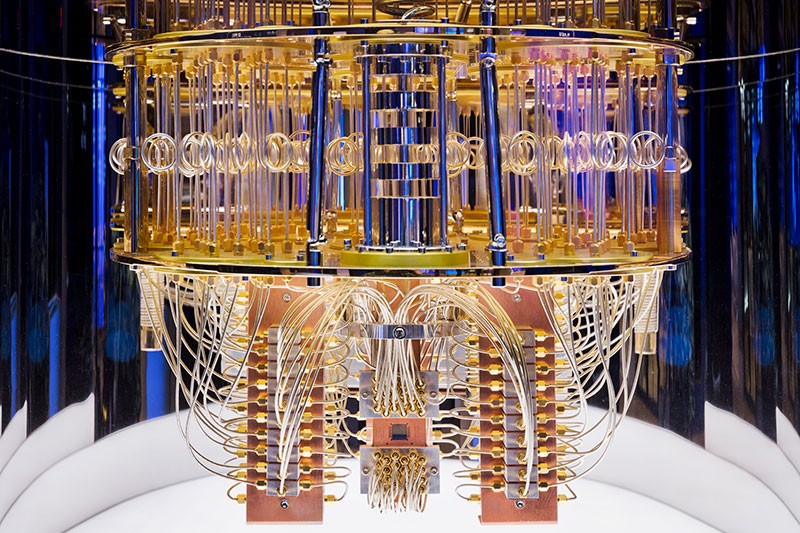
**Quantum Computing**



*Figure 1: Showing the inside of IBM’s 127 Quantum bit (qubit) computer.*

*Photo Provided by: IBM, 2021*

**James Norbert Kroll**

**Computer Science & Information Systems**

**Senior Capstone Seminar**

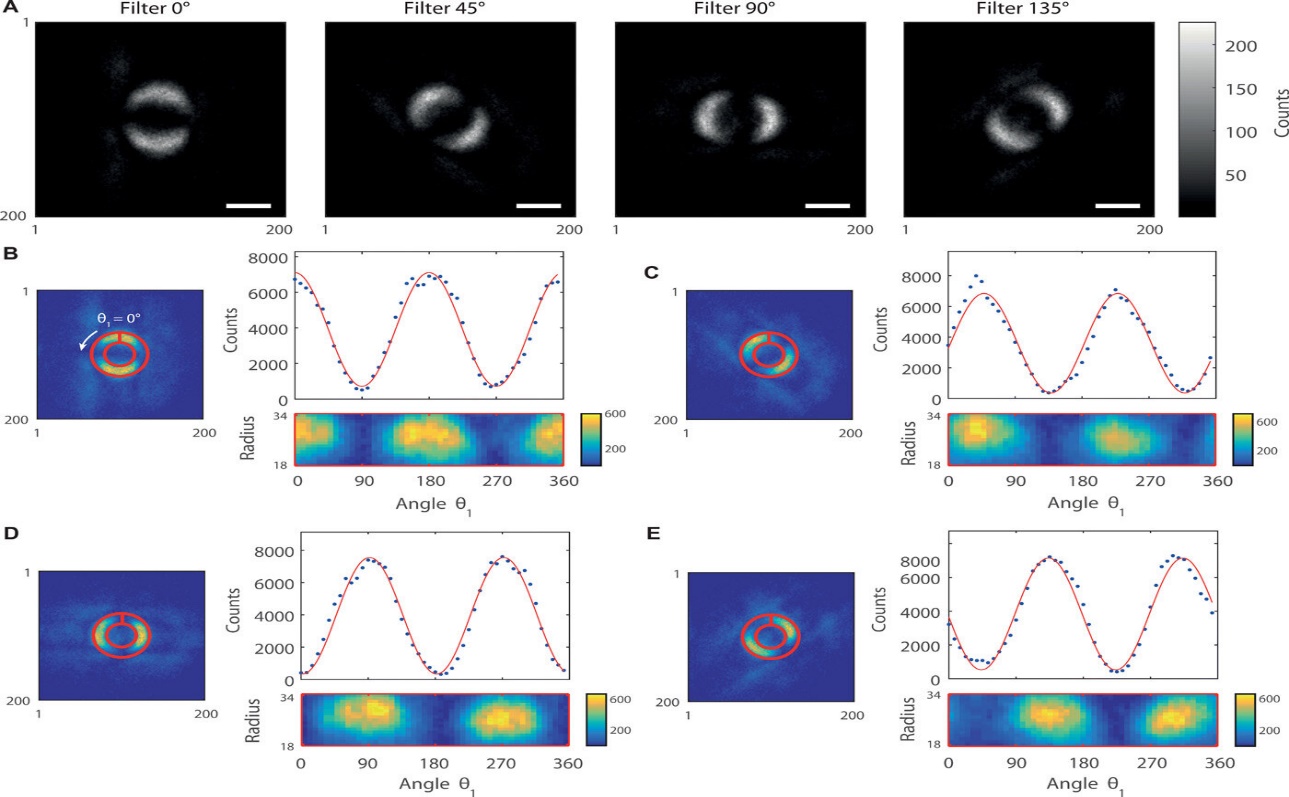
**Spring 2022**

**Introduction**

Quantum computing is a fascinating area of scientific research that has captured the minds of thousands of brilliant researchers around the world for decades. In this paper I will be diving into the history of quantum computing, the origins of some of the terminology, along with some of the bigger discoveries that have helped progress the field through its early hurdles. I will discuss the important scientists that have made those possible. I will be taking a deeper look into the modern hardware required to run a quantum computer and discussing which organizations currently have operational quantum technology. With that I will present the current options that consumers have for accessing this technology, as some companies such as IBM offer cloud access to their quantum resources. I will be discussing the many countries throughout the world that have signed their own versions of a quantum initiative, funneling millions and sometimes even billions of dollars into governmental and private sector research groups. We will discuss the *first world quantum powers,* which is the core group of countries at the fore front of quantum breakthroughs. After which, we will be discussing which research groups have discovered breakthroughs in the field, and finally I will be discussing what difficulties research currently faces, and I will discover what challenges lie ahead hindering certain advances in the field. I will wrap up with a discussion on the benefits of quantum computing vs supercomputing vs classical computing and a discussion on the advantages quantum computing could bring to different industries, and what this means for the future of humans and our understanding of the different phenomenon that exist in our world.

**Definitions**

Quantum Computing is a method of computing that requires extremely specialized hardware, and a specific set of requirements to operate in its current state. When exploring what quantum computing is you come across a lot of unfamiliar terms that understanding the definition of is quintessential to the understanding of quantum computing. According to Merriam-Webster, a **quantum computer** is defined as: “*a computer that takes advantage of the quantum properties of qubits to perform certain types of calculation extremely quickly compared to conventional computers”. (Quantum computer, 05-07-2022).* To fully understand this definition, **qubit** must also be defined: “*a unit of computing information that is represented by a state of an atom or elementary particle (such as the spin) and can store multiple values at once due to the principles of quantum mechanics”. (Qubit, 2022).* To allow us proper understanding of this definition, we must also define **quantum** **mechanics**: *“a theory of matter that is based on the concept of the possession of wave properties by elementary particles, that affords a mathematical interpretation of the structure and interactions of matter on the basis of these properties, and that incorporates within it quantum theory and the uncertainty principle” (Quantum mechanics, 2022).* This definition provides us with a couple of new terms requiring definition, **quantum** **theory**: *“a theory in physics based on the concept of the subdivision of radiant energy into finite quanta and applied to numerous processes involving transference or transformation of energy in an atomic or molecular scale” (Quantum theory, 2022),* and the **uncertainty** **principle**: *“a principle in quantum mechanics: it is impossible to discern simultaneously and with high accuracy both the position and the momentum of a particle (such as an electron)” (Uncertainty principle, 2022).*  A final important definition is for **quantum** **entanglement**, “a property of a set of subatomic particles whereby a quantum characteristic (such as spin or momentum) of one particle is directly and immediately correlated with the equivalent characteristic of the others regardless of separation in space”. (Quantum entanglement, 2022). The scientific community was provided with photographic proof of quantum entanglement for the first time from the University of Glasgow. In the article they published on phys.org they state, “They devised a system which fires a stream of entangled photons from a quantum source of light at 'non-conventional objects' – displayed on liquid-crystals materials which change the phase of the photons as they pass through.” (University of Glasgow, 2019). For capturing it, “They set up a super-sensitive camera capable of detecting single photons which would only take an image when it caught sight of both one photon and its entangled 'twin', creating a visible record of the entanglement of the photons.” (University of Glasgow, 2019).



*Figure 2: depicting the quantum entanglement captured by the University of Glasgow, 2019.*

*Photo Provided by: University of Glasgow, 2019*

**Historically Notable Research**

There are many influential mathematicians and physicists throughout the 20th century that helped propel research in quantum computing. We will be focusing on the most influential of them beginning with the earliest mention of quantum in our language and move through the decades until we get to the modern age of quantum research. In 1900 Max Planck introduced the scientific community to the word quantum which he derived from its Latin meaning “minimum amount of a quantity which can exist;” (*Definition and Etymology of Quantum*, n.d.). Planck developed quantum theory in a study he published observing the effect of radiation on a substance he called “blackbody”. Planck is considered the father of modern Quantum Mechanics. In 1905 “*Albert Einstein explains the photoelectric effect—shining light on certain materials can function to release electrons from the material—and suggests that light itself consists of individual quantum particles or photons.”* (Gil Press, 2021), further reinforcing Planck’s definition, allowing it to gain traction in the scientific community. In the 1920’s a group of German physicists consisting of Max Born, Werner Heisenberg and Wolfgang Pauli coined the term “quantum mechanics”, and in 1924, Born was the first to publish a study using the term quantum mechanics. The following year, Heisenberg and Born, along with theoretical physicist Pascual Jordan, formulate matrix mechanics. Over the next few years, Niels Bohr alongside Heisenberg, developed the Copenhagen Interpretation and Heisenberg’s uncertainty Principle. The Copenhagen Interpretation is still commonly taught today. In 1927 John Von Neuman, who is known for his mathematical advances, published his own contribution to quantum mechanics in a framework for quantum statistics, according to Leon Van Hove, a Belgian physicists that went on to be General Director at CERN (1976-1980), states, *“The statistical matrix (now often called p-matrix although von Neumann's notation was U) has become one of the major tools of quantum statistics and it is through this contribution that von Neumann's name became familiar to even the least mathematically minded physicists.”* (van Hove, 1958). In 1930, Paul Dirac publishes the first textbook on quantum mechanics, “The Principles of Quantum Mechanics”, which is still used today for referencing. In 1935, after discussing quantum superposition with Einstein, Erwin Schrödinger developed his famous thought experiment, Schrödinger’s cat, in which the cat is both dead and alive. Through this experiment Schrödinger was able to theorize quantum entanglement. in 1947, while being studied by Einstein, he described the phenomenon in a letter to Max Born as “spooky action at a distance”. Through this description Einstein dismisses quantum entanglement, which is later to be refuted by countless experiments and discoveries in the scientific community for decades to come.

Nearly thirty years later we find ourselves talking about Roman Ingarden, a Polish Physicist, affiliated with Nicolaus Copernicus University in Toruń, Poland, published what’s considered the first attempt at creating and defining quantum theory in 1976. Ingarden may not achieved the popularly accepted quantum theory, but our next scientist who proposed his own Quantum theory in the 80’s did. Paul Benioff gave quantum computing its first influential figure that helped propel the field for research. and he is regarded today as one of the greatest influences in the field. Born in 1930, Benioff obtained his Ph.D. from the University of California at Berkeley, and in 1961 started his research with the Argonne National Laboratory. Benioff along with others helped lay the groundworks for the future of Quantum Computing research. During the 1970’s and 80’s Benioff’s research focus was Quantum Information Theory demonstrating the theoretical possibility of quantum computers. With his first influential publication in May 1980 “*The computer as a physical system: A microscopic quantum mechanical Hamiltonian model of computers as represented by Turing machines”*, Benioff demonstrates how a computer could operate within quantum mechanics, using a Schrödinger equation description of Turing machines. He continued to publish research at Argonne through 2020. Benioff passed away March 29th, 2022.Another important figure to help propel the field is Richard P. Feynman. At a keynote speech in 1981, Feynman theorized how physics could properly be simulated using a quantum computer. He first argued how it is impossible to properly simulate physics on a classical computer, being that physics in nature, relies on the properties of quantum mechanics, and a classical computer is not capable of simulate quantum mechanics. Feynman states, *“nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical.”* (Feynman, 1981). The next physicist is a founding member of the Centre for Quantum Computation at the Clarendon Laboratory and has been awarded the Dirac Prize alongside Charles Bennet & Peter Shor which will be discussed later, David Deutsch of the University of Oxford. Deutsch was also awarded the Micius Quantum Prize 2018 and most recently the Isaac Newton prize in 2021. When he was elected Fellow of the Royal Society in 2008, they stated, “*David Deutsch laid the foundations of the quantum theory of computation, and has subsequently made or participated in many of the most important advances in the field, including the discovery of the first quantum algorithms, the theory of quantum logic gates and quantum computational networks, the first quantum error-correction scheme, and several fundamental quantum universality results. He has set the agenda for worldwide research efforts in this new, interdisciplinary field, made progress in understanding its philosophical implications (via a variant of the many-universes interpretation) and made it comprehensible to the general public, notably in his book The Fabric of Reality.”* (David Deutsch, 2022). In 1985 Deutsch formulates and publishes a description for a quantum Turing machine, and in 1992 The Deutsch-Joza algorithm is possibly the earliest example of a quantum algorithm that is exponentially faster than anything able to run on a classical computer.

The next decade brought another wave of notable advances in quantum research and in 1993, Charles Bennet alongside a team of colleagues, published in American Physical Society, an article titles “*Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels”.* As the title suggests it delves into the possibility of how quantum teleportation would work described using mathematical models. The following year continued to deliver in two ways. First, when Peter Shor of Bell Laboratories developed a quantum algorithm for factoring integers that possessed the capabilities to decrypt RSA-encrypted communications. At the time RSA was widely used for secure data transmission, as it was considered impenetrable. Secondly, The National Institute of Standards and Technology organizes a quantum computing conference sponsored by the US government, signaling a shift in our government’s confidence toward quantum research. In 1996, the quantum database search algorithm, also known as Grover’s algorithm, is published. Lov Grover worked at Bell laboratories during this time and his algorithm is still taught today.

in 1998 a team of researchers at MIT published “*Experimental Quantum Error Correction”.* The report states, “*We describe the implementation of a quantum error-correcting code which compensates for small phase errors due to fluctuations in the local magnetic field*.” (Cory, 1998). This technique is used as a compliment to quantum computing to assist in stabilizing the magnetic fields. The study failed to produce strong evidence of success and cited a weak polarization as the most limiting factor. 1998 had a greater discovery in quantum and that came from a team comprised of Isaac Chuang (Los Alamos National Laboratory), Neil Gershenfeld (MIT) and Mark Kubinec (University of California at Berkeley). They created the first 2-qubit quantum computer that was able to do input and output. Although the experiment only lasted for nanoseconds, it demonstrated the principles of quantum computing on a physical device. To accomplish this feat, “they *dissolved a large number of chloroform molecules (CHCL3) in water at room temperature and applied a magnetic field to orient the spins of the carbon and hydrogen nuclei in the chloroform. (Because ordinary carbon has no magnetic spin, their solution used an isotope, carbon-13.) A spin parallel to the external magnetic field could then be interpreted as a 1 and an antiparallel spin as 0,* *and the hydrogen nuclei and carbon-13 nuclei could be treated collectively as a 2-qubit system”* (*Quantum Computer | Description & Facts*, 2022). 1999 continued to innovate through Yasunobu Nakamura, a Japanese physicist and professor at the University of Tokyo and principal researcher within RIKEN’s quantum research group. That year, Nakamura demonstrates that qubits can also be made on superconducting circuits through the application of what He describes as a “sharp voltage pulse to the pulse gate” (Nakamura et al., 1999), Nakamura was able to demonstrate the ability to control energy levels and to manipulate the quantum state in a single-pair-cooper box, which is a “*small metallic island which is connected to a reservoir via a tunnel junction. In the superconducting state, Cooper-pairs are free to tunnel to and from the island, whose potential can be controlled by a gate voltage, Vg*” (Bladh et al., 2005). When the voltage is applied the charge qubit takes on the characteristics of ~1 or 0.

This leads us to our final major achievement by the community of researchers working towards bringing quantum computing to life. In 2002, we have a team of scientists comprised of members from some of the most advanced quantum research teams in our country, that create the first draft of a Quantum Roadmap. This was a living roadmap that had annual updates based on the discoveries from research over the past year. It was last modified in 2009. This would be a precursor to a lot of countries signing their own versions of quantum initiatives, which are still in place today as the race for quantum supremacy becomes more achievable. Next, I will discuss the hardware and environmental requirements needed to run a modern quantum computer and provide some examples of quantum computers currently in operation today.

**Hardware Requirements**

When talking about the specific requirements for operating a modern quantum computer, it is important to understand that the quantum components work cooperatively with and communicate between classical digital computers. Figure 3 below will help illustrate the interactions present.

Diagram

Description automatically generated

*Figure 3: Depicts the interaction between quantum computing components and classical computers.*

*Photo Provided by:* (Hajjar, 2022); source cited by author: IEEE Explore journal article

There are a few components present in quantum computers, that may sound relatable to components found in classical computing, but function differently. The main component to discuss is Qubits, as opposed to bits used by classical computers which can be set to a 1 or a 0, a qubit is the basic unit of quantum computing and can hold both 0 and 1 state simultaneously creating a probability amplitude. This occurs due to superposition. To expand on this, a string of 4 classical bits can be used in a string, allowing it to represent any singular value 0-15. The same size string of 4 qubits could represent every value 0-15 simultaneously.Diagram

Description automatically generated

*Figure 4: Depicts the difference between a digital bit (left) and a qubit (right).*

*Photo Provided by:* (Research Gate, 2022); source cited by author: IEEE Explore journal article

To achieve this state in qubits, researchers use multiple approaches:

**Photonics** defined as “*a branch of physics that deals with the properties and applications of photons especially as a medium for transmitting information” (Photonics, 2022).* Photons have weak interactions with the environment around them allowing for a natural isolation property to occur. allowing them to be great candidates for data transmission. Their weak interaction allows for them to accurately represent qubits while operating at room temperature. An advantage of the photon approach “*is that photonic quantum computers can be integrated into existing fiber optic-based telecommunications infrastructure. However, one of the challenges that face photonic quantum computing is the limitations in fault tolerance and error correction.” (Hajjar, 2022a).* A few companies researching this approach include Amazon Quantum Solutions Lab, Xanadu, Orca Computing and PsiQuantum.

**Trapped Ions** is a process where *“scientists start with a steel vacuum chamber, housing electrodes on a chip that is chilled to nearly 450 degrees below zero Fahrenheit.” (A Trapped-Ion Pair May Help Scale up Quantum Computers, 2020).* Once chilled, using multiple lasers, you chip electrons away from the atoms, ionizing them. Electrodes and then used to generate an electric field and capture the ions. That is the general method used by most companies experimenting with trapped ion qubits, which include IonQ and Honeywell.

**Semiconducting material** is a process that simulates electrons in materials such as germanium, diamonds, selenium, or silicon carbide. Through “*Applying microwaves and magnetic fields to these materials will allow them to exhibit superposition, entanglement, and other quantum properties.” (Hajjar, 2022a).* Companies researching this method include Google, IBM, and Intel.

**Superconducting material** is a process using “*microwave and low-frequency electrical signals, both of which are communicated through wires that run into cooling refrigerators to reach the qubits inside the controlled environment.” (Hajjar, 2022a)*. Intel is the only company to have announces research in this area with the release of their 49-qubit superconducting chip labeled ‘Tangle Lake’ in 2018.

**Quantum register** is a designated set of qubits, the simultaneously holds all the possible combinations of input data. Quantum algorithms are sent to an n-qubit register and result in the register outputting all combinations of [0,1] states.

**Quantum reversible gate** is a gate that allows for the input to be manipulated by looking at the output. A classical logic gate allows for reversal when using the NOT inverter gate. “*It is necessary for quantum gates to be reversible because quantum mechanics is reversible and quantum operations are unitary. Unitary operations are such that their inverses are also their conjugates” (Hajjar, 2022).*

**Quantum Processing Unit** is the component that relies on quantum mechanics to function. The quantum processing unit is comprised of multiple parts. The Quantum RAM is comprised of the quantum register + logic gates. The Quantum control unit is what drives the system and operates on quantum mechanics to achieve a desired state.

**Quantum Interface** is the hardware & software required for a user, on a classical computer, to communicate instructions to the quantum components. A close-up of a computer chip

Description automatically generated with low confidence

*Figure 5: Depicts Google & D-Wave’s quantum processor.*

*Photo Provided by:* (*Quantum Processor*, n.d.)

**Benefits of Quantum Computing**

If you are wondering why the race for quantum supremacy is so important among the superpowers in the world, then consider what might happen if one of those powers were to achieve supremacy. It would allow them to hack all the infrastructure in any country they choose. Doing this would allow the country to gain access to important research from their competitors, providing a much-needed edge in the global climate. This country would be able to set the stage for the future of cyberwar. That is the scary side of a single entity gaining supremacy. On the flip side, research in a lot of areas gets shared readily to help accelerate advancements in that field. If one country were to obtain supremacy, it is assured that others would soon follow in their advancements and retaining their edge would become a constant commitment to advancing the field, which is beneficial to human society.

Now why is quantum computing so necessary for us to solve? To answer this, I will be comparing it against supercomputing and classical computing. Classical computing is the standard laptop, desktop, phone, or tablet that consumers have access to daily. Classical computers for most of us will be the only one on the list we ever deal with. Supercomputers have been around since 1964 and have been used in enterprises since their creation. The advantage they serve over classical computing is their ability to simulate models and perform statistical analysis at speeds not possible on classical computers. Supercomputers are in use heavily by the government and large technology corporations. The modern supercomputer is currently reaching the boundaries of what a digital computer can accomplish. Quantum computers run on quantum algorithms and to accelerate digital computations, specifically those with an enormous number of possible outcomes. With a digital computer. the computational speed increases at a rate of 1:1 as you advance the hardware. Using quantum algorithms allows the quantum computers to increase their computational speed exponentially as you increase the number of qubits in the machine. This exponential increase is where quantum computing gains its edge, allowing it to compute all the permutations in a few minutes, what would take a supercomputer multiple days to achieve, performing at optimal capacity. Below are two charts (fig. 3 & fig. 4) showing some of the key differences between quantum computers, supercomputers, and classical computers.

Diagram

Description automatically generated Graphical user interface, application

Description automatically generated

*Figure 6: Chart depicting the differences between supercomputers and quantum computers.*

*Photo Provided by: Supercomputing vs Quantum Computing, 2021)*

*Figure 7: depicting the benefits and challenges of quantum computers vs classical (digital) computers.*

*Photo Provided by:(Quantum Computing vs Digital Computing, 2021*

Once quantum computing is truly achieved researchers in every field will benefit. It will help in researching the origins of the universe, how to replicate the fusion power of a star, how to stop human impact on climate change, drug and vaccine development and AI consciousness. With quantum entanglement comes the ability revolutionize our communication. Quantum entanglement could in theory, break the laws of physics and instantaneously transfer data over large distances, given enough relays, reducing latency to 0. Quantum computing will be a gamechanger in information security, according to Ali El Kaafarani, a Forbes council member and CEO of PQShield cybersecurity firm, “*quantum computers will have the power to break through the public-key encryption widely relied upon today to protect information, meaning that data, no matter how secure it may be right now, could be vulnerable to future attack.”* (Kaafarani, 2022). As scary as that prospect may be, the benefit to breaking through that next barrier is enormous for network protections. It also requires hackers to become smarter with their approaches, reducing the overall size of that community, reducing the number of attacks on everyday citizens.

**Challenges**

In a similar way that scientists have viewed nuclear fusion for decades as “30 years away”, the same could be said for quantum computing. Even though efforts to reach quantum computing in the last decade have broken though a lot of the hurdles, there is still a lot more that needs to be discovered before we can label something a true quantum computer. Modern quantum technology allows us to perform computations that a classical or even supercomputer cannot compute, but scientists are still far away from being able to harness the true powers of a quantum computer. One of the biggest challenges is recreating perfect isolation to produce consistent results in the lab. The research discoveries have been amazing in taking strides towards our quantum future however, those results are so hard to produce that get consistent results running the same experiment is still a major hinderance. Both heat and light can cause decoherence in a quantum environment which means that the slightest difference in the isolation environment could trigger drastically different results. Signal control is another variable that is hard to consistently control. Signal control is what causes the qubit to rotate through the logic gate. This step is prone to a lot of error in the current conditions. Quantum error correction is put in place to try and alleviate some of the inconsistencies, but it still requires a lot of improvements to help stabilize the experiments.

“*It has been found that there is a kind of universal computer that can do anything, and it doesn't make much difference specifically how it's designed. The same way we should try to find out what kinds of quantum mechanical systems are mutually intersimulatable, and try to find a specific class, or a character of that class which will simulate everything. What, in other words, is the universal quantum simulator*?”. (Feynman, 1981) This sentiment has helped spark the decades long debate over what exactly makes a computer quantum. When talking about the difficulties that exist in advancing Quantum Computing as a field, a common sentiment is summed up In Benioff’s 1980 article, where he concludes “Such machines would have the advantage that there is no energy dissipation and resultant heat buildup, which are problems in the large computers. On the other hand, the model Hamiltonians constructed here are very complex. As a result, it is difficult to conceive how one would actually build such a machine.” (Benioff, 1980) Four decade later and this remains one the most persistent problems in Quantum Computing, as the definition of what is required for a computer to be considered Quantum is still being debated today, making the next steps forward seeming that much more insurmountable. A lot of the modern researchers mimic the same sentiments, when I was trying to research how many qubits is required to be considered a good quantum computer, the best answer I found came from a professor at Michigan answering a Quora post from 4 years ago. Near the end of his response, he states “*Two papers published in Nature in November 2017 describe systems with 51 and 53 qubits that were used to simulate other quantum systems of interest. That is the closest we have to quantum computers today, but those systems are very specialized. An important difference between a lab device and a computer is reliability — something that happens once in ten attempts may be a good result in applied physics, but not a great result in computer engineering.”* (Markov 2018). This is a problem that never goes away and knowing it would help make our perception of where we are in the field more realistic. I read a lot of articles on the new discoveries coming out in this field, and I believe the media always makes it sound as if we are close to having the technology close at hand, when we are just making baby steps each with each new discovery. In 2021 we had the first 100-bit Quantum Computer built surpassing another hurdle in the progress. IBM is trying to achieve 4000 qubits within the next 3 years. This is a bold claim for an extremely large task but with small milestones along the way quantum computing will make it there.

**Quantum Initiative**

The push for a quantum future has become the focal point in some cases for billions of dollars of government funded research. Now that we have progressed from baby steps into what’s considered the “toddler” phase of quantum research, governments are not only believing in the potential the technology has to offer, but they are providing the much needing funding to help achieve goals that could otherwise take a much longer time to accomplish. When discussing the countries involved there are a few, that have gone above and beyond with the funds they provide, allowing them to become competitive as the global quantum leader. I will be referring to these countries as first world quantum powers.

To begin, there is more than 20 countries that have passed legislation to help fund quantum computing research. Small or large, taking that first step towards a quantum future is an important one that governments do not make lightly. I will be detailing the first world quantum powers, while including some of the lesser players. The start of that list is United States of America. Beginning in 2017 and being signed into law in 2018, the National Quantum Initiative came into existence. As stated in section 101, “*This bill directs the President to implement a National Quantum Initiative Program to, among other things, establish the goals and priorities for a 10-year plan to accelerate the development of quantum information science and technology applications.”* (*H.R.6227 - 115th Congress (2017–2018): National Quantum Initiative Act*, 2018). The bill allocates $1.2 billion to quantum research over the course of 5 years. The most recent article published by U.S. congress subcommittee assigned to QIST, they are asking for a push towards quantum sensors, to be used with GPS for navigation, MRI for magnetic sensing and radiation detectors as some examples.

The next big player and largest competitor is China, and, in many ways, they have been seen as the underdog who is constantly catching up in the quantum computing space. It has been made a key priority in China’s 14th 5-year plan, and being mostly controlled by the government, the research is moving at record pace. in 2017 China invested $10 billion into the creation of a national laboratory which later created the Jiuzhang prototype quantum computer. In December 2020, a team from Hefei university “*had established the world’s first integrated quantum communication network, combining over 700 optical fibers on the ground with two ground-to-satellite links to achieve “quantum key distribution over a total distance of 4,600 kilometers.”* (Yi-An Chang, 2021).

Europe will be discussed together, as a lot of their research is collaborative. In the next four years, Germany will add $2.4 billion to assist in the advancements of its first home-built quantum computer, giving them a total investment of $3.1 billion. They currently have infrastructure from IBM and partnerships with NASA among others. These have helped keep them in the race and led to their decision to establish themselves as a quantum superpower. France has signed legislation that announces a 5-year, $2.2 billion investment towards creating their own quantum future. The U.K. has legislation in place worth $1.3 billion in funding over the coming years. The European union has also dedicated $1.1 billion to research into quantum computing.

India has earned its spot as a player at the table after launching their QSim toolkit (Quantum computer simulator toolkit) in 2020. With just over $1 billion invested by the government, India is starting to build their own quantum infrastructure, allowing them to stay competitive in the global race. India has stated that they do not create enough parts internally, forcing them to lag in research while investing in the required hardware to bootstrap their own production. Canada, being the first country to bring enterprise solutions in the quantum computing space through their company D-Wave, has invested nearly $1 billion to date. They have remained a top player in the quantum space and continue to increase their investment into quantum computing research.

Some of the smaller investors in Quantum Computing include. Russia has invested over $700 million and in 2021 created their first 4-qubit quantum computer taking them one step closer to becoming a major competitor. Japan has upped their investment to nearly $500 million and is becoming another major player in the quantum space. They have partnered with IBM and Tokyo Universities research team allowing them to make strides in being a major competitor. Israel who has funded $350 million managed to create their first 5-qubit quantum computer in March 2022, this will help secure further investment into their quantum future. Taiwan, which has invested over $250 million is currently in the process of building their own quantum infrastructure. Construction is planned to be done in 2024, allowing them to become a major competitor. Netherlands which is home to the centre of quantum technology and computing in Delft and Qtech, remain a top player in the EU’s quantum efforts. As a county, Netherlands has invested $175 million toward quantum research. Austria, investing $125 million so far, had an announcement in February 2022 that quantum cybersecurity firm ID Qauntique will be locating its center of competence in Austria. (Quantique Sa, 2022). Singapore, just breaking $100 million announced in February 2022 a plan to develop a quantum network that will demonstrate “crypto-agile-connectivity”, Australia nearing $100 million has a vision for quantum technologies that will create thousands of jobs and support the adoption of quantum technologies in their commercial space (Industry, 2022). Korea, who has invested less than $50 million is mostly working towards quantum cryptography in their commercial companies, and New Zealand how has invested less than $40 million but has plans to increase funding through 2029 assisting in the research at Dodd-Walls centre for Photonic and Quantum Technologies. (New Zealand, 2021).

As you can see, there are plenty of players beginning to create their own infrastructure, with others starting to gauge an interest in how important the technology may be for them allowing them to decide whether it is worth joining the quantum race for supremacy.

**Modern Research**

In 2014*“Physicists at the Kavli Institute of Nanoscience at the Delft University of Technology, The Netherlands, teleport information between two quantum bits separated by about 10 feet with zero percent error rate”.* (Gil Press, 2021). This is the first instance of documented quantum entanglement working with a 0% error rate. It only made it 10 feet but that 10 feet was a massive leap in quantum entanglement research. Since then, China reports successful transmission of single photon qubits from an observatory on earth, to a satellite in low earth orbit.

In 2018 CERN’s openlab joined forces with IBM’s quantum network. CERN’s experiments using the Large Hadron Collider produce 1 petabyte of data per second of operation. In order to analyze this data requires “*almost 1 million classical CPU cores in 170 locations across the world” (IBM, n.d.).* IBM has consolidated this duty into a fleet of 23 quantum computers. With CERN’s successor in production and knowing how much larger it will be, the amount of data that it will produce will be astronomical and they will need a fleet of Quantum ready devices to analyze it.

In 2019 Google releases the first 100+ qubit quantum computer, claiming 127 qubits of processing power. Previously, most quantum computers only had dozens of qubits, breaking 100 was a milestone. Other companies have claimed to possess those processes prior, but scrutiny from the community places the milestone with Google. That same computer in 2021 created what is being called a time crystal. A time crystal is defined as cycling between states without consuming energy. This research was conducted using Google’s 127-bit quantum computer and was conducted by a team from google, Stanford, Princeton, and other universities. This concept of a quantized time crystal was theorized by Frank Wilczek, professor at MIT, in 2012. Time crystals have since been created by other research groups, including in February 2022, a team at QuTech, corresponding with Berkeley, and Element Six states “*We set out to build a discrete time crystal using one of our quantum processors based on spins in diamond,”* (Flikweert, 2022). The team used 9 quantum bits and manipulated them until they satisfied the theoretical requirements for a time crystal.

Possibly the most influential advancement for quantum networking to date, came in March 2021, when the world’s first multi-node quantum network turned on. The research team at QuTech, out of the Netherlands, designed a 3-node quantum network that brings us one step closer to the quantum internet. Quantum networks are expected to unlock computations across networks that were previously unachievable using classical computers. Matteo Pompili, a member of QuTech’s research team states “*It will allow us to connect quantum computers for more computing power, create unhackable networks and connect atomic clocks and telescopes together with unprecedented levels of coordination,*” (Turner, 2021).

In January 2022, a partnership between ColdQuanta and Classiq was announced, which would harness the full power of ColdQuanta’s Hilbert Quantum Computer, using Classiq’s 100 quantum algorithm design platform. The platform will allow you to develop complex quantum circuits starting from a “*high-level functional model of the circuit and then automatically synthesizing and optimizing a working quantum circuit from it.”* (HPCwire, 2022).

In February 2022, a team consisting of IonQ members and a plethora of collegiate research groups, created a new quantum logic gate based on trapped ion qubits via spin-dependent squeezing. “*The central idea behind trapped ion quantum gates is the coupling between spins and motion (phonons) through spin-dependent forces … their motion around equilibrium can be expressed by collective normal modes of harmonic oscillation.” (Katz, 2022).* This is a technique that can only be used on the IonQ Quantum systems, according to the study.

In March 2022, NASA announced a partnership with the German Aerospace Center (DLR) to “*develop open source software for quantum computers to solve real-world aerospace applications.”* (*StackPath*, n.d.). The DLR has an established quantum research group that started in 2015 and NASA has its Quantum Artificial Intelligence Laboratory (QuAIL). NASA and DLR have been conducting join research on quantum since 2016, but the announcement solidifies the strong cooperation between the two organizations moving forward, with the hope of producing state of the art open-source quantum software that can expediate research for everyone.

**Commercialization**

In 2011 D-Wave made history by becoming the first company to offer its product commercially. Purchased by a company in Maryland for $10 million, the systems operate due to a process called quantum annealing. *Quantum annealing is the process of using optimization in terms of minimalizing required energy input. At the end of the quantum annealing process, the qubit collapses into a 0 or a 1.* (D-Wave, 2020).

IBM offers quantum cloud resources available for enterprise use along with commercializing their IBM Quantum System One, which has a userbase of over 400k users. They have 20 systems installed between their Poughkeepsie and Yorktown locations, along with having on site quantum computers installed in both Fraunhofer, Germany & Tokyo, Japan, with plans for installations in Quebec, Canada, Yonsei, Korea, and Cleveland, Ohio. According to their website their userbase has run over 1 trillion circuits on their quantum network. (*IBM Quantum Computing | Systems Technology*, n.d.).

Microsoft’s Azure Quantum is a collaborative initiative that started in 2019 to allow companies access to a wide range of quantum technologies. ON the Azure main page, it lists the providers midway down the page. The list contains available systems provided by: Quantinuum, IonQ, Quantum Circuits inc., Rigetti Quantum, Pasqal, 1Qbit, Microsoft, and Toshiba. It offers a range of quantum processors running on multiple frameworks such as, Trapped Ion, Superconducting, Neutral Atom, Optimization. They started offering the service to clients in 2021 and are continuing to grow the available services along with their available user base.

Google offers Quantum AI services to approved research groups across the world, for use with simulating experiments. They also offer an open-source software, Cirq. Cirq is used for “*building and experimenting with noisy intermediate scale quantum (NISQ) algorithms on near-term quantum processors.”* (Google, n.d.) They provide the user with tutorials offering up sample problems and experiments that help the user learn the fundamentals of Cirq.

**Final Thoughts**

Now that I have presented you with an overview of the history of quantum computing and its current climate, both commercial and research, I hope you too see the advantages the technology has to offer. Quantum computing will change the way we look at the world and the universe beyond it with the potential of simulating the origins of existence. It has amazing potential in medical research, providing more in-depth testing than currently possible and being able to simulate drugs and vaccines at a much greater speed than currently available. Imagine another corona type pandemic happening and instead of takings months or years to develop the vaccine, it would take only days. Quantum simulations have the potential to replace laboratory experiments altogether. Additionally, I believe that quantum simulations could help in solving the current global climate crisis, it could help end the debate that stalls so much progress, in doing so, it may save humanity. We must not forget the dangers that are also presented with new technology, as the first country to claim quantum supremacy may have a chance at global supremacy. The last couple of years have made me extremely hopeful that we will see this technology in full use within my lifetime and because of this I hope to acquire a job in this field before ending my career.

***References***

1. *A huge leap: Israeli researchers build country’s first quantum computer*. (2022, March 22). Israeli Quantum Leap. Retrieved May 15, 2022, from <https://www.timesofisrael.com/a-huge-leap-israeli-researchers-build-countrys-first-quantum-computer/>
2. *A trapped-ion pair may help scale up quantum computers. (2020, January 28). MIT News | Massachusetts Institute of Technology. Retrieved May 12, 2022, from* [*https://news.mit.edu/2020/trapped-ion-pair-may-help-scale-quantum-computers-0128*](https://news.mit.edu/2020/trapped-ion-pair-may-help-scale-quantum-computers-0128)
3. *Azure Quantum - Quantum Service*. (n.d.). Microsoft Azure. Retrieved May 15, 2022, from <https://azure.microsoft.com/en-in/services/quantum/>
4. B. (2022, April 1). *The qubit in quantum computing - Azure Quantum*. Microsoft Docs. Retrieved March 15, 2022, from <https://docs.microsoft.com/en-us/azure/quantum/concepts-the-qubit>
5. *Benioff, P. (1980). The computer as a physical system: A microscopic quantum mechanical Hamiltonian model of computers as represented by Turing machines. Journal of Statistical Physics, 22(5), 563–591.* [*https://doi.org/10.1007/bf01011339*](https://doi.org/10.1007/bf01011339)
6. *Benioff, P. (1998). Quantum robots and environments. Physical Review A, 58(2), 893–904.* [*https://arxiv.org/pdf/quant-ph/9802067*](https://arxiv.org/pdf/quant-ph/9802067)
7. *Bennett, C. H., Brassard, G., Crépeau, C., Jozsa, R., Peres, A., & Wootters, W. K. (1993). Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels. Physical Review Letters, 70(13), 1895–1899.* [*https://doi.org/10.1103/physrevlett.70.1895*](https://doi.org/10.1103/physrevlett.70.1895)
8. *Bub, J. (2006, May 29). Quantum computation from a quantum logical perspective. arXiv.Org. Retrieved December 4, 2022, from* [*https://arxiv.org/abs/quant-ph/0605243v2*](https://arxiv.org/abs/quant-ph/0605243v2)
9. *Choi, C. Q. (2016, June 27). Quantum Computer Could Simulate Beginnings of the Universe. Livescience.Com. Retrieved May 13, 2022, from* [*https://www.livescience.com/55196-quantum-computers-simulate-beginning-of-universe.html*](https://www.livescience.com/55196-quantum-computers-simulate-beginning-of-universe.html)
10. *Classical bit vs qubit. (n.d.). [Illustration].* [*https://www.researchgate.net/*](https://www.researchgate.net/)
11. *Cory, D. G. (1998, February 6). Experimental Quantum Error Correction. arXiv.Org.* [*https://arxiv.org/abs/quant-ph/9802018*](https://arxiv.org/abs/quant-ph/9802018)
12. *David Deutsch. (2022). David Deutsch. Retrieved April 12, 2022, from* [*https://www.daviddeutsch.org.uk/about-me/*](https://www.daviddeutsch.org.uk/about-me/)
13. *Definition and etymology of quantum. (n.d.). Etymonline. Retrieved April 10, 2022, from* [*https://www.etymonline.com/word/quantum*](https://www.etymonline.com/word/quantum)
14. *D-Wave System Documentation. What is Quantum Annealing?. documentation. (September, 2020). D-Wave Systems. Retrieved May 13, 2022, from* [*https://docs.dwavesys.com/docs/latest/c\_gs\_2.html*](https://docs.dwavesys.com/docs/latest/c_gs_2.html)
15. *Feynman, R. (1981) Simulating Physics with Computers. International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 467-488.* [*https://web.archive.org/web/20190108115138/https:/people.eecs.berkeley.edu/~christos/classics/Feynman.pdf*](https://web.archive.org/web/20190108115138/https:/people.eecs.berkeley.edu/~christos/classics/Feynman.pdf)
16. *Flikweert, R. (2022, February 28). creates a time crystal. QuTech. Retrieved May 15, 2022, from* [*https://qutech.nl/2021/11/04/qutech-creates-a-time-crystal/*](https://qutech.nl/2021/11/04/qutech-creates-a-time-crystal/)
17. *Gil Press. (2021, May 18). 27 Milestones In The History Of Quantum Computing. Forbes.* [*https://www.forbes.com/sites/gilpress/2021/05/18/27-milestones-in-the-history-of-quantum-computing/?sh=397a986c7b23*](https://www.forbes.com/sites/gilpress/2021/05/18/27-milestones-in-the-history-of-quantum-computing/?sh=397a986c7b23)
18. *Google |*. (n.d.). Google Quantum AI. Retrieved May 15, 2022, from <https://quantumai.google/software>
19. *Google’s time crystal. (2021, December 17). Eternal Change for No Energy: A Time Crystal Finally Made Real. Quanta Magazine. Retrieved May 15, 2022, from* [*https://www.quantamagazine.org/first-time-crystal-built-using-googles-quantum-computer-20210730/*](https://www.quantamagazine.org/first-time-crystal-built-using-googles-quantum-computer-20210730/)
20. GreyB, T. (2022, April 6). *Top 10 Quantum Computing Companies in 2022*. GreyB. Retrieved April 15, 2022, from <https://www.greyb.com/quantum-computing-companies/>
21. *Hagar, Amit, & Cuffaro, Michael. (2019). Quantum Computing. The Stanford Encyclopedia of Philosophy, Edward N. Zalta (ed.).* [*https://plato.stanford.edu/archives/win2019/entries/qt-quantcomp/*](https://plato.stanford.edu/archives/win2019/entries/qt-quantcomp/)
22. *Hajjar, A. J. (2022, March 25). Quantum Hardware Components, Interfaces & Challenges [2022]. AIMultiple. Retrieved May 14, 2022, from* [*https://research.aimultiple.com/quantum-computing-hardware/*](https://research.aimultiple.com/quantum-computing-hardware/)
23. *Home*. (2022, March 29). Institute for Quantum Computing. Retrieved May 15, 2022, from <https://uwaterloo.ca/institute-for-quantum-computing/>
24. HPCwire. (2022, January 25). *New Quantum Computing Partnership Makes 100-Qubit Algorithms a Reality*. Retrieved May 5, 2022, from <https://www.hpcwire.com/off-the-wire/new-quantum-computing-partnership-makes-100-qubit-algorithms-a-reality/>
25. *H.R.6227 - 115th Congress (2017–2018): National Quantum Initiative Act. (2018, December 21). Congress.Gov | Library of Congress. Retrieved October 5, 2022, from* [*https://www.congress.gov/bill/115th-congress/house-bill/6227*](https://www.congress.gov/bill/115th-congress/house-bill/6227)
26. IBM. (n.d.). *The quest to understand what sews the universe together*. IBM. Retrieved April 15, 2022, from <https://www.ibm.com/case-studies/cern/>
27. *IBM Quantum Computing | Systems Technology*. (n.d.). IBM System One. Retrieved March 15, 2022, from <https://www.ibm.com/quantum-computing/systems>
28. Industry, D. S. O. (2022, April 7). *Australia’s vision for quantum* [Video]. YouTube. <https://www.youtube.com/watch?v=8chx9Enq2po&feature=youtu.be>
29. *Kaafarani, A. E. (2022, April 14). Four Ways Quantum Computing Could Change The World. Forbes. Retrieved May 13, 2022, from* [*https://www.forbes.com/sites/forbestechcouncil/2021/07/30/four-ways-quantum-computing-could-change-the-world/?sh=13de09024602*](https://www.forbes.com/sites/forbestechcouncil/2021/07/30/four-ways-quantum-computing-could-change-the-world/?sh=13de09024602)
30. Katz, O. (2022, February 9). *$N$-body interactions between trapped ion qubits via. . .* arXiv.Org. Retrieved May 15, 2022, from <https://arxiv.org/abs/2202.04230>
31. *Markov, I. M. EECS Professor at Michigan. (2018). How many qubits does the current state-of-the-art quantum computer have? [Comment on the article “User Question”]. Quora.* [*https://www.quora.com/How-many-qubits-does-the-current-state-of-the-art-quantum-computer-have*](https://www.quora.com/How-many-qubits-does-the-current-state-of-the-art-quantum-computer-have)
32. *Maunz, Peter, & Wilhelm, Lukas (2017, April 1st). Trapped Ion Qubits. United States.* [*https://doi.org/10.2172/1365489*](https://doi.org/10.2172/1365489)
33. *MIT Quanta. (n.d.). MIT Quanta Group. Retrieved May 15, 2022, from* [*http://web.mit.edu/%7Ecua/www/quanta/*](http://web.mit.edu/%7Ecua/www/quanta/)
34. *Nakamura, Y., Pashkin, Y. A., & Tsai, J. S. (1999). Coherent control of macroscopic quantum states in a single-Cooper-pair box. Nature, 398(6730), 786–788.* [*https://doi.org/10.1038/19718*](https://doi.org/10.1038/19718)
35. *New Zealand Takes a Step into the Second Quantum Revolution*. (2021, July 19). OpenGov Asia. Retrieved May 15, 2022, from <https://opengovasia.com/new-zealand-takes-a-step-into-the-second-quantum-revolution/>
36. *photonics. (2022). The Merriam-Webster.Com Dictionary. Retrieved May 13, 2022, from* [*https://www.merriam-webster.com/dictionary/photonics*](https://www.merriam-webster.com/dictionary/photonics)
37. *Quantiki. (n.d.). Qauntiki. Retrieved May 13, 2022, from* [*https://www.quantiki.org/wiki/main-page*](https://www.quantiki.org/wiki/main-page)
38. Quantique Sa, I. D. (2022, February 11). *ID Quantique sets up a Center of Competence in Quantum Communications in Austria to support Europe’s leadership in quantum technologies*. Austia Quantum. Retrieved May 14, 2022, from <https://www.prnewswire.com/news-releases/id-quantique-sets-up-a-center-of-competence-in-quantum-communications-in-austria-to-support-europes-leadership-in-quantum-technologies-301475883.html>
39. *Quantum computation: a tutorial*. (n.d.). Quantum Tutorial. Retrieved October 3, 2022, from <https://www-users.cs.york.ac.uk/schmuel/comp/comp.html>
40. *quantum computer | Description & Facts. (2022). Encyclopedia Britannica.* [*https://www.britannica.com/technology/quantum-computer*](https://www.britannica.com/technology/quantum-computer)
41. *Quantum computer. In* Merriam-Webster.com dictionary*. Retrieved May 7, 2022, from* [*https://www.merriam-webster.com/dictionary/quantum%20computer*](https://www.merriam-webster.com/dictionary/quantum%20computer)
42. *Quantum Computing (Stanford Encyclopedia of Philosophy). (2019, September 30). Stanford Encyclopedia. Retrieved April 5, 2022, from* [*https://plato.stanford.edu/entries/qt-quantcomp/#WhatQuanQuanComp*](https://plato.stanford.edu/entries/qt-quantcomp/#WhatQuanQuanComp)
43. *Quantum computing vs digital computing. (2021, February). [Comparison Chart].* [*https://www.cbinsights.com/research/quantum-computing-classical-computing-comparison-infographic/*](https://www.cbinsights.com/research/quantum-computing-classical-computing-comparison-infographic/)
44. *Quantum entanglement. In* Merriam-Webster.com dictionary*. Retrieved May 8, 2022, from* [*https://www.merriam-webster.com/dictionary/quantum%20entanglemen*](https://www.merriam-webster.com/dictionary/quantum%20entanglemen)*t*
45. *Quantum mechanics. In* Merriam-Webster.com dictionary*. Retrieved April 10, 2022, from* [*https://www.merriam-webster.com/dictionary/quantum%20mechanics*](https://www.merriam-webster.com/dictionary/quantum%20mechanics)
46. *Quantum processor. (n.d.). [Photograph].* [*http://www.nas.nasa.gov/quantum/quantumcomp.html*](http://www.nas.nasa.gov/quantum/quantumcomp.html)
47. *Quantum theory. In* Merriam-Webster.com dictionary*. Retrieved April 10, 2022, from* [*https://www.merriam-webster.com/dictionary/quantum%20theory*](https://www.merriam-webster.com/dictionary/quantum%20theory)
48. *Qubit. In* Merriam-Webster.com dictionary*. Retrieved April 10, 2022, from* [*https://www.merriam-webster.com/dictionary/qubit*](https://www.merriam-webster.com/dictionary/qubit)
49. *StackPath*. (n.d.). NASA + DLR. Retrieved May 15, 2022, from <https://www.militaryaerospace.com/commercial-aerospace/article/14235119/nasa-dlr-quantum-computing>
50. *Subcommittee on quantum information science, Committee on science of the National Science and Technology Council. (2022, March). Bringing Quantum Sensors To Fruition.* [*https://www.quantum.gov/wp-content/uploads/2022/03/BringingQuantumSensorstoFruition.pdf*](https://www.quantum.gov/wp-content/uploads/2022/03/BringingQuantumSensorstoFruition.pdf)
51. *Supercomputing vs quantum computing. (2021). [Comparison Chart].* [*http://www.differencebetween.net/technology/difference-between-supercomputing-and-quantum-computing/*](http://www.differencebetween.net/technology/difference-between-supercomputing-and-quantum-computing/)
52. Swayne, M. (2020, November 17). *ColdQuanta to Preview its Cold Atom Quantum Computer Technology*. The Quantum Insider. Retrieved February 10, 2022, from <https://thequantuminsider.com/2020/11/17/coldquanta-to-preview-its-cold-atom-quantum-computer-technology/>
53. *Tacchino, F. (2019, July 8). Quantum computers as universal quantum simulators: state-of-art. . . arXiv.Org. Retrieved October 4, 2022, from* [*https://arxiv.org/abs/1907.03505*](https://arxiv.org/abs/1907.03505)
54. *Top governments budget for quantum computing*. (2022). Global Quantum Spending. Retrieved April 12, 2022, from <https://www.analyticsinsight.net/top-governments-budget-for-quantum-computing-in-2022/>
55. Turner, B. (2021, May 3). *World’s 1st multinode quantum network is a breakthrough for the quantum internet*. Livescience.Com. Retrieved March 21, 2022, from <https://www.livescience.com/three-node-quantum-network.html>
56. *Uncertainty principle. In* Merriam-Webster.com dictionary*. Retrieved April 10, 2022, from* [*https://www.merriam-webster.com/dictionary/uncertainty%20principle*](https://www.merriam-webster.com/dictionary/uncertainty%20principle)
57. *University of Glasgow. (2019, July 13). Scientists unveil the first-ever image of quantum entanglement. Phys.Org. Retrieved April 12, 2022, from* [*https://phys.org/news/2019-07-scientists-unveil-first-ever-image-quantum.html*](https://phys.org/news/2019-07-scientists-unveil-first-ever-image-quantum.html)
58. *van Hove, L. (1958). Von Neumann’s contributions to quantum theory. Bulletin of the American Mathematical Society, 64(3), 95–99.* [*https://doi.org/10.1090/s0002-9904-1958-10206-2*](https://doi.org/10.1090/s0002-9904-1958-10206-2)
59. *VCQ Quantum*. (2022, May 10). VCQ. Retrieved May 15, 2022, from <https://vcq.quantum.at/>
60. Yi-An Chang, B. (2021, May 26). *Quantum Wars*. CKGSB. Retrieved April 15, 2022, from <https://english.ckgsb.edu.cn/knowledges/quantum-wars/>