Sabneet Bains

Data Visualization – EN.605.662

Final Paper

Introduction

Since my undergraduate in Physics, I have been fascinated with quantum computing and progressively trying to learn more over time.

- Well, for starters, quantum computing is a domain of computing that leverages collective properties of quantum states, such as superposition, interference, and entanglement, to perform calculations. With the much hyped-up advantage being faster integer factorization than classical computers, i.e., Bye-Bye encryption! [1]

Now given the field is still analogically at the same stage as vacuum-tube computers of the 1940s, there is ongoing progress in visualizations explaining the core concepts. Thus, I propose a Tableau dashboard simulating single-qubit Bloch spheres for the following quantum gates: Pauli-X, Pauli-Y, Pauli-Z, and Hadamard.

Background

- A Bloch sphere is a 2-D sphere in 3-D Euclidean space representing pure state basis vectors $|0\rangle$ and $|1\rangle$ at the antipodal points and mixed (entangled) states at the interior points.

[1] https://www.quantamagazine.org/why-is-quantum-computing-so-hard-to-explain-20210608/

- Quantum logic gates operate on qubits or quantum bits and are fundamental circuit building blocks, just like their classical counterparts.

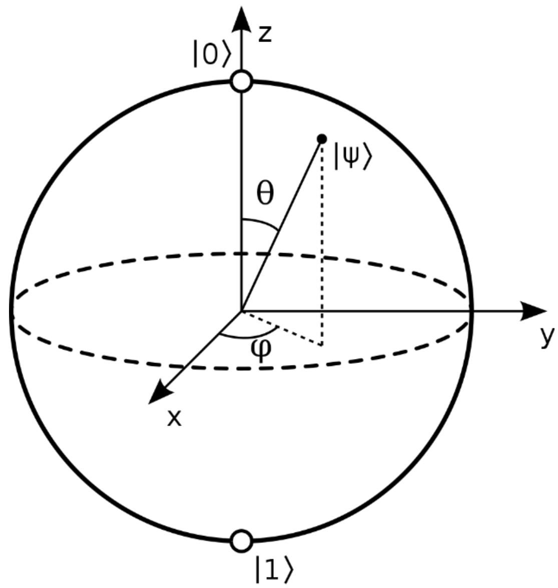


Figure 1: Bloch Sphere for a two-level quantum system [2]

Approach

I used Tableau 2022.1 to create a dashboard simulator with two semitransparent wire frame unit spheres, a single point emerging from the origin representing the state vector, and the corresponding quantum gate transformation. Due to Tableau's inherent lack of three-dimensional graphing, the unit spheres are split into XZ and YZ perspectives to grasp three-dimensional transformations.

[2] https://en.wikipedia.org/wiki/Quantum_logic_gate#/media/File:Bloch_sphere.svg

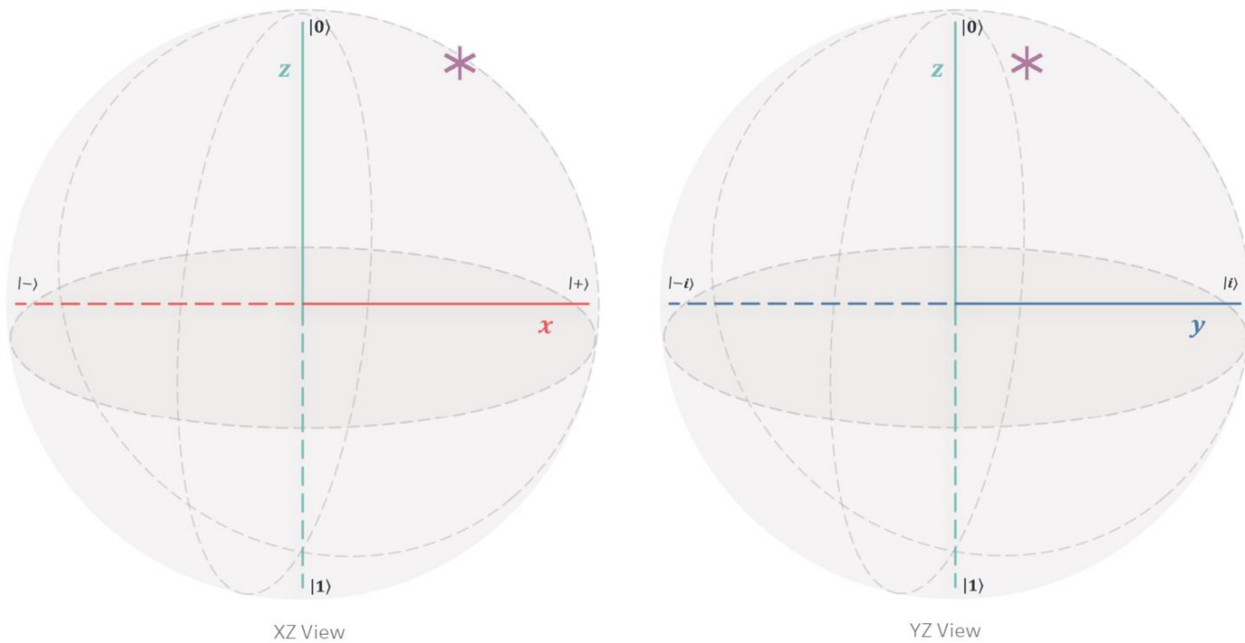


Figure 2: Original Bloch Spheres depicting a resultant state

Likewise, the dashboard has a drop-down box for the four quantum gates operating on the current quantum state in addition to spherical coordinates parameters of theta and phi.

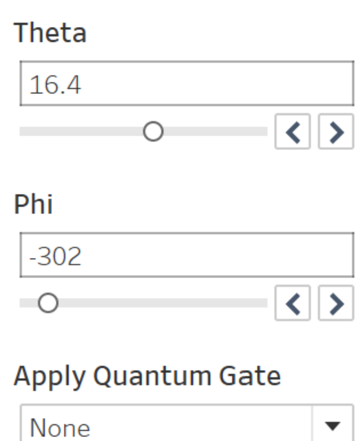


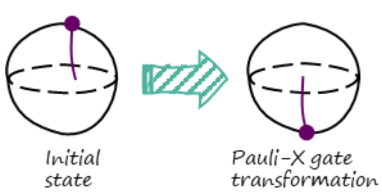
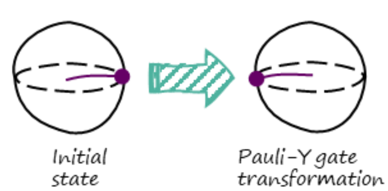
Figure 3: Parameter controls and quantum gate drop-down box

In principle, these quantum logic gates function as follows:

Pauli-X:	*Pauli-Y:*
⊕ $\|0\rangle \rightarrow \|1\rangle$	⊕ $\|0\rangle \rightarrow \quad i\|1\rangle$
⊕ $\|1\rangle \rightarrow \|0\rangle$	⊕ $\|1\rangle \rightarrow -i\|0\rangle$

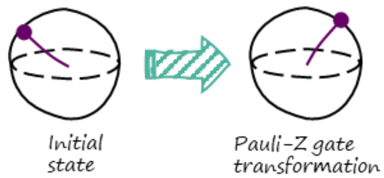
Pauli-Z:	*Hadamard:*
⊕ $\|0\rangle \rightarrow \|0\rangle$	⊕ $\|0\rangle \rightarrow \frac{\|0\rangle + \|1\rangle}{\sqrt{2}}$
⊕ $\|1\rangle \rightarrow -\|1\rangle$	⊕ $\|1\rangle \rightarrow \frac{\|0\rangle - \|1\rangle}{\sqrt{2}}$

Visually, these logic gate operations are represented in Tableau as:

Pauli-X:	*Pauli-Y:*
rotation around X-axis	rotation around Y-axis
	

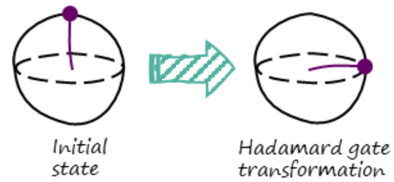
- *Pauli-Z:*

rotation around Z-axis



- *Hadamard:*

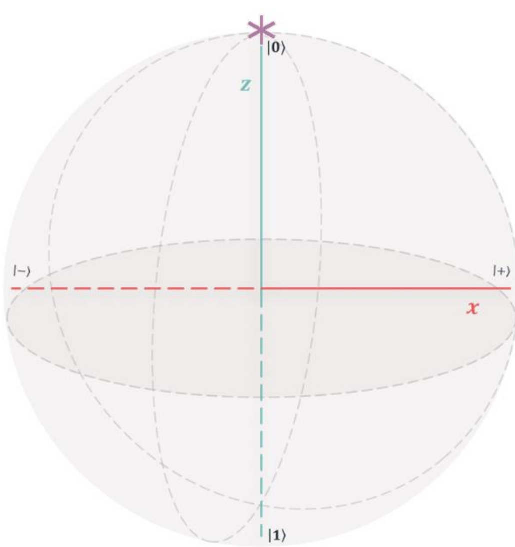
rotation around X & Z axes



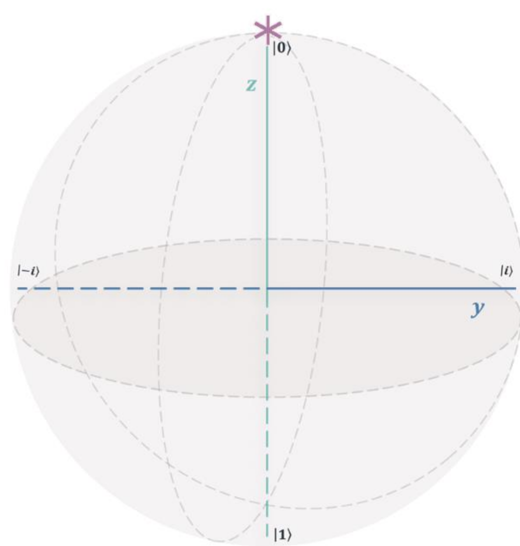
As mentioned earlier, the lack of three-dimensional graphing rotation matrices and spherical trigonometry needed to be applied to simulate the effects of these quantum logic gates on a given basis state while providing interactive parameters.

Results

Original state at $\theta = 0$ and $\phi = 90$

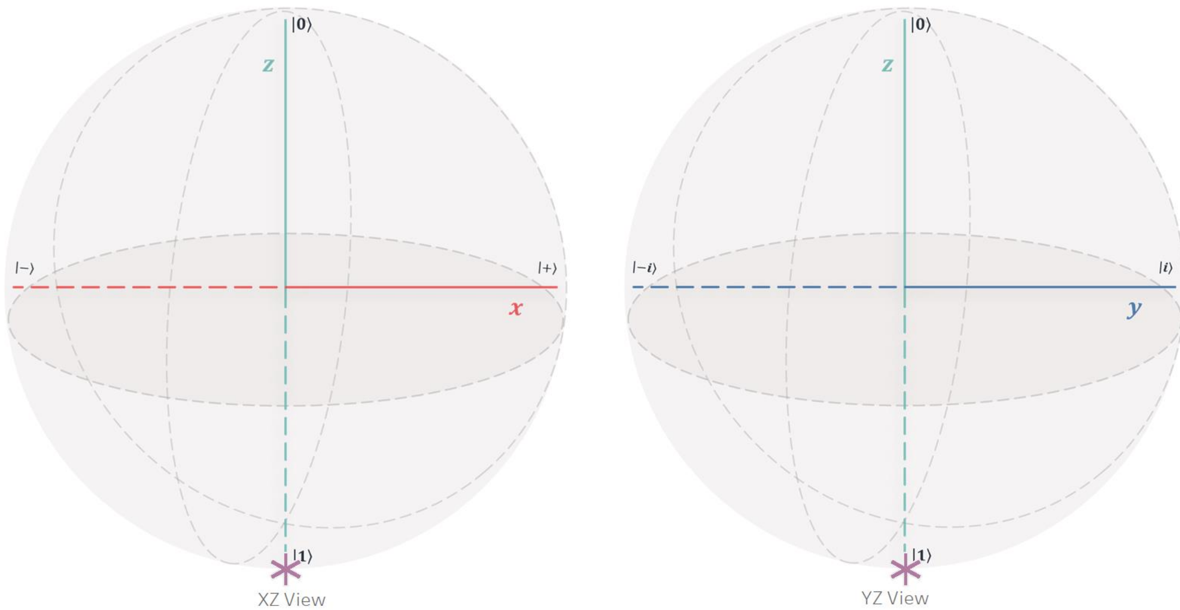


XZ View

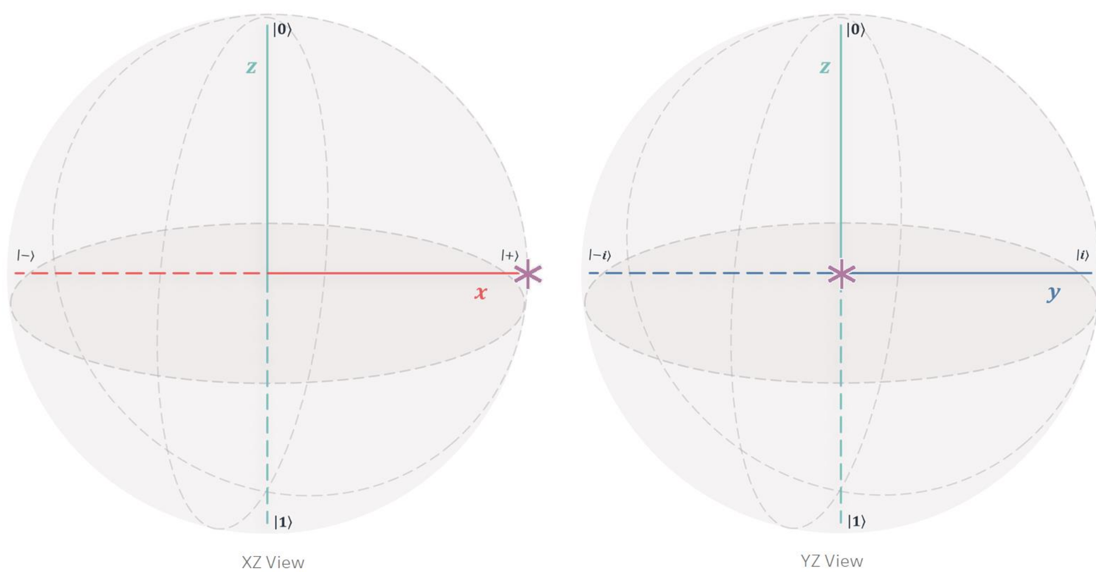


YZ View

Pauli-X state at $\theta = 0$ and $\phi = 90$



Hadamard state at $\theta = 0$ and $\phi = 90$



***** See the Tableau project for a plethora of more combinations.

Conclusion

Therefore, given throughout this project, I wanted to visually learn more about the effect of quantum gates on single-qubit states, I ended up utilizing the following skills learned during the course:

- **Visual Encoding** – to neatly map a complex quantum physics topic
- **Visual Design Guidelines** – to keep the visualization consistent and minimalistic
- **Graphical Integrity** – to stay true to the underlying physics
- **Color Palettes** – to focus attention on the changes in the quantum states
- **Interaction** – to allow the user to explore different (outcome) quantum states

"Unfortunately, given my ongoing health issues and certain family affairs this month, I could not fully execute the project I had initially promised. And I felt extremely disappointed in myself, especially compared to the earlier efforts and results I had shown in the semester."

Abstract

Given the nature of the project, my bibliography reflects a two-pronged approach to comprehending the complexities of quantum computing while exploring visualization techniques to augment the learning experience that, in turn, facilitates me in creating a Bloch sphere simulator in Tableau.

From Aaronson, I understood the substantial responsibility of topical integrity when depicting/ teaching any quantum computing principle to avoid confusion and embellishments.

From Okrut, I learned the significance of an adequately tuned visual aide in explaining complex subjects.

From the NIST article, I learned the significance of keeping it simple and minimalist to tell a story-like narrative when working on the paper portion.

From Shetty, I grasped the trigonometric projections needed to create an interactive dashboard in Tableau while providing an illusion of three-dimensionality in the sphere.

Annotated Bibliography

Aaronson, S. (2021, June 8). *What Makes Quantum Computing So Hard to Explain?* Quanta Magazine. https://www.quantamagazine.org/why-is-quantum-computing-so-hard-to-explain-20210608/

Quantum computing researcher, Dr. Scott Aaronson from the University of Texas at Austin, sets the record straight about the overzealous hype and mislabeling of the quantum principle of superposition and the inherent difficulty of breaking down the complexity of quantum computing into simpler terms. He explains quantum computing as achieving better scaling behavior as a function of n for algorithms that would otherwise take n^2 or more steps to calculate classically. To keep topical integrity, Dr. Aaronson reckons one must discuss quantum decoherence - unwanted interactions between a quantum computer and its environment, and the proposed quantum error correction algorithms from a practical sense of building quantum computers.

Okrut, O. (2020, June 3). *Introduction to quantum logical gates. Part I.* Medium. https://medium.com/qc-applied-approach-to-build-your-own-quantum/introduction-to-quantum-logical-gates-part-i-80f95fa851a2

Quantum computing researcher Olga Okrut from the Dark Start Quantum Lab introduces quantum logic gates as ways of manipulating quantum information, the quantum state of a qubit, or a collection of qubits in direct analogy to classical NOT, AND, OR gates. She

describes the significance of a three-dimensional Bloch sphere representation as a visual aide in conjunction with matrix-based results when applying quantum gates on qubits. Moreover, each presented quantum gate - Hadamard, Pauli-X, and Pauli-Y gets accompanied by an animation on the Bloch sphere with a further breakdown of the complex mathematics involved.

Quantum Logic Gates. (2018). *NIST*. https://www.nist.gov/physics/introduction-new-quantum-revolution/quantum-logic-gates

National Institute of Standards and Technology (NIST) offers a superficial overview and an introduction of “A New Quantum Revolution” through a historical retelling of their efforts into quantum computing and quantum logic gates. The article’s primary quantum logic gate of interest is the CNOT or the controlled-NOT after David Wineland, and his team began the initial experiments in 1996. Likewise, the article offers a visualization aide to present quantum states on pseudo-Bloch spheres and the resulting possible measurement outcomes after a particular Fourier operation.

Shetty, A. (2021, March 8). *Visualizing Quantum Logic Gates (Part 1)*. Quantum Untangled. https://medium.com/quantum-untangled/visualizing-quantum-logic-gates-part-1-515bb7b58916

Amogh Shetty, while writing for Medium, dissects the visualization that is a three-dimensional Bloch sphere uniquely by correlating it to a two-dimensional cartesian circle

and analyzing the required trigonometric functions to achieve particular results with quantum logic gates. He takes his time painstakingly and goes through each matrix operation to supplement the visuals with mathematical proofs. Accordingly, the core mission is to learn visualization of the effects of quantum gates to comprehend quantum logic gates and follow through with more complex algorithms at an efficient rate, rather than delving into a series of mathematical equations.