From Classical to Quantum

Introduction to Quantum Computing

Tara Bahadur Rana
St. Xavier's College
Tribhuvan University

Table of Contents

All Is Not Well with Classical Mechanics

Study of Classical physics

Particles

- localized bundles of energy and momentum

Waves

Study of Classical physics

Particles

- localized bundles of energy and momentum
- described by q and $\dot{q}$ (or q and P)

Waves

Study of Classical physics

Particles

- localized bundles of energy and momentum
- described by q and $\dot{q}$ (or q and P)
- evolves according to some EOM

Waves

Study of Classical physics

Particles

- localized bundles of energy and momentum
- described by q and $\dot{q}$ (or q and P)
- evolves according to some EOM

Waves

- disturbance in a medium

Study of Classical physics

Particles

- localized bundles of energy and momentum
- described by q and $\dot{q}$ (or q and P)
- evolves according to some EOM

Waves

- disturbance in a medium
- described by $\Psi(x,t)$

Study of Classical physics

Particles

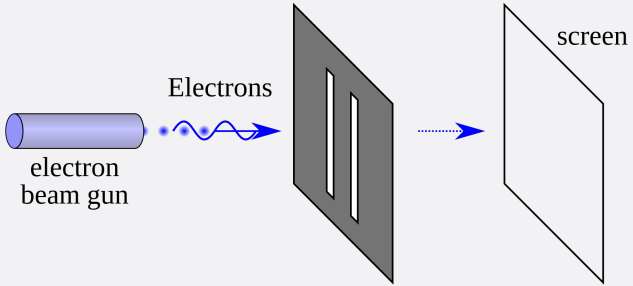
- localized bundles of energy and momentum
- described by q and $\dot{q}$ (or q and P)
- evolves according to some EOM

Waves

- disturbance in a medium
- described by $\Psi(x,t)$
- evolves according to wave equation:

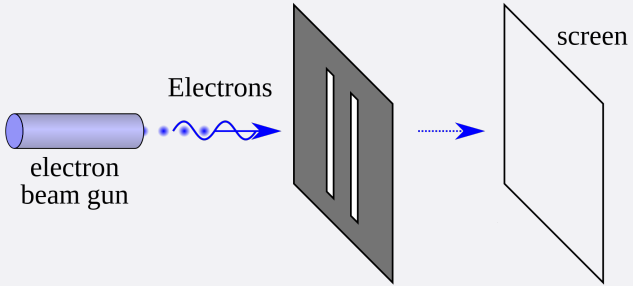
$$\nabla^2\psi = \frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2}$$

The Double-Slit Experiment with Electrons



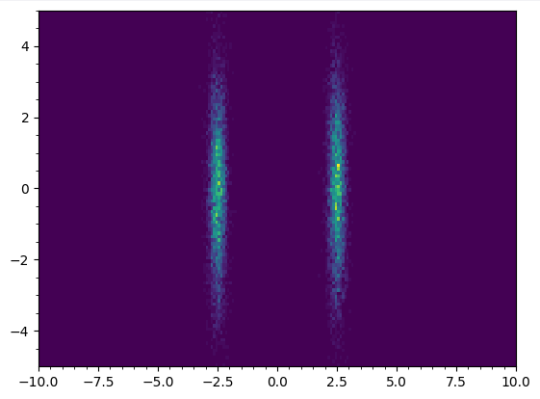
- One electron at a time; negating the possibility that electrons coming out of slits may collide with each other.

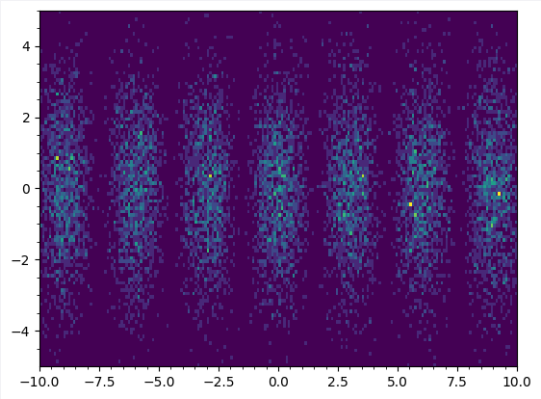
The Double-Slit Experiment with Electrons



- One electron at a time; negating the possibility that electrons coming out of slits may collide with each other.
- If electron is a particle, then Classical mechanics unambiguous prediction: $I_{1+2} = I_1 + I_2$.

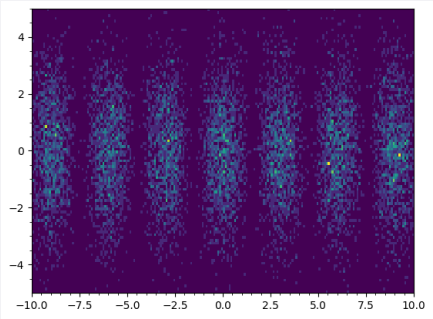
Which pattern do you expect to see?





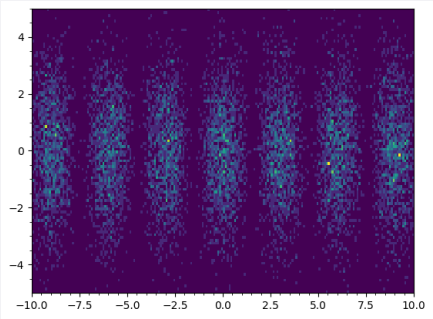
*no. of electrons = 10,000

Conclusions



- **Interference**; which is peculiar to waves and is not exhibited by particles

Conclusions

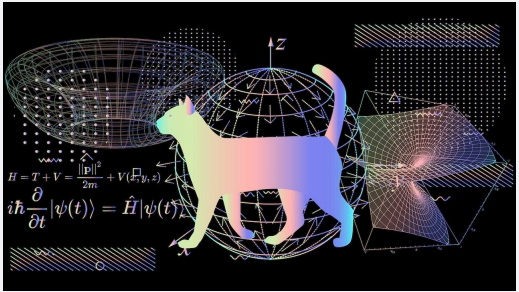


- **Interference**; which is peculiar to waves and is not exhibited by particles
- Electron is a wave!... maybe?

What is so different about Quantum Mechanics?

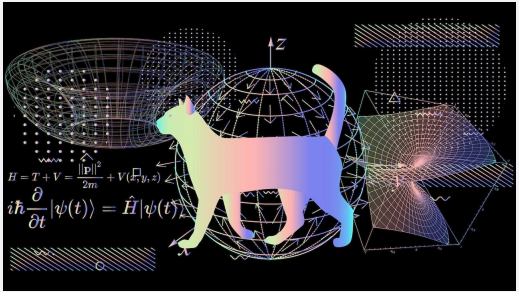
What is Quantum Mechanics?

- **Quantum Mechanics**, also called Quantum Physics, describes our nature in tiny realms (atoms, electrons, and more).



What is Quantum Mechanics?

- **Quantum Mechanics**, also called Quantum Physics, describes our nature in tiny realms (atoms, electrons, and more).
- It is the most successful and enigmatic physical theory.



What makes Quantum Mechanics *Quantum Mechanics*?

- Interference

What makes Quantum Mechanics *Quantum Mechanics*?

- Interference
- Superposition

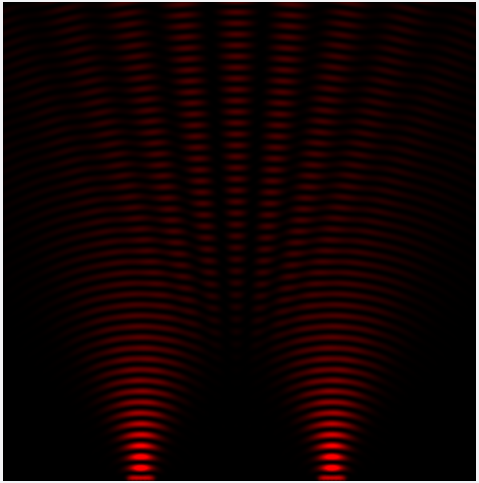
What makes Quantum Mechanics *Quantum Mechanics*?

- Interference
- Superposition
- Entanglement

What makes Quantum Mechanics *Quantum Mechanics*?

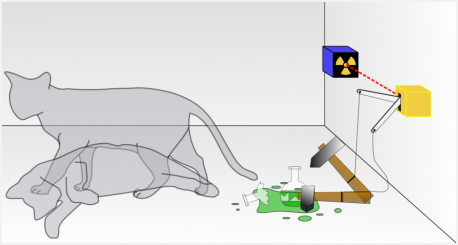
- Interference
- Superposition
- Entanglement
- Measurement, and more...

Interference



- Quantum states can interact with each other; interfering *constructively* or *destructively*.

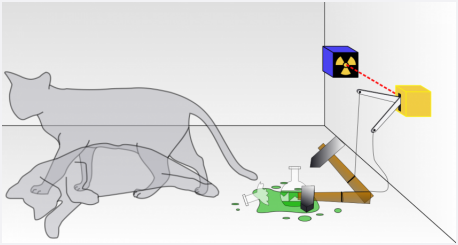
Superposition



- A quantum system can be in multiple states at the same time.

Schrödinger's daughter: "*I think my father just didn't like cats.*"

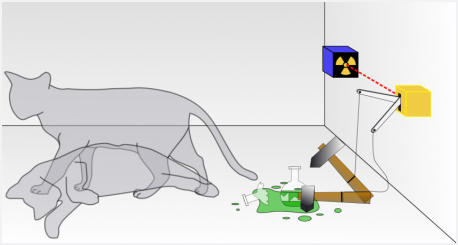
Superposition



- A quantum system can be in multiple states at the same time.
- A **classical** cat is in definite awake/sleep state.

Schrödinger's daughter: "*I think my father just didn't like cats.*"

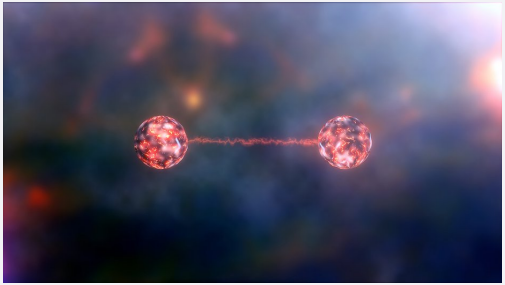
Superposition



- A quantum system can be in multiple states at the same time.
- A **classical** cat is in definite awake/sleep state.
- A **quantum** cat can be in superposition of both awake and sleep state at the same time.

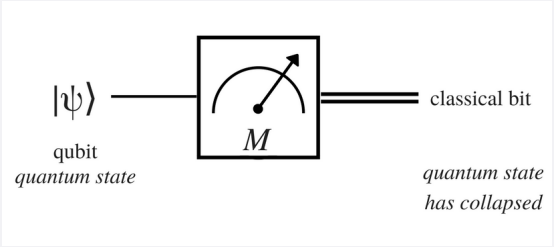
Schrödinger's daughter: "*I think my father just didn't like cats.*"

Entanglement: Spooky action at a distance



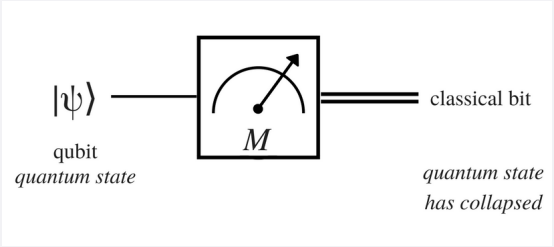
- Two particles which are entangled can influence each other in seemingly impossible ways.

Measurement



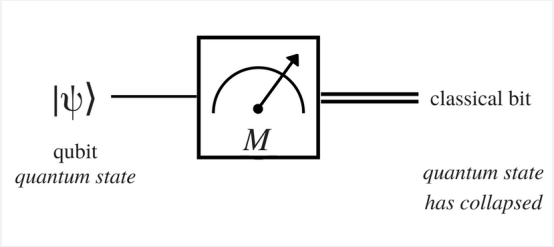
- Before measurement a quantum system is in superposition of different states.

Measurement



- Before measurement a quantum system is in superposition of different states.
- We want to know what is going inside the system, so we make a measurement.

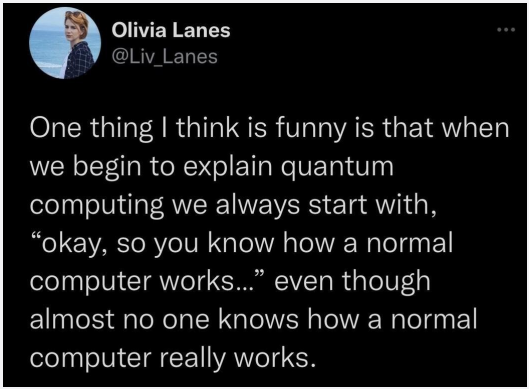
Measurement



- Before measurement a quantum system is in superposition of different states.
- We want to know what is going inside the system, so we make a measurement.
- Our measurement *supposedly* forces the system to "collapse" into a definite state.

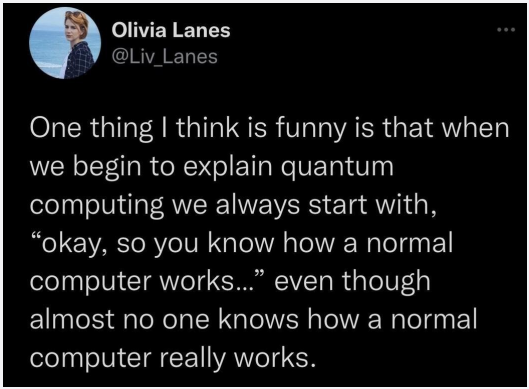
Classical Stack vs. Quantum Stack

Beyond Input and Output



- **Input → Device → Output**

Beyond Input and Output

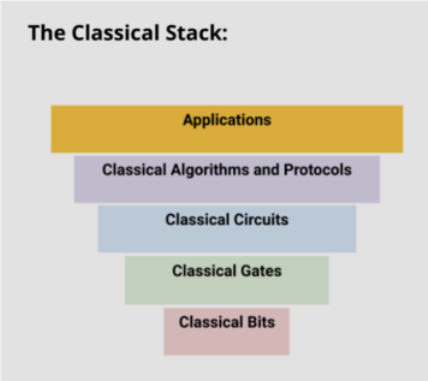


- **Input → Device → Output**
- **What goes inside the device?**

Classical Stack

A **stack** organizes all layers of computer operation, starting with the most fundamental at the bottom of the stack.

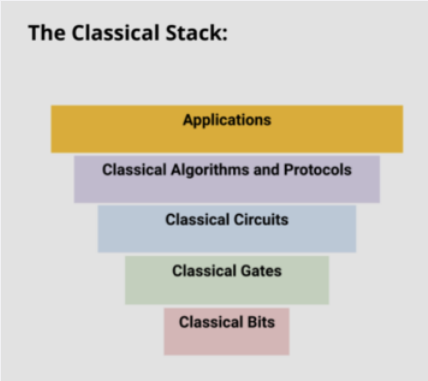
- **Bits** are the fundamental unit of information.



Classical Stack

A **stack** organizes all layers of computer operation, starting with the most fundamental at the bottom of the stack.

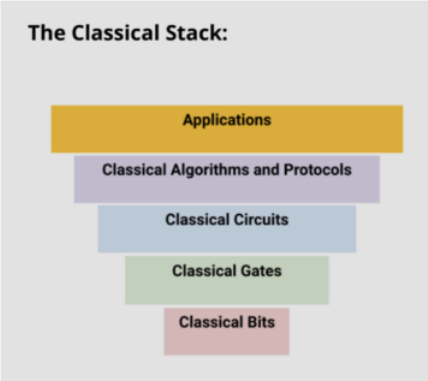
- **Bits** are the fundamental unit of information.
- **Gates** manipulate the bits.



Classical Stack

A **stack** organizes all layers of computer operation, starting with the most fundamental at the bottom of the stack.

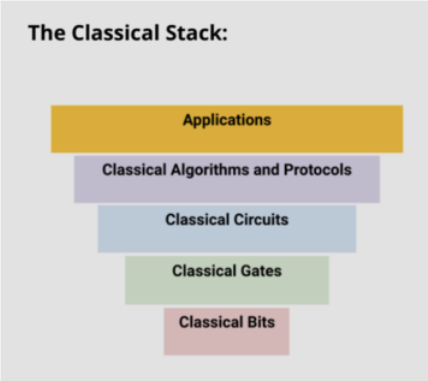
- **Bits** are the fundamental unit of information.
- **Gates** manipulate the bits.
- **Circuit** is combination of different gates that performs a certain task.



Classical Stack

A **stack** organizes all layers of computer operation, starting with the most fundamental at the bottom of the stack.

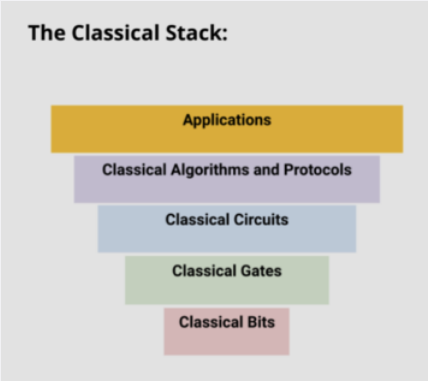
- **Bits** are the fundamental unit of information.
- **Gates** manipulate the bits.
- **Circuit** is combination of different gates that performs a certain task.
- **Algorithms and protocols** are the agreed-upon steps computers use to solve the problems.



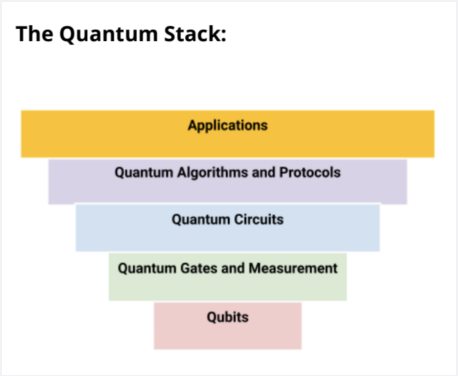
Classical Stack

A **stack** organizes all layers of computer operation, starting with the most fundamental at the bottom of the stack.

- **Bits** are the fundamental unit of information.
- **Gates** manipulate the bits.
- **Circuit** is combination of different gates that performs a certain task.
- **Algorithms and protocols** are the agreed-upon steps computers use to solve the problems.
- **Applications** are what we see and use.

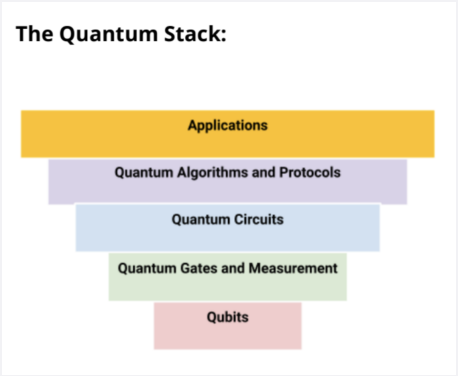


Quantum Stack



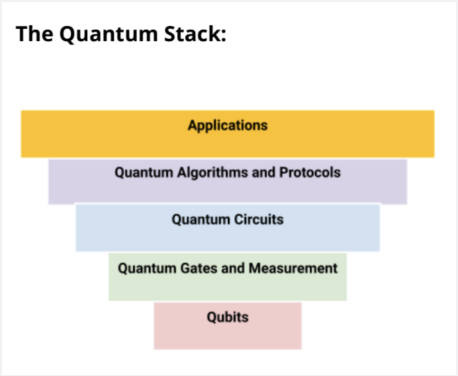
- **What is a quantum computer?**

Quantum Stack



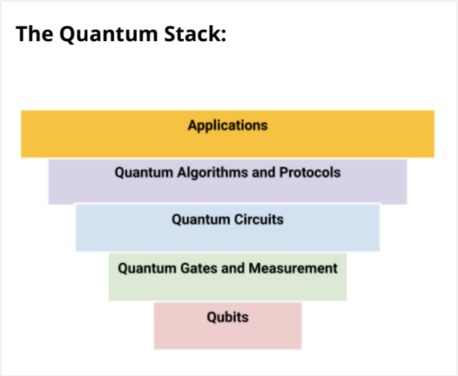
- **What is a quantum computer?**
- A device that leverages the quantum mechanical properties like: superposition, entanglement (and more...) to solve problems.

Quantum Stack



- **What is a quantum computer?**
- A device that leverages the quantum mechanical properties like: superposition, entanglement (and more...) to solve problems.

Quantum Stack



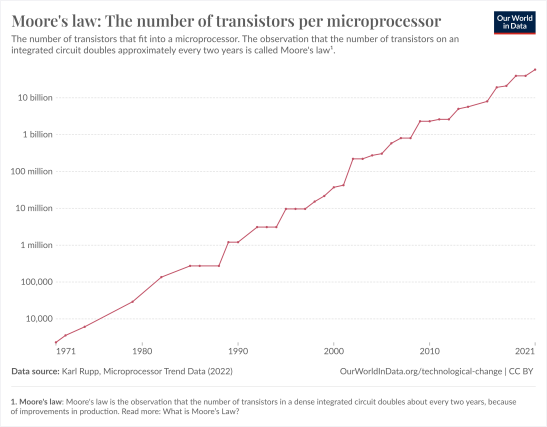
- **What is a quantum computer?**
- A device that leverages the quantum mechanical properties like: superposition, entanglement (and more...) to solve problems.

Why do we need a Quantum Computer?

Moore's Law, and its End!

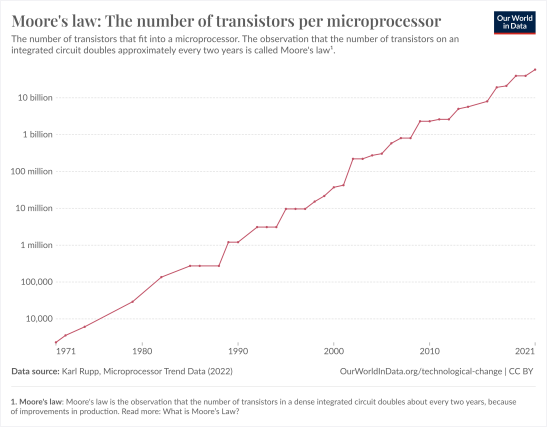
Moore’s Law

- Gordon Moore in 1965 predicted that *computer power will double for constant cost roughly once every two years* – a prediction now called **Moore’s Law**.



Moore’s Law

- Gordon Moore in 1965 predicted that *computer power will double for constant cost roughly once every two years* – a prediction now called **Moore’s Law**.
- Amazingly enough, Moore’s law has approximately held true in the decades since the 1960s.



So, what's the problem?

- Making computers more powerful means making transistors smaller and closer together.

So, what's the problem?

- Making computers more powerful means making transistors smaller and closer together.

So, what's the problem?

- Making computers more powerful means making transistors smaller and closer together.

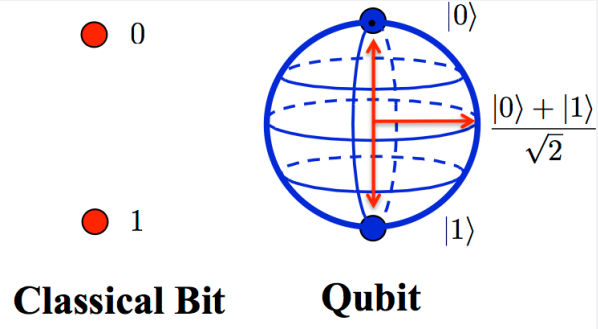
But after certain size quantum effects begin to manifest and cause a problem!

- **Quantum effects**, like tunneling, **cause classical computer to work incorrectly**. This is the *end of Moore's Law*.

Representing Qubits: Ket, Vector and Bloch Sphere

What is a Qubit?

A **qubit** is a quantum bit, which is the fundamental unit of quantum information and can be in 0 or 1 or superposition of 0 and 1.



Representing Qubits: Ket

Paul Dirac invented this notation, which helps to represent a quantum state and offers a neat notation to do maths.

$$|\psi\rangle$$

- Our zero state is represented as:

$$|0\rangle$$

Representing Qubits: Ket

Paul Dirac invented this notation, which helps to represent a quantum state and offers a neat notation to do maths.

$$|\psi\rangle$$

- Our zero state is represented as:

$$|0\rangle$$

- Our one state is represented as:

$$|1\rangle$$

Representing Qubits: Ket

Paul Dirac invented this notation, which helps to represent a quantum state and offers a neat notation to do maths.

$$|\psi\rangle$$

- Our zero state is represented as:

$$|0\rangle$$

- Our one state is represented as:

$$|1\rangle$$

- Our superposition state is represented as:

$$\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

Representing Qubits: Vector

$$\text{Vector} = \begin{bmatrix} a \\ b \end{bmatrix}$$

- Our zero state is represented as:

$$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

Representing Qubits: Vector

$$\text{Vector} = \begin{bmatrix} a \\ b \end{bmatrix}$$

- Our zero state is represented as:

$$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

- Our one state is represented as:

$$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Representing Qubits: Vector

$$\text{Vector} = \begin{bmatrix} a \\ b \end{bmatrix}$$

- Our zero state is represented as:

$$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

- Our one state is represented as:

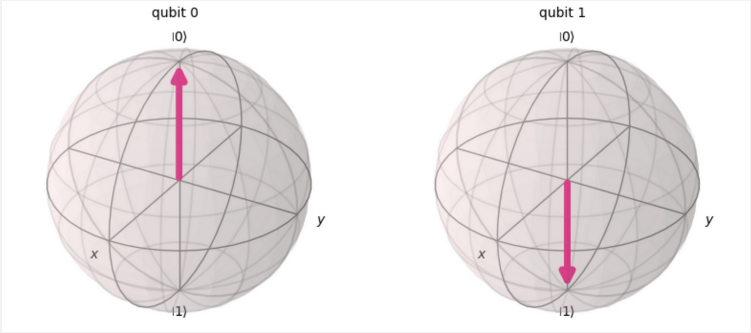
$$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

- Our superposition state is represented as:

$$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

Representing Qubits: Bloch Sphere

Bloch Sphere is a fantastic way of visualizing a qubit.



References I


R.P. Feynman, R.B. Leighton, and M. Sands.
The Feynman Lectures on Physics, Vol. III: The New Millennium Edition: Quantum Mechanics.
The Feynman Lectures on Physics. Basic Books, 2011.


David J Griffiths and Darrell F Schroeter.
Introduction to quantum mechanics.
Cambridge university press, 2018.


Makoto Katsumori.
Niels Bohr's complementarity: its structure, history, and intersections with hermeneutics and deconstruction, volume 286.
Springer Science & Business Media, 2011.

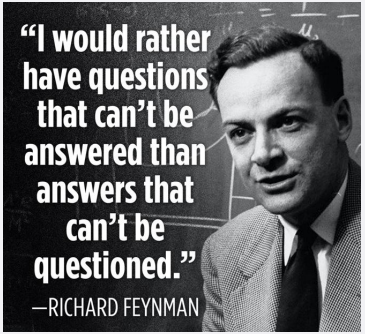
References II


Michael A Nielsen and Isaac L Chuang.
Quantum computation and quantum information.
Cambridge university press, 2010.


Ramamurti Shankar.
Principles of quantum mechanics.
Springer Science & Business Media, 2012.


Nouredine Zettili.
Quantum mechanics: concepts and applications.
2009.

Thank You!


“I would rather have questions that can’t be answered than answers that can’t be questioned.”
—RICHARD FEYNMAN