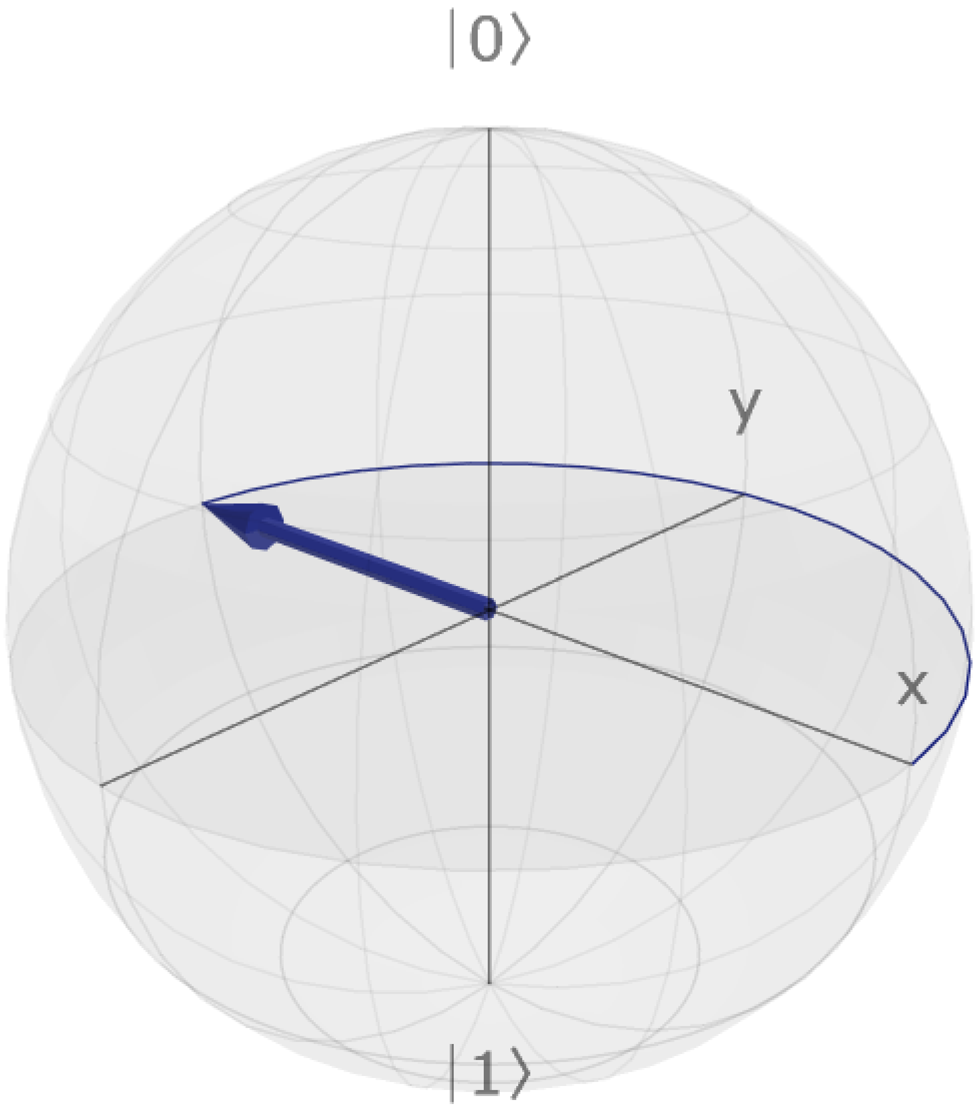
$$|0\rangle \to |0\rangle,$$
$$|1\rangle \to -|1\rangle.$$

  But when applying a Z gate to |+⟩ results in |-⟩, and vice versa, flipping the phase of the qubit.

$$Z|+\rangle = \begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix} \frac{1}{\sqrt{2}}\begin{bmatrix}1\\ 1\end{bmatrix} = \frac{1}{\sqrt{2}}\begin{bmatrix}1\cdot 1 + 0\cdot 1\\ 0\cdot 1 + (-1)\cdot 1\end{bmatrix} = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\ -1\end{bmatrix} = |-\rangle.$$

$$Z|-\rangle = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -1 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \cdot 1 + 0 \cdot (-1) \\ 0 \cdot 1 + (-1) \cdot (-1) \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = |+\rangle.$$

Showing the rotation on a Bloch sphere.



```
q>: sv
Statevector:
|0> : (1.000000 + 0.000000i)
|1> : (0.000000 + 0.000000i)

q>: g H 0
Applying gate H to qubit 0...

q>: sv
Statevector:
|0> : (0.707107 + 0.000000i)
|1> : (0.707107 + 0.000000i)

q>: g Z 0
Applying gate Z to qubit 0...

q>: sv
Statevector:
|0> : (0.707107 + 0.000000i)
|1> : (-0.707107 + 0.000000i)
```

Unitary Nature of Gates

You may have realized something by this point - generally re-applying the same gate "undos" the changes to the qubit.

Quantum gates are **unitary transformations**, which means they preserve the overall norm of a quantum state and are fully reversible. In mathematical terms, a unitary operator U satisfies $U^\dagger U=I$, ensuring that no information is lost or gained during the operation. This contrasts with many classical operations, which can be irreversible (and thus lose information). The unitary property is fundamental for quantum mechanics: it guarantees probability conservation (the sum of squared amplitudes remains 1) and allows one to “undo” a gate by applying its inverse, a concept essential for the coherence and reversibility of quantum computations.

Calibration Challenge 1

- Calibration 1a: Using a single qubit, initialize it to a $|-\rangle$ state using the gates above. Then print out the statevector using the `hash` command and submit it to `calibrate` to confirm the calibration.

$$|\psi\rangle = \frac{|0\rangle - |1\rangle}{\sqrt{2}} = |-\rangle$$

- Calibration 1b: Using two qubits, initialize each into a superposition state $|+\rangle$. This will put the two qubits into a superposition of all possible measurements. Once doneprint out the statevector using the `hash` command and submit it to `calibrate` to confirm the calibration.

$$|\psi\rangle = |+\rangle \otimes |+\rangle = \frac{1}{2}\Big(|00\rangle + |01\rangle + |10\rangle + |11\rangle\Big)$$

- Calibration 1c: Using three qubits, initialize qubit 0 and 2 to a |-⟩ state, while qubit 1 should be initialized to a |+⟩ state. Once done print out the statevector using the `hash` command and submit it to `calibrate` to confirm the calibration.

$$|\psi\rangle = |-\rangle_0 \otimes |+\rangle_1 \otimes |-\rangle_2 = \left(\frac{|0\rangle - |1\rangle}{\sqrt{2}}\right) \otimes \left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right) \otimes \left(\frac{|0\rangle - |1\rangle}{\sqrt{2}}\right)$$