Week 3

WHAT IS A QUANTUM COMPUTER?

A quantum computer is a device that takes inputs, ***Processes them in a fundamentally quantum mechanical way***, and outputs the results.

WHAT IS A CLASSICAL COMPUTER?

A classical computer is a device that takes inputs, ***processes them without the use of quantum physics*** , and outputs the results.

THE STACK:

The **stack** organizes all layers of a computer's operation, starting with the most fundamental and hidden from sight on the bottom

We will work our way from the bottom, **Classical Bits**, to the top, **Applications**

Key Terminologies:

1.BITS

Bits are the fundamental unit of information in a computer, Every app, website, image, text, program, and more is built from bits

Each bit of information can either be a 0 or a 1

Physically, bits can be represented by a switch where:

- 0 = switch off
- 1 = switch on

Small electrical switches called transistors are the standard in computers today.

2.GATES

Gates manipulate bits, they allow us to manipulate bits and turn simple inputs into simple outputs.

3.CIRCUITS

A circuit is a sequence of gates. By combining many different gates in a certain orders, we can start to process inputs into outputs in more complex and interesting ways.
A classic example of a circuit is the one that can add two numbers, called a full adder.

4.ALGORITHMS AND PROTOCOLS

Algorithms and Protocols are the agreed-upon steps computers used to **solve problems.**

These are how **applications perform their tasks** throughout **search algorithms**, streaming protocols, and more.

5.Applications

Applications are what you see and use! For example google, Netflix , etc.

PROBLEMS WITH CLASSICAL STACK

The reality is **classical computers** are getting so powerful, **they are hitting physical limits posed by nature.**

In 2005, Gordon Moore said:
"In terms of size (of bits) you can see that we're approaching the size of atoms, which is a fundamental barrier... We have another 1- to 2- years before we reach a fundamental limit".

MOORE'S LAW

In the 1960s, Moore predicted that we'd be able to double the power of computers every two years, a prediction now called **Moore's Law.**
Squeezing more power into computers means we must make **transistors (bits) smaller and closer together.**
IBM's new 2-nm chips have transistors smaller than a strand of DNA

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

Problematic Quantum Effects

One example of quantum effects causing a problem is:

Quantum Tunelling

An object can teleport to the other side of a closed barrier without touching it.

Critical Thinking:

How could Quantum Tunneling affect our classical computations?

- Transistors act as electric switches, meaning electricity is stopped by the transistor being 'OFF'.
- Electricity is made of quantum objects, electrons, that can tunnel through barriers.
- So, electricity *could* appear on the other side of the transistor even when it's 'OFF'! **This could cause 0's to look like 1's and create errors in our calculations.**

THE END OF MOORE'S LAW

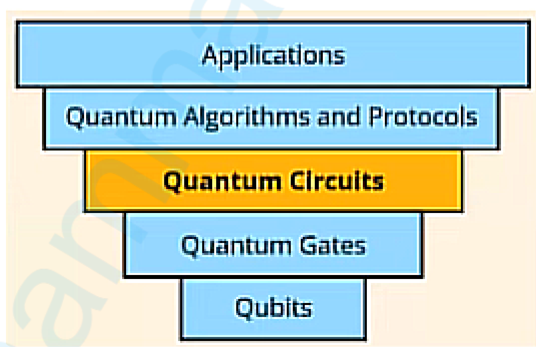
Main Takeaway

Quantum effects, like tunneling, **cause classical computers to work incorrectly,** meaning we cannot continue making classical computers moe powerful for much longer. *This is the end of Moore's Law.*

So instead of trying to fight these quantum behaviors, Lets use them!

THE QUANTUM STACK

The quantum stack looks similar to the classical stack, but uses quantum mechanics. Qubits, gates, and measurements together make up quantum circuits.



Key Terminology

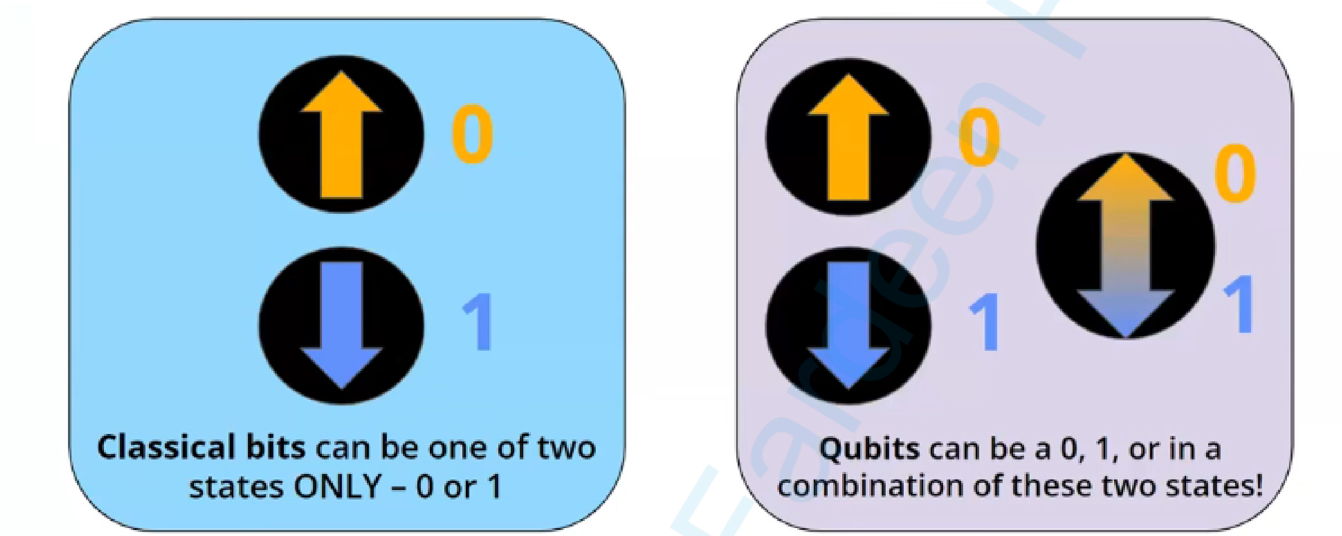
Qubits

A **qubit** is a quantum bit. it is the fundamental unit of quantum information and can be in the 0 or 1 state or a superposition.
***Qubit** = *Quantum Bit**
A Qubit **is a 0 or a 1 that is** manifested in a quantum mechanical way. **It means it can be a 0 or a 1 or in a** *state of superposition* **which means it has a** probability distribution** that is in 0 as well as in 1.

We can build physical qubits in many different ways. Only time will tell if there is a best way, analogous to transistors, or if each way will server its own purpose.

Classical vs. Quantum Bits

Unlike classical bits, **qubits demonstrate quantum behaviors** like being able to be in a superposition of 0 and 1.



Super Position Analogy: Flipping a Coin

We can think of a qubit like tossing a coin.

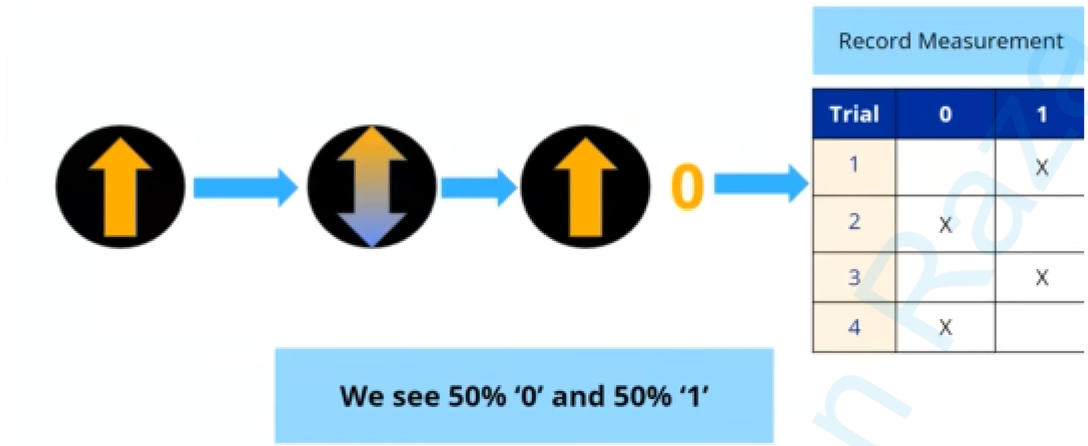
- Head = 1
- Tails = 0

Flipping in the air is like **superposition.** We don't know if it's both 0 or 1 until we force it to stop flipping.
Once we catch the coin and look at it, it collapses to either heads, "1", or tails, "0".
If we want to know the probability of seeing heads versus tails, then we have to try flipping the coin many times.

Takeaways:-
When a coin is flipping in the air, it could land as either heads (0) or tails (1). **We seemingly can't know what state it will be in until we force it to stop spinning.**

However, **we technically *could* find out beforehand** if we knew everything about how we flipped the coin.

Superposition: Qubit Experiment



Takeaways:-
A qubit in superposition is like a coin flipping in the air. **We seemingly can't know what state it will be in until we force it to be in one or the other** (measurement).

But unlike the coin, there is nothing we could do to know what state it will be in beforehand.
It is truly random

Today, The largest number of Qubits are 433 so far, and it is growing everyday!

Quantum Gates

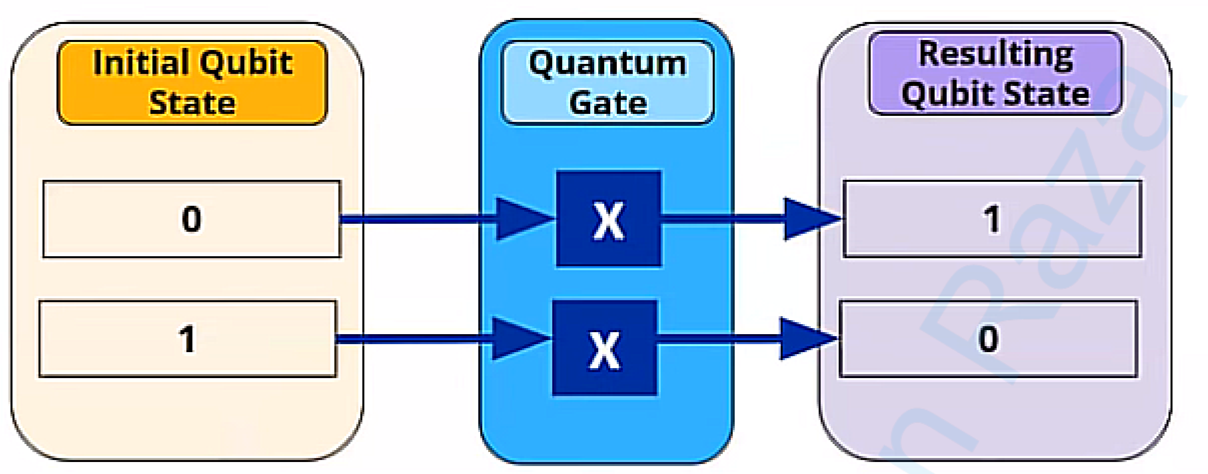
Quantum gates perform some quantum operation on qubits to change their state in order to perform quantum computations.

Today We look at 2 Different Gates:

- **X Gate**
- **H Gate**

X GATE

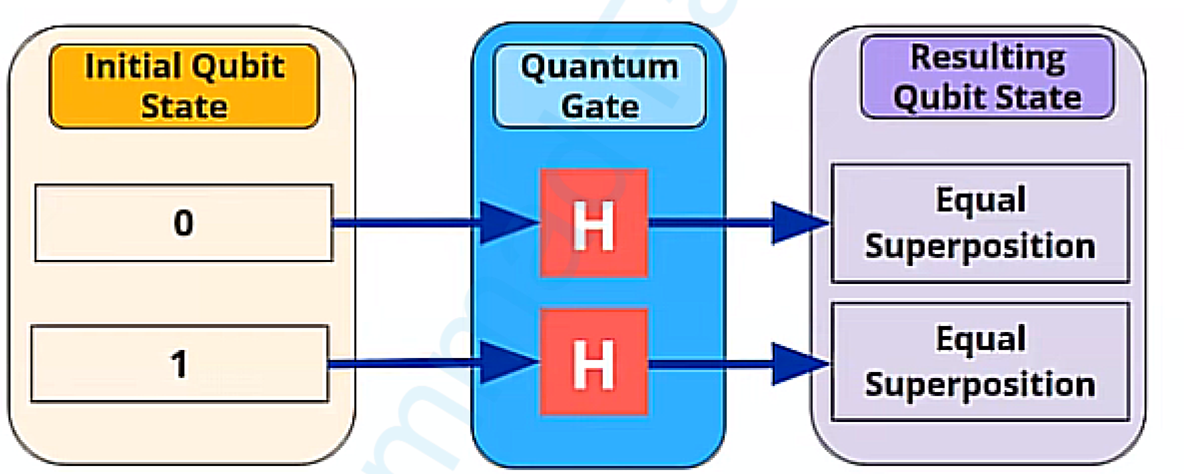
The **X gate** gives the opposite of the input.



If we apply an X gate to a qubit with an initial state of **0**, We then go to measure the qubit and **observe 1.**

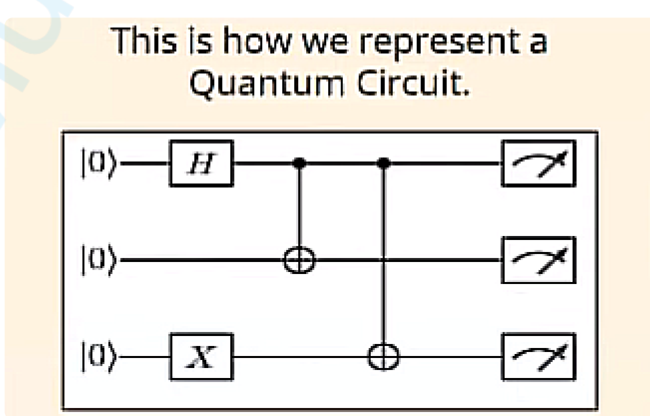
H GATE

The H gate creates equal superposition



Quantum Circuits

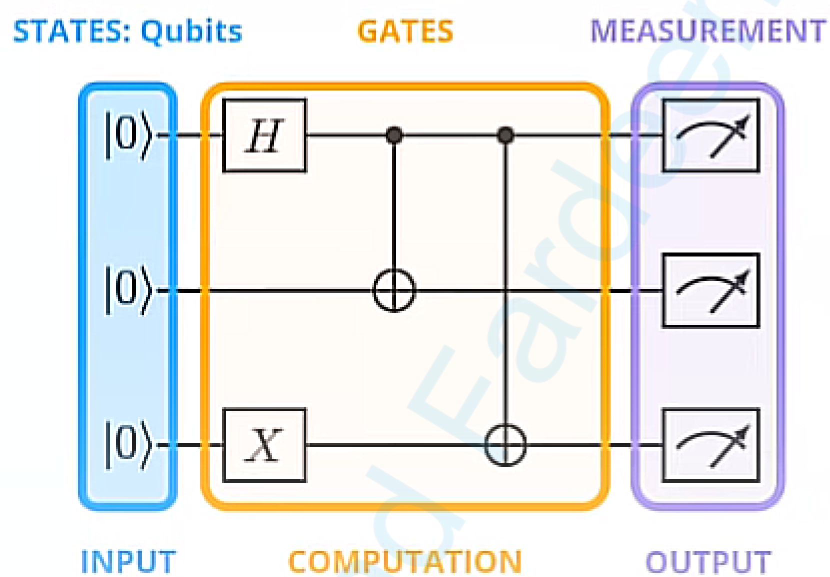
Quantum circuits are a sequence of **quantum gates** acting on a **qubit** or a group of qubits.



The Quantum Circuit Model

This is the Quantum Circuit Model, This framework shows us the three parts of a quantum circuit.

- States (Qubits)
- Gates
- Measurement



Quantum measurement is a crucial step as it is our **only way** to extract information about an **unknown quantum state**.

Quantum Algorithms and Protocols

Algorithms and Protocols are the agreed-upon steps computers used to solve problems. **They are implemented with special purpose quantum circuits.**

Some famous examples include:

Algorithms:-

- **Grover's** search algorithm.
- **Shor's** factoring algorithm.
- **Variational Quantum Eigensolver*** optimization algorithm

Protocols:-

- **Quantum Teleportation** for sending quantum information.
- **Superdense Coding** for sending classical information

- **Quantum Key Distribution** for sending secure information

Applications

Applications of quantum computers range from enhancing cybersecurity to simulating other quantum mechanical systems.

Discovering new applications is an active area of research, particularlt those that may apply to:

- Climate change solutions
- Supply chain and other logistics
- Finance prediction and planning
- Medicine discovery and enhancement

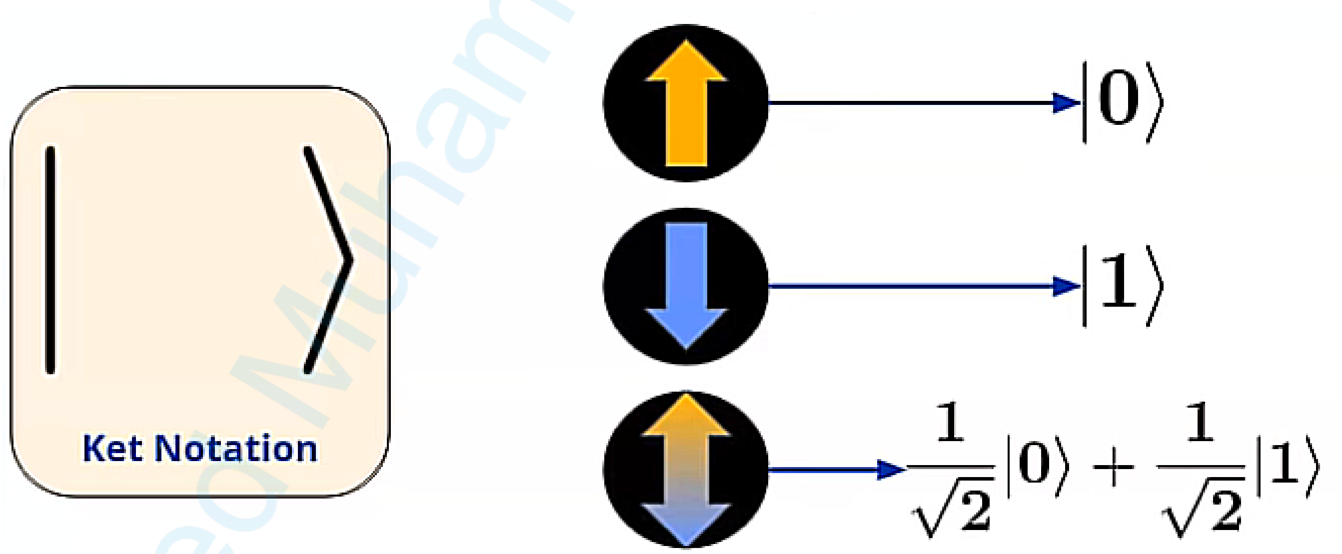
REPRESENTING QUBITS

There are three main representations of qubits:-

- Ket notations
- The Bloch Sphere
- Vectors

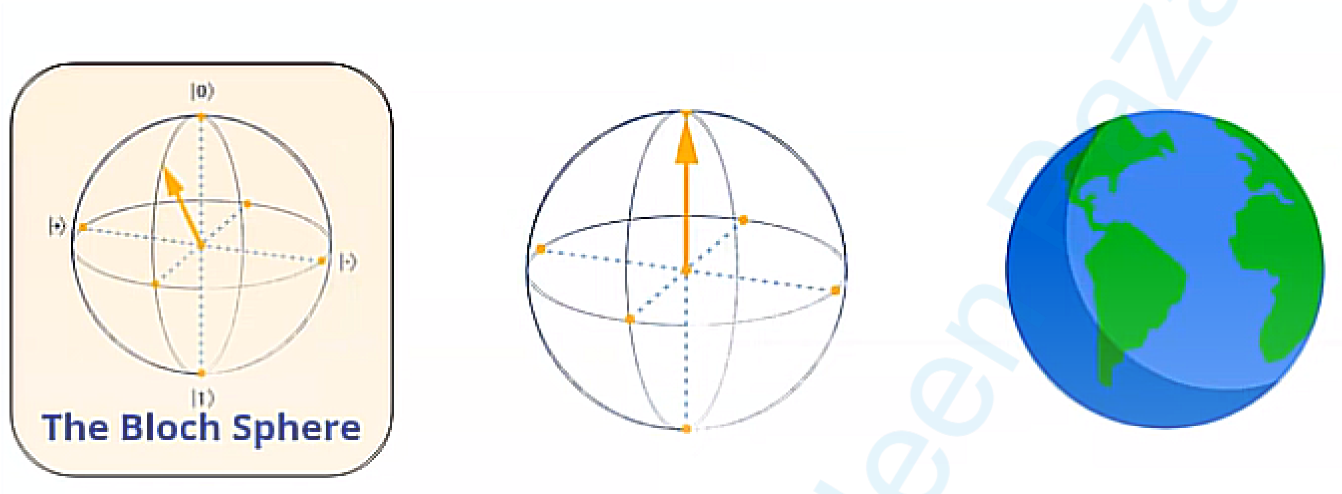
Ket Notation

Ket Notation was developed by Quantum Physicists to make **quantum calculations easier.** Here are some **common qubits states** we'll work with:



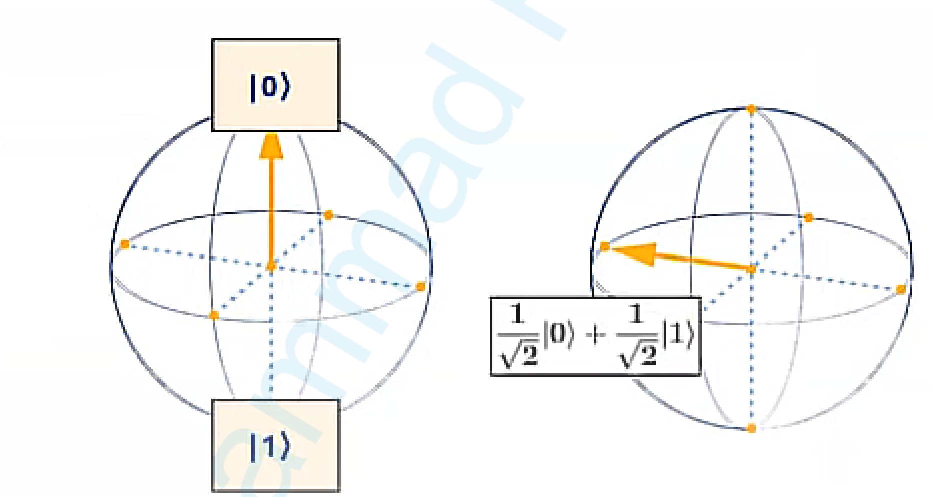
Bloch Sphere

Kets are powerful **mathematical tools**, but they make it really hard to **visualize** what qubits are doing. This is where the **Bloch Sphere** shines:



It was named after **Professor Felix Bloch**, an outstanding Quantum Physicist.

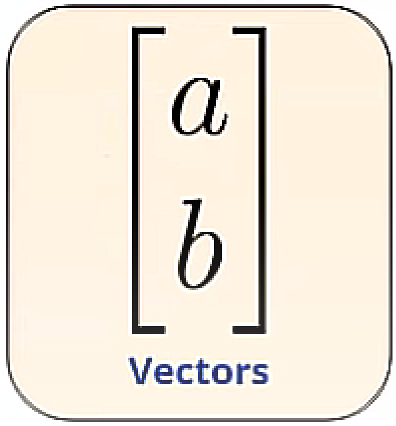
In the bloch sphere, we have the **top of the sphere being 0 and the bottom being 1** and similarly, the earth has a North and South pole

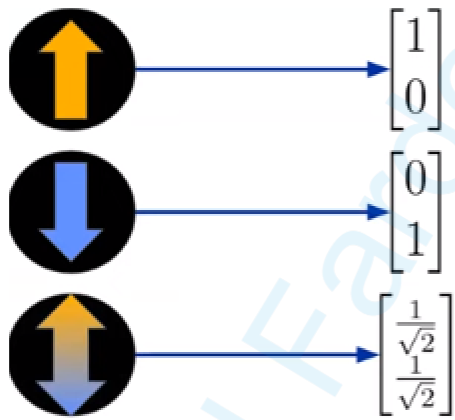


The Bloch sphere can be anywhere from 0 to the 1 to anywhere in between. It can be 50 50 or it can also be 75 % 0 and 25% 1 for example. Becuase there are so many combinations, it is easier to visualise it as a Bloch sphere.

Vectors

Bloch Spheres are **difficult** to properly **represent on a computer.** This is one of many reasons to use **vectors**. Here are the same states as **Vectors:**





- The **yellow one** represents up state, in which **1 is written on top**
- The blue one represents down state, in which **1 is written on bottom**
- The **mixture of Yellow and Blue** is a **superposition**, in which both have the same chance so they are both **written as** $1/\sqrt[2]{2}$ **both on top and on bottom**, which is equal to one half so 50 50 %

They actually contain the **same information** as kets, **for example:**

Kets

$$\begin{aligned} 1 * |0\rangle \\ + 0 * |1\rangle \end{aligned}$$

.

$$\begin{aligned} 0 * |0\rangle \\ + 1 * |1\rangle \end{aligned}$$

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

Vectors

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

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

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

When to Use Each One

Kets:

These are specific to **quantum mechanics.** They are good for:

- Understanding quantum computing resources(papers, textbooks, talks,e.t.c) and coming across as a professional **quantum computing scientist.**
- Doing "quantum math" without writing as much as you have to with vectors.

Bloch Spheres:

These are also specific to **quantum mechanics** (and the **study of light: optics**). They are good for:

- **Visualizing** (single) qubit states.

Vectors:

These are **very general** (physics, math, Computer Science, and most other technical fields). They are good for:

- Communicating "quantum math" to **general technical audiences.**
- **Coding** "quantum math".