Drawn to Discovery:

The Quantum Computing Coloring Book

Aedan Gardill & Sarah Parker

This book was made **without** the intentional aid of any generative artificial intelligence. The illustrations are hand-drawn and the information was gathered and written by the authors.

To learn more information about the book and access free downloads of the coloring pages, visit
wonders.physics.wisc.edu/quantum/quantum-computing-coloring-book/

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What is Quantum Computing?

When someone talks about “quantum,” they are talking about the smallest scale of things in our universe. At the “quantum” scale, particles and energy act in ways that seem contrary to what we know about the world. At the quantum scale, under the right conditions, particles can act like they are in multiple places at once, they can be linked with other far-away particles, and the line between particles and pure energy is blurred! In fact, scientists only started to notice these bizarre behaviors about 100 years ago, and thus the field of quantum mechanics was born.

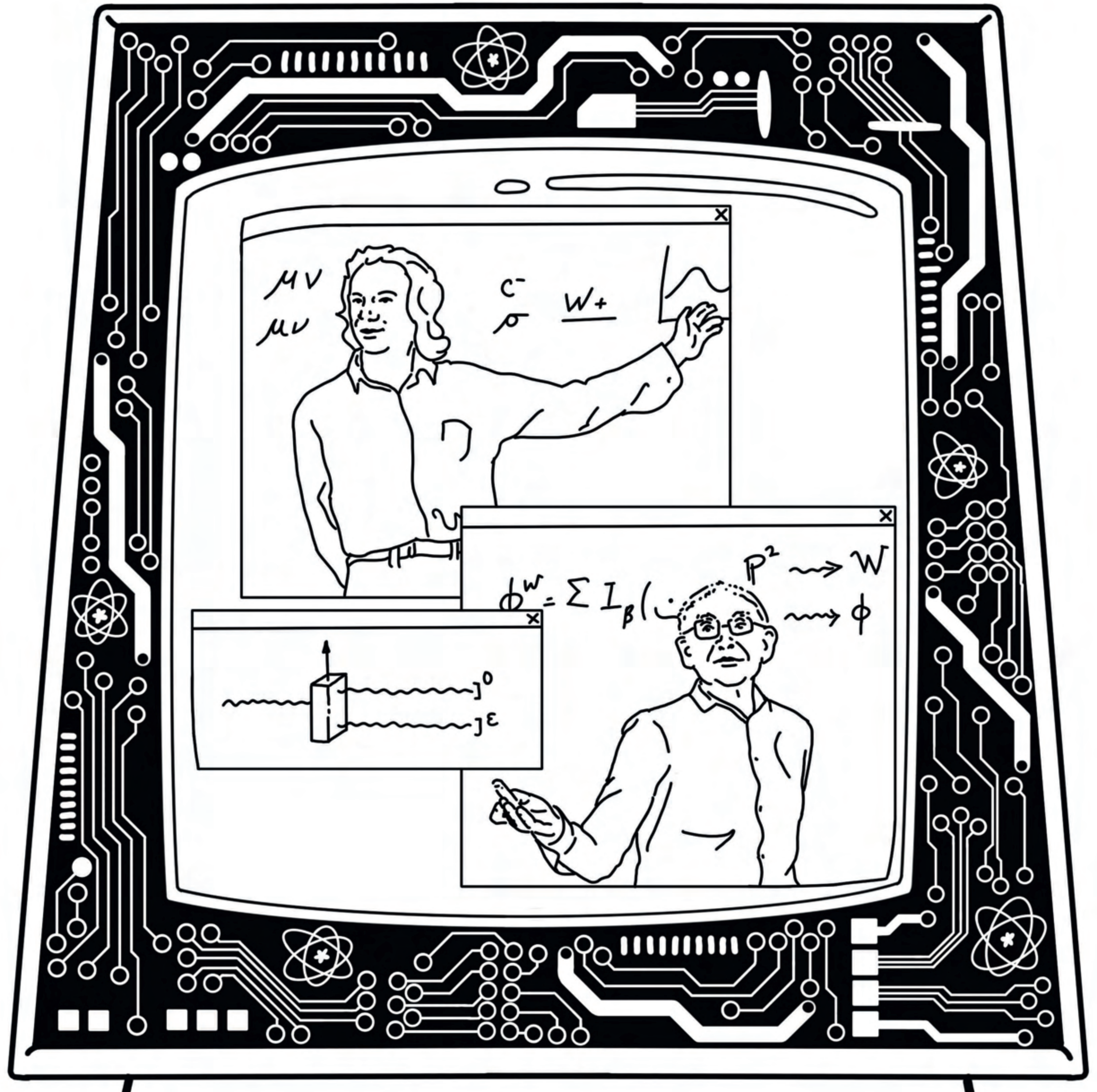
In the modern day, scientists and engineers are trying to harness the power of these quantum phenomena. They are working hard to build computers that are stronger, faster, and more secure than the computers we use today. These computers will use the main principles of quantum mechanics to process large amounts of data in a small amount of time, all while ensuring hackers can’t steal information. Quantum computers may not necessarily replace our laptops, phones, or video game consoles, but they will be able to securely encode and decode information, simulate molecules and chemical reactions for medicine, develop better models of climate change, and help to better understand the world around us.

As we begin to understand the quantum realm better, we expect quantum computers to help us in many industries—medicine, banking, energy, and more. As you color your way through this book, we hope that you discover something new about quantum computing.

Aedan Gardill & Sarah Parker

The Origins of Quantum Computing

Who came up with the idea of quantum computing? Well, it's difficult to pinpoint one single person. In 1980, Russian mathematician Yuri Manin was the first to suggest that a computer could run on quantum behavior instead of classical behavior, in a mathematics book about computable functions. The following year, American physicist Richard Feynman independently suggested a similar idea, stating in a famous lecture: "If you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy." These were the first instances of this idea of **quantum simulation**, which paved the way for quantum computing as we know it today.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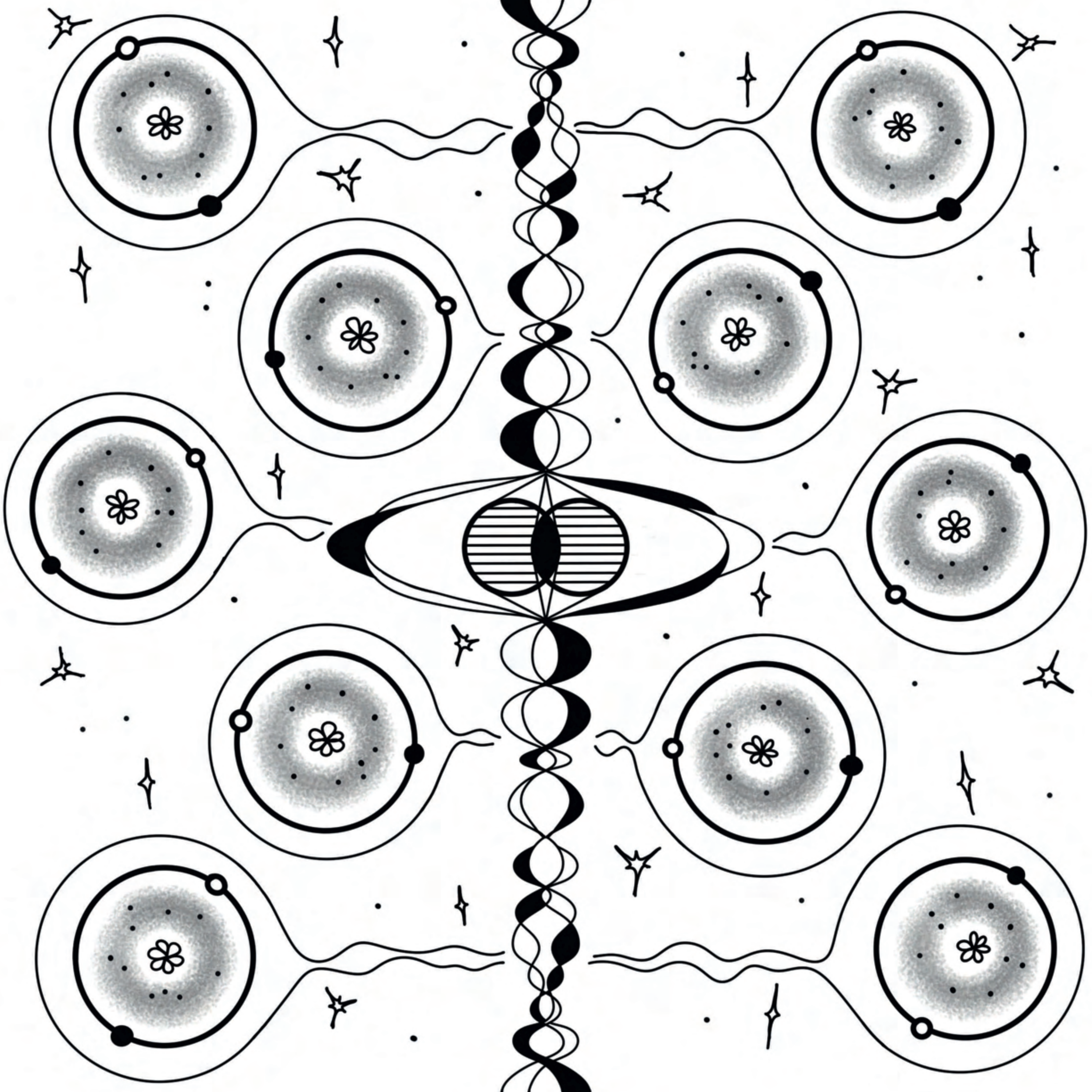
The Father of Quantum Computing

In 1985, David Deutsch, otherwise known as “the father of quantum computing,” was the first to dream up a universal quantum computer. He imagined it acting like a Turing machine, which is a simple machine able to simulate any computer algorithm (like cracking encrypted code in World War II). Like a Turing machine, a universal quantum computer would use universal quantum gates, which follow simple rules the quantum computer would follow, to simulate any problem it was given. Deutsch also proved in 1992 that quantum computers will be able to solve certain problems faster than any classical computer that could ever be built. Today’s classical computers store information in bits, which can be 0 or 1. Quantum computers store information in **qubits**, which are not restricted to being only 0 or 1 but can be a combination of both at the same time. Deutsch proved that this unique property allows quantum computers to solve some problems much faster.

Entanglement

Entanglement is a concept that describes how two particles can be tied together. Particles have properties like **position**, **momentum**, and **spin**. Think of a particle like a spinning top—it has a place, somewhere it is moving to, and a direction that it spins. Tops can spin clockwise or counterclockwise, and similarly, particles can spin up or down. However, unlike tops, particles can be entangled. When particles are entangled, measuring the properties of one particle instantly tells us something about the other particle, no matter how far apart they are. For example, if two particles are entangled, their spins must be equal and opposite: one up and one down.

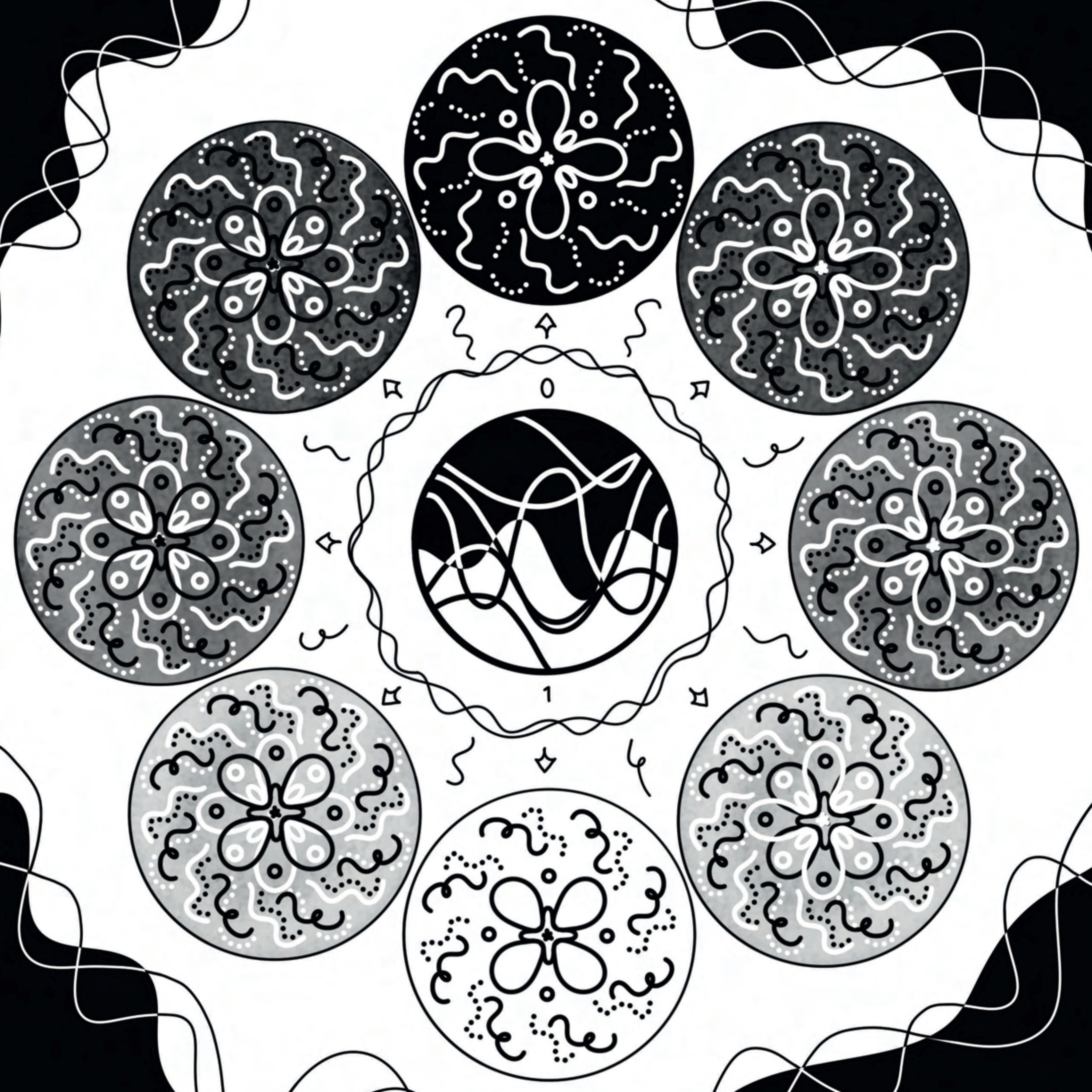
Quantum computers use fundamental quantum characteristics like entanglement to solve certain types of problems in ways that regular computers cannot. Entanglement lets the computers explore more possibilities at once for answers to problems, making them exponentially faster than regular computers in some cases.



Superposition

Qubits (quantum bits) are what store data in a quantum computer. Unlike regular computer bits that can only be 0 or 1, qubits can exist in multiple states at the same time—this is called **superposition**. Imagine a coin spinning on a table—when it's spinning, it's kind of both heads and tails at once; but when it stops spinning and falls, it has to be either one or the other.

When a qubit is in superposition, it can be a combination of the 0 and 1 states until it's measured. When scientists measure a qubit, it **collapses** to either 0 or 1, just like how a spinning coin falls to either heads or tails. Superposition is what makes entanglement between qubits possible. When multiple entangled qubits work together, quantum computers can explore many possible solutions at once, which helps them solve difficult problems in an efficient way.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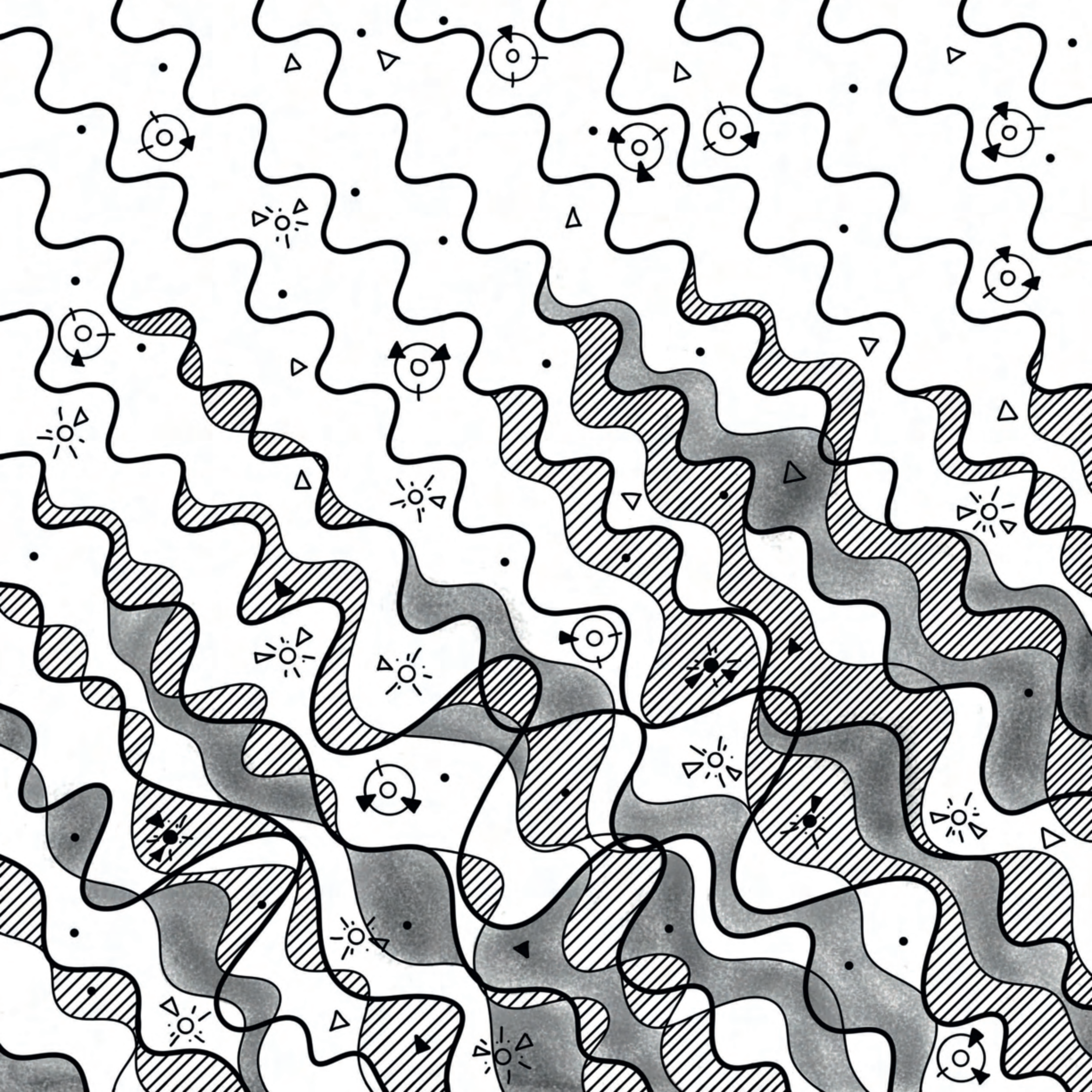
Coherence

Particles have properties like position, momentum, and spin. Anything that happens in the environment around a particle can affect these properties, or the **state**, of the particle. If the temperature changes or the particle is bumped, it can go through **decoherence**, or lose its special quantum properties. We can think of **coherence** like trying to keep a spinning top perfectly balanced—any small disturbance can make it wobble and fall.

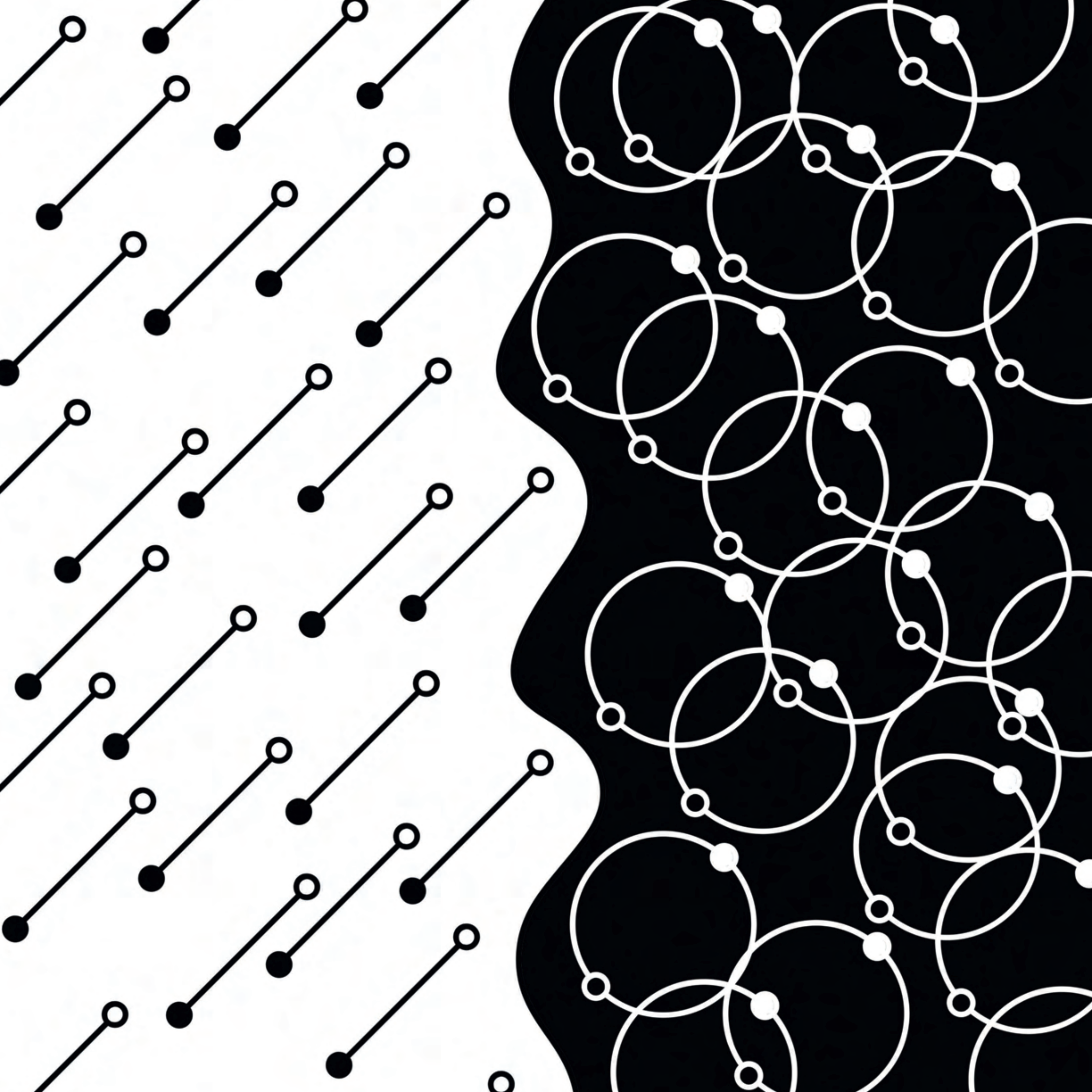
In quantum computers, scientists need the **qubits** to stay coherent long enough to solve problems, or in other words, complete calculations. Scientists work hard to protect qubits from disturbances so they can get accurate results when solving problems with quantum computers.



Bits vs. Qubits

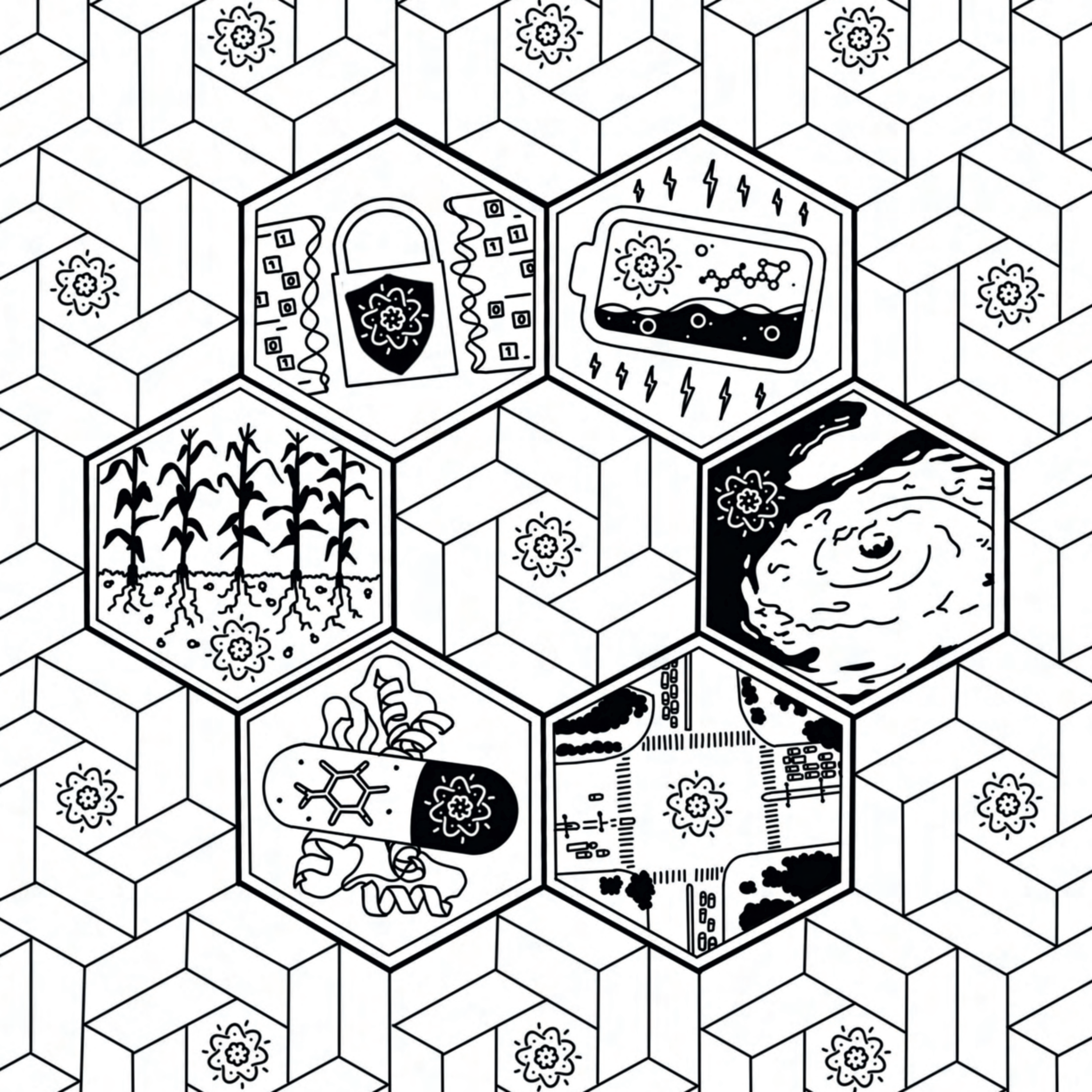
The general concept of any computer is that you can use it to store and process information, called **data**. The smallest piece of information is a **bit**—something that is either on or off, like a light switch. When a computer writes data, it assigns a 0 or 1 to each bit, and the bit has that value until it is read. To store more data, bits can be put together in a string of 1's and 0's, which we call **binary code**. Computers are able to read the binary code bit by bit and translate the data into the visuals that we see in our internet browsers, video games, and so on.

The smallest piece of information in a quantum computer is a quantum bit, or a **qubit**. Qubits are different from bits because they can exist in a **quantum state** of both 0 and 1. However, once we read the value of the qubit, it collapses into either 0 or 1. The quantum state determines how **probable**, or likely, it is that you read a 0 or a 1. Multiple qubits can be entangled together, which increases the processing power of the quantum computer twofold: it exponentially increases the amount of data the qubits can hold and allows the quantum computer to simultaneously translate the data from each of the qubits.



Uses of Quantum Computing

While we don't expect quantum computers to take over all of the uses of **classical computers** (like our phones, laptops, and video game consoles), we do anticipate that quantum computers will greatly improve our lives in many ways. Quantum computers will be able to stop hackers from getting information by making **encryption** of digital information more secure, allow engineers to discover new materials for making better batteries, solve traffic and scheduling problems more efficiently, give meteorologists the ability to better predict the weather and improve current models of climate change, assist doctors to find new medicines, and even help farmers by identifying new fertilizer compounds for their crops! Quantum computers will be able to solve cumbersome problems that even the supercomputers of today struggle to solve.



How Does a Quantum Computer Work?

The essence of classical computers comes from their bits: the most basic unit of information: a 1 or 0, an on or off, a “yes” or “no”. All computers work by controlling these bits, building **logic**—a set of rules that computers follow to make decisions—from them, and finally stringing them together to create code. These bits can be made in different ways: from holes in a punch card, to the direction of the magnetic field in some magnetic material, to the electrical signals in a vacuum tube. Modern computers have optimized the use of transistors—microscopic electronic switches—because of their ability to be made super small.

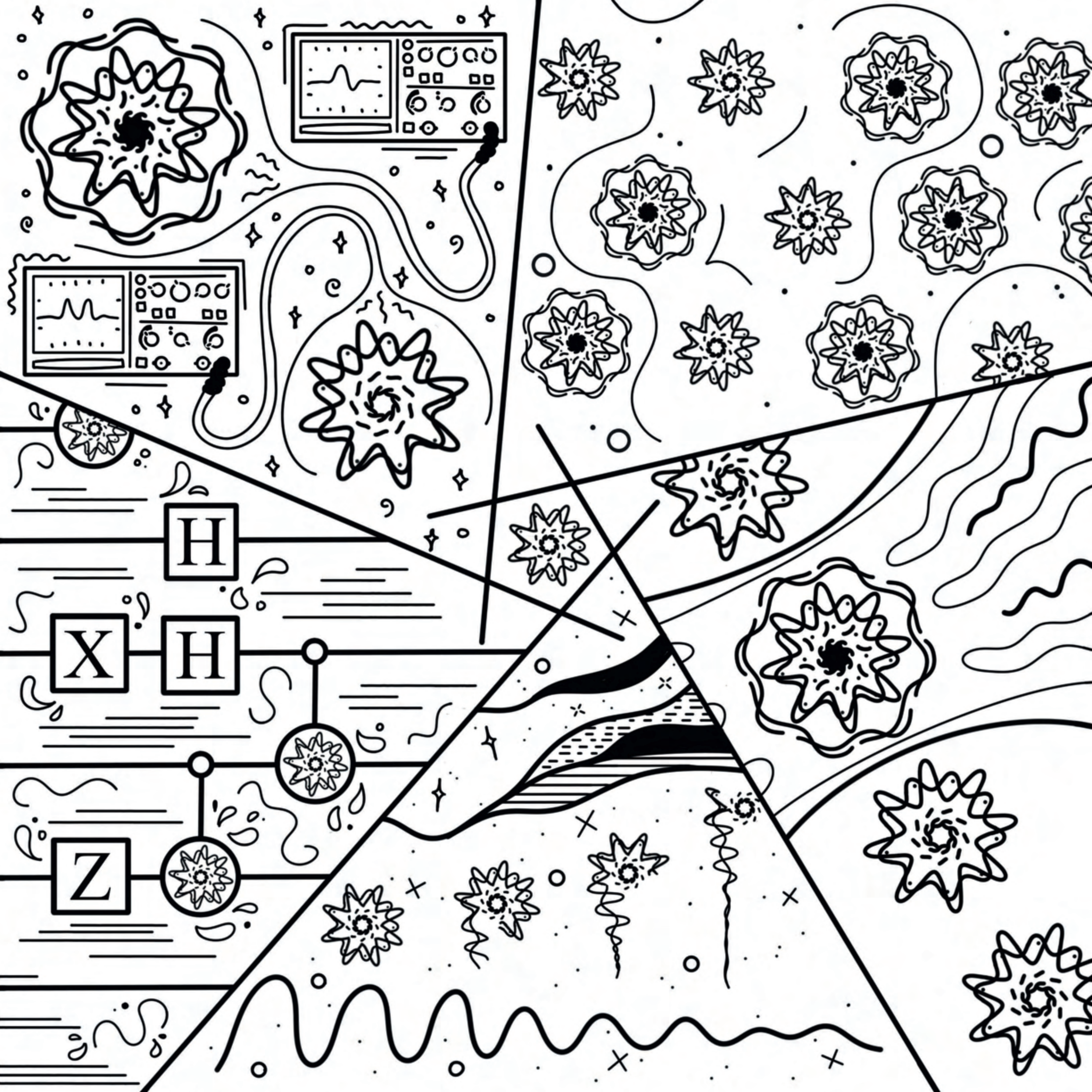
Right now, quantum computing is just in its infancy, and shares many parallels to the history of classical computing. Quantum computing is built on the foundation of **qubits**: a quantum counterpart to the bit that can be 1 or 0 or a superposition of both. Qubits are created by manipulating quantum objects, then assigning information to its state, and performing computations with it. Scientists and engineers can entangle multiple qubits, increasing their processing ability, and build systems of qubits that will one day become powerful quantum computers.

The requirements to make a useful qubit come from the DiVincenzo Criteria, which is a very broad set of guidelines and has allowed a wide array of quantum objects to be used. Right now, there are multiple different types of qubits that researchers are using, built from a multitude of particles, each technique with its own advantages and disadvantages. It is not clear yet if one technology will be better than all the rest. More likely, researchers will have to collaborate and use the advantages of multiple types of qubits together to achieve useful quantum computing. The following section explores the various types of qubits that exist and how they work.

DiVincenzo Criteria

What do scientists need to make a quantum computer? In 1996, theoretical physicist David DiVincenzo came up with five important rules, known as the DiVincenzo criteria, needed for qubits to form a functional quantum computer:

1. Lots of **qubits** that work well together: Qubits are the smallest units of information used in quantum computers. A useful quantum computer needs a large number of qubits that can handle calculations without losing their special quantum properties.
2. Ability to set up the qubits in certain states: Before they can be used in calculations, qubits need to be prepared in the right set of conditions, or starting state.
3. Long **coherence** times: Once qubits are set up, they have to stay in the same state until the quantum computer applies changes to the qubits according to a set of rules. This is called "coherence". If qubits lose coherence too quickly, the calculations won't work.
4. Universal set of **quantum gates**: The quantum computer needs to be able to change the state of the qubits according to a set of rules in order to perform calculations.
5. Ability to measure each qubit: After the quantum computer finishes a set of calculations, each qubit needs to be measured so that we can understand the results.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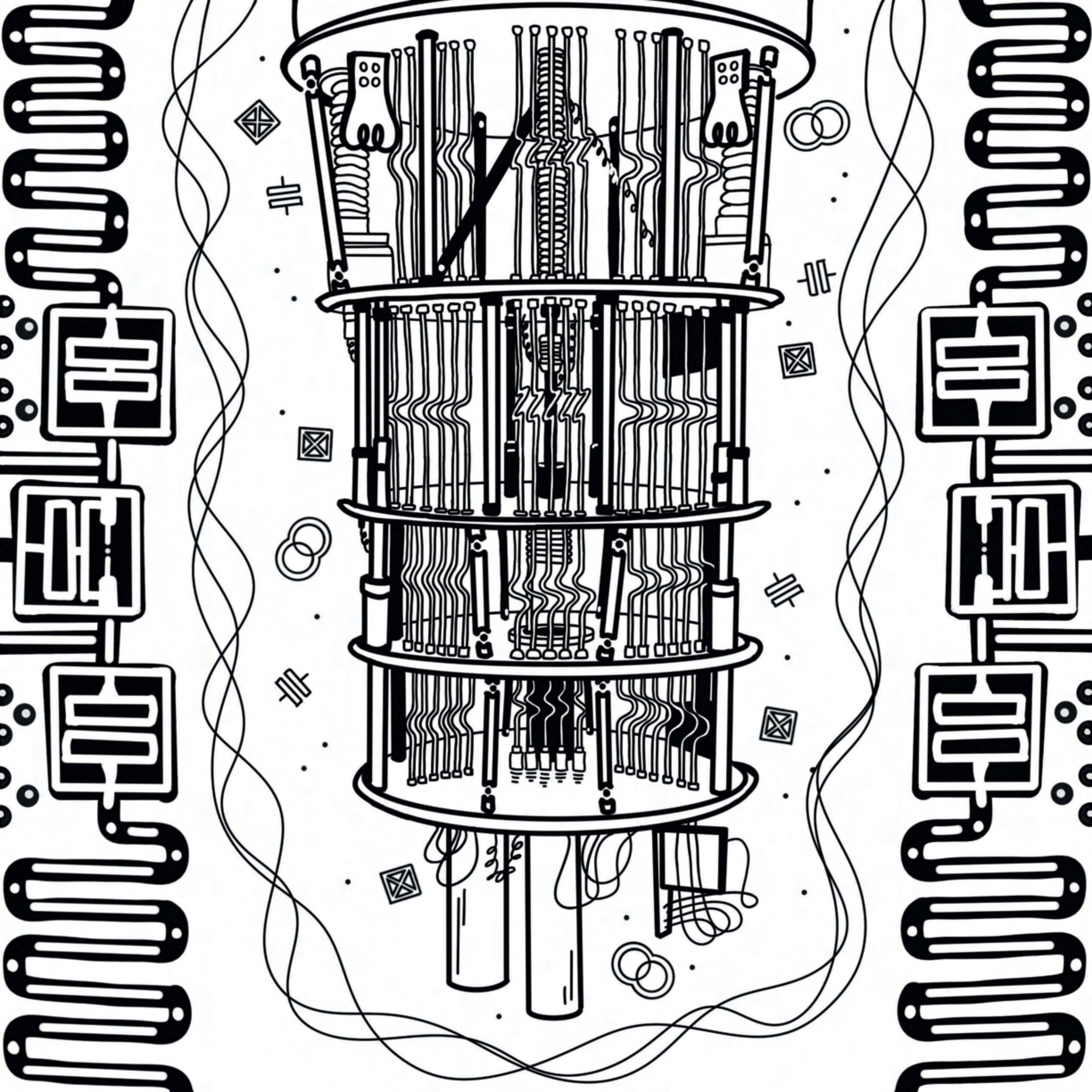
Superconducting Circuits

An electrical current is the flow of electrons within an object. The electrical current powering a 60 Watt lightbulb is made of 3 quintillion electrons per second. Would it be possible to measure the flow of a single electron? Scientists are able to do this, but it needs to be in a **circuit** made of **superconducting** material, in which electrons can flow without any resistance. The qubit of this superconducting circuit is formed by the characteristics of the current, down to a single electron flowing.

Right now, the way we make the best superconducting material is to cool it to an extremely cold temperature (a few millionths of a degree above absolute zero—the coldest temperature possible!) using a very large, yet intricate device called a **dilution refrigerator.** These superconducting qubit circuits, which are made in very similar ways to classical computer chips, are put inside of the dilution refrigerator to stay cool.

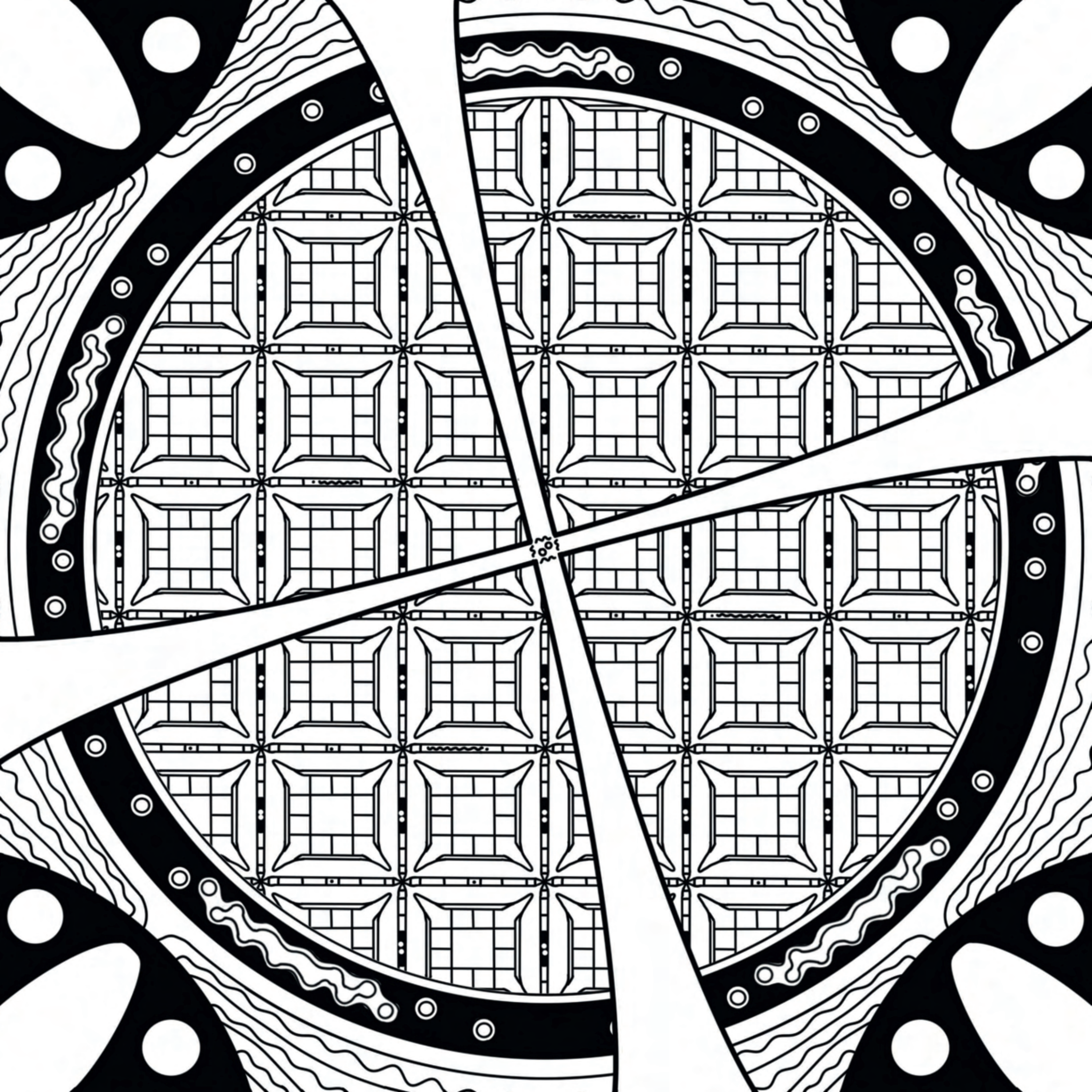


Neutral Atom Qubits

One method of quantum computing uses individual atoms to form qubits, which is grounded in the fact that every atom behaves the same exact way. This type of qubit uses the traits of the electrons, such as **energy** or **spin**, within the atom to hold information. However, since these atoms are neutral, or don't have a charge, they don't normally interact with each other. In other words, the qubits normally won't interact… unless you make the atoms massive! When the atoms are given more energy, the orbit of their electrons can grow in size. Scientists are able to isolate single atoms and precisely target them with a laser to give it a lot of energy, which can make the atom up to 1,000 times bigger (larger than some bacteria!). The extremely large atoms can then influence the surrounding atoms, allowing for entanglement and interactions to occur between qubits.

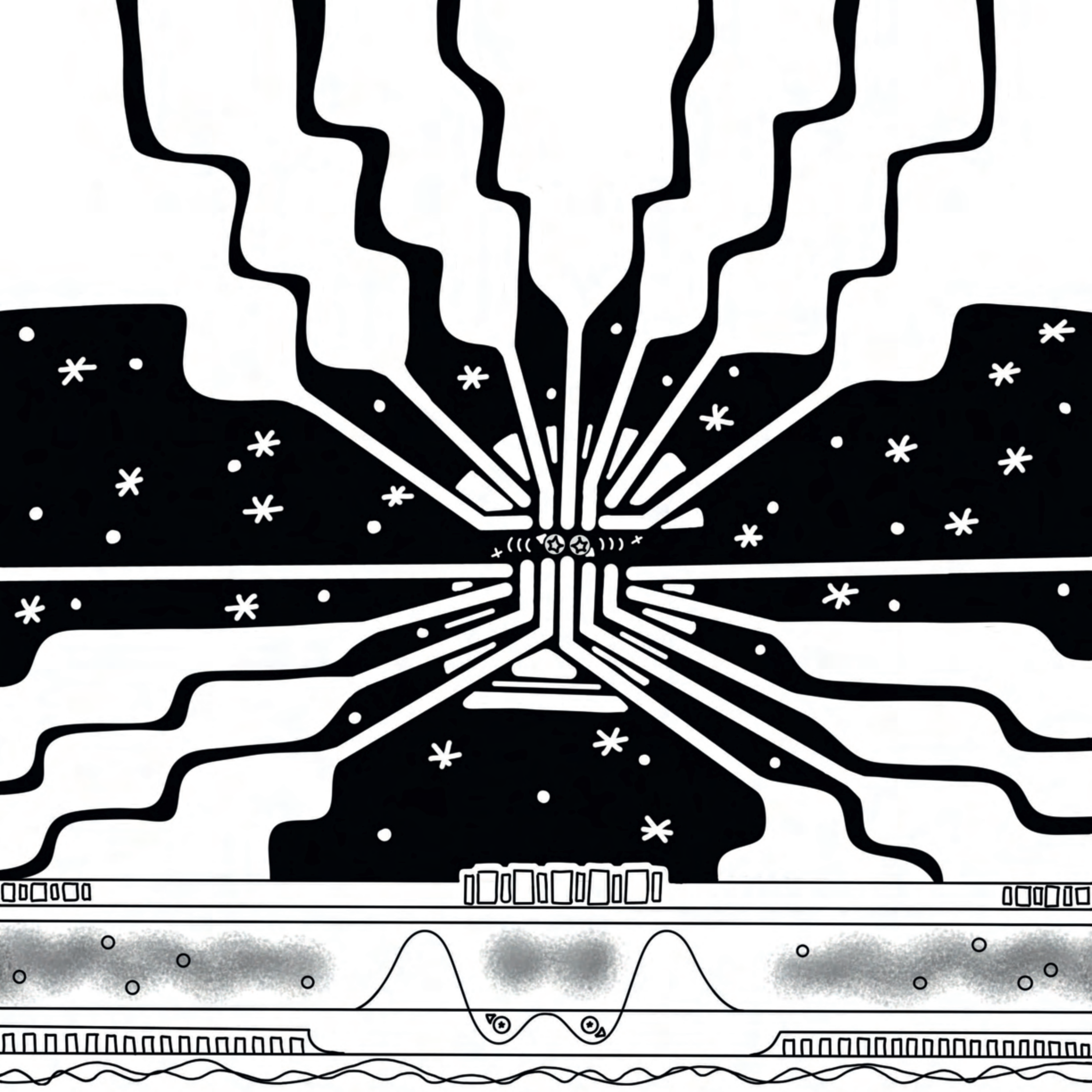
Trapped Ion Qubits

One type of qubit is made from charged atoms, called **ions**. Ions are created when you add or take away electrons from an atom, changing whether it is negatively or positively charged. One common example of an ion that you may know about is the electrolytes in sports drinks! These charged particles make convenient qubits because they easily interact with each other through electric forces. The downside to using ions, however, is that they are easily influenced by the surrounding electrical environment. Scientists must work hard to isolate these ions from their surroundings and carefully move them close to each other. Then, the qubits, which are made up of qualities of the ion, like energy or spin, can communicate. This was first done with large three-dimensional electromagnetic “traps”, but new advancements have allowed scientists to make precise electronic structures to trap ions on a two-dimensional surface.



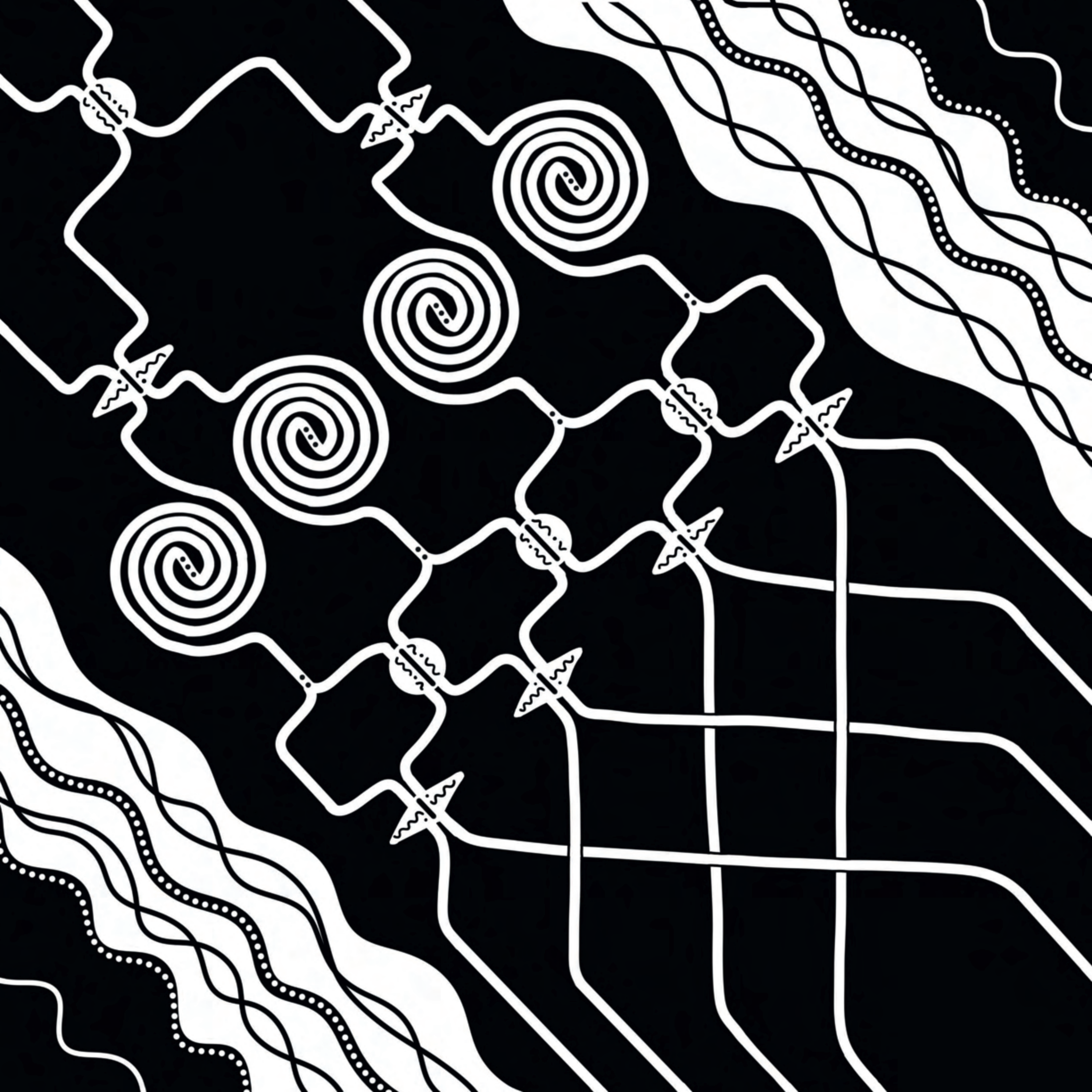
Silicon Quantum Dots

Could humans actually create an atom? To quantum computing scientists—yes! But all they care about is the electron. In quantum computing, electrons are the most important part of the atom, and researchers are able to trap individual electrons and create artificial atoms. To do this, scientists use layers of material to sandwich electrons into a two-dimensional area and trap single electrons in the places they want, creating nanocrystals called **quantum dots**. This technology might even be in your living room already! Engineers use a version of these quantum dots for creating vibrant images in QLED television screens. Certain properties of the electron in the quantum dot can be used as building blocks to make qubits. When the quantum dots interact, they can be used to solve problems and calculate mathematical equations.



Photonic Qubits

Photons are all around us—they are light! The beginning of quantum physics can be traced back to photons, when scientists were confused about their peculiar quantum behavior of acting like a wave and a particle. When light acts like a wave, it can **interfere** with itself like two waves crashing into themselves on the shore. Each light wave can wiggle—or **oscillate**—around in all different directions. Scientists can use this to their advantage by filtering out light that only oscillates in one particular direction. This is called **polarization**. The polarization of the light can act as a qubit. After polarizing the light, scientists carefully control when light interacts and can entangle it with other light particles. The photons travel through intricate, microscopic paths, which are similar to the much larger fiber optic cables that bring the internet to your home.

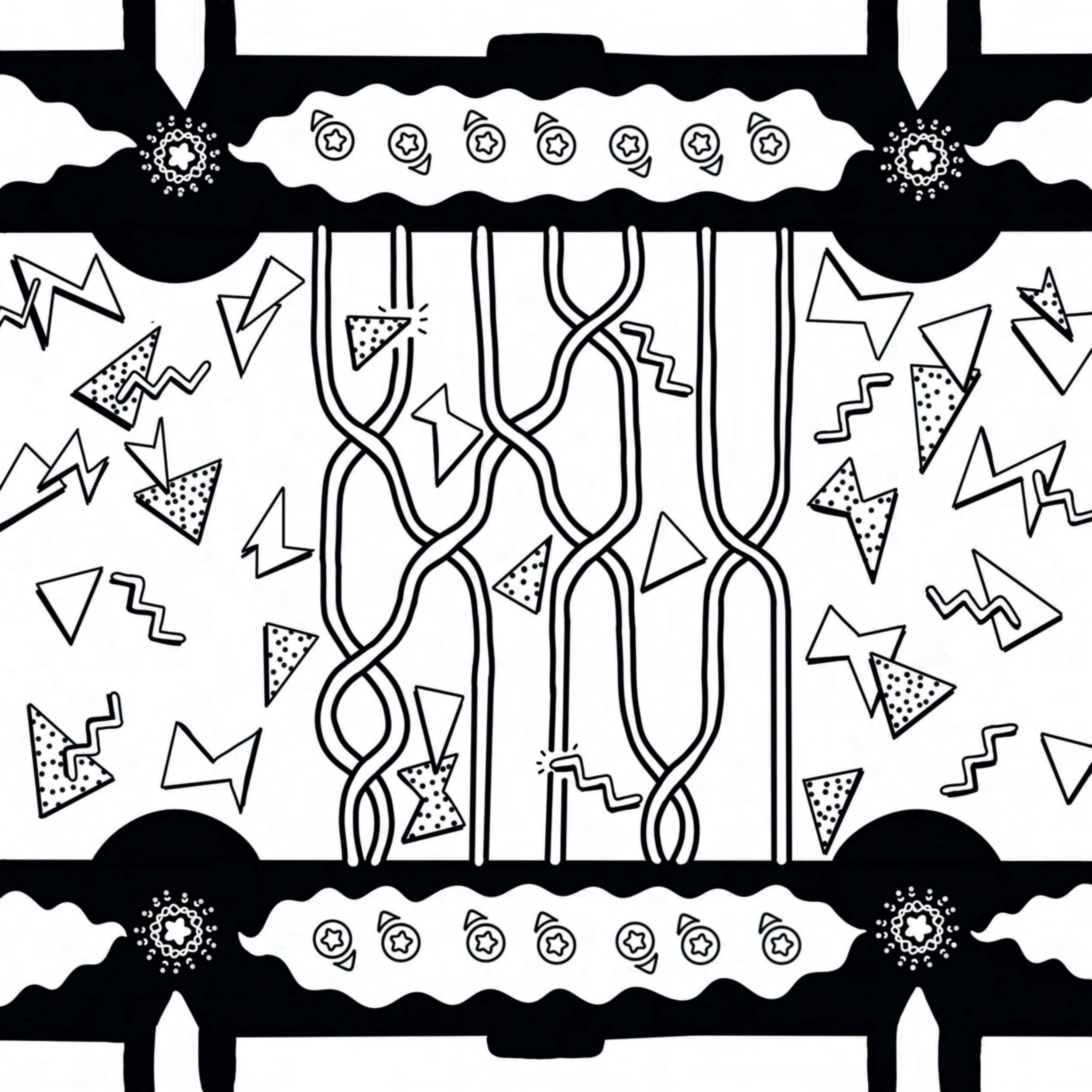


Solid-State Defects

Jewelry isn't the only use for diamonds; they are also used for quantum computing! Diamond is formed from many carbon atoms held together in a strong grid-like structure; however, there are often **defects**, or tiny imperfections, in this grid of atoms. Sometimes, these defects are made when a nitrogen atom takes the place of a carbon atom. These defects may seem like a bad thing, but researchers like them because nature has already done the hard work of isolating an atom for them. Currently, these defects are used for quantum sensors and can measure very weak magnetic fields, for example. However, there are scientists and engineers working to use them in quantum computing. Specifically, researchers hope to use them as **quantum repeaters**, which are devices that would allow communication between distant quantum computers without losing information.

Topological Qubits

All the other qubit methods are prone to getting ruined by their environment: one particle bumping into your qubit ruins your qubit. What if the qubit could be based on the collective properties of a group of particles, rather than just one? Scientists are working on a way to do this by creating a qubit from the **topology** of multiple electrons. Topology describes the geometric fundamentals of an object regardless of its actual shape: for example, a Mobius strip, topologically, has one single side. When we look at a group of electrons, their topography could be described by having an even or odd number in the group. Scientists can trap electrons in a super-cooled wire, and the qubit information is formed from the topology of those electrons. They can perform computations between two of these wires and then measure the topology at the end. It doesn't matter if the electrons have had some interaction with the environment, but as long as their topology is the same (there are still an odd number in the wire, for example), the qubit information is still there!



Who are Quantum Computing Scientists?

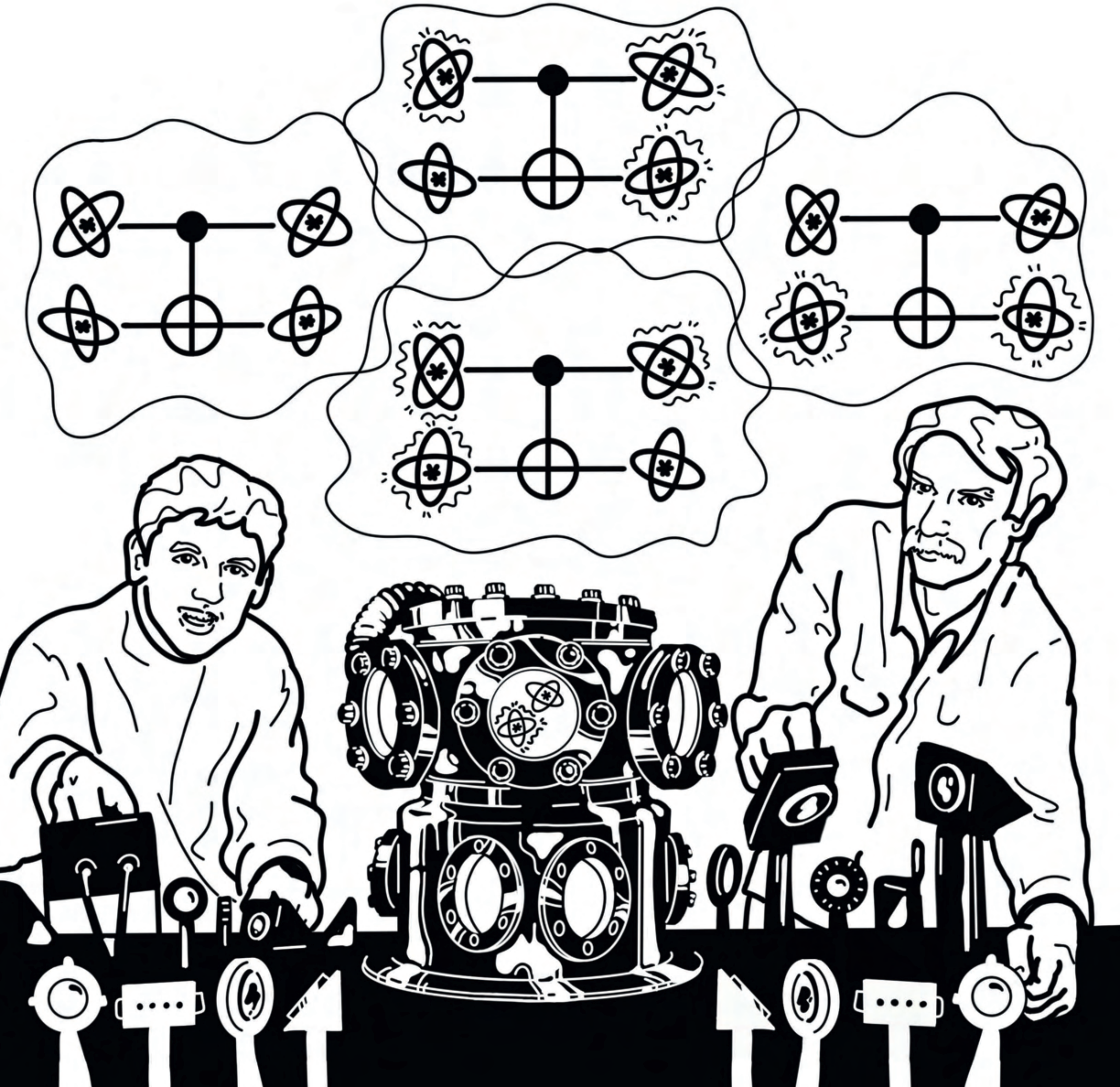
Quantum computing is a growing field that requires input from all sorts of people. You need physicists, engineers, computer scientists, chemists, and more to work together to achieve the incredible feat of making a quantum computer. Each person has a different role, from developing the theory of how to make quantum computers work, to running experiments to test the theory, building hardware for the computers, writing software and code for when the computers are functional, and coming up with ways that we can connect the computers together through a quantum internet.

The following section highlights scientists who fill all of these roles while working with quantum computing, from theory to direct application. The research that is featured also covers many of the types of qubits being used.

The field of quantum computing is very new, less than 100 years old. Its history is actively being written, which means we all get to define its future. Quantum computing has already shown to be a global effort that requires new ideas from all sorts of people. It is important for the field to continue recruiting fresh faces with diverse backgrounds, as each person will bring new ideas to the table. This coloring book strives to show the importance of maintaining a space where all people can thrive and contribute to this scientific field. The best way for science to advance is to include everyone at the lab table.

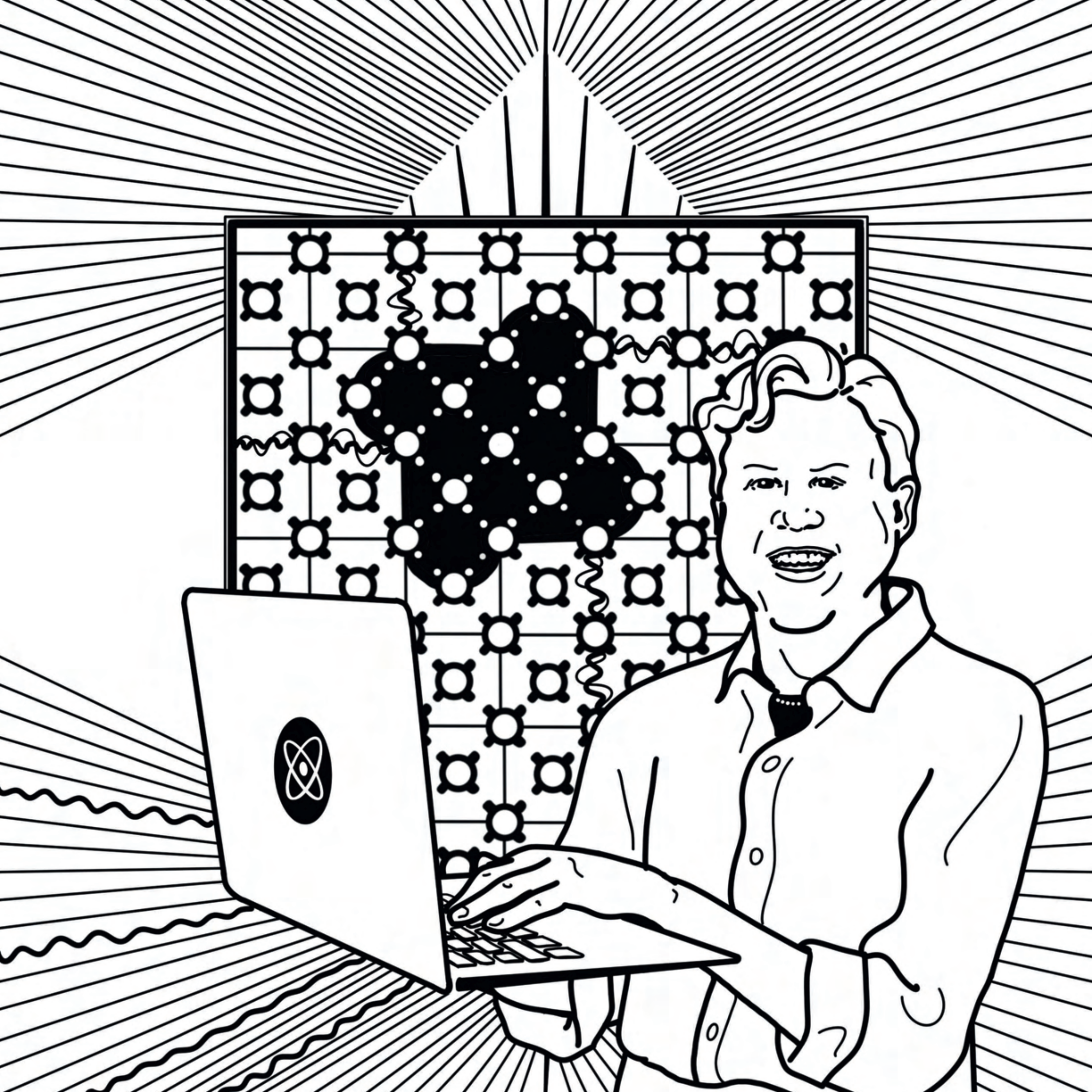
David Wineland & Christopher Monroe

All computers, including quantum ones, need a set of rules to follow to be able to solve problems. In quantum computing, we call this set of rules **quantum gates**. The most important of these quantum gates is called a **Controlled-Not gate**, in which one qubit's state is directly influenced by the state of another entangled qubit. In the 1990s, researchers David Wineland and Christopher Monroe were studying trapped ions and came up with a way to control the interaction between them. Wineland, Monroe, and their team successfully applied a Controlled-Not gate on their trapped ions. This was the first time that anyone had physically shown that it was possible to have these logic gates act on individual qubits, which was the first huge experimental step towards quantum computing.



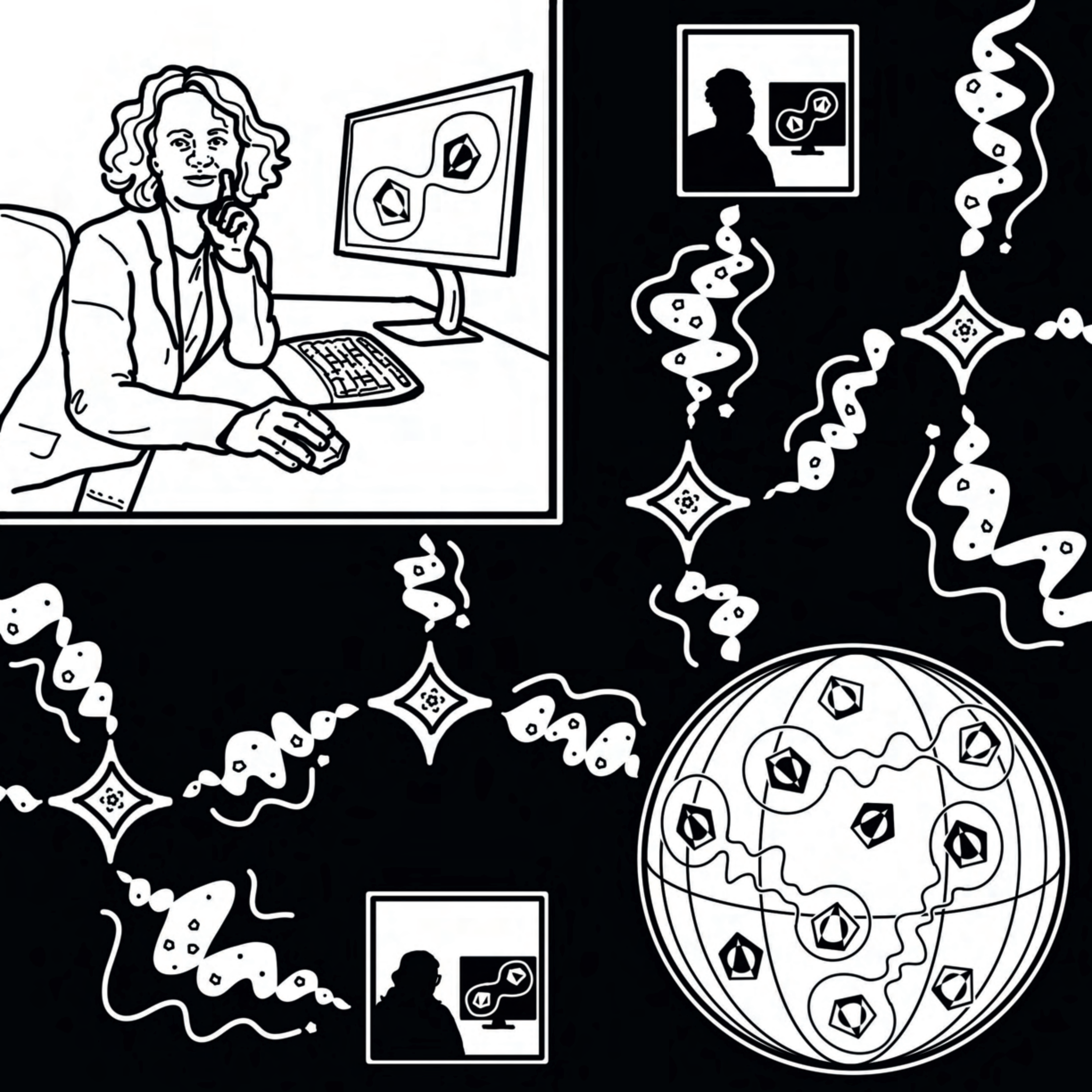
Dave Bacon

Quantum computers will be able to solve problems that a classical computer can't, such as figure out complex molecular structures. This **quantum advantage**, or sometimes called "the beyond classical experiment" limit was first shown by Google with superconducting qubits in 2019. While the complex problem that Google solved was not extremely interesting—they showed they could perform complicated computational operations in 200 seconds that would have taken a supercomputer 10,000 years to complete—it was a huge step forward in quantum computing. Dave Bacon was part of the team that achieved quantum supremacy and is now the head of software development for Google's quantum computer team. He works hard to figure out things like "what kind of programming language do you write a quantum computer in?" and other key software questions. Without Bacon and his team, there would be no way to send computer code to the quantum computer to solve these complex problems.



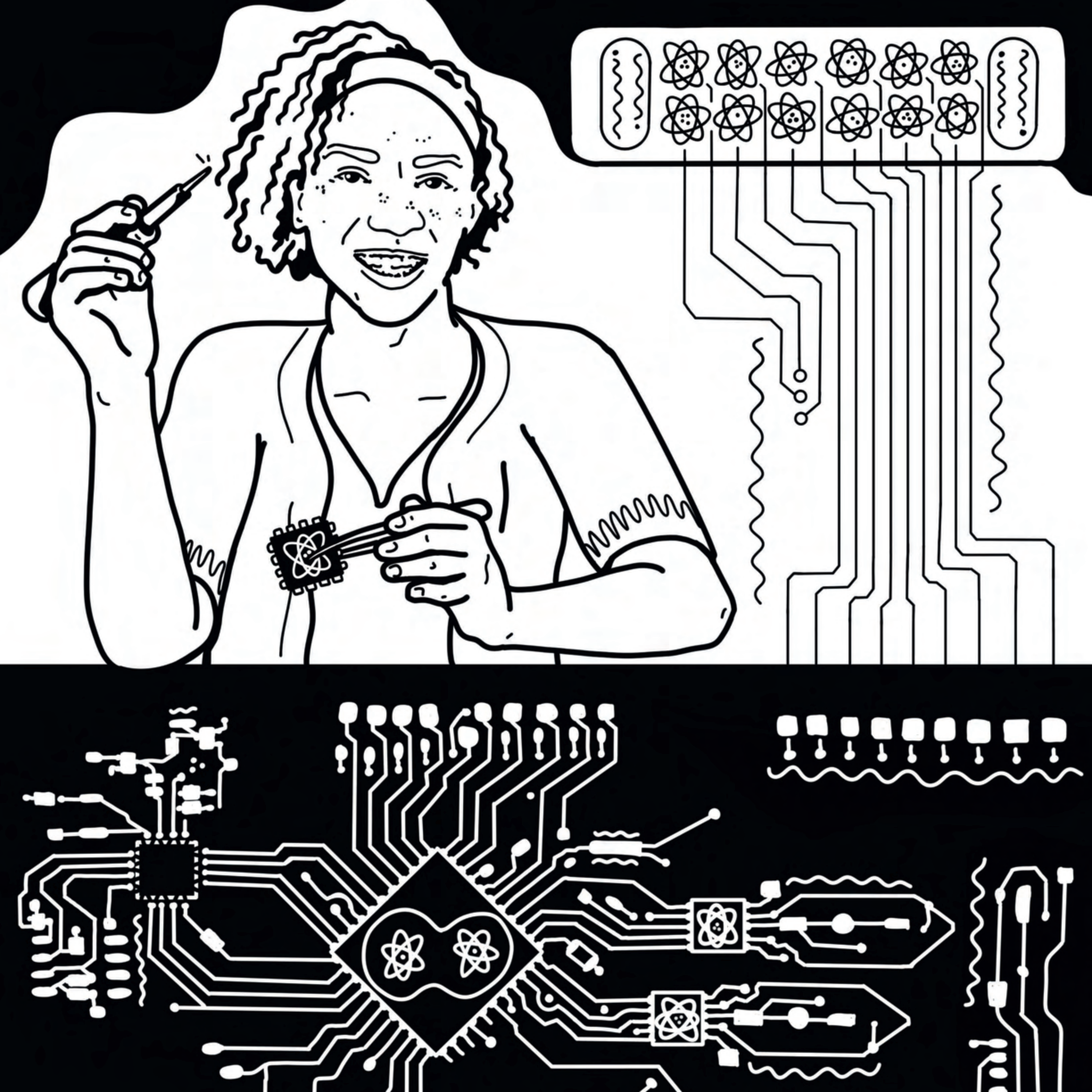
Stephanie Wehrner

Once quantum computers are more readily available, how will they communicate with each other? There will need to be a network between quantum computers, much like a **quantum internet**. Stephanie Wehner leads the Quantum Internet Alliance, a group of researchers around the globe who are starting to build a prototype quantum internet between very basic quantum computers. For Wehner and the Quantum Internet Alliance, an important aspect of the quantum internet will be the ability to access quantum computers anywhere. They envision anyone having access to the powerful computational power of a quantum computer. Additionally, they think your security on the quantum internet is important—what you do on the quantum processor should be hidden from hackers. Lastly, they believe the quantum internet shouldn't be built just for universities or big projects, but for everyone to be able to program and play with.



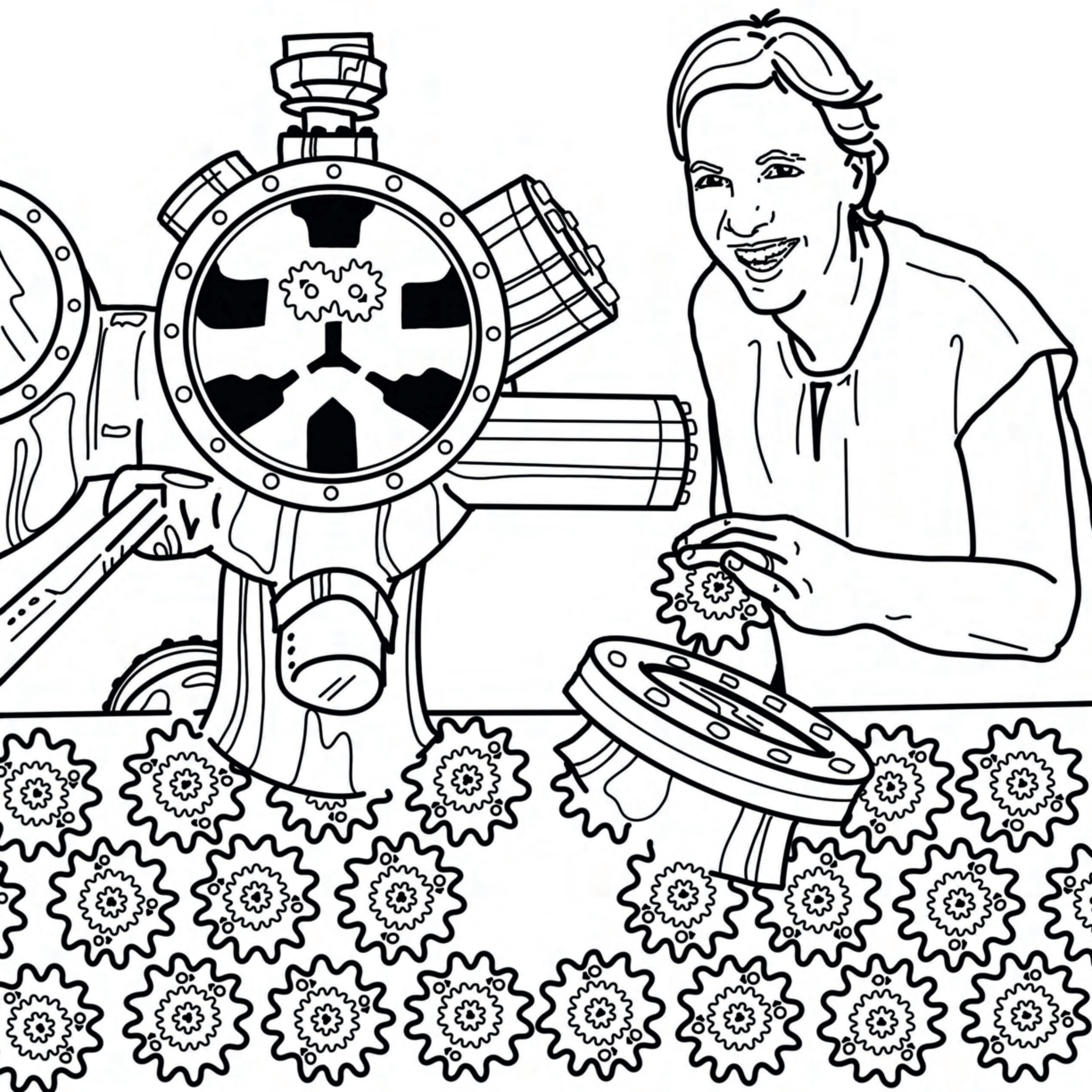
Michaela Amoo

The field of quantum computing needs all hands on deck to work towards building powerful systems. To provide better access to quantum computing resources for traditionally underrepresented students, IBM founded the Historically Black Colleges and Universities (HBCU) Quantum Center in 2020 to create education, research, and career opportunities at more than two dozen HBCUs across the United States. Michaela Amoo, a professor at Howard University and one of the directors of the Quantum Center, provided both guidance for the program and her students. Amoo specialized in designing electronic hardware, specifically control and readout hardware between quantum and classical devices. Amoo also created educational tools to teach students about quantum engineering and **machine learning**—computer systems that learn and adapt based on the data it is given—by using classic games like chess, tic-tac-toe, or mancala. Amoo passed away in 2023, but her contributions to the HBCU Quantum Center and the quantum field have had a lasting impact.



Michelle Simmons

The first computers filled up entire rooms, and today they are small enough to fit in your pocket. How small could you make a computer—could you make a computer out of individual atoms? One Australian scientist is doing just that. Michelle Simmons works towards building atomic-scale devices: **transistors**, conducting wires, and other 3D electronics. She must carefully control individual atoms to perfect the devices down to the atomic scale. This level of precision also allows them to create qubits out of silicon quantum dots. In fact, Simmons was the first to perform a **quantum gate** on two qubits made of silicon. Simmons and her company hope to eventually fit millions of these small qubits into a single device to make a powerful quantum processor.



Nathalie de Leon

How smooth can you make the surface of something? On the atomic scale, what does smooth really mean? While to the eye, a flat surface might look completely organized, the actual atoms themselves might be all mangled at the surface. A smooth and organized surface is important for creating very sensitive nanometer-scale devices in materials, which is called **nanofabrication**. Nathalie de Leon is leading the way in understanding the tangle of atoms at the surface of a material. By making them more ordered and smooth, she can improve quantum properties like coherence times in the materials she makes for use in quantum computing. She and her research group study ways to improve and master nanofabrication for creating superconducting qubit devices and creating solid-state defects in diamond. In fact, de Leon was awarded the American Physical Society Quantum Computing award in 2023 for her work in nanofabrication.

Nia Pollard

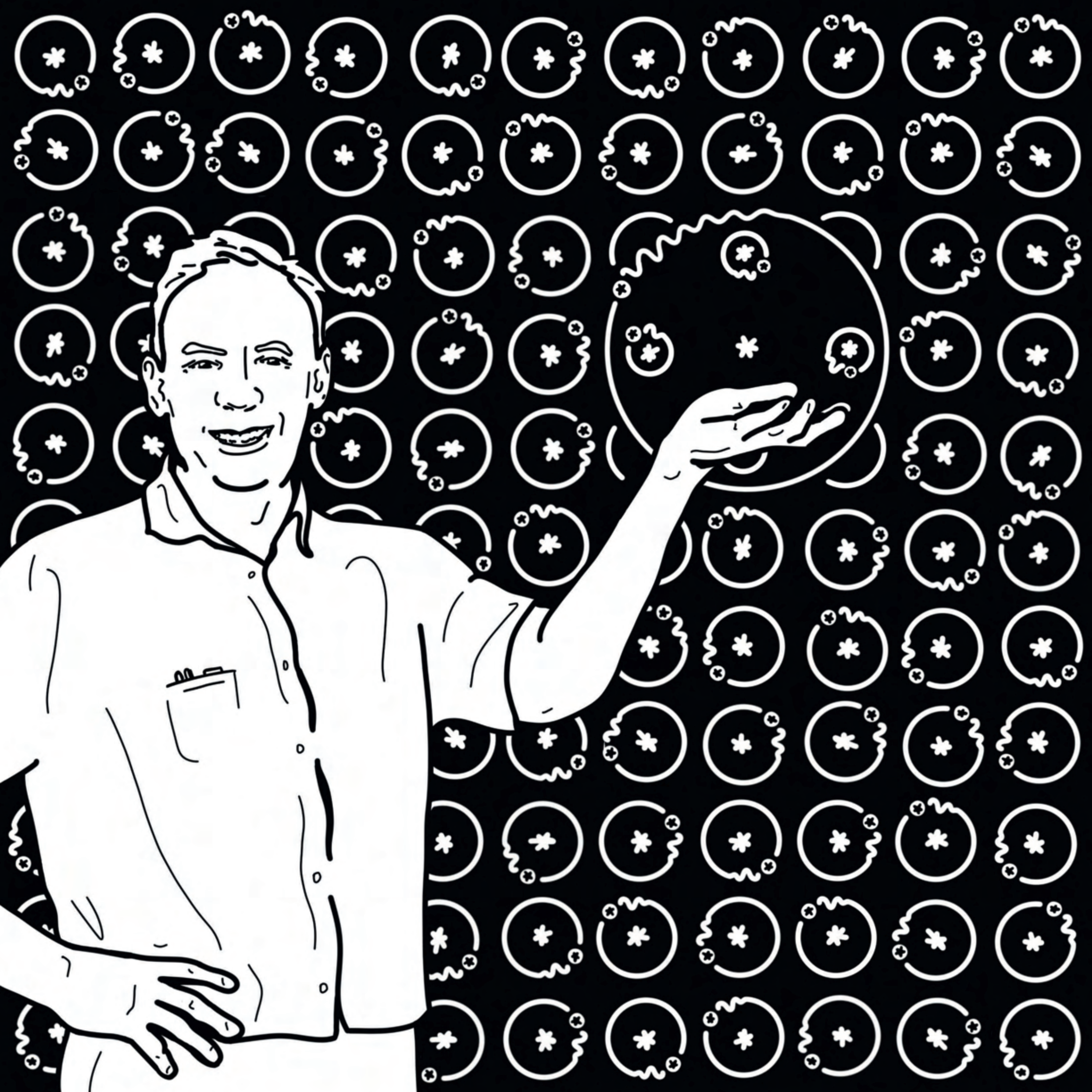
Since quantum computing delves into the realm of particles, it is very closely tied to the field of chemistry. Chemistry studies what **molecules** and substances are made up of, how they react with each other, and how we can create new ones. So, it is natural that scientist Nia Pollard's journey intertwines chemistry and quantum computing. Her work enhances classical computing methods with quantum computing simulations in order to help discover new materials. Some molecules can be really complicated, so by using quantum computing, Pollard can explore many possible ways that atoms can arrange themselves to create new materials much quicker than just by using classical computers. Discovering new materials can push technology to new limits and revolutionize industries. Pollard is showing one of the real-life applications of quantum computing and paving the way for other scientists to combine quantum computing with their work.

Barbara Terhal

Scientists have been able to make qubits since the 1990s. But how many qubits do you need to make a quantum computer? While you could make very simple programs with just a handful of qubits, more useful programs will need hundreds of qubits. However, qubits are super sensitive to their environment and susceptible to decoherence, which can mess up the qubit when information is stored, during computation, or when the final state is measured—all leading to errors in the quantum computation. Normal computer bits can be duplicated to avoid errors, but qubits can't be copied—or else their quantum state is lost. Barbara Terhal is a pioneering theoretical physicist who studies special techniques called **quantum error correction** used to retain qubit information despite errors. These techniques entangle multiple error-prone qubits into one error-protected group. Because one qubit is entangled with multiple others in a web of quantum error correction connections, the answer to "how many qubits are needed to make a computer" will likely be millions!

Mark Saffman

We know from the DiVincenzo criteria that quantum computers need to have many qubits working together, upwards of millions—we call this **scalability**. One major challenge that the field of quantum computing faces today is how exactly to do this. Using neutral atoms for qubits has its advantages because every atom is the exact same and can be put into large arrays, held in place with lasers. Mark Saffman and his team are on a mission to solve the problem of scalability. They have been able to make arrays containing more than 800 neutral atom qubits at the same time, and are working to achieve arrays with thousands of qubits! Saffman collaborates with other quantum physicists around the United States as part of a research institute called Hybrid Quantum Architectures and Networks (HQAN). In a time when universities and companies are racing to find the best type of quantum computer, collaborations like HQAN are critical. These collaborations bring together scientists who test the advantages of all different types of qubits.



Conclusion — Quantum Computing & You

The year 2025 marks 100 years since the birth of the field of quantum science and has been dubbed the “International Year of Quantum Science and Technology.” While large strides have been made to get to this point, the mysteries of quantum science are far from being solved. At this point, while research groups and companies have been able to make small working quantum computers, they are far from mainstream applications. These quantum computers have been made from different qubits, but it's unclear which qubit—superconducting circuits or quantum dots, neutral atoms or trapped ions, photons or topological qubits—will prove best to build scalable quantum computers. Scientists are working their hardest to improve each component needed in the process, from the hardware to the software to the very material the quantum computers are made of. We are still in the early phases of developing the field of quantum computing, but the future is promising and brimming with answers to be answered by powerful quantum computers.

Many of the people featured in this coloring book are PhD scientists, but the field of quantum is fast-growing and needs people at various levels in their educational and professional journey to join the efforts. Recent analysis from Chicago Quantum Exchange shows that many jobs in the quantum industry don’t require graduate degrees. Quantum computing needs people with different skill sets and backgrounds, ranging from technical skills like soldering to engineering skills like part design in drafting software to computer skills like coding. If you have an interest in applying your knowledge and skills to the smallest scale of the universe, quantum computing may just be your calling.

Whether you were drawn to this book because it piqued your curiosity in a new topic or it helped you find your future career path, we hope that you walk away having discovered something new.

Glossary

Binary Code - A bit only represents one of two options: 0 or 1. By stringing multiple bits together, more information can be represented based on all the combinations of the values of the bits: two bits can give four different combinations, three bits lead to eight, four bits lead to 16, and so on. Using strings of bits to represent information is called binary code. *See page*: *18*

Bit - The smallest possible unit of information for computing. A bit is either on or off, and all computers are built from individual bits. *See pages*: *10, 14, 18, 22, 56*

Circuit - A connection of electrical components. *See page*: *26*

Classical Computer - A machine that runs programs automatically and uses bits to store information. All computers in the 20th and the beginning of the 21st century, like gaming computers, laptops, and smartphones, are all classical computers. *See pages*: *10, 18-22, 26, 44, 48, 54*

Coherence - When a quantum object has quantum-ness. Often, if a quantum object is disrupted, it loses its coherence. See Decoherence. *See pages*: *16, 24, 52, 56*

Collapse - When a quantum object is put into a superposition of two values, it is both values at once. However, once the value is measured, the value collapses into one or the other. *See pages*: *14, 18*

Controlled-Not Gate - A special program/rule that can be applied to two qubits, where one qubit controls the state of the other qubit. Specifically, when the first qubit is "on", the second qubit's value is swapped. See Quantum Gates. *See page*: *42*

Decoherence - When a quantum system loses its quantum-ness, like superposition or entanglement. *See pages*: *16, 56*

Dilution Refrigerator - Scientific equipment that cools its inside to as cold as 0.002 Kelvin (-459°F or -273°C) using liquid helium. They usually take up most of a room. *See page*: *26*

Encryption - A way to ensure that a message sent to someone is only seen by that person by translating the message into a secret code. The encoded message might be seen by someone else, but only the other person knows how to decode it. *See pages*: *10, 20, 46*

Entanglement - Two quantum objects can be specially linked so that the behavior of one is tied to the other. The entangled objects are so connected that their behavior cannot be described without one another, even if they are moved miles apart. *See pages*: *12-14, 18, 28, 34, 42, 56*

Error Correction - A method to protect quantum information stored in a qubit from being disrupted by noise. The information from the qubit is shared among multiple entangled qubits. *See page*: *26*

Interfere, or Interference - Waves, like those on the surface of water, can interact, or interfere, with each other when they meet at the same place. Interference is the ability for waves in the same medium to add or subtract their amplitude when they meet. *See page*: *34*

Ion - An atom that has electrons added or removed. An ion has a different number of electrons and protons, meaning it has a non-zero electric charge. *See pages*: *30, 42*

Logic - Computers use bits as the basis of all their programs, and logic is the set of rules that perform calculations on these bits. Computer logic is similar to how arithmetic operations, like addition or multiplication, are a set of rules for math calculations, but it performs operations on bits. *See pages*: *22, 42*

Machine Learning - A subfield of artificial intelligence that develops algorithms that train off of a dataset and then can be applied to new data, so it can perform tasks and analysis without explicit instructions. Machine learning is used in various places, like speech-to-text programs or fraud detection. *See page*: *48*

Molecule - A group of two or more atoms held together by chemical bonds. *See page*: *54*

Momentum - A moving object with mass has momentum - the faster or more massive the object, the more momentum. Even subatomic particles have momentum. *See pages*: *12, 16*

Nanofabrication - Methods in nanotechnology to engineer and create structures on the nanometer scale. *See page*: *52*

Neutral Atom - When atoms have the same number of protons and electrons, they are neutral in charge. These atoms can be optically trapped in laser beams and do not interact with each other, which allows many of them to be contained together. The properties of the electrons of the atom are used as the qubit. *See pages*: *28, 58*

Oscillate - Repetitive motion about a central position, like with a swinging pendulum or water waves. *See page*: *34*

Photon - A bundle of electromagnetic energy that makes up all light, from ultraviolet to visible light to radio waves. *See page*: *34*

Polarization - A property of a wave that describes which direction the wave moves, such as up and down or right and left. For example, when plucking a taut string, the direction that it's plucked determines its polarization. *See page*: *34*

Position - An important characteristic of a subatomic particle is where it is, like where an electron is in its orbit around the nucleus. *See pages*: *12-16*

Probability, or Probable - How likely an event will occur. Probability can range from 0% (very unlikely to occur) to 100% (very likely to occur). *See page*: *18*

Quantum Advantage - Quantum computers can solve certain problems much faster than classical computers. Quantum advantage, or "the beyond classical experiment", is the achievement of a quantum computer solving a problem that a classical computer could not solve within any feasible amount of time. The term "quantum supremacy" was initially used to describe these achievements, but has been replaced because of negative connotations with the word "supremacy". *See page*: *44*

Quantum Dot - A semiconductor material that contains a nanometer structure that traps an individual electron. They have a lot of uses in biology, nanotechnology, and quantum computing. *See pages*: *32, 50*

Quantum Gate - Similar to operations in math, like addition, multiplication, or square roots, quantum gates are operations performed with two qubits. *See pages*: *10, 24, 42, 50*

Quantum Internet - A network between physically separated quantum computers, with the idea that other personal devices will be able to connect and use the capabilities of the quantum computers. *See pages*: *40, 46*

Quantum Repeater - To transmit digital information over long distances of cables, the signal will become weaker with longer distances. Repeaters are a way to copy the digital information and boost its signal. For quantum computers, qubit information cannot be copied, so quantum repeaters use entanglement to extend the range of quantum signals. *See page*: *36*

Quantum Simulation - A special use case of quantum computers that allows individual quantum objects to be manipulated or arranged into a simulation of some natural phenomenon, such as arranging atoms into special configurations to observe how they interact. *See pages*: *8, 54*

Quantum State - In quantum mechanics, "state" refers to the characteristics and values of a quantum object. For example, an electron can be in an excited state, with more energy, or a ground state, with less energy. *See pages*: *14-18, 22-24, 42, 56*

Qubit - Analogous to classical computing, qubits are the smallest possible unit of quantum information for quantum computing. A qubit can be on or off, but importantly, it can be both on and off at the same time. *See pages*: *10, 14-18, 22-34, 38-44, 50-52, 56-60*

Scalability - The challenge of increasing and controlling the number of qubits, likely millions, in a quantum computer **required** to solve complex problems. *See page*: *58*

Solid State Defect - Solid state materials are those in a rigid form -- a solid. A crystal is a solid state material where the individual things making it up (atoms or molecules) are arranged in a very organized structure on the microscopic scale. Defects often occur in these crystal structures, where one of the atoms or molecules is missing, replaced, or misplaced. *See pages*: *36, 52*

Spin - In quantum mechanics, spin is a characteristic of quantum particles, just like how a particle has mass or an electric charge. Spin can be thought of as how fast the particle is spinning—like a top. Surprisingly, the value of the spin of quantum particles can only be specific values! *See pages*: *12, 16, 28-30*

Superconducting Qubit - A qubit that is identified from certain properties of a superconducting circuit. One example of a property used is the charge, or specifically, the number of electron pairs in a section of the circuit. *See pages*: *11, 20, 24*

Superconductor - A special material, when cold enough, that has absolutely no electrical resistance — it is a "super" conductor. The electrons in a superconductor can flow without any obstacles, meaning an electric current in a loop of superconducting wire can flow forever with no power source. Usually, these materials have to be below 100 Kelvin (-280°F or -173°C) to achieve superconductivity. *See pages*: *26, 44, 52*

Superposition - The measurement of a quantum object can only be one of its multiple states, say state 1 or 0. However, before it is measured, the quantum object can be in a superposition of states. For example, it could be a 50/50 superposition of both 0 and 1, and the probability of the measurement will be completely random. *See pages*: *14, 22*

Topology - The mathematical study of how geometric shapes keep certain properties when they are stretched, twisted, crumpled, or bent, without closing holes, opening holes, tearing, gluing, or passing through itself. The study of topology has numerous applications in physics, computer science, robotics, and biology. *See page*: *38*

Transistor - A small device made out of semiconductor material that has three electronic ports: a voltage or current is applied to one of the ports, which controls the current between the other two ports. Because of their versatility and microscopic size, they are one of the building blocks of modern computers. *See pages*: *22, 50*

Trapped Ion - By using controllable magnetic fields, ions can be trapped in place or moved across small distances. The ions can be isolated from each other or brought near each other so controlled interactions can occur between them. *See pages*: *30, 42*

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