Bloch Ball: Allowing for Exploratory Learning of Quantum Computing Through an Interactive Bloch Sphere

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I. Introduction

With the field of Quantum Computing rapidly growing, it is crucial that a variety of learning tools are available for learners. Unlike many fields of Computer Science, Quantum Computing is a multidisciplinary field, making it particularly difficult to teach. This is due to learners coming from a variety of learning backgrounds. These backgrounds include Physics, Computer Science, Math, Biology, and Chemistry. Due to the field being relatively new, not many tools have been developed for teaching Quantum Computing. This paper introduces the *Bloch Ball*, a Tangible User Interface (TUI) that supports the teaching of quantum gates and the Bloch sphere.

II. Background

Before detailing the Bloch Ball, a brief explanation of quantum concepts used in the tool will be given.

A. Qubits

When comparing classical bits to qubits, one can think of the former as a binary light switch, which can either be on or off, and the latter as a dimmer light switch. Like the binary light switch, the dimmer light switch can be completely on or off, but it can also be at a state between the two. When a qubit is not completely 'on' or 'off', it is said to be in superposition.

When it is measured, a qubit will take on a state of either 0 or 1. The act of measuring a qubit is sometimes referred to as causing it to collapse to a single value.

B. Quantum Gates

Like how classical logic gates can be applied to classical bits, quantum gates can be applied to a qubit to change its state. Two gates that students are introduced to early on in introductory Quantum Computing classes are the *NOT-gate* and the *HADAMARD-gate*. The quantum *NOT-gate* is identical to the classical *NOT-gate*, which changes the value of the bit to its opposite value. The *HADAMARD-gate* is one of the many gates that can be used to put qubits into superposition [1]. When applied to a qubit with a value of 0 or 1, it puts the qubit into equal superposition, meaning that the qubit has an equal possibility of collapsing to 0 or 1.

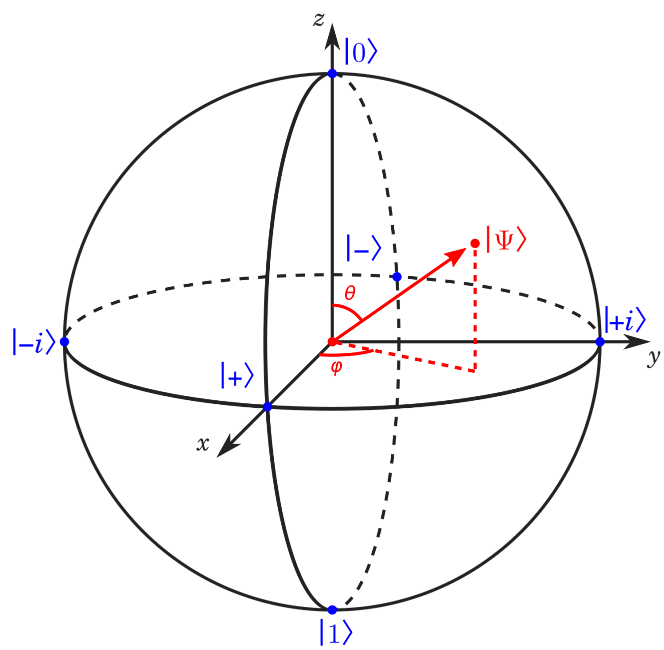

Fig. 1. An illustration of the Bloch Sphere. The three bases are denoted along the three axes. A quantum state is denoted on the end of each axis. The red vector denotes the value held by the qubit.

C. Quantum Bases and the Bloch Sphere

Like classical bits, the state of a qubit is typically referred to using 0 and 1. This is referred to as describing its state using the computational basis. Unlike in classical computing, however, multiple bases are used in Quantum Computing. The ability to switch between quantum bases is a fundamental and critical operation in many quantum experiments and applications. This process, known as basis transformation, is achieved through the precise application of quantum gates. These gates manipulate the

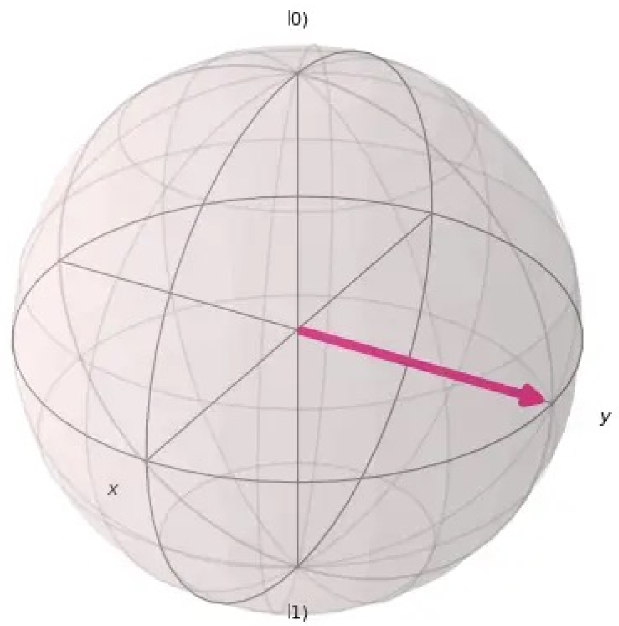

Fig. 2. A Bloch sphere generated using Qiskit code showing the state $|+i\rangle$, which sits along the y-axis [3].

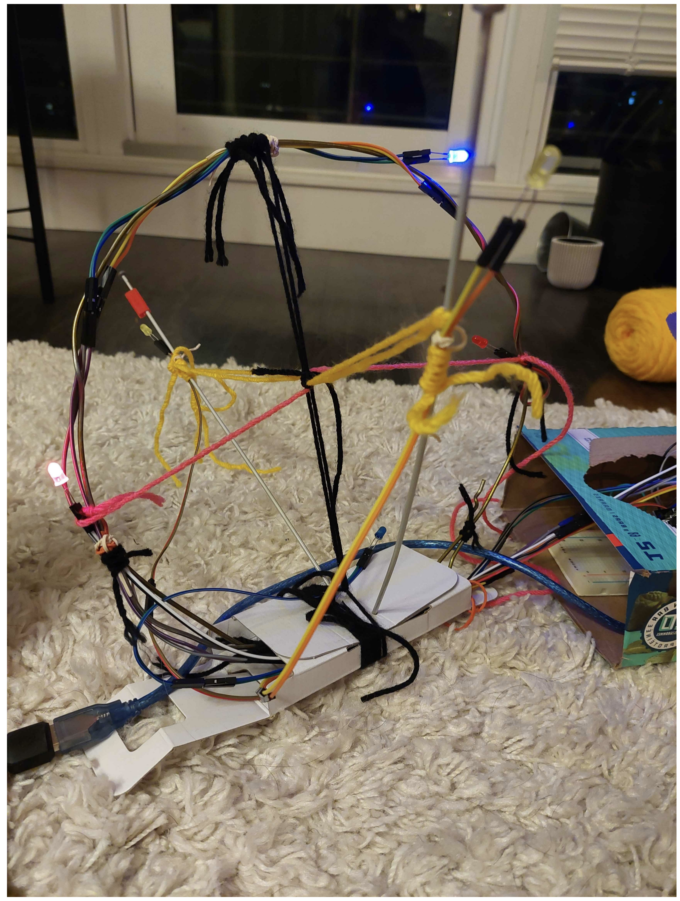

Fig. 3. The states $|0\rangle$ and $|-i\rangle$ selected on the Bloch Ball.

quantum states of qubits, allowing researchers to explore different aspects of quantum superposition.

The Bloch sphere is a visual tool used in Quantum Computing to visualize the state of a qubit [2]. One of its strengths is its ability to allow users to see the qubit's state in reference to the three main bases used in Quantum Computing: the Hadamard basis, the phase basis, and the computational basis. These bases each denote an axis which helps make up the Bloch Sphere, while the qubit state itself is represented as a vector. Figure 1 displays the components of the Bloch sphere.

III. Motivation and Related Work

Currently, the Bloch sphere is only used as an output visualization. The placement of the vector in the Bloch sphere, seen in Figure 1, can be derived manually. This derivation is often done in introductory Quantum Computing classes, but it is not practical. Many quantum software libraries allow for the Bloch sphere representation of a qubit to be generated. Figure 2 displays a Bloch sphere generated using IBM's quantum library, Qiskit [4].

The Bloch Ball takes inspiration from the 2-qubit dance, a *Dance Dance Revolution*-like dance routine created by *l'Université de Sherbrooke*. In the dance, dancers use their arms to denote the states of two qubits. Each 'move' of the dance is done by applying a quantum gate to the dancer [5].

IV. Bloch Ball

The Bloch Ball is an innovative tool designed to address the limitations of static Bloch sphere representations. It transforms the traditional Bloch sphere into an interactive input mechanism, enhancing the learning experience for quantum computing concepts. This tool seamlessly integrates the understanding of quantum gates, phases, and state representations on the Bloch sphere by allowing users to actively explore and manipulate quantum states.

A. Implementation

The Bloch Ball consists of three main components: the control box, the Bloch sphere sculpture, and the console. The control box hides most of the hardware from the user and hosts on top of it the joystick that is used to navigate around the Bloch Sphere sculpture. The skeleton of the Bloch sphere sculpture is made of several rods. These

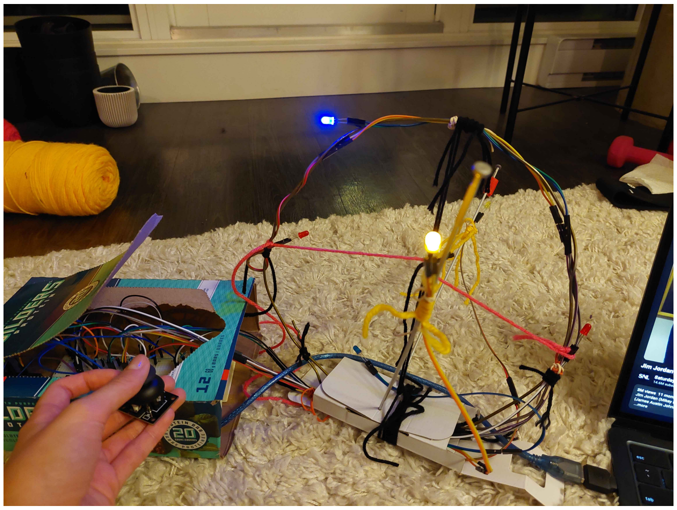

Fig. 4. The joystick being used to navigate around the different points on the Bloch Ball.

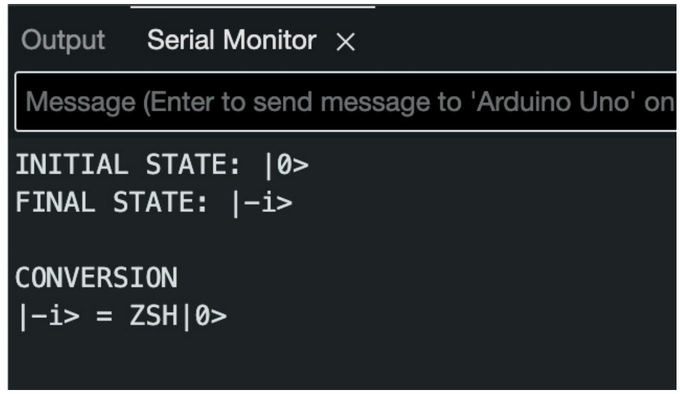

Fig. 5. Output after choosing $|0\rangle$ as the initial state and $|-i\rangle$ as the final state It is important to note that quantum equations are read from right to left in this notation, meaning that the *HADAMARD-gate* is the first gate to be applied. This output corresponds to the input seen in Figure 3.

rods represent the vertical hoops seen in Figure 1. The six LEDs on the sculpture represent the points of each axis seen on the Bloch sphere. The colours of the LEDs correspond to an axis with the blue LEDs representing the z-axis, the red LEDs representing the y-axis, and the yellow LEDs representing the x-axis. String is used to represent the lines of each axis. Figure 3 shows the Bloch sphere sculpture. The Bloch sphere sculpture makes the tool a TUI. It falls into both the spatial and relational categories of TUIs. It can be classified as the former as the location of the LEDs around the sculpture hold informational significance, and it can be classified as the latter as the location of each LED relative to the others has meaning (ex. LEDs directly parallel to each other denote an axis).

The joystick is used to navigate between the different points on the sculpture. The user's current location on the Bloch sphere is denoted by the LED at the point being lit. The Bloch Ball always starts off at $|0\rangle$. This is because the majority of quantum computing examples starting off with all qubits set to $|0\rangle$. The joystick can be seen in Figure 4. The user navigates between different states chosen on the Bloch sphere and generates the gates needed to convert between the states in the console. Figure 5 shows an example of the output received in the console.

The following steps detail how to use the Bloch Ball:

1) Navigate around the Bloch Ball using the joystick provided. The current location is denoted by the LED at the location being lit.
2) Once the desired initial state has been found, press down on the remote.
3) Repeat steps 1 and 2 for the second state. The LED denoting the initial state will continue to be lit during this process.
4) Observe the gate pattern shown in the console to see how to navigate between the two points chosen.
5) Press down on the joystick to restart.

The simple and quick workflow allows for users to try different inputs several times, allowing for them to begin to recognize patterns in their generated results. The code for the Bloch Ball can be found on GitHub.

B. End User Profile and the Creative Goals of the Bloch Ball

The end user of the Bloch Ball is a someone who is taking their first Quantum Computing course. Due to Quantum Computing's multidisciplinary nature, it cannot be assumed that the user has coding experience. While the exact background of the end user is not known, it is known that they will likely learn about gates and the Bloch sphere during their studies. In their survey of introductory quantum computing courses, Meyer et al. found that 98% of courses teach quantum gates and 84% of courses incorporate the Bloch sphere [6].

The Bloch Ball helps users at the pre-ideation phase of their creative learning process as it helps them form initial ideas and recognize patterns in foundational concepts [7]. By being able to answer questions such as

- How are the X and *Z-gate* similar when converting within the same basis?
- Is there a single gate that can be used to perform multiple different basis changes?

- Is the *S-gate* always used when converting to and from the phase basis?

users are able to improve their understanding of the foundations of quantum computing. This type of discovery falls into the mini-c category of creativity as the experiences of users are personally significant and expand the users personal understanding of the field.

C. Future Work and Conclusion

As seen in Figure 1, qubits are not limited to being in a states that lie directly on axes seen within the Bloch sphere. Currently, only states along the axes can be inputted into the Bloch Ball. Future iterations of the tool will allow for users to select precise locations all around the Bloch sphere.

While only a subset of states can be represented on the Bloch Ball, the tool acts as an example of how TUIs can be used in Quantum Computing Education. It specifically shows how the traditionally static Bloch sphere can be made into a creative support tool.

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