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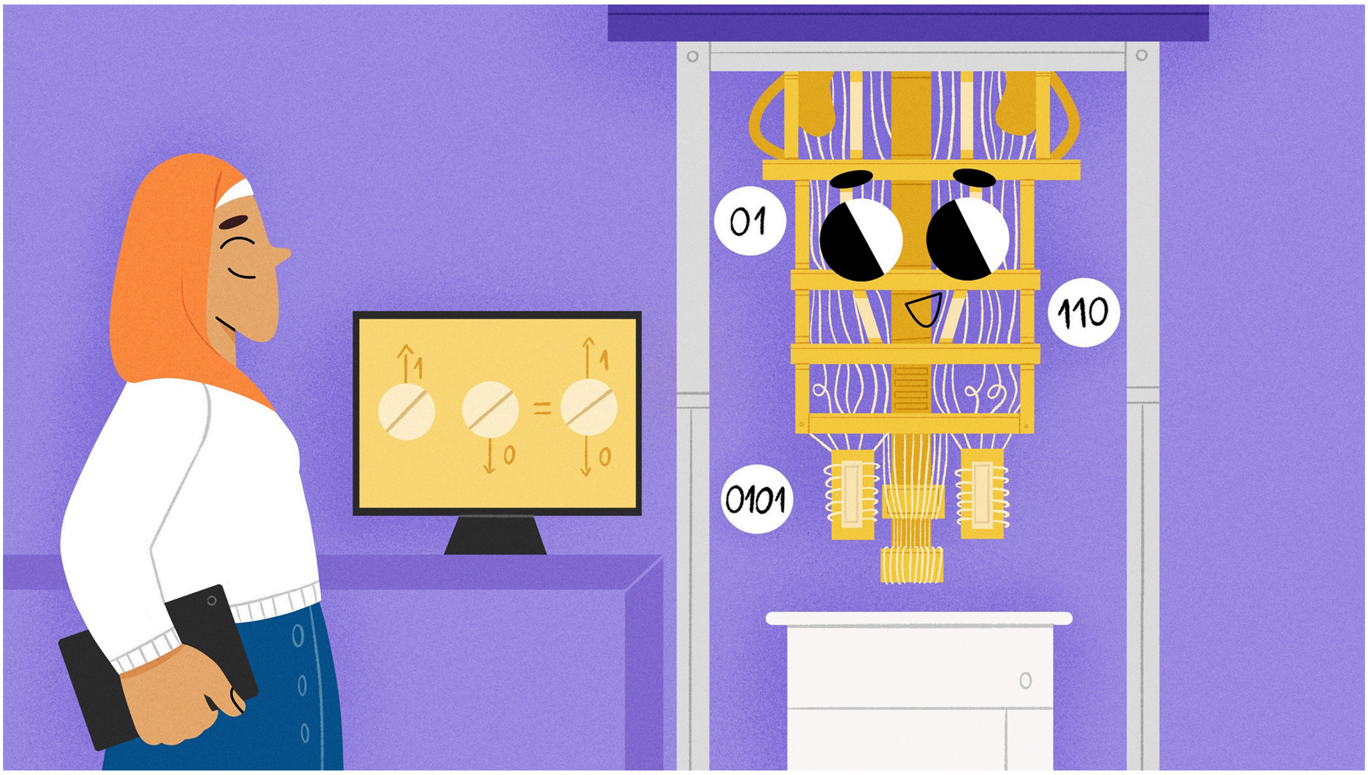

THE AWE-INSPIRING POWER OF QUANTUM COMPUTERS

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Quantum computing is an emerging field of research and technology that harnesses a science called quantum mechanics to create computers with revolutionary capabilities. Although existing quantum computers are limited in size and prone to significant errors, future quantum computers might be capable of performing tasks that were once considered unimaginable using even the world's most powerful supercomputers. This means that quantum computers could revolutionize many important areas of our lives! In this article, we will explore quantum computing by first reviewing how our current computers work. Then, we will dive into what makes quantum computers potentially far more powerful. We will especially focus on the source of their immense power: the ability of tiny particles to be in multiple states at the same time!

HOW DO COMPUTERS STORE INFORMATION?

Before we dive into the powerful world of quantum computing, it will be very helpful for you to understand how existing computers store information. Computers store individual units of information known as **bits**. Each bit can store a value of either 0 or 1 and many bits can be combined to represent information. For example, we can combine 6 bits to make the string "101010", which stores the number 42. If we combine millions or even billions of bits together, then we can store more complex information, such as images, videos, and video games.

BIT

The smallest unit of data that a computer can store. Each bit stores a value of either 0 or 1.

Bits are stored using tiny electrical devices known as **transistors**. Transistors are like on-and-off switches. If a transistor is switched off, then it stores a value of 0. On the other hand, if a transistor is switched on, then it stores a value of 1. Figure 1 shows a very simple representation of how this logic can be used to create bit strings, such as "101010". To have enough bits to store more complex information, a typical modern phone contains billions of closely packed transistors.

TRANSISTOR

A miniature electronic device that acts like a switch. Each transistor stores one bit.

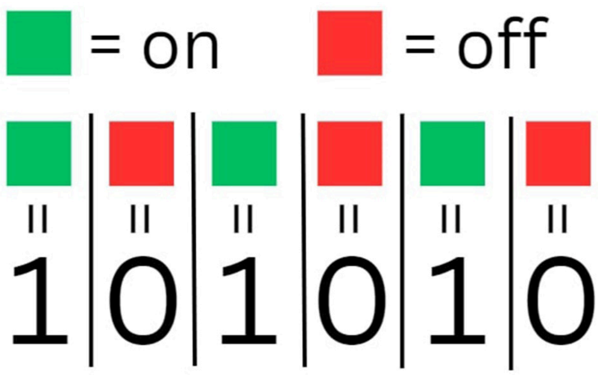

Figure 1

Figure 1

A simple representation of how transistors can store information. Each transistor is either "on" (green) or "off" (red). If a transistor is "on" then it stores a value of 1, and if a transistor is "off" then it stores a value of 0. In this case, we use six transistors to store the binary string "101010", which is code for the number 42.

To summarize, our existing computers store information in memory using billions of transistors, each of which stores one bit (either a 0 or a 1), and that combine to represent potentially complex information. Historically, computer advancement has followed a trend known as **Moore's Law**, which predicts that the number of transistors we can fit on computer chips doubles every two years. Modern computer chips can contain more than 100 million transistors per square millimeter, and we are potentially approaching a physical limit on how many we can fit. This has led to a heated debate around whether Moore's Law is "dead".

MOORE'S LAW

The observation that the number of transistors in a microchip doubles every two years.

WHAT IS A "QUANTUM" COMPUTER?

A quantum computer is a device that uses the unique behavior of **quantum particles** to make calculations. But where does the word

QUANTUM PARTICLES

The smallest units of matter and energy, described by quantum mechanics. Examples include electrons and photons.

QUANTUM MECHANICS

The field of physics that describes behavior of nature at the smallest scales. It tells us how particles behave and interact.

"quantum" come from, and what does it mean? It comes from the name of **quantum mechanics**, which is a theory that describes physics on the smallest scales of our universe. The relevance of quantum mechanics to quantum computing is that it tells us how particles behave and interact with each other. Quantum mechanics describes a fascinating world where particles can spread out across space, be in different states at the same time, and interfere with one another like waves in the ocean [1]. Behavior in the quantum world is quite different to the predictable behavior of the world we can see around us! Despite the surprising behavior of particles described by quantum mechanics, it is one of the most accurate theories ever developed in the history of science [2].

SUPERPOSITION

To be in multiple states at the same time.

The behavior of tiny particles is best described by quantum mechanics. For example, electrons, photons (particles of light) and atomic nuclei all exhibit quantum behavior and are therefore examples of quantum particles. So, what is it about these particles that we can use to make powerful quantum computers? One of the most fundamentally important properties is the principle of **superposition**. In essence, this property allows quantum particles to store far more information than we can store using transistors.

QUBITS AND THE MYSTERY OF SCHRÖDINGER'S CAT

QUBITS

A quantum bit of information. Each qubit can be in a superposition of storing 0 and 1.

The key difference between quantum computers and ordinary computers is the use of quantum particles instead of transistors to store information and make calculations. Just like how we call the information stored by transistors "bits", we call the information stored by quantum particles "**qubits**"—which is short for "quantum bit". To understand why qubits can be more powerful than normal bits, you first need to understand the principle of superposition from quantum mechanics.

Superposition might seem like a bit of a scary term, but it just means to "be in multiple states at the same time". As weird as it sounds, quantum particles can be in many types of superpositions, such as being in multiple locations at the same time while traveling in different directions. It can help a lot to think of particles as being more like waves that spread out across space rather than point-like particles.

Believe it or not, you can learn a lot about quantum superposition from a famous but simple story about a cat, imagined by the Austrian physicist Erwin Schrödinger in 1935 [3]. The story begins by placing a cat in a sealed box with a radioactive element and a flask of poison. If the source of radiation emits a particle (which happens randomly), then the particle triggers a hammer to swing down and break the flask of poison, which kills the cat (Figure 2). Do not worry about what exactly causes the flask of poison to break—just know that it is a random process that cannot be predicted ahead of time.

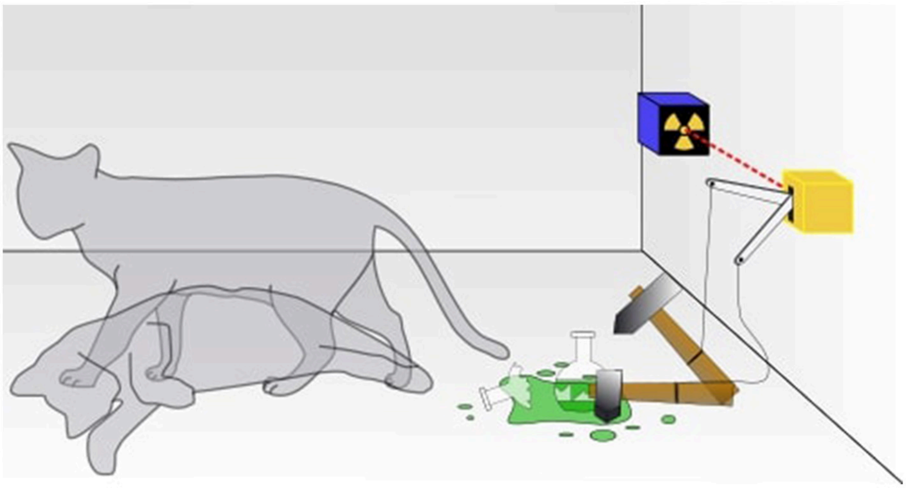

Figure 2

Figure 2

The Schrödinger's cat thought experiment. The radioactive element (the small blue cube with a black radioactive sign on it) can randomly emit radiation. If it does, it triggers a chain of events leading to the release of the green poison. Before we open the box, the cat is (hypothetically) in a superposition of being dead and alive. This story is a bit ridiculous, but it is a great analogy for how smaller objects like quantum particles behave—they can be in multiple states simultaneously.

If the box remains sealed, then we do not have any way of knowing whether the poison has been released and whether the cat is dead or alive. Schrödinger declared that, until we open the box, we must consider the cat to be *both* dead and alive at the same time. In other words, the cat is in a superposition of being dead and alive. However, once we open the box and look inside, then this superposition disappears, and we know the state of the cat with certainty.

It certainly does seem silly to consider cats to be simultaneously dead and alive, but this story is a great analogy for how quantum mechanics describes the behavior of particles. For example, if we do not measure the state of a particle, then it can truly be in a superposition of many states. However, once we do measure its state, this superposition disappears, and it will "collapse" into one of its possible states. In essence, particles can hold huge amounts of information in superposition, but when we try to measure this superposed state, we get only one piece of that information.

QUANTUM COMPUTING: THE POWER OF DOUBLING

Quantum mechanics tells us that particles have an intrinsic property called **spin** that can either point upwards or downwards [1]. For the sake of this explanation, let us say that "spin up" represents a value of 1, and "spin down" represents a value of 0. So, you can see that, much like transistors, quantum particles can store bits of information (in this case, qubits), and we can combine quantum particles to create strings. However, quantum mechanics tells us that quantum particles can be in a superposition of "spin up" and "spin down"—meaning that qubits can store the values of 0 and 1 *simultaneously*, which is simply impossible for a transistor (Figure 3).

SPIN

Refers to "spin angular momentum", an intrinsic property of particles. Spin can either point upwards or downwards.

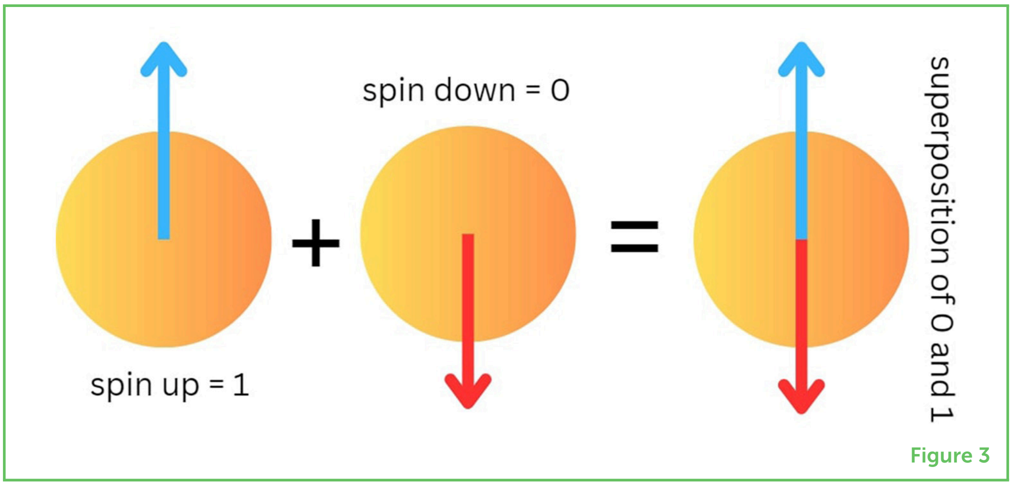

Figure 3

A simple representation of a qubit in a superposition of 1 and 0. The arrow on the electron (represented as an orange circle) points in the direction of the electron's spin. Spin can be either up (stores a value of 1) or down (stores a value of 0). Due to the principle of superposition in quantum mechanics, the electron can have spin up and spin down at the same time. It can therefore store a value of 1 and 0 simultaneously.

If we combine two qubits together, this 2-qubit system can store the states "00", "01", "10" and "11" simultaneously (four states), whereas a 2-bit transistor system can only store one of these states at one time. If we increase to 3-qubits, we can store "000", "001", "010", "011", "100", "101", "110" and "111" simultaneously—eight states! In fact, if we combine n-qubits, then we can store 2^n states simultaneously. If we have just 50 qubits, then we can store more than 1 quadrillion states at one time—potentially giving a quantum computer access to more states than a supercomputer with trillions of transistors. This is the power of doubling! However, when we measure the state of the quantum computer, its superposition will collapse, and we will only get a little bit of information at a time. It is like picking just one piece from a big puzzle. Designing quantum algorithms that take this into account is very important! The key is to construct an effective quantum algorithm that examines all possibilities in superposition and strategically extracts the maximum possible information.

QUANTUM COMPUTERS ARE BECOMING A REALITY

Today, we are in what is known as the noisy intermediate scale quantum (NISQ) era of quantum computing, which means that current quantum computers are limited in size and prone to large errors. Most of these machines are not yet useful for real-world applications [4]. The path to bigger and error-proof quantum computers is being paved by researchers and innovative private companies all around the world. Incredibly, 2023 heralded the arrival of the first 1,000-qubit computers, but there is much progress to be made in reducing the error rate of these machines [5]. Although the future of quantum computing remains unknown, the advancement of quantum technology could bring humanity a wealth of new possibilities for communication and information processing. It may also bring a new set of challenges, such as making sure that this powerful technology is used ethically. But one thing seems likely: quantum computing will change the world around us.

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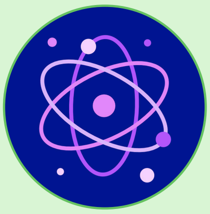
CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

CLARE, AGE: 12

Clare, age 12, has been homeschooled for her entire educational career. She is a self-starter and is known to take on both intellectual and creative challenges. Clare enjoys teaching herself Japanese, drop-spindling wool to make yarn, needle felting, learning to code, participating on a local robotics team, learning to sew clothing, playing violin and piano, experimenting with recipes in the kitchen, and of course reading all the books. Her favorite Science topic is geology, and she hopes to be a librarian.



TEAM VON ZEKI, AGES: 8–10

We are team von Zeki, a curious duo (ages 8 and 10). We love learning how the world works. Our motto is: "Occam's razor in action".

AUTHORS

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Josh is an Honors student specializing in computational physics at the University of Western Australia in Perth. Passionate about quantum theory and many-body quantum systems, Josh's research focuses on encoding information into the state of quantum computers. Josh is a tutor for high school and university students, as well as being an advocate for education through the Quantum Girls Project to promote the uptake of quantum science in Australia. Josh enjoys surfing in his spare time.
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