The Hitchhikers Guide to Qubits and the Standard Gate Set

Quantum Mechanics are easy. So easy in fact, that it is part of the curriculum for elementary school aged children on Betelgeuse Five. The only species that has not yet gotten a hang of this very basic and stupidly simple concept are the half monkeys of the planet called earth. As the aim of the hitchhikers guide is to bring knowledge to even the simplest life forms, this article is written so that even the average half monkey of the planet earth can grasp the concepts behind this subject, generally learned as a collection of nursery rhymes on Vogsphere.

Just what the hell are qubits?!?!

Qubits are more complex than the normal, everyday, black and white bits, used in the prehistoric computation machines. While the boring, current based bits can either be a 1 or a 0, the qubits can have states corresponding to 1, 0, or a linear combination of both these states, called a superposition. To help the monkeys visualize this concept, all they have to do is look out of the window. There is a likelihood of the weather being either good (0) or bad (1), depending on what state the monkey is in. If the monkey was smart and moved to a southern country, the likelihood that he will be greeted by the sun while looking outside of his sad mud hut is (suspend your disbelieve for this one) 100%. If he moved, for whatever reason, to the north pole, the probability of having nice, toasty weather is 0%. Normal Bits can either be at the north pole or relaxing in the Caribbean. Qubits add a whole new array of locations, that have an uncertain probability of having nice weather every time the monkey looks out of his window, let's say for example Sheffield, UK, somewhere along the Myrtle Road. Given the monkey looks out of the window in this country, the probability he will see nice weather is 20%, the probability he will see clouds and rain and the unbearable UK fog is 80%. Swap out the Monkey for a Qubit, the looking-out-of-the-window for a measurement of the qubit and the weather for a 1 or 0, and the common earthling might get an idea of what a qubit is, and how it differentiates itself from the common, everyday bit, which is most commonly used on earth to deliver news about the Hibernian FC loosing yet another game, followed by a query asking where the next pub is located.

But wait, isn't it a bit simplistic to think of Qubit states as points on a sphere?!?!

You are absolutely right! Which is the reason why not-so-bright lifeforms love to do it. The monkeys couldn't wrap their head around the qubit without a neat little visual representation, the so-called Bloch Sphere, presumably named after one of their many religious leaders, the New Kids on the Bloch:

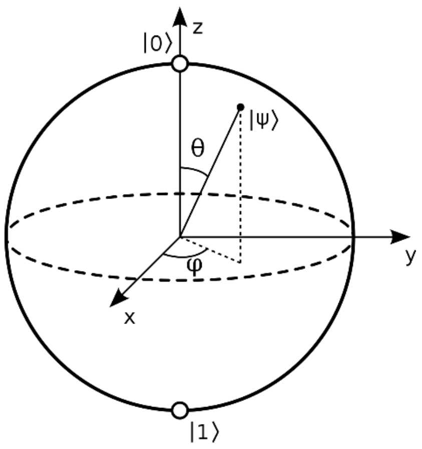

Figure 1: the Bloch sphere (source: https://en.wikipedia.org/wiki/Bloch_sphere)

Similar to our weather example, every point on this sphere is a state that a qubit can be in. On the northern pole, we have a guaranteed 0 measurement (given we use the right measurement method, but let's not get ahead of ourselves), and on the southern pole we have a guaranteed 1 measurement (again, this fact is to be taken with a grain of minerals mammals produce while crying). Why the human scientists decided to add weird brackets around their states, as an attentive reader might have noticed, is lost in translation, and really just a given fact, much like the heat death of the universe. Every other point/state represents a combination of probabilities that a measurement returns good or bad weather.

<u>That's real groovy, but what about the other axes?</u>

The Humans like to cling themselves to things that make them feel safe and in control of what is happening, maybe to make up the fact that they are sentient clumps of cells being trapped on a marry-go-round around a flaming star going roughly 107,000 kilometers per hour. One of these things are the 6 states of a qubit, represented as the end points of the x, y and z axes on the Bloch sphere. The humans where so fond of these particular states that they even named them:

- The |0⟩ state (located on the z axis)
- The |1⟩ state (located on the z axis)
- The |+⟩ state (located on the x axis)
- The |-⟩ state (located on the x axis)
- The |↺⟩ state (located on the y axis)
- The |↻⟩ state (located on the y axis)

The scientists at the hitchhiker's guide publishing house are still working hard on finding out how the monkeys pronounce the last two states, as it even gives the babel fish a run for its money. If the same measurement method is used as the one we assumed in the previous explanations (for simplicity we will call it a z measurement going forward, which, coincidently, is also its real name. As there are endless quantum states there are also infinite ways to measure the qubits in the different states. The following results are always measured in the z basis) we receive a 0 or 1 respectively for the |0⟩ and |1⟩ states, where it gets interesting are the results of the other 4 states, these are in the aforementioned superposition, meaning they are actually in both states (0 and 1) at the same time, only being decided what it actually is upon measurement. This decision is determined by a given probability, in the case of |+⟩, |-⟩, |↺⟩ and |↻⟩, these probabilities are exactly 50/50, meaning the measurement is completely random. Did we lose the pre-space exploration civilizations yet? Yes? Well, lets look at it this way:

You, a feline traveling through our mostly boring universe, take a stroll through the amazing sites of Magrathea, when you stumble upon a human called Schrödinger. Your primal instincts for revenge kick in and you entrap Schrödinger in a cave, together with a device that, with a 50% chance, kills Schrödinger by dropping an unspecified amount of cat feces on him upon activation. In this very simplified example, Schrödinger is in a superposition, 50% alive and 50% dead, and upon the activation of your awesome device we "measure" the state of Schrödinger, meaning we lock in one of the two states that he is in. Of course, getting revenge with only a 50% probability goes against your cat instinct, so you keep pushing the stupid red button a hundred times, leaving Schrödinger alive with a chance of 7.8886091e-31.

<u>Okay okay, I get it. But how do we work with the qubits?</u>

Depends. Are you a electrically charged cloud monster from Omicron Persei 8? No? Well in this case, you have to use the same primitive earth technology as the half monkeys, called “gates”. Earthlings used gates since before they stumbled upon quantum theory (which presumably happened when a drunken physicist tried to impress a girl at a frat party and started mumbling completely random, yet somehow deeply profound and complex theories about the universe), to trick innocent minerals into thinking for them. So what is a gate in the computer science world? Hint: its not a giant metal door you go through to get to a fancy dinner party. Gates are, in the ancient computing systems of earth, electrical circuits designed to perform one task. These circuits receive one or more inputs and (normally) return one output. One example of such a classical gate is the OR gate: it receives two inputs, the output is 1 if either or both of the inputs are 1, otherwise it is 0.

INPUT		OUTPUT
A	B	A OR B
0	0	0
0	1	1
1	0	1
1	1	1

Figure 2: truth table of an OR gate (source: https://en.wikipedia.org/wiki/OR_gate)

The quantum equivalents of the classical computing gates follow the same basic concept, but they are way harder to actually implement, since the aim of the hitchhikers guide to the galaxy is not to teach people anything actually useful, but rather vaguely inform people about as many things as possible, we will just have a look at what the different quantum gates do, instead of how they do it.

While not being the only type of quantum gates, the Clifford gates are certainly some of the most important gates used in primitive quantum computing. Named after a big red dog, they provide very simple operations to manipulate and change qubits. Let us take a look at some of the Clifford gates:

- The H gate: This gate transforms a qubit in the $|0\rangle$ state into the $|+\rangle$ state, and the $|1\rangle$ state into the $|-\rangle$. This is extremely useful, since humans, as of now, have not found a way to physically measure a qubit with something else beside the Z measurement, which means they need an H gate to access the information of a qubit along the x axis on the Bloch sphere.
- The X gate: have you ever had a $|0\rangle$, but wanted a $|1\rangle$? Well, the X gate can do that for you! This also works the other way around. It gets more complicated when the qubit is in another state, so let us ignore that, just imagine the state rotating around the x axis on the Bloch sphere.
- The Y gate: This gate will rotate your qubit around the y axis, similarly how the X gate rotates the state around the x axis
- The Z gate: last, but not least, a rotation around the z axis of the Bloch sphere

Clifford gates are certainly cool, but to achieve true greatness, we will also need more complex gates:

- $R_x(\theta)$: while the previous axis rotations always stay the same (e.g. always rotate π radians), this gate allows us to rotate arbitrarily around the x axis
- $R_y(\theta)$: The same as above but around the y axis
- $R_z(\theta)$: The same as above but around the z axis

Funnily enough, the $R_y(\theta)$ and $R_z(\theta)$ gates aren't even really needed and are mostly included in this article so they don't feel left out, since we can simulate these gates with the $R_x(\theta)$ gate and a Clifford gate. In fact, combining the $R_x(\theta)$ gate with a Clifford gate is such a powerful idea, that this allows the quantum computers to perform any task that a normal computer can also perform, thus making the quantum computers at least as powerful as any other computer.

<u>So if quantum computers are at least as powerful as other computers, what could make them better than the others?</u>

Leaving out the fact that humans can feel special and intelligent when using the word quantum, it also has some real applications. Searching through lists very fast or helping them secure their bank accounts are some examples. To explain why would go far beyond the paygrade of an editor of the hitchhiker's guide, and since this is enough to make the reader look smart and sophisticated but incredibly boring at his next social gathering, we end the article at this point. We do not take any responsibility for accidents involving quantum suicide or other science shenanigans. All complaints about inaccuracies should be directed to:

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