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Navigating Quantum Realities: A Comprehensive Analysis of Quantum Computers, Providers, and Qiskit Compatibility Challenges and Opportunities

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Declaration

I hereby certify that the material, which I now submit for assessment on the programmes of study leading to the award of Master of Science, is entirely my own work and has not been taken from the work of others except to the extent that such work has been cited and acknowledged within the text of my own work. No portion of the work contained in this thesis has been submitted in support of an application for another degree or qualification to this or any other institution.

Weverton de Souza Castanho
12 December 2023

Acknowledgements

I remember that on cold mornings in southern Brazil, I used to wake up very early on weekends to watch episodes of Carl Sagan's Cosmos. I still keep the letters from Carl's wife, Ann Druyan. Science has always occupied a significant space in my childhood. I recall my uncle telling me that one day I would be a doctor, and I am still pursuing my PhD; I believe this goal has always been within me, and I cannot deny it.

Returning to the significant people in my life, beyond my parents, someone who greatly influences my life and holds special meaning is my wife, Andrea. We met when she needed help with her computer to finish her doctoral thesis. During my master's degree, I had the chance to meet very special and important professors who guided me in the pursuit of knowledge, especially Mary Hendrick, who was always tireless and ready to help in any way needed, and Professor David White, an incredible person I had the chance to meet.

A special thanks to Professor Gary Clynch, who believed in the project of testing something new like quantum computers. It was easy to sell him this idea, and he bought into the concept of quantum computing, which was amazing and motivating. The journey to running the first program was long, but the first complete run was exhilarating. I believe scientists share the same excitement when they discover something significant. Although quantum computers are now available from various providers, it is not easy to set up the first application, understand how quantum effects work, and how to work with them.

Finally, I would like to express immense gratitude to the esteemed professors Dr. Alberto Tufaile and Dr. Adriana P. Tufaile for dedicating their precious time to clarify details about quantum physics and quantum computing. The discussion about simulating quantum photosynthesis originated in a conversation with them. Currently, they are professors at the University of São Paulo and have a brilliant contribution to the field of Optical Physics.

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Abstract

One of the major pillars of current technological development is silicon-based processors. Numerous publications discuss the production of 2-nanometer chips, referring to the size of transistors within the chips. For many years, there has been talk about the protective barrier around Taiwan, an island currently contested by China, which was part of agreements the U.S. made with China, recognizing the island as Chinese. Approaching a potential nuclear conflict, the heightened interests of both the West and the East in this small island revolve around chip technology. This technology has been developed for many years by companies with the support of the local government. All initiatives in economic, technical, and scientific development hinge on these chips, providing increasing processing performance and enabling reduced processing time and quicker decision-making.

The advancement of Artificial Intelligence technology is demanding ever-increasing processing volumes, and consequently, greater performance from current chips. However, according to Moore's Law, where processors double in performance every 18 months, there is a gradual decrease in the size of transistors. We are a few years away from reaching molecular sizes, where nanotechnology could produce transistors with only 3 atoms. Yet, at this size, quantum laws prevail. Many researchers are facing challenges in maintaining the stability of transistor behavior at this scale. When reaching molecular sizes, we will be at the maximum limit of chip construction.

On the other hand, quantum computers offer processing capabilities by leveraging quantum effects and have the potential to significantly increase the number of qubits, enabling continuous and limitless growth for the coming years. Therefore, it presents a significant opportunity for humanity to continue advancing economically, technologically, and scientifically. Although much has been said about quantum computers, they are not yet widely used in the industry, as they are not machines ready for every application today. We are only at the beginning of the development, production, and application of these quantum computers. While research is progressing and the development of new algorithms and applications is expanding possibilities for the use of these computers, the reality is that we cannot

use them for all applications, and many current applications are related to the use of available algorithms.

Keywords: Quantum Computing, QisKit, Excitons, Photosynthesis , Diamond NV, Bitcoin, Energy Consumption, DWave, QisKit, Artificial Inteligence, Godel's Incompletude..

1 Introduction

The present study aimed to analyze the degree of availability, capacity, and compatibility of quantum infrastructure service providers and types of quantum computers when running a compatible application. The goal was to assess the maturity level of the available services and infrastructure. Since quantum computers represent a promise for the present and future, it is crucial to examine their compatibility and determine the best development framework that can run on various quantum computers, preserving the investment applied in code. Initially, Qiskit, a Python-based framework developed by IBM with open-source code(QISKIT,2023), was chosen. It is compatible with all tested providers and has been confirmed by the service providers themselves as being compatible.

Initially, the project focused on initial tests on the AWS (Amazon Web Services) platform, a cloud service provider that also offers quantum computing, like other providers. AWS provides the same types of computers, such as those from IonQ and Rigetti. Therefore, using servers from AWS, as well as those available on Microsoft Azure, would have the same effects on the tests. Under certain measures, the Microsoft Azure environment proved to be more user-friendly and more available than AWS, which offers these computers through its AWS Braket service. This service, in addition to being an AWS offering, gives its name to a set of libraries that allow access to quantum computers in the AWS environment. It is important to note that AWS Braket is not a programming language but, as mentioned earlier, a service that includes a set of libraries for quantum computing access.(AGARWAL, 2022)

The programming language used was Qiskit, which is the main focus of the thesis. Microsoft has Q Sharp (QSHARP, 2022), a language derived from C Sharp with quantum libraries, but it was not used since the goal was to analyze the interoperability of Qiskit on various quantum computers with different architectures and processors.

The quantum computers used in the tests included models from Microsoft Azure, IonQ, Rigetti, Quantinuum, and finally, a model on the IBM Quantum Platform with 127 qubits and Eagle r3 processor. This machine had the highest number of qubits. It is important to note that the number of qubits limits the tests, as it is not possible to include more qubits than the hardware architecture can provide. A test with 64 qubits was conducted on the IBM quantum computer, which was successful. However, the same test was not possible with 127 qubits due to memory limitations in the Jupyter IDE container.

The tests were intended to include algorithms from Peter Shor and Grover (BHATTACHARYYA, 2021), leveraging the use of the Quantum Fourier Transform (JAFFALI, 2022). The Peter Shor algorithm was not used due to incompatibility with different platforms, requiring changes in the source code to work on all proposed quantum servers. Even after removing the Peter Shor algorithm, the modification process required considerable effort. Another significant change was necessary in Bitcoin-related tests, where intensive memory usage for processing the Shor algorithm in the simulation of blockchain address generation required 11 qubits. In the Quantum Photosynthesis simulation, the number of qubits was reduced to 32, as above this value, applications experienced memory overflow.

For IonQ, it was necessary to limit to 10 qubits due to restrictions on the number of qubits on the server with the highest availability, which was the IonQ QPU with 11 qubits (WRIGHT, 2019). Even so, the server did not remain available, and Jupyter lost connection after hours of waiting to run the application. Even when running the applications in a queue, the results were only dumped into files provided in the Microsoft Azure environment, providing not usable results but rather processing reports.

The Bitcoin simulation tests involved multiple iterations to increase processing complexity and identify potential code compatibility limitations. In each iteration, the same initial quantum circuit was added to the existing one, essentially summing up the circuit "n" times. The goal was to heighten the complexity of the outcome, generating a random address. Although it may seem like a nonsensical process, it introduces something impossible to achieve in a classical computing process. A quantum circuit introduces uncertainty in results, in contrast to a classical computer that adheres to logic. The quantum computer accommodates the quantum uncertainty of nature.

Currently, IBM is heavily involved in the quantum computing market. The largest number of quantum computers available for use is on its platform (PROCESSOR, 2023), offering computers with 10, 32, 63, and 128 qubits in free testing mode, along with a simulator with up to 5000 qubits. IBM provides 10 minutes of quantum processing per month, enabling various tests. Another crucial aspect of IBM's platform is that Qiskit is a language developed by the company. Although versions may encounter issues due to different processor architectures, it remains the most reliable environment to initiate an application in Qiskit, both for quantum simulators and quantum computers.

There were no costs when using the quantum environments of Microsoft Azure and IBM. The only environment that incurred expenses was AWS, where an instance with 16 GBytes of memory was created to test up to 128 qubits (see figure 1). However, the tests were unsuccessful due to the constant unavailability of quantum computers. The instance was created and queued, but there were often timeout issues, and the results recorded in files did not contain the expected data, providing only information about memory usage and quantum processor. AWS was discarded as a quantum service provider.

Another crucial aspect throughout the process is the need for in-depth study of the discipline. The texts often raise more questions than they attempt to answer. Quantum mechanics is a challenging discipline. Looking at a simplified quantum circuit of a Quantum Fourier Transform (QFT) doesn't mean much to someone trying to understand it (JAFFALI, 2022). It's not possible to see an equation in the circuit, but the QFT is there. The quantum paradigm is complex and requires considerable effort to grasp, even when seeking simple results. Much sweat, invested time, and few tangible results. However, quantum computing still holds great promise, and hope persists in the quest for what it can still offer us!

Every journey begins with a first step, whether it be large or small. It is possible to assert that this is a very long, exciting, and inspiring journey. It is not easy to start describing this journey by weaving comments about giants who laid the foundations of our current science. Few theories have had as much impact on our world in such a short time as Max Planck's quantum theory (PLANCK, 2020).

At the end of the 19th century, Lord Kelvin declared the end of science and that we were destined to measure and apply the laws of classical physics (LINDLEY, 2004). However, there were two clouds hovering over scientific progress, and one of these clouds was the black body problem. Max Planck was responsible for developing a new theory called quantum theory. This theory produced, in a short time, Einstein's theory of the photoelectric effect in the annus mirabilis, which, like the theory of quanta, was awarded a Nobel Prize(HENTSCHEL, 2018).

Many other scientific discoveries based on quantum theories, as we call them today, continue to be awarded the Nobel Prize in Physics. Niels Bohr commented in the preface to Planck's autobiography that his theory of quanta produced significant scientific results in less than 30 years(PLANCK, 2014). It is challenging today to imagine our world without this great gift from Max Planck. Our entire scientific and technological foundation is largely grounded in quantum theory, and the future of humanity will pass through this scientific construction in the coming years.

Digital computers are one of the great pillars of our current society. They enable the development and progress of our society through storage, processing, and message exchange among other computers, allowing our world to integrate on various fronts of economic, political, and social action (LUCA, 2021). The advancement of computers has made our society profoundly dependent on them while bringing progress. However, the threats we face due to conflicts between the current hegemonic world and a future multipolar world have generated disturbances in this development horizon due to an island called Taiwan. This island is disputed by China and the U.S. (MIN-HUA, 2023), and even though the U.S. has recognized Taiwan as part of China, political, military, and economic movements demonstrate a future threat to global economies. This is because the world is deeply dependent on chips produced in Taiwan due to its scale production capacity and the high technology incorporated into chip production. In 1979, the U.S. Congress enacted the Taiwan Relations Act (TRA), recognizing the government of the People's Republic of China (mainland China) as the only legitimate government of China (TRA, 1979). This severed formal relations with Taiwan, considering it part of China. Over the years, Taiwan has developed sophisticated technology in chip production through a company called TSMC, which produces the latest generations of processors for the most advanced computers, thanks to its silicon doping technologies on a nanometric scale.

The advancement of Artificial Intelligence technology is demanding ever-increasing processing volumes and consequently more performance from current chips. However, according to Moore's Law, where processors double in performance every 18 months, there is a gradual decrease in the size of transistors (YIN, 2022). We are a few years away from reaching molecular sizes, where nanotechnology could produce transistors at the Angstron scale (JAN, 2002), such as 3-atom transistors. However, at this size, quantum laws prevail. Many researchers are facing challenges in maintaining the stability of transistor behavior at this scale. When reaching molecular sizes, we will be at the maximum limit of chip construction (POPESCU, 2006). On the other hand, quantum computers offer a great processing possibility by leveraging quantum effects and have the potential to significantly increase the number of qubits, enabling continuous and limitless growth in the coming years. Thus, it is a great opportunity for humanity to continue advancing economically, technologically, and scientifically.

Richard Feynman was an excellent drummer who attended samba schools in Brazil and participated in the carnival parades in Rio de Janeiro. This same drummer formulated the Quantum Electro Dynamic (QED) theory (DIRAC, 1043). Although quantum theory was a significant leap in theoretical abstraction, Niels Bohr remarked that Feynman and other theoretical scientists like him were out of control (FEYNMAN, 2006). As Feynman once said, if you say you understand quantum theory, you didn't understand anything!(VAIANO, 2023)

Feynman was one of the first scientists to understand the importance of mathematical simulation on computers (FEYNMAN, 1986). He was part of a group of engineers and scientists who built a supercomputer called the Connection Machine. It was practically a calculator built with thousands of processors for complex mathematical calculations. There are comments that Richard Feynman himself performed welding activities on the boards of this computer and mathematically assisted in designing the architecture, defining bits for the bus, required memory, etc (DANIEL, 1989). The effort to build the Connection Machine helped introduce ideas like those of Stephen Wolfram, who developed solutions such as Wolfram Mathematica (WOLFRAM. 2021), a sophisticated software for scientific areas still used and very famous. At the same time, Feynman gave the world the idea that in the future, we could create a quantum computer that could elevate human scientific capacity to unprecedented levels, with the clear vision that nature could be a great quantum computer.

In 1962, Brian Josephson discovered a physical effect that allowed two weakly linked superconductors physically separated by a thin insulating layer at temperatures near zero to create a macroscopic quantum effect with various applications (JOSEPHSON, 1962). One of the applications that has been making significant scientific and technological progress is quantum computers, which use the quantum effect generated in the so-called Josephson junctions as quantum gates for quantum computers. These are the same computers that Feynman had speculated about in his scientific work on physical simulation with computers (HEY, 1999). The Josephson effect is the basis for the construction of current quantum computers that we will discuss in this thesis. The current number of quantum gates has been increasing significantly, with a race to develop quantum computers with more quantum gates and a race for the so-called quantum supremacy among major market players such as Google, IBM, DWave...

One of the first algorithms developed to run on quantum computers was Shor's algorithm (SHOR, 2002). However, there is already a growing set of algorithms, albeit small, that has been continuously expanding over the past few years with the aim of exploring the quantum effects produced within quantum processors. In the coming years, we may see quantum computers reaching the desks of developers. Currently, some companies produce quantum computers for personal use, such as those produced by the Chinese company SpinQ with 2 and 3 qubits and the company Quantum Brilliance (SPINQ, 2023), which has quantum computers that operate without cryogenic cooling. Significant strides in quantum computing progress very quickly, becoming a strategic discipline for scientific and economic development in the coming years. Currently, few countries have the technology to produce these computers, and at the same time, there is a significant demand for their use. Accessing one of these computers for a project is not an easy and automatic task.

Although computer science may seem recent, cuneiform texts from the time of Hammurabi (1750 B.C.) report that the Babylonians had examples of very sophisticated algorithms, which could be more advanced generations of historically more remote algorithms (CHARPIN, 2012). But the significant advancement that we can highlight is Alan Turing's 1936 studies and his programmable abstract machine known as the Turing machine, which theoretically could have the processing capability of any type of algorithm (COPELAND, 1999). One of the most significant efforts in modern computer theory is the so-called Turing machine and, finally, the universal Turing machine, which is an abstract machine and has played an important role in building the modern theory of computer science. One of the great results based on Alan Turing's studies was the first electronic computer called Colossus, a computer used to decrypt encrypted messages used by German forces in World War II. Turing's work gave the Allies a strategic advantage so that the war effort could lead to victory over the German forces in World War II (RANDELL, 1980). An important caveat within this context is the understanding that Colossus was aimed at decrypting encrypted messages. One of the first algorithms that demonstrated the performance viability of a quantum computer was Peter Shor's algorithm, whose main goal is to decrypt messages through number factorization (BRUBAKER, 2023). Note that the history of computing repeats itself; currently, our computers are much closer to the universal Turing machine, although the universal Turing machine is still within the context of an abstract machine. At the end of World War II, researchers J. Presper Eckert and John Mauchly from the University of Pennsylvania built ENIAC (Electronic Numerical Integrator and Computer) (ENIAC, 2023), which adopted concepts developed by Alan Turing but used thermionic valve technology as relays for building the logic circuit. The use of relays, which were the backbone of the Colossus's logic circuits, was abandoned and replaced by thermionic valves. In 1947, there was another significant technological leap where William Shockley, John Bardeen, and Walter Brattain discovered the transistor, enabling a dramatic reduction in computer logic circuits, paving the way for greater processing capacity and miniaturization that triggered the microchip revolution. This led Gordon Moore to create the so-called

Moore's Law, where the capacity of computers doubles every two years.

Over the past few years until recently, Moore's Law has proven its longevity and truthfulness regarding the doubling of processing capacity in computers. The leading chip producer, TSMC, started producing 4-nanometer chips in 2022 (TSMC, 2023). Although there is continuous progress in chip miniaturization, it does not always reflect a significant improvement in performance. However, there are still resources for a review of processor architecture as proposed by Gene Amdahl in 1967, modeling the performance gain by improving only one part of a system. In this case, the overall performance of a system is the result of the maximum performance of the system's worst-performing element.

The basic formula of Amdahl's Law is as follows:

$$Speedup = \frac{1}{(F + \frac{(1-F)}{P})} \tag{1}$$

The Amdahl's Law emphasizes the importance of critical bottlenecks by identifying them to seek improvements in overall performance, allowing a specific part of the system to be optimized (AMDAHL, 2012). If a large part of the program cannot be improved (i.e., F is large), the performance gain will be limited, regardless of how significant the improvements in the improved part are.

The conclusion is that there is still the possibility of improvements and performance gains in the coming years. However, we are approaching the limits of Moore's Law (YIN, 2022), which could bring serious problems for the development of computers and digital systems in a few years. There are physical limits imposed by Moore's Law. Will we build transistors with 3 atoms in the coming years (CALIGA, 2016), taking our computer architecture to the development of molecular chips? If this happens, will molecular structures still be stable at angstrom-sized scales? The questions increasingly sharpen our abilities to seek more and more answers. Instead of avoiding problems of quantum interference in the reduction of internal components of silicon chips, we can use quantum effects.

In the early 20th century, David Hilbert predicted that there should be an algorithm that could solve any mathematical problem. Unfortunately, the answer was no, initially exposed by the works of Gödel's incompleteness (GODEL, 1931) and later by Church and Turing, who delved into the concept of mathematics to translate it into the concept of an algorithm. The efforts of Church and Turing resulted in the modern definition of algorithms and the definition of modern computer science theory. Turing's proposal gave rise to Turing machines, which are the basis of current modern computers. Another important figure in this scenario was Richard Feynman's work on building a future quantum computer that could simulate all possible physical phenomena. Although Feynman gave an important boost to the construction of quantum computers, he did not present a theoretical proposal for their construction. Some years after Feynman's work on quantum computing, the first proposal for building a quantum computer was entrusted to David Deutsch, who used Turing's works based on the universal Turing machine. Deutsch proposed a universal quantum computer in the same mold as the universal Turing machine. Along with this proposal, Deutsch presented a quantum algorithm that could use the resources of a quantum computer more efficiently than any other classical computer at the time (COLLINS, 1998).

The increasing data generated from mobile phones, wearable devices, and the growing use of the internet have generated an enormous volume of data used for processing artificial intelligence and machine learning systems (RATHOD, 2023). All this growth in data volume inherently implies an increase in information processing capacity, just as the use of blockchain is responsible for a large volume of information processing. The use of quantum computers can give a significant boost to these analytical and cryptographic areas through the speed of quantum computers and their low power consumption. We are seeing an inflection point in our computer science with a new computing paradigm that not only depends on investments in hardware but also on education investments. The use of quantum computers implies a new way of teaching for our IT students, with variables and concepts more complex than before. Although the use of quantum computing is not currently widespread, the diffusion of quantum computers will happen, and perhaps it will not take much time!

1.1 The First Quantum Computer

"Few discoveries in the history of science have produced such extraordinary results, in the brief period of a generation, as those that arose directly from the proposal of the elementary quantum of action formulated by Max Planck. In ever-increasing progression, this discovery has provided the means to interpret and harmonize the results obtained in the study of atoms, which have made marvelous progress in the last thirty years. But the theory of quanta did more. It provoked a radical revolution in the scientific interpretation of natural phenomena and shook the foundations of our ideas." Niels Bohr (PLANCK, 2020)

It is undeniable that Max Plack's work managed to transform our understanding of the world. Still, quantum theory remains one of the most challenging theories to understand and assimilate. However, just by looking around us, plants use quantum processes all the time without knowing the laws of physics, something that has been replicated on our planet for billions of years. The nature around us acts like a large quantum computer that processes life and cosmic information. In the early 1980s, Richard Feynman commented in his memorable work on Simulation Physics with Computers (FEYNMAN, 1981) that quantum machines could imitate any physical system, including our physical world. Feynman's first steps in seeking machines that could simulate physical systems were the works with the Connection Machine, a machine with parallel processors that allowed massive data processing for physical simulations. Regardless of the progress that Feynman tried to achieve in simulating physical effects, he himself took the first steps toward building a quantum machine using the principles of classical computer logic (FEYNMAN, 1986). Quantum computers based on Nuclear Magnetic Resonance (NMR) were the first approach to building quantum computers based on nuclear spectroscopy. However, they were still very rudimentary and had significant limitations compared to universal quantum computers, also known as full-circuit quantum computers (XIN, 2018). NMR-based quantum computers lack scalability, making them unable to perform very complex calculation processing and limiting them to scientific applications. NMR-based quantum computers were surpassed by a new class of computers that are universal quantum computers, which form the basis of the development of this document.

1.2 Universal Quantum Computer

A universal quantum computer is, in turn, constituted by a universal circuit based on:

Qubits - Qubits are the fundamental units of information in a quantum computer. Compared to classical bits, their operation is similar; however, qubits can work in superposition, presenting both binary states simultaneously. Quantum superposition is a state in which elementary particles can assume more than one state, called quantum states. This behavior allows quantum computers to process combinations of possibilities simultaneously, thus achieving performance gains in data processing. (NIELSEN, 2010, P.8)

Quantum Gates - These are analogous to logic gates in classical computers but can work in a superposition state and be combined, allowing quantum entanglement of information from more than one gate. Not all quantum gates are available in the same quantum computers, but the main ones include CNOT (Controlled-NOT) gates and Hadamard gates, with Hadamard being one of the most important as it places the initial states in superposition. The Toffoli gate has three output qubits; if the first two qubits have a state of 1, it applies a CNOT output on the third gate, and so on. (NIELSEN, 2010, P.17)

Quantum Algorithms - One of the first quantum algorithms was Shor's algorithm, created by the mathematician Peter Shor, aiming to break encryption keys by factoring numbers. Shor's algorithm's advantage is the ability to factor multiple numbers and process them in parallel on a quantum computer, yielding the result of an encryption key in record time, surpassing classical computer processing capabilities (NIELSEN, 2010, P.28). Shor's algorithm initially transformed quantum computers into cryptographic machines (NIELSEN, 2010, P.17), similar to Alan Turing's first computer built at Bletchley Park during World War II. Although Turing's primitive computer was a machine with a specific purpose, over the years, it evolved into the foundation of our society's technological advancement. With the growing progress in quantum computing studies, the trend is an increase in algorithms and consequently the advancement of quantum computing applications, gradually following the same path as Alan Turing's first computer to our current time, becoming indispensable machines for scientific and technological progress in our society.

Portability - Aims to define a universal quantum computer capable of working with a varied range of tasks and algorithms. Currently, there are programming languages like Qiskit, which is open source and compatible with various quantum computers on the market. The possibility of a universal programming language for quantum computers is an incentive for the development and research of new algorithms that can run on these machines, significantly expanding their use and applications.

Technical Challenges - One of the current major challenges is quantum coherence. Quantum coherence is the ability of qubits to remain in an entangled state. The problem is that this state does not last long due to noise generated in nature and by humans through radio transmitters and temperature differences (NIELSEN, 2010, P.278). One technique used to maintain the quantum coherence of quantum computers is the use of temperatures close to absolute zero, where quantum effects begin to appear. However, maintaining this constant temperature and protecting quantum computers from external noise interference has been a significant challenge (HORNIBROOK, 2015). One advancing technique in recent years is the use of diamonds with nitrogen vacancies, which have the ability to work at ambient temperatures without relying on advanced cooling systems. This topic will be discussed further later.

1.3 Quantum Computers Available in the Current Market

Superconductors - These quantum computers are built with superconducting electrical circuits and need to operate at very low temperatures close to absolute zero for superconductive and quantum effects to be used for task processing (GAMBETTA. 2017). Superconductor circuits can work on both macro and nano scales. The advantage of using superconductive materials is their ability to work on a macro scale due to individual material characteristics, and on a nano scale, quantum effects can accumulate to create a quantum circuit (HORNIBROOK, 2015).

Nano wires, considered one-dimensional materials, confine electrons in two spatial dimensions, forcing the current between them to flow in a single direction and dimension, making electrons tunnel through. Although nano wires are considered an approach to low-power quantum computer construction, they are still in the early stages of development. Josephson junctions, constructed with two superconductive wires separated by an insulator, allow electrons to pass through the insulating material, enabling Josephson junctions to create continuous wave functions for each wire, forming a quantum entanglement state. (FROLOV, 2013)

Trapped Ions - IonQ and the University of Maryland in the USA have been working with this computer architecture. This approach involves isolating individual atoms in a 3D space. After trapping and isolating the atom, lasers are applied to control the atom's spin. The precision optical and mechanical engineering of the system creates the expected quantum effects for quantum computing (BROWN, 2021). Ytterbium ionized atoms, taken from rare earth materials, are used to create quantum effects. Ytterbium atoms are advantageous because every ytterbium atom is perfectly identical throughout the universe (MATJELO, 2020). The precision in the creation of the ytterbium ionization system involves a specific chip developed by IonQ, trapping the ytterbium ion in a 3D space surrounded by 100 electrodes created by precision lithography. These electrodes are controlled by electromagnetic forces, aiming to keep the ytterbium ion in place and minimizing quantum decoherence and environmental noise interference. (IONQ, 2023)

Solid State - Solid-state technology has been present in our industry for decades. Companies like Google, IBM, and Rigetti (SETE, 2016) are investing in this type of quantum computer topology, and it seems promising as the number of available qubits per machine has been gradually increasing over the years. (STEFFEN, 2011)

Hybrid Quantum Computers - Universal quantum computers depend on classical computers working in conjunction with them. This has opened the possibility for the development of programming languages that enable compatibility between different architectures. Classical computers integrated with quantum computers provide more than language compatibility; they control these computers and serve as an interface between humans and quantum machines. One of the well-known providers of hybrid quantum computers is D-Wave Systems. (HU, 2019)

NMR (Nuclear Magnetic Resonance) Quantum - Nuclear Magnetic Resonance has been studied since 1930 based on the works of Isidor Rabi, R.V. Pound, E.M. Purcell, and Felix Bloch, which led to the development of NMR spectroscopy by Fourier transform, earning Isidor Rabi a Nobel Prize in 1944 and later awarded to F. Bloch and E.M. Purcell in 1952. (DIEGUES, 2018) Nuclear Magnetic Resonance is based on the superposition of quantum mechanics of nuclear spin states, allowing for quantum information processing. Over the past years, it has gained interest from the scientific community interested in quantum computing. However, this technique relies on electronic devices and mobile electrical devices for the microscopic control of coherent nuclear spin. In recent years, the adoption of devices at the nanoscale has given a new direction to the technique, where semiconductor devices are responsible for detecting electron spins. These devices apply a pulsed frequency field to create multiple spins with quantum superposition, which are detected and define the qubits of the system, making them usable in quantum computing. Research has been advancing over the years, although it is not as common currently due to the limited number of qubits that can be manipulated compared to other types of quantum computers used today. (YUSA, 2005)

Quantum Computers with Nitrogen Vacancy (NV) - They promise to be a new type of quantum computing that could be made available for future domestic use, due to the ability to operate at room temperature, requiring no cryogenic system to lower the temperature of quantum devices. While not depending on large cooling systems, these systems can be the size of boards that can be installed in personal desktop computers (ZHANG, 2020). A startup in Australia called Quantum Brilliance, along with Fraunhofer Institute for Applied Solid State Physics IAF and the University of Ulm (HPCWIRE, 2022), is designing and manufacturing computers in a 2U size, similar to servers installed in data centers. The machine uses nitrogen vacancy technology for quantum processing; the diamonds used for the production of these quantum computers are synthetic diamonds where an imperfection within the crystal structure of the diamond is bombarded with lasers, creating a vacancy of an atom within the structure. This vacancy generated within the structure creates a quantum superposition effect that can be used as a qubit.

Quantum Computers with Nitrogen Vacancy (NV) - A startup in Australia called Quantum Brilliance is developing quantum computers based on Diamonds with Nitrogen Vacancy (NV). The diamonds are synthetic and bombarded with ions to remove nitrogen atoms, creating a vacancy within the diamond's structure (BRILLIANCE, 2023). This vacancy allows the generation of a superposition state of the qubits. More details will be clarified in the sections below, but it is possible to mention that this construction process allows the use of these quantum computers at room temperatures and in small machines or boards that can be adapted to personal use computers. (ZHANG, 2020)

1.4 Quantum Supremacy

On October 23, 2019, Google announced to the world that it had achieved quantum supremacy with its quantum computer using a Sycamore quantum processor. In 200 seconds, the quantum computer processed a calculation that the world's best supercomputers would take 10,000 years to complete (ARUTE, 2019). Although the achievement was contested by IBM and later rebutted by Google against IBM (CRANE, 2019), it is important to note that we are witnessing an advance in science. As the saying goes, all the confusion in science is always a good thing! This discussion presents a new scenario where quantum computers are becoming a reality. After much effort by human science to turn Richard Feynman's old dream into reality, to build a quantum computer and understand that nature itself can be a quantum computer, we have transformed quantum computers into a reality. This reality could be a turning point in science and human progress.

Current climate change has become a major problem for humanity. Modern agriculture relies on accurate information and data; untimely rains can create serious problems in food production. Once again, we are haunted by the threat of famine, beyond what already exists in poorer countries. This threat could become global. To optimize planting execution and streamline harvest processes, we depend on informatics. Currently, all modern machines rely on GPS systems. Criticisms of

India for investing in moon travel and not paying attention to the population's hunger are not true. The GPS technology used in Indian agriculture has made the country progress and alleviated hunger for a significant portion of the population (ARMSTRONG, 2011). Some important elements within the context of GPS use are:

- Precision Agriculture - Crop Monitoring - Logistics and Distribution - Monitoring Food Reserves - Identification of Food Insecurity Areas - Monitoring Natural Disasters

Where could quantum computers help in all this? Simply put, processing speed aids in the enhancement of climate models, distribution models (KAKU, 2023), probability analysis, and global productivity processing. To advance in solving current human problems, we need more processing power and speed in problem resolution. Quantum computers can help elevate our engineering and science to a higher level. Simulation of new medicines, simulation of cells and more complex cell sets, simulation of biological and genetic processes, simulation of social behaviors, and natural effects such as disasters—all can benefit from quantum computing.

Although the advances are promising, it's important to note that during the tests presented later, one of the major challenges was the difficulty in finding available quantum computers. It was not possible to evaluate whether this lack of availability is due to higher demand for these machines or some kind of contract made by service providers such as AWS, Microsoft Azure, IBM, and Google Cloud Platform. The machines were unavailable for many hours and had incompatibilities between the types of quantum ports available.

Another aspect that has become a hindrance to the advancement of quantum computing is error correction. Quantum machines are highly susceptible to errors generated by environmental noise, which can be temperature, magnetic fields, electromagnetic radiation (radio or light waves), creating serious problems for increasing the number of quantum ports in computers. The more quantum ports, the greater the possibility of use in more complex calculations.

1.5 Not Intelligent, Much Less Artificial

Intelligence is a characteristic of living beings, not machines. Although we are experiencing the era of artificial intelligence, it is important to emphasize that artificial intelligence is neither intelligent nor artificial (KAUFMAN, 2021). Alan Turing himself commented in his work on the Turing machine that at a certain point, an oracle would be necessary. The oracle Turing refers to is the human being. All information produced by ChatGPT, resulting from neural networks and statistics, does not create knowledge. According to Noam Chomsky, knowledge arises at the periphery of information (DEBEAUGRANDE, 1991), where elements connect and create conjectures. Programs and algorithms of artificial intelligence are being applied to quantum computers, but it is crucial to note that this will not bring singularity to these machines or the programs running on them. The use of intelligence relies on organized statistical information to provide solutions to the challenges of our society but does not generate the knowledge that possesses one of the most singular characteristics—creativity.

In the 1930s, disciples of Hilbert discussed the unification of mathematics as something possible and achievable. Still, at the Königsberg conference, a young mathematician, Kurt Gödel, proved that Hilbert's program of unifying mathematics would never be possible! At this conference, Gödel presented his incompleteness theorem for the first time. A set of rules is limited only to the boundaries of its rules, something that human intelligence can transcend through creativity. For example, the idea of parallel worlds, quantum theory, and relativity theory transformed our science and understanding of the universe. Our brain is the true creator of the universe. A universe without intelligence is a universe that never existed. Human intelligence can work with the future, something not possible in our mathematics or in our machines using mathematical laws for artificial intelligence processing. The future has never been and never will be computable, and it is this challenge that human intelligence has been built over billions of years by the universe. If humanity renounces its efforts for new discoveries, abandoning this wonderful inheritance that nature has given us, we risk producing nothing new. The new is the true construction of human intelligence!

Gödel's Third Incompleteness Law: "No consistent mathematical system can prove its own consistency" (GODEL, 1931)

A classical or quantum computational system operates based on logic, and logic is the means we use to access and validate mathematics. However, mathematics is greater than logic. Therefore, validation becomes inaccessible to logical standards, and intuition becomes valuable at this point—something humans excel at, unlike computers confined to logic (PENROSE, 1994).

1.6 The Hadamard gate

The Hadamard gate, often denoted as H, is a fundamental quantum gate used in quantum computing. It plays a crucial role in creating superpositions and is often employed at the beginning and end of quantum algorithms. Let's discuss in detail what the Hadamard gate does: (NIELSEN, 2010, P.19, 28)

1. Operation on the $|0\rangle$ and $|1\rangle$ basis states:
- The Hadamard gate acts on a single qubit but can be simultaneously applied to multiple qubits, as shown in the quantum photosynthesis simulation circuit.
- If applied to a qubit in the $|0\rangle$ state, it transforms it into $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$.
- If applied to a qubit in the $|1\rangle$ state, it transforms it into $\frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$.

2. Creation of Superpositions:
- One of the most important properties of the Hadamard gate is its ability to create superpositions, an essential action for initializing a quantum circuit.
- When applied to a qubit initially in the $|0\rangle$ state, you obtain a uniform superposition of $|0\rangle$ and $|1\rangle$: $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$.
- This means that, after the application of H, the qubit is in a linear combination of both basic states.

3. Phase Annihilation: - The Hadamard gate also annuls phases, and when applied twice consecutively, the qubit returns to its initial state.
- $H \cdot H = I$ (where I is the identity matrix).

4. Relation to the Quantum Fourier Transform (QFT):
- The Hadamard gate is a key component in the construction of the Quantum Fourier Transform (QFT). The QFT, which was used in a simplified form in the quantum photosynthesis simulation, is employed in many quantum algorithms, including Shor's algorithm.

5. One-Qubit Gate:

- The Hadamard gate is a one-qubit gate. This means that it operates on only one qubit at a time.

Mathematically, the Hadamard matrix is given by:

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

The transformation matrix presented above is applied to a vector, in this case, a qubit, placing the vector defining the qubit in a quantum superposition.

1.7 Understanding the Logic of Simulations

The fundamental process involves the incidence of a light beam on a leaf, allowing the passage of specific light frequencies. The color of the leaf filters out all non-green light, reflecting only green light. Different light frequencies exhibit different photon polarizations.

In the circuit, we introduce qubits in superposition, considering two simple types of polarization: $|0>$ and $|1>$. We create these qubits in superposition and apply the Quantum Fourier Transform (QFT) using the SWAP (JAFFALI, 2022) command, adding complexity to the circuit's structure. The Fourier Transform represents a signal, a wave, or a natural behavior. All these elements are present in the structure of the quantum circuit, where each qubit in superposition represents photons from a light beam.

After assembling the circuit simulating a wave, we proceed to measure the states of the qubits a thousand times, once per round, or the "shots." Finally, we filter the initial qubit from all measurements (q0). By filtering all qubits $= 0$, we are excluding information related to even states. The even state represents the polarization of the qubit or, abstractly, the photon that traversed the layers of the leaf cell. This polarization represents a specific light frequency, in this case, the assumed light frequency absorbed by the leaf.

All even polarizations are summed, resulting in the sum of qubits representing the generated energy. In simple terms, out of a thousand photons, approximately half of them are absorbed in the process. This value may vary, being less or more than half of the original light beam.

1.8 Quantum Computers of project

The project was initially designed to be fully implemented in the AWS (Amazon Web Services) environment, using AWS Braket, which initially provided a variety of quantum computers. However, over the months, the availability of these computers decreased significantly, to the point where some of them were retired from the service, leaving only a few options available. Following this change, Microsoft Azure and IBM Quantum Platform (SANTOS, 2016) environments were chosen. Below are the offered quantum computers, and it's important to note that IBM has many other quantum computers available for use. However, the main choices were two quantum computers with Eagle r3 processors of 127 qubits.

Target name	Target ID	Number of qubits	Description
Rigetti QVM (simulator)	rigetti.sim.qvm	20 qubits	Rigetti's cloud-based, open-source "Quantum Virtual Machine" simulator. Free to use.
Aspen M-3 (hardware)	rigetti.qpu.aspen-m-3	80 qubits	Rigetti's "Aspen-M-3" universal, physical QPU. Read more at Rigetti's website.
Quantum simulator	ionq.simulator	29 qubits	IonQ's cloud-based idealized simulator. Free of cost.
Aria 1	ionq.qpu.aria-1	23 qubits	IonQ's Aria 1 trapped-ion quantum computer. This is real quantum hardware, not a simulation.
Quantum computer	ionq.qpu	11 qubits	IonQ's trapped-ion quantum computer. This is real quantum hardware, not a simulation.
H1-1 Syntax Checker	quantinuum.sim.h1-1sc	20 qubits	Quantinuum's H1-1 Syntax Checker. This will return all zeros in place of actual or simulated results. Use this to validate quantum programs against the H1-1 compiler before submitting to hardware or emulators on Quantinuum's platform. Free of cost.
H1-2 Syntax Checker	quantinuum.sim.h1-2sc	20 qubits	Quantinuum's H1-2 Syntax Checker. This will return all zeros in place of actual or simulated results. Use this to validate quantum programs against the H1-2 compiler before submitting to hardware or emulators on Quantinuum's platform. Free of cost.
H2-1 Syntax Checker	quantinuum.sim.h2-1sc	32 qubits	Quantinuum's H2-1 Syntax Checker. This will return all zeros in place of actual or simulated results. Use this to validate quantum programs against the H2-1 compiler before submitting to hardware or emulators on Quantinuum's platform. Free of cost.
H1-1 Emulator	quantinuum.sim.h1-1e	20 qubits	Quantinuum's H1-1 Emulator. Uses a realistic physical model and noise model of H1-1.
H1-2 Emulator	quantinuum.sim.h1-2e	20 qubits	Quantinuum's H1-2 Emulator. Uses a realistic physical model and noise model of H1-2.
H2-1 Emulator	quantinuum.sim.h2-1e	32 qubits	Quantinuum's H2-1 Emulator. Uses a realistic physical model and noise model of H2-1.
H1-1	quantinuum.qpu.h1-1	20 qubits	Quantinuum's H1-1 trapped ion device.
H1-2	quantinuum.qpu.h1-2	20 qubits	Quantinuum's H1-2 trapped ion device.
H2-1	quantinuum.qpu.h2-1	32 qubits	Quantinuum's H2-1 trapped ion device.
IBM Brisbane	ibm_brisbane	127 qubits	IBM Quantum Platform with Eagle r3 processor
IBM Osaka	ibm_ osaka	127 qubits	IBM Quantum Platform with Eagle r3 processor

Figure 1: Available Quantum Computers

1.9 Understanding the Logic of Simulations

1.9.1 Photosynthesis

The fundamental process involves the incidence of a light beam on a leaf, allowing the passage of specific light frequencies. The color of the leaf filters out all non-green light, reflecting only green light. Different light frequencies exhibit different photon polarizations.

In the circuit, we introduce qubits in superposition, considering two simple types of polarization: |0> and |1>. We create these qubits in superposition and apply the Quantum Fourier Transform (QFT) using the SWAP command, adding complexity to the circuit's structure. The Fourier Transform represents a signal, a wave, or a natural behavior. All these elements are present in the structure of the quantum circuit, where each qubit in superposition represents photons from a light beam.

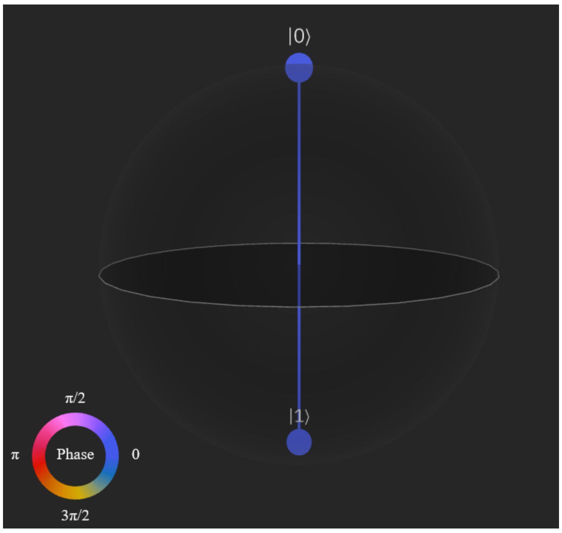


Figure 2: Superposition State of 1 Qubit

After assembling the circuit simulating a wave, we proceed to measure the states of the qubits a thousand times, once per round, or the "shots." Finally, we filter the initial qubit from all measurements (q0). By filtering all qubits = 0, we are excluding information related to even states. The even state represents the polarization of the qubit or, abstractly, the photon that traversed the layers of the leaf cell. This polarization represents a specific light frequency, in this case, the assumed light frequency absorbed by the leaf.

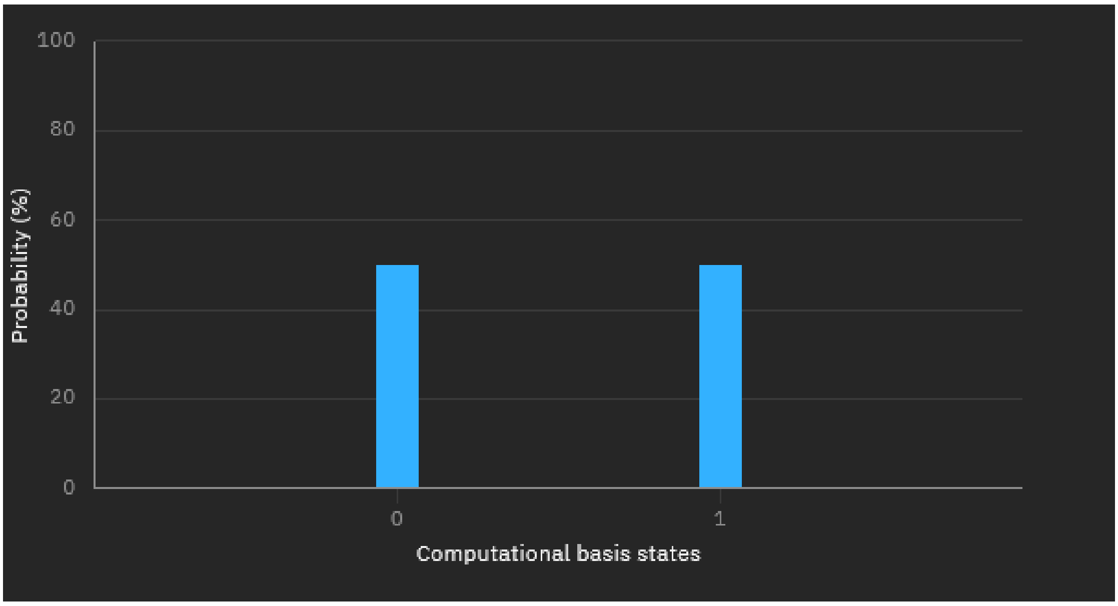


Figure 3: State of Superpositon after Hadamard Gate applied - 1 Qubit

All even polarizations are summed, resulting in the sum of qubits representing the generated energy. In simple terms, out of a thousand photons, approximately half of them are absorbed in the process. This value may vary, being less or more than half of the original light beam.

1.9.2 Bitcoin

The first step is create a keyword and after, it's examined the keyword size, which determines how many qubits will be used in constructing the quantum circuit. The circuit organization is based on Grover's algorithm(BHATTACHARYYA, 2021). We place all qubits in a superposition state and then apply the Toffoli gate through the MCT method, generating a quantum state. After measuring these values, the Bitcoin address generation becomes a stochastic process. While cryptography is a deterministic application (BLACKLEDGE, 2008) that uses the computer clock and algorithms to generate a number, it is challenging to predict the number due to the complexity of the cryptography system, but the system is still deterministic. On the other hand, the number generated in the quantum circuit is entirely indeterminate, as it is a quantum process.

The circuit follows an iteration routine, adding the same circuit to the previous one n times, increasing the system's complexity. After measurement, we take the maximum value found in the measured samples, obtaining the address as a result.

1.9.3 Histograms

Histograms display the readings taken from the measured qubits. There is no clear sense for understanding the process; the histograms merely represent the probabilistic distribution of the circuit's measurement results (JIANG, 2020). In this case, the histograms are there to demonstrate their approximate equivalence when executed on different quantum computers. This ensures Qiskit's compatibility.

2 Photosynthesis

Photosynthesis, besides being a vital process for plants, is crucial for all life on planet Earth. Plants, some bacteria, and algae rely on this chemical process for energy production in the form of glucose. Oxygen is released as a byproduct of the photosynthesis process, which is utilized by all other living beings on the planet. Although oxygen production is essential for life on the planet, plants produce food based on this chemical process that sustains life. The photosynthesis process is divided into two phases: the light phase and the dark phase.(EATON, 2011, P.35,112)

The light phase occurs in thylakoid structures found in chloroplasts, which are the cells of plants, in this case called thylakoid membrane (SCHUNEMANN, 2007). Light is absorbed by photosynthetic pigments, such as chlorophyll. The role of light is to split the water molecule (H2O) into oxygen (O2) and hydrogen ions (H+) (RITZ, 2002). Oxygen, in this chemical process, is a byproduct released into the atmosphere. Hydrogen ions are transported throughout the thylakoids, generating a concentration gradient of hydrogen ions. The energy from light is captured and used to send ions through the thylakoid membrane, creating a gradient that stores potential energy. This process of passage through the thylakoid membranes consumes energy, but light photons pass through the membrane with an efficiency close to 100%, something classical physics cannot explain (LERNER, 2023). This will be simulated in this work using an application running on quantum computers. The goal of the experiment is to demonstrate the ability of quantum computers to simulate physical effects that cannot be simulated on classical computers and, at the same time, analyze the performance of different quantum computer platforms using Qiskit.

The dark phase, also known as the Calvin Cycle, occurs in the chloroplast region where thylakoids are not present. In this phase, the energy stored in the H+ ion (proton) gradient converts carbon dioxide (CO2) into glucose and other types of sugars. In this process, CO2 is fixed in an organic molecule called ribulose-1,5-bisphosphate (RuBP) with the help of the enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO). Carbon dioxide (CO2) is then fixed and con-

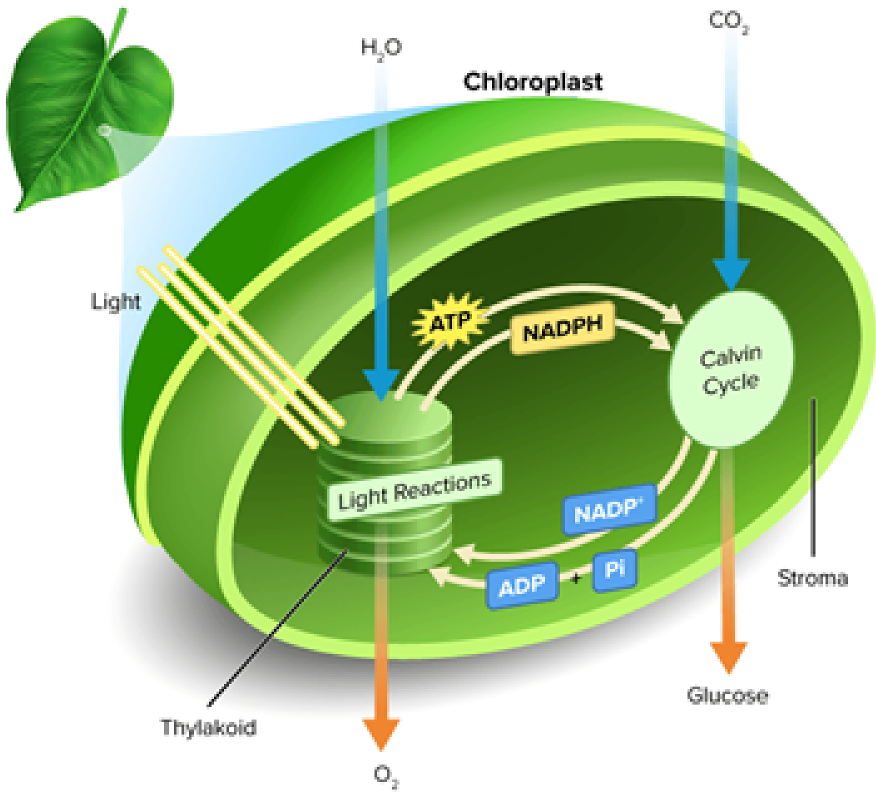


Figure 4: Photosynthesis Process (source: CK-12 Foundation)

verted into glucose. Meanwhile, ATP (adenosine triphosphate) and NADPH (nicotinamide adenine dinucleotide phosphate reduced), produced in the light phase, provide the energy necessary for this conversion. (RAINES, 2003)

Life is characterized by its complexity and negative entropy; it organizes and propagates within a universe constantly characterized by the pursuit of incessant entropy increase (from organization to disorganization). With the dedication and effort of many scientists over the last century, we have achieved a partial understanding of quantum theory inaugurated by Max Planck. As Niels Bohr commented, "Few discoveries in the history of science have produced such extraordinary results in the brief period of a generation as those which arose directly from the proposal of the elementary quantum of action formulated by Max Planck" (PLANCK, 2014).

Quantum computers are a beautiful example of the result of this effort in the pursuit of understanding and applying quantum theory. However, nature puts us in our proper place. Nature shows us our humility. Richard Feynman once said that the world could be a large quantum computer. You only need to look around and see our planet covered by plants that use quantum effects to produce energy for themselves and oxygen for the animals and insects that share our planet (FEYNMANN, 1986). You open your room window, and there is nature producing energy and life for the planet in different types of plants, repeating this process several times. Based on DiVicenzo's criteria:

"Have qubits with long coherence time: Coherence time is the period during which the qubit maintains its quantum state before degrading. It is important to have a sufficiently long coherence time to perform quantum operations accurately" (DiVicenzo).

One of the significant challenges for quantum computing today is error control due to environmental interference. For this, we need to place our quantum computers at temperatures close to absolute zero to ensure long-term coherence. Plants produce energy with efficiency close to 100% in physical processes for which classical physics has no answers. For years, scientists have been developing theories and conducting lab tests to understand the energy transformation process through

CO_2 molecule breakdown. The only answer found for this process is quantum processes that can explain the efficiency of photosynthesis. Even though it is an extremely efficient process, the question remains: how does the nature around us have quantum processes that repeat themselves and apparently have little interference noise from nature? The efficiency of nature's quantum processes may be one of the great challenges for science in the coming decades. Returning to the question of photosynthesis based on quantum processes, the possibility of developing similar processes will enable space exploration and interplanetary travel through machines using the same quantum processes of photosynthesis to produce oxygen for life support in long space journeys or even for life support in the near future in the exploration of the planet Mars. But not only the production of oxygen through an artificial leaf (KAKU, 2023) can be considered a progress factor; understanding the quantum processes of photosynthesis may be the key to building future quantum computers at room temperature.

Recently, a team of researchers from the University of Chicago successfully observed the fifth state of matter in experiments based on excitons. Excitons are quasiparticles formed in solids where an electron generates a hole in the electronic layers that are connected through Coulomb interaction—a process that occurs in semiconductors and insulators. However, the process of photosynthesis generates excitons when a photon passes through the chloroplast, exciting an electron in the valence band and generating a hole.

What the scientists at the University of Chicago identified were islands of exciton condensation in their experiments. However, this exciton condensation process occurred when the atoms cooled near absolute zero. Excitons are created in the photosynthesis process of plants, and the scientists' experiment suggests that the same exciton condensation process is similar in photosynthesis. Creating excitons near absolute zero is considered the fifth state of matter, also known as the Bose-Einstein condensation effect. According to the scientists, this opens the possibility for the future design of new types of electronic systems.(LERNER, 2023)

"As far as we know, these areas have never been connected before, so we find this very convincing and exciting," said the study's co-author, Prof. David Mazziotti.

This type of experiment is not visible to the naked eye. Still, Mazziotti's laboratory specializes in modeling complex atomic and molecular interactions as new properties emerge in experiments that use computational models for simulation. (LERNER, 2023)

When a photon hits a leaf, it releases an electron, creating a hole where that electron was previously. In this case, an exciton generated creates a condensate of excitons similar to the Bose-Einstein condensate, interconnecting and propagating like a set of bells ringing in perfect harmony. This kind of effect allows excitons to propagate around the chloroplast with almost zero friction in a quantum state. The research could advance to enable the creation of machines based on superconductivity in the future. (LERNER, 2023)

2.1 AWS Braket versus Qiskit

AWS Braket is a service provided by AWS (Amazon Web Services) aimed at offering an environment and infrastructure for running quantum applications (ATCHADE-ADELOMOU, 2021). AWS Braket also includes a set of libraries that enable the integration of applications across various quantum computing providers, ensuring compatibility and the ability to run on different quantum computers. On the other hand, Qiskit is an open-source framework for quantum computing developed by IBM (WILLE, 2019). It comes with an extensive set of libraries that facilitate compatibility with various providers and types of quantum computers in the market.

During the analysis of different providers, it was possible to verify and use the same development framework, Qiskit. However, it's important to note that Qiskit may not be entirely compatible with all types of gates on different quantum computers, presenting a significant challenge in building an application based on Qiskit that runs seamlessly on diverse quantum computers.

Despite these differences, the fact that constructing a Qiskit-based application that runs on more than one type of quantum computer and provider provides developers with a path that may lead to a code compatibility solution. This ensures future investment in a common language for various quantum computers, fostering interoperability across different platforms.

Note: The Amazon AWS Braket environment was abandoned due to constant unavailability of quantum computers for simulation execution.

2.2 Code Description

The simulation of quantum photosynthesis does not encompass all the elements and physical effects involved in a real process. To this day, quantum photosynthesis remains a subject of discussion, and there is still no clear definition of how it functions. There are even theories suggesting a possible connection between the fifth state of matter and the high performance in the propagation of photons and their transformation into energy during the photosynthetic process.

The primary goal of the simulation was to test the capabilities of quantum computers from various providers. Initially, the IBM quantum computer with 127 qubits was utilized, with IBM offering a free package of 10 minutes per month for using these machines. However, the tests proceeded with 32 qubits due to memory limitations of the instances running the Jupyter IDE.

The preparation of the quantum circuit involves creating a 32-bit quantum register. For the Quantinuum quantum computers (quantinuum.qpu.h1-1) on the Azure Portal, 20 bits were used due to the backend's qubit limitation. After creating the quantum register, Hadamard gates are applied to each qubit to place them in a quantum superposition state. Following this, a simplified Quantum Fourier Transform (QFT) is applied using the "SWAP" method (DORAI, 2005). Finally, all qubits are measured.

The decision to use QFT aimed to leverage the initial quantum superposition of gates, which are already in a combination of states. With QFT(JAFFALI, 2022), more complex patterns of superposition are created, simulating an effect of light that alters the arrangement of qubits as it passes through the chloroplast layers of the plant's leaf. During measurement, the quantum state collapses, presenting the state of each measurement, ranging between 1000 and 1024 shots. Counts are obtained from the results, and the energy produced in the process is calculated by summing the counts of states where the first qubit is in the '1' state.

The histogram is finally employed to conduct an analysis of the probabilistic behavior of the quantum circuit. The goal is to understand stochastic variability, thereby simplifying the complexity of the probability associated with the execution of measurements.

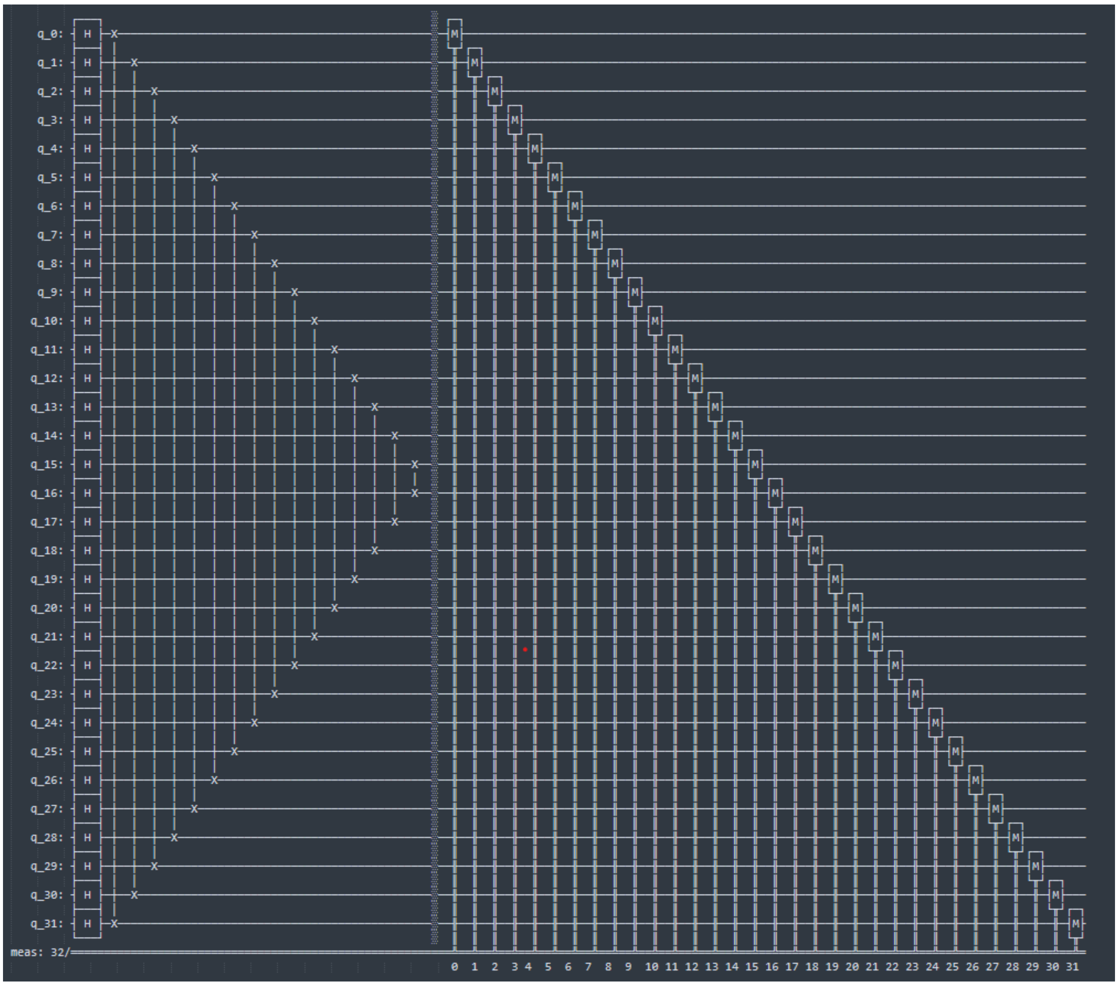


Figure 5: Photosynthesis Quantum Circuit

2.3 Code - Photosynthesis - IBM

```
from qiskit import QuantumCircuit, QuantumRegister
from qiskit import ClassicalRegister, Aer, execute
from qiskit.utils.quantum_instance import QuantumInstance
from qiskit.algorithms import Shor
from qiskit.circuit.library import QFT
from qiskit.circuit.library.standard_gates import CU1Gate
from azure.quantum.qiskit import AzureQuantumProvider
from azure.quantum.target.rigetti import RigettiTarget
from qiskit.tools.monitor import job_monitor
import numpy as np

# Create a 32-qubit quantum register
qr = QuantumRegister(32, 'q')

# Create a quantum circuit with the quantum register
photosynthesis_circuit = QuantumCircuit(qr)

# Apply Hadamard gate to each qubit
photosynthesis_circuit.h(qr)

# Apply Quantum Fourier Transform (simplified for illustration)
# Applying swap gates for simplicity; you might need
# a more complex pattern
for i in range(16):
    photosynthesis_circuit.swap(qr[i], qr[31 - i])

# Measure the qubits
photosynthesis_circuit.measure_all()

#print(photosynthesis_circuit)
```

```python
backend_name = 'ibm_brisbane'
shots = 1024
# Load a previously saved account.
provider = IBMProvider()

# Select a different hub/group/project.
provider = IBMProvider(instance="ibm-q/open/main")

# Transpile the circuit for the target backend
backend = provider.get_backend(backend_name)
transpiled_circuit = transpile(photosynthesis_circuit,
                              backend, optimization_level=3)

# Run the transpiled circuit on the quantum computer
job = execute(transpiled_circuit, backend, shots=shots)
result = job.result()

# Print and visualize the results
counts = result.get_counts(photosynthesis_circuit)
#print("Measurement results:", counts)

energy_produced = 0
for state, count in counts.items():
    if state[0] == '1':
        energy_produced += count

print(f"Final state: {counts}")
print(f"Energy produced: {energy_produced / 1000}")

plot_histogram(counts)
```

2.4 Results - IBM 127 Qubits

Final state: '01111001001111110001101000011101': 1, '00101100000101110011110111011000': 1, '11000111000101110000101101000101': 1, '10111010100100001111111001011111': 1, '10111000101010000100010101011001': 1, '01010100101010101011111110101101': 1, '10111101011011101001000111001010': 1, '01011110001101010000011110100001': 1, '11011111001000111110111111000111': 1, '11110011110011110101100100001110': 1, '11000111100111011101110001111010': 1, '01000010010011111101001010010111': 1, '01100110101111001101001100010110': 1, '10000000001111000010000101010110': 1, '01110110011110000011101011001110': 1, '10101010000101110001111101010001': 1, '01111001110100010111110011111110': 1, '00010001000111011011011011010010': 1, '01010111000110100010111010010111': 1,...

Energy produced: 0.514

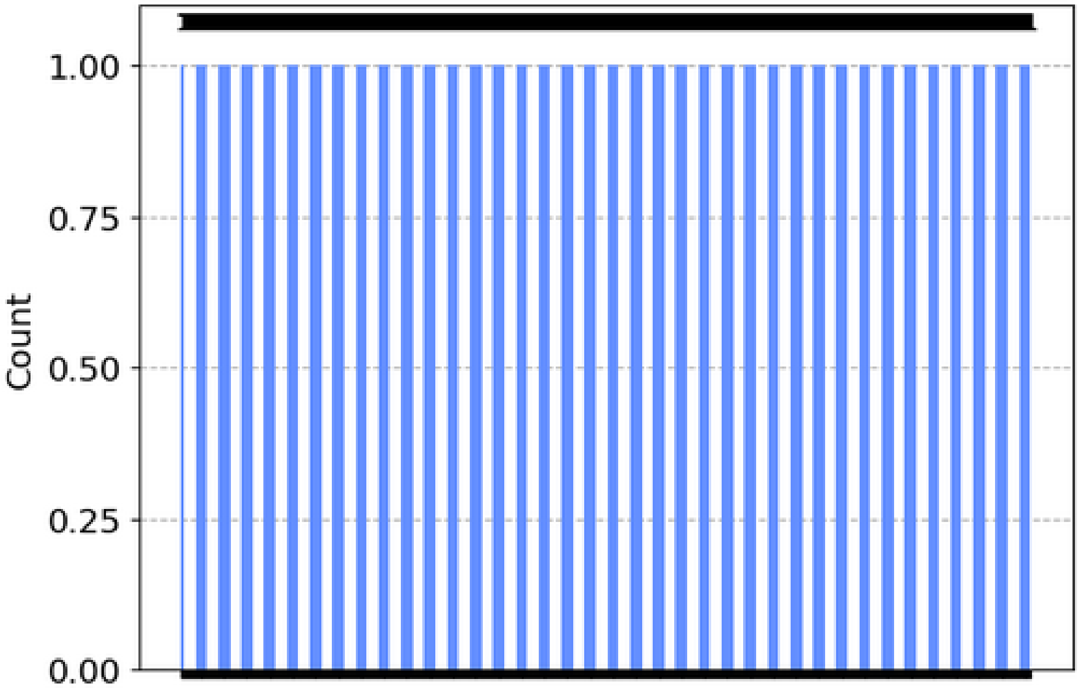


Figure 6: Photosynthesis Histogram - IBM 127 Qubits - Eagle r3

2.5 Code - Rigetti - ASPEM

```
from qiskit import QuantumCircuit, QuantumRegister
from qiskit import ClassicalRegister, Aer, execute
from qiskit.utils.quantum_instance import QuantumInstance
from qiskit.algorithms import Shor
from qiskit.circuit.library import QFT
from qiskit.circuit.library.standard_gates import CU1Gate
from azure.quantum.qiskit import AzureQuantumProvider
from azure.quantum.target.rigetti import RigettiTarget
from qiskit.tools.monitor import job_monitor
import numpy as np

# Create a 32-qubit quantum register
qr = QuantumRegister(32, 'q')

# Create a quantum circuit with the quantum register
photosynthesis_circuit = QuantumCircuit(qr)

# Apply Hadamard gate to each qubit
photosynthesis_circuit.h(qr)

# Apply Quantum Fourier Transform (simplified for illustration)
# Applying swap gates for simplicity;
# you might need a more complex pattern
for i in range(16):
    photosynthesis_circuit.swap(qr[i], qr[31 - i])

# Measure the qubits
photosynthesis_circuit.measure_all()

#print(photosynthesis_circuit)
```

```
# Create an object that represents Rigetti's  target, "
# rigetti.qpu.aspen-m-3" using the packaged constant.
# Note that any quantum computing target you have enabled
# in this workspace can be used here. Azure Quantum makes
# it extremely easy to submit the same quantum program to
# different providers.
rigetti_backend = provider.get_backend(RigettiTarget.ASPEN_M_3)

# Using the Rigetti simulator target, call "run" to submit
# the job. We'll use 100 shots (simulated runs).
job = rigetti_backend.run((photosynthesis_circuit), count=100)
job_monitor(job)
result = job.result()

# Print and visualize the results
counts = result.get_counts(photosynthesis_circuit)
print("Measurement results:", counts)

energy_produced = 0
for state, count in counts.items():
    if state[0] == '1':
        energy_produced += count
print(f"Final state: {counts}")
print(f"Energy produced: {energy_produced / 1000}")

plot_histogram(counts)
```

2.6 Results - Rigetti Aspen 80 Qubits

It was not possible to run the application on Rigetti's backend, the simplification of the Quantum Fourier Transform creates a quantum circuit that is incompatible with the architecture of Rigetti's processors, Error message: Problem compiling quil program: Unhandled error in host program: User program incompatible with chip: The program uses operations on qubits that cannot be logically mapped onto the chip topology. This set of qubits in the program cannot be assigned to qubits on the chip compatibly under a greedy connected component allocation scheme: ((15 16) (14 17) (13 18) (12 19) (11 20) (10 21) (9 22) (8 23) (7 24) (6 25) (5 26) (4 27) (3 28) (2 29) (1 30) (0 31)). The chip has the components ((100 107 101 106 102 105 103 104)).

Therefore, the swap simplification was modified for the use of CX (CNOT) operations as follows:

```
from qiskit import QuantumCircuit, QuantumRegister
from qiskit import ClassicalRegister, Aer, execute
# Create a 32-qubit quantum register
qr = QuantumRegister(32, 'q')

# Create a quantum circuit with the quantum register
photosynthesis_circuit = QuantumCircuit(qr)

# Apply Hadamard gate to each qubit
photosynthesis_circuit.h(qr)

# Apply Quantum Fourier Transform using CX gates
for i in range(16):
    photosynthesis_circuit.cx(qr[i], qr[31 - i])

# Measure the qubits
photosynthesis_circuit.measure_all()
```

The error persisted with the same message!

2.7 Code - Quantinuum

```
from qiskit import QuantumCircuit, QuantumRegister
from qiskit import ClassicalRegister, Aer, execute
from qiskit.utils.quantum_instance import QuantumInstance
from qiskit.algorithms import Shor
from qiskit.circuit.library import QFT
from qiskit.circuit.library.standard_gates import CU1Gate
from azure.quantum.qiskit import AzureQuantumProvider
from qiskit.tools.monitor import job_monitor
import numpy as np
from qiskit.visualization import plot_histogram

# Create a 32-qubit quantum register
qr = QuantumRegister(20, 'q')

# Create a quantum circuit with the quantum register
photosynthesis_circuit = QuantumCircuit(qr)

# Apply Hadamard gate to each qubit
photosynthesis_circuit.h(qr)

# Apply Quantum Fourier Transform (simplified for illustration)
# Applying swap gates for simplicity; you might need a
# more complex pattern
for i in range(10):
    photosynthesis_circuit.swap(qr[i], qr[19 - i])

# Measure the qubits
photosynthesis_circuit.measure_all()

#print(photosynthesis_circuit)
```

```
# Use the Aer simulator to run the circuit and obtain the results
quantinuum_backend = provider.get_backend("quantinuum.qpu.h1-1")
job = quantinuum_backend.run(photosynthesis_circuit, shots=1000)

job_monitor(job)
result = job.result()

# Print and visualize the results
counts = result.get_counts(photosynthesis_circuit)
print("Measurement results:", counts)

energy_produced = 0
for state, count in counts.items():
    if state[0] == '1':
        energy_produced += count
print(f"Final state: {counts}")
print(f"Energy produced: {energy_produced / 1000}")
```

2.8 Results - Quantinuum

Final state: {'10100010100001001101': 1, '01000011100111110001': 1, '00001100100100001001': 1, '11100101100100010001': 1, '11001111000010001011': 1, '11111110011100010111': 1, '11110000010011100010': 1, '10011111101110101001': 1, '00110011100000100111': 1, '10001001100110011000': 1, '01001010101000000111': 1, '00000001001100001000': 1, '01100011110011101011': 1, '01100000101000111101': 1, '00010010101000010000': 1, '01100101101101110001': 1, '11011100110100001111': 1, '01001000101010100011': 1, '10000011000100101110': 1, '11001001111000101010': 1, '01001101001001011000': 1, '10111110110100011000': 1, '01101101100010000011': 1, '11110011111111101100': 1, '11011011110110101100': 1, '11011011011110011001': 1, '11100101111001011101': 1, '11011111100000111100': 1, '10110010010001000001': 1, '11000100001111011101': 1, '00000111001010000000': 1, '10010000000101011101': 1, '00101000010011010011': 1, '10011011100100111011': 1, '00101111100100011001': 1, '01111010000100101011': 1, '10100100100001100010': 1, '01111100100001001111': 1, '00111111011111100001':

1, ’10011111110100101000’: 1, ’00100001100100000111’: 1, ’10100001001100010111’:
1, ’11011110001100100111’: 1, ’11011011001011110110’: 1, ’00011000000001101101’:
1, ’10100001101000110010’: 1, ’10111010111010001100’: 1, ’11110100110110101011’:
1, ’11010110110100100011’: 1, ’00000110000010110110’: 1, ’11011010000100110001’:
1, ’01011110111111010001’: 1, ’11001001011111001001’: 1, ’10100001101111011100’:
1, ’00101111001000001001’: 1, ’10101001110011111110’: 1, ’10011001110101111011’:
1, ’10111000101110000000’: 1, ’11101111101010010101’: 1, ’10100001100010110000’:
1, ’01001100101011100101’: 1, ’01111011110111110000’: 1, ’10001111101110101110’:
1, ’01101010001110110001’: 1, ’01000100000100001001’: 1, ’10011110110110100101’:
1, ’00100111000010110111’: 1, ’11010110111000111100’: 1, ’00010000110101100010’:
1, ’00100110101111111110’: 1, ’01010111011011111100’: 1, ’11110010110000000111’:
1, ’11111010010000111101’: 1, ’01100110000001111101’: 1, ’01000100010011100000’:
1, ’10110011010001110001’: 1, ’01101100101011011100’: 1, ’11111000101001101110’:
1, ’00110001110100011010’: 1, ’10100011111000111100’: 1, ’11101101001101011010’:
1, ’11000110010110001101’: 1, ’10000110100111011010’: 1, ’10111110000011110111’:
1, ’00101001011110111010’: 1, ’11110101110001101001’: 1, ’00110010100000010111’:
1, ’10000101010110100100’: 1, ...}

Energy produced: 0.507

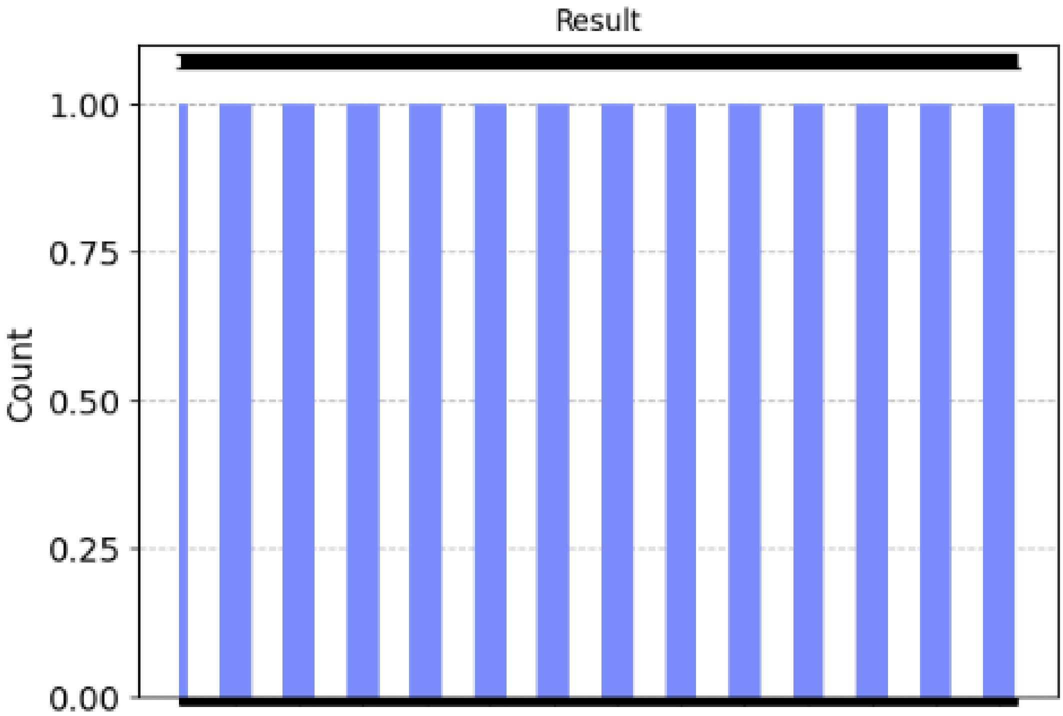


Figure 7: Photosynthesis Histogram - Quantinuum

2.9 Code - IonQ - 23 Qubits

```
from qiskit import QuantumCircuit, QuantumRegister
from qiskit import ClassicalRegister, Aer, execute
from qiskit.utils.quantum_instance import QuantumInstance
from qiskit.algorithms import Shor
from qiskit.circuit.library import QFT
from qiskit.circuit.library.standard_gates import CU1Gate
from azure.quantum.qiskit import AzureQuantumProvider
from qiskit.tools.monitor import job_monitor
import numpy as np

# Create a 22-qubit quantum register
qr = QuantumRegister(22, 'q')

# Create a quantum circuit with the quantum register
photosynthesis_circuit = QuantumCircuit(qr)

# Apply Hadamard gate to each qubit
photosynthesis_circuit.h(qr)

# Apply Quantum Fourier Transform (simplified for illustration)
# Applying swap gates for simplicity; you might need a
# more complex pattern
for i in range(11):
    photosynthesis_circuit.swap(qr[i], qr[21 - i])

# Measure the qubits
photosynthesis_circuit.measure_all()

# Use the IonQ Provider to run the circuit and
# obtain the results
ionq_backend = provider.get_backend("ionq.qpu.aria-1")
```

```
job = ionq_backend.run(photosynthesis_circuit, shots=1000)
job_monitor(job)
result = job.result()

# Print and visualize the results
counts = result.get_counts()
print("Measurement results:", counts)

energy_produced = 0
for state, count in counts.items():
    if state[0] == '1':
        energy_produced += count
print(f"Final state: {counts}")
print(f"Energy produced: {energy_produced / 1000}")

plot_histogram(result.get_counts(photosynthesis_circuit),
                                            title="Result")
```

Note: It was not possible to test IonQ's quantum computers on the Microsoft Azure environment, let alone on the company's own environment, due to the complete unavailability of the platform.

2.10 IonQ Unavailability

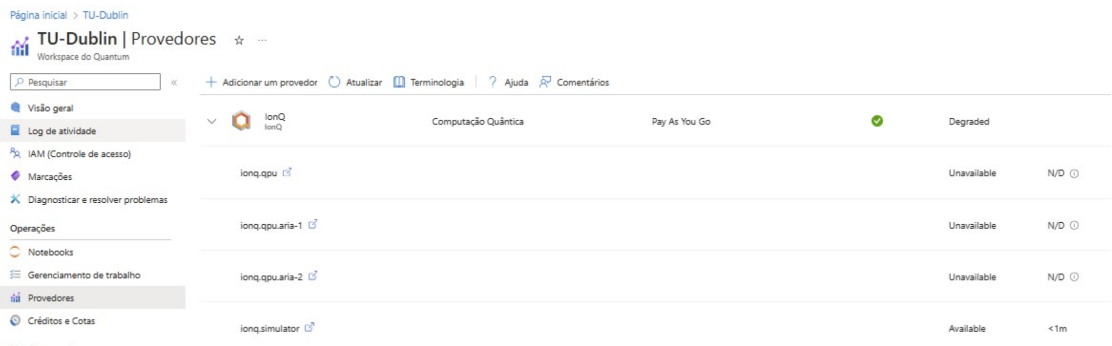


Figure 8: IonQ unavailability in Microsoft Azure

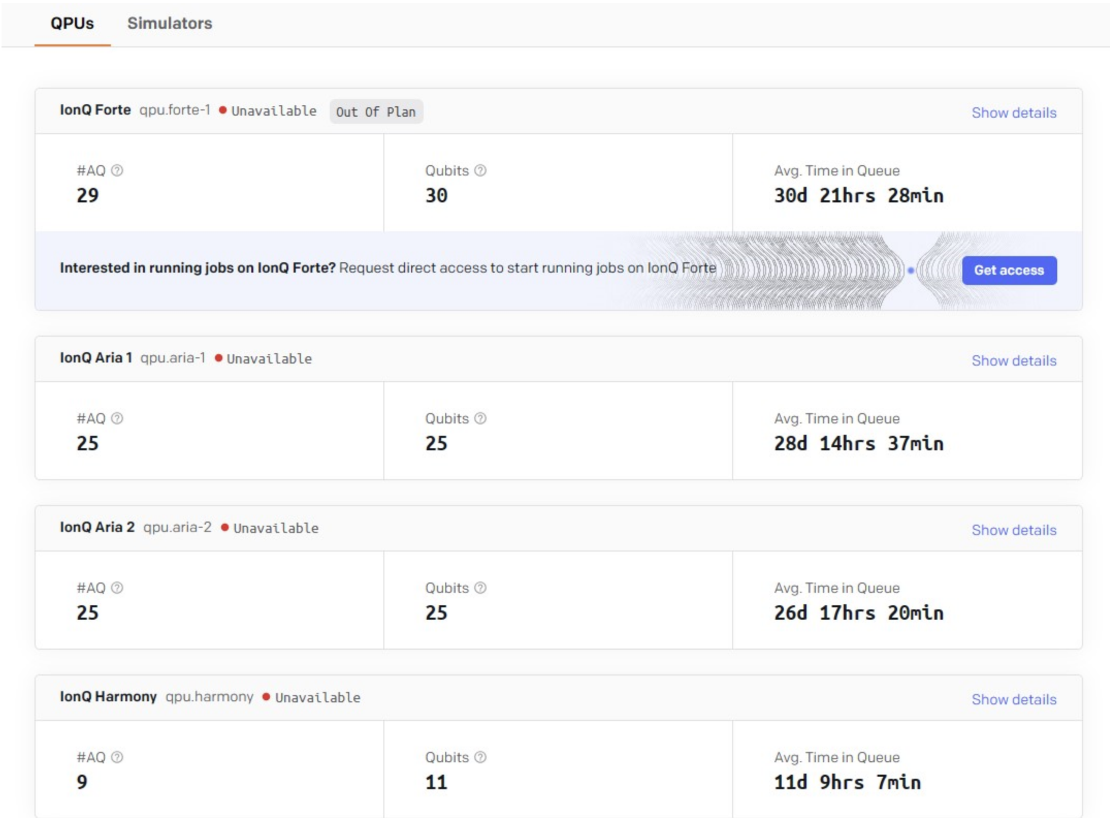


Figure 9: IonQ unavailability in IonQ Console

3 Quantum Bitcoin Mining

According to a study from the University of Cambridge, the energy consumption used by bitcoin mining machines corresponds to the energy consumption of Argentina—equivalent to 121.36 TeraWatt-hours (TWh) per year (BITCOIN, 2021). This has raised concerns about the environmental impact of bitcoin mining activity. Economics, though some may declare it a science, is nothing more than an abstraction constructed by human society. Both the US and China, possibly foreseeing future economic sanctions, invested in creating a payment system that would run outside the SWIFT payment system controlled by the US and using the dollar as the exchange currency (ROTBLAT, 2017). With control of the dollar and the SWIFT payment system used as a weapon of war, the US can block assets from any country, company, or person without stating reasons, simply by imposing sanctions as they see fit. Russia and China invested heavily in buying gold and acquiring bitcoin, possibly anticipating economic sanctions and avoiding financial problems. Bitcoin has become an essential element for protecting assets and values in a world where assets can be seized at any time depending on the situation your country faces with the rules imposed by the US government (HK, 2023). Amid so many conflicts occurring in the developed world and the Global South for the definition of a hegemonic or multi-hegemonic world, the trend is towards seeking financial protection. This protection may very well involve an increased use of bitcoin and, consequently, greater energy consumption for bitcoin processing. New processors in the iPhone 15, expected to have a significant performance gain with 7-nanometer technology, did not deliver the expected performance for Apple (TARASOV, 2023). It is undeniable that the world increasingly depends on greater processing power, as challenges grow for humanity. Low performance in processors could result in a horizontal growth of computer architecture for bitcoin processing, with mining operations likely to increase in number and energy consumption. The use of quantum computers for bitcoin mining could be a perfect solution for the future computational aspect of virtual currency. Quantum computers have very low power consumption compared to classical computers.

3.1 Grover's Algorithm

Grover's algorithm does not aim to break asymmetric cryptographic keys like RSA; nevertheless, it can impact the security of symmetric keys and hash functions. Grover's algorithm has been making strides in post-quantum cryptography (GYEONGJU, 2023), which could significantly enhance security in the near future. The complexity of Grover's algorithm is approximately $O(\sqrt{N})$, whereas corresponding classical algorithms for unstructured search have a complexity of $O(N)$. Therefore, Grover provides a quadratic advantage over classical algorithms, making it more efficient for search problems, although this gain has not been identified significantly due to issues in the machines that ran the Jupyter Notebook.

The quantum tunneling that occurs from particle to wave generates a quantum transfer process similar to Grover's algorithm (YU, 2022), one of the few algorithms that can be efficiently utilized in quantum computers with Hamiltonians describing low power consumption.

3.2 Code Description

This code is a basic implementation of the Grover's algorithm for a fictional scenario of searching for a Bitcoin address. Grover's algorithm is particularly powerful for unstructured search problems, offering a significant quantum advantage compared to classical algorithms.

Marking Operator The marking operator is a crucial part of the Grover's algorithm. It is designed to increase the probability of measuring the desired state, which in this case is the state associated with the secret key. During each iteration of the loop, the function applies a sequence of quantum gates (such as the X gate and the controlled-T gate) to mark the desired state.

Diffusion Operator: The diffusion operator is another vital part of the algorithm. It is designed to amplify the amplitude of the marked state and reduce the amplitudes of the unmarked states. This significantly increases the probability of measuring the desired state in the next iteration.

Measurement and Simulation After the implementation of the diffusion operator, the code performs measurements on the qubits to collapse the quantum state. Then, the quantum circuit is simulated using the Qiskit simulator to obtain the simulation results.

Circuit Visualization The 'visualize_circuit' function uses the Qiskit 'circuit_drawer' functionality to generate a visual representation of the quantum circuit. This is helpful for understanding the circuit's structure and visualizing how the quantum gates are applied.

Secret Key and Parameters The code defines a fictional secret key, which is essential for the Bitcoin address search. Additionally, the number of iterations of the marking/diffusion operator (the core of the Grover's algorithm) is specified.

Search and Output The main function, 'grover_bitcoin_address_search', is called with the secret key and the number of iterations as input. The generated Bitcoin address is compared with the real address (calculated by the 'generate_bitcoin_address' function). The address found by the Grover's algorithm is printed, allowing for a comparison with the real address.

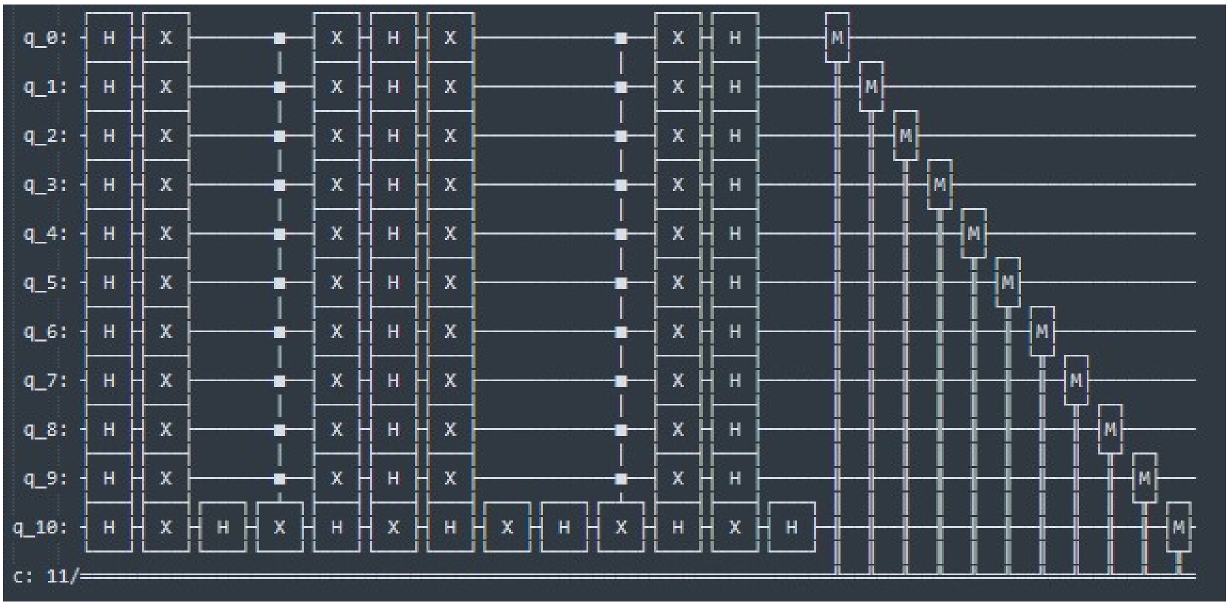


Figure 10: Quantum Bitcoin Circuit with 11 Qubits

3.3 Code - Bitcoin - IBM 127 Qubits - Eagle r3

```
from qiskit import QuantumCircuit, Aer, execute
import matplotlib.pyplot as plt
from ibm_quantum_widgets import CircuitComposer
from qiskit_ibm_provider import IBMProvider
from qiskit import transpile, assemble

# Function that simulates the generation of a fictitious
# Bitcoin address
def generate_bitcoin_address(secret_key):
    return "1" + secret_key + "abcd"

# Implementation of Grover's algorithm to find Bitcoin address
def grover_bitcoin_address_search(secret_key, num_iterations):
    n = len(secret_key)  # Input size
```

```
num_qubits = n  # Number of qubits required to represent all inputs

# Quantum circuit initialization
qc = QuantumCircuit(num_qubits, num_qubits)

# Initial state preparation
qc.h(range(num_qubits))

# Implementation of the marking operator
for _ in range(num_iterations):
    qc.x(range(num_qubits))
    qc.h(num_qubits - 1)
    qc.mct(list(range(num_qubits - 1)), num_qubits - 1)
    qc.h(num_qubits - 1)
    qc.x(range(num_qubits))

# Implementation of the diffusion operator
qc.h(range(num_qubits))
qc.x(range(num_qubits))
qc.h(num_qubits - 1)
qc.mct(list(range(num_qubits - 1)), num_qubits - 1)
qc.h(num_qubits - 1)
qc.x(range(num_qubits))
qc.h(range(num_qubits))

qc.measure(range(num_qubits), range(num_qubits))

backend_name = 'ibm_brisbane'
shots = 1024
# Load a previously saved account.
provider = IBMProvider()
```

```
    # Select a different hub/group/project.
    provider = IBMProvider(instance="ibm-q/open/main")

    # Transpile the circuit for the target backend
    backend = provider.get_backend(backend_name)
    transpiled_circuit = transpile(qc, backend, optimization_level=3)

    # Run the transpiled circuit on the quantum computer
    job = execute(transpiled_circuit, backend, shots=shots)
    result = job.result()

    # Print Quantum circuit
    print(qc)
    counts = result.get_counts()
    plt.bar(counts.keys(), counts.values())

    # Find the most likely Bitcoin address
    most_probable_address = max(counts, key=counts.get)
    return most_probable_address

# Dummy secret key for example
secret_key = "10101110001" # 11 bits

# Number of iterations for Grover's algorithm (can be adjusted for
# better results)
num_iterations = [1, 5, 10, 20, 100, 1000]

# Perform Bitcoin address lookup using Grover
for interations in num_iterations:
    found_address = grover_bitcoin_address_search(secret_key
                                                  ,interations)
```

```
print(f"- - - Number of Interactions: {interations} - - -")
print("Generated Bitcoin address:"
                    ,generate_bitcoin_address(found_address))
print("Real Bitcoin Address:"
                    ,generate_bitcoin_address(secret_key))
print("Bitcoin address found by Grover's algorithm:"
                    , found_address)
print("\n")
```

3.4 Results - IBM 128 Qubits - Eagle r3

- - - Number of Interactions: 1 - - -
Generated Bitcoin address: 110111110000abcd
Real Bitcoin Address: 110101110001abcd
Bitcoin address found by Grover's algorithm: 10111110000

- - - Number of Interactions: 5 - - -
Generated Bitcoin address: 100000000000abcd
Real Bitcoin Address: 110101110001abcd
Bitcoin address found by Grover's algorithm: 00000000000

- - - Number of Interactions: 10 - - -
Generated Bitcoin address: 100011000101abcd
Real Bitcoin Address: 110101110001abcd
Bitcoin address found by Grover's algorithm: 00011000101

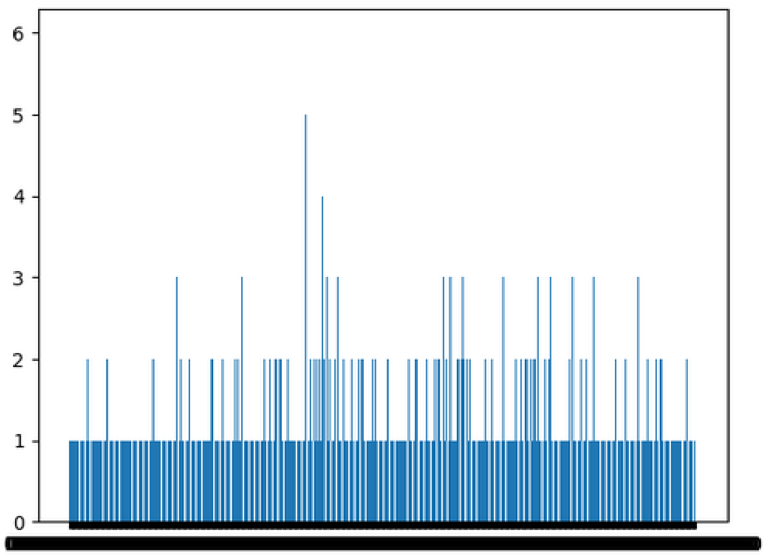
- - - Number of Interactions: 20 - - -
Generated Bitcoin address: 101011000001abcd
Real Bitcoin Address: 110101110001abcd
Bitcoin address found by Grover's algorithm: 01011000001

- - - Number of Interactions: 100 - - -
Generated Bitcoin address: 100110001111abcd
Real Bitcoin Address: 110101110001abcd
Bitcoin address found by Grover's algorithm: 00110001111

- - - Number of Interactions: 1000 - - -
Generated Bitcoin address: 100001101011abcd
Real Bitcoin Address: 110101110001abcd
Bitcoin address found by Grover's algorithm: 00001101011

3.4.1 IBM Result Histogram

Figure 11: Histogram (IBM Quantum Computer - ibm brisbane)



The provided code implements Grover's algorithm for a Bitcoin address search using a quantum circuit. The plt.bar(counts.keys(), counts.values()) line generates a bar plot that represents the measurement outcomes (counts) of the quantum circuit. Each bar in the plot corresponds to a different measurement outcome, and the height of the bar indicates the frequency of that outcome.

In this context, the x-axis of the bar plot represents the possible measurement outcomes, and the y-axis represents the frequency (number of occurrences) of each outcome. The bar plot visually displays the probability distribution of measurement outcomes after running the quantum circuit.

Note: It's important to mention that the visualization provided by the bar plot may not be directly meaningful in the context of a quantum algorithm. Quantum algorithms often leverage interference effects, and the bar plot represents the statistical distribution of measurement results obtained from multiple runs of the quantum circuit.

3.5 Code - Bitcoin - IonQ Similator

```
from qiskit import QuantumCircuit, Aer, execute
import matplotlib.pyplot as plt
from qiskit.visualization import circuit_drawer
from qiskit.tools.monitor import job_monitor

# Function that simulates the generation of
# a fictitious Bitcoin address
def generate_bitcoin_address(secret_key):
    return "1" + secret_key + "abcd"

# Implementation of Grover's algorithm to
# find Bitcoin address
def grover_bitcoin_address_search(secret_key, num_iterations):
    n = len(secret_key)  # Input size
    num_qubits = n # Number of qubits required to represent all inputs

    # Quantum circuit initialization
    qc = QuantumCircuit(num_qubits, num_qubits)

    # Initial state preparation
    qc.h(range(num_qubits))

    # Implementation of the marking operator
    for _ in range(num_iterations):
        qc.x(range(num_qubits))
        qc.h(num_qubits - 1)
        qc.mct(list(range(num_qubits - 1)), num_qubits - 1)
        qc.h(num_qubits - 1)
        qc.x(range(num_qubits))

    # Implementation of the diffusion operator
```

```
    qc.h(range(num_qubits))
    qc.x(range(num_qubits))
    qc.h(num_qubits - 1)
    qc.mct(list(range(num_qubits - 1)), num_qubits - 1)
    qc.h(num_qubits - 1)
    qc.x(range(num_qubits))
    qc.h(range(num_qubits))

    qc.measure(range(num_qubits), range(num_qubits))

    #print(qc)

    ionq_backend = provider.get_backend("ionq.simulator")
ionq.qpu
    # Using the IonQ simulator target, call "run" to submit the job.
    # We'll use 100 shots (simulated runs).
    job = ionq_backend.run(qc, shots=100)
    job_monitor(job)
    result = job.result()
    counts = result.get_counts()
    plt.bar(counts.keys(), counts.values())

    # Find the most likely Bitcoin address
    most_probable_address = max(counts, key=counts.get)
    return most_probable_address

# Function to visualize the circuit
def visualize_circuit(qc):
    # Display the circuit with Qiskit's circuit_drawer method
    circuit_drawer(qc, output='mpl').show()

# Dummy secret key for example
```

```python
secret_key = "10101110001" # 11 bits

# Number of iterations for Grover's algorithm
# (can be adjusted for better results)
num_iterations = [1, 5, 10, 20, 100, 1000]

# Perform Bitcoin address lookup using Grover
for interations in num_iterations:
    found_address = grover_bitcoin_address_search
                                    (secret_key, interations)

    print(f"- - - Number of Interactions: {interations} - - -")
    print("Generated Bitcoin address:",
                                generate_bitcoin_address(found_address))
    print("Real Bitcoin Address:",
                                generate_bitcoin_address(secret_key))
    print("Bitcoin address found by Grover's algorithm:",
                                found_address)
    print("\n")
```

3.6 Results - IonQ 11 Qubits - Simulator

Job Status: job has successfully run
- - - Number of Interactions: 1 - - -
Generated Bitcoin address: 101010111111abcd
Real Bitcoin Address: 110101110001abcd
Bitcoin address found by Grover's algorithm: 01010111111

Job Status: job has successfully run
- - - Number of Interactions: 5 - - -
Generated Bitcoin address: 101011011001abcd
Real Bitcoin Address: 110101110001abcd

Bitcoin address found by Grover's algorithm: 01011011001

Job Status: job has successfully run
- - - Number of Interactions: 10 - - -
Generated Bitcoin address: 100101001001abcd
Real Bitcoin Address: 110101110001abcd
Bitcoin address found by Grover's algorithm: 00101001001

Job Status: job has successfully run
- - - Number of Interactions: 20 - - -
Generated Bitcoin address: 100000100010abcd
Real Bitcoin Address: 110101110001abcd
Bitcoin address found by Grover's algorithm: 00000100010

Job Status: job has successfully run
- - - Number of Interactions: 100 - - -
Generated Bitcoin address: 100011011010abcd
Real Bitcoin Address: 110101110001abcd Bitcoin address found by Grover's algorithm: 00011011010

Job Status: job has successfully run
- - - Number of Interactions: 1000 - - -
Generated Bitcoin address: 100010100000abcd
Real Bitcoin Address: 110101110001abcd
Bitcoin address found by Grover's algorithm: 00010100000

3.7 Code - Bitcoin - Rigetti

```
from qiskit import QuantumCircuit, Aer, execute
import matplotlib.pyplot as plt
from qiskit.visualization import circuit_drawer
from qiskit.tools.monitor import job_monitor
from azure.quantum.qiskit import AzureQuantumProvider
from qiskit.providers.ibmq import least_busy
from azure.identity import InteractiveBrowserCredential
from azure.quantum.target.rigetti import RigettiTarget

# Function that simulates the generation of a
# fictitious Bitcoin address
def generate_bitcoin_address(secret_key):
    return "1" + secret_key + "abcd"

# Implementation of Grover's algorithm to find
# Bitcoin address
def grover_bitcoin_address_search(secret_key, num_iterations):
    n = len(secret_key)  # Input size
    num_qubits = n # Number of qubits required to represent all inputs

    # Quantum circuit initialization
    qc = QuantumCircuit(num_qubits, num_qubits)

    # Initial state preparation
    qc.h(range(num_qubits))

    # Implementation of the marking operator
    for _ in range(num_iterations):
        qc.x(range(num_qubits))
        qc.h(num_qubits - 1)
```

```
        qc.mct(list(range(num_qubits - 1)), num_qubits - 1)
        qc.h(num_qubits - 1)
        qc.x(range(num_qubits))

    # Implementation of the diffusion operator
    qc.h(range(num_qubits))
    qc.x(range(num_qubits))
    qc.h(num_qubits - 1)
    qc.mct(list(range(num_qubits - 1)), num_qubits - 1)
    qc.h(num_qubits - 1)
    qc.x(range(num_qubits))
    qc.h(range(num_qubits))

    qc.measure(range(num_qubits), range(num_qubits))

    #print(qc)

    rigetti_backend = provider.get_backend(RigettiTarget.QVM)
    #rigetti_backend = provider.get_backend(RigettiTarget.ASPEN_M_3)

    # Using the Rigetti target, call "run" to submit the job. We'll
    # use 1000 shots (simulated runs).
    job = rigetti_backend.run(qc, count=100)

    job_monitor(job)
    result = job.result()
    counts = result.get_counts(qc)
    plt.bar(counts.keys(), counts.values())

    # Find the most likely Bitcoin address
    most_probable_address = max(result.get_counts(qc).keys())
    return most_probable_address
```

```
# Dummy secret key for example
secret_key = "10101110001"  # 11 bits

# Number of iterations for Grover's algorithm
# (can be adjusted for better results)
num_iterations = 1

# Perform Bitcoin address lookup using Grover
found_address = grover_bitcoin_address_search
                    (secret_key, num_iterations)

#if found_address is not None:
print("Generated Bitcoin address:",
                generate_bitcoin_address(found_address))
print("Real Bitcoin Address:",
                generate_bitcoin_address(secret_key))
print("Bitcoin address found by Grover's algorithm:",
                found_address)
```

3.8 Results - IonQ 11 Qubits (Simulator)

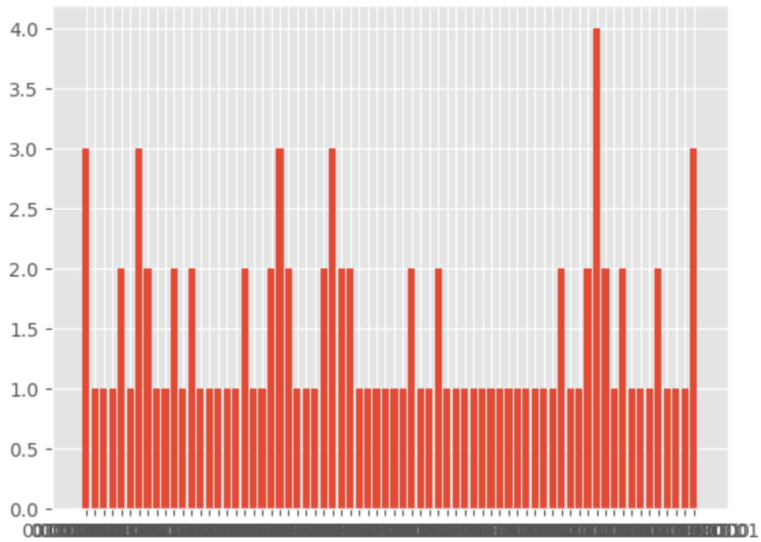
Job Status: job has successfully run
Generated Bitcoin address: 111110100101abcd
Real Bitcoin Address: 110101110001abcd
Bitcoin address found by Grover's algorithm: 11110100101

3.8.1 Rigetti Result Histogram

3.9 Rigetti Issues

The Bitcoin application ran successfully on the Rigetti backend only in the simulation environment. However, the same application failed to run on the real quantum computing environment, the Aspen M3 backend. Attempts were made to update

Figure 12: Histogram (Rigetti Quantum Computer - Aspen M3)



libraries.

In tests conducted on the Rigetti backend, the Bitcoin application executed only in the simulated environment. Conversely, in the real quantum computing environment, specifically the Aspen M3 backend, it was not possible to run the same application by simply switching the backend, as shown in the example below:

```
```python
rigetti_backend = provider.get_backend(RigettiTarget.QVM)
```
to
```python
rigetti_backend = provider.get_backend(RigettiTarget.ASPEN_M_3)
```
```

4 Building an Open Source Quantum Computer

Diamonds are generally associated with perfection, but that is not the case in nature, and this imperfection has been explored by the diamond industry in the form of nitrogen vacancy (NV) diamonds. The industry uses artificial growth techniques for diamond construction. This technology allows more effective control over the amount of impurities inserted into the crystalline structure of diamonds, altering their physical and dielectric properties. Impurities generated within diamonds create color centers that can interact with light and electrons, delivering certain characteristics useful in quantum experiments and even in the quantum computing industry, as described in the following work. (HAQUE, 2017)

Color centers are created by inserting a nitrogen atom into the carbon crystalline structure of the diamond. The nitrogen atom then replaces a carbon atom, creating a void within the crystalline structure, as if an atom were missing, with four adjacent atoms around this vacancy, one of which is the nitrogen atom. As nitrogen has one extra electron in the outer orbit, this additional electron remains unpaired and trapped within this vacancy, generating the nitrogen vacancy. When there is an electron within this vacancy, it becomes electronically unstable and captures an additional electron within this center through a nitrogen donor atom within the crystalline network, as shown in the figure below (PEZZAGNA, 2021). Thus, this nitrogen vacancy center becomes negatively charged. This vacancy can have the spin of its electrons quantum-controlled through microwave pulses and measured through photoluminescence measurement. Depending on the spectrum range of light incident on this light center, fluorescence can emit a photon in the red spectrum, and when excited by microwaves, the external magnetic field can be determined. The use of these nitrogen vacancy diamonds' characteristics can be applied in various areas, including quantum computing, as developed in Germany with the support of the German Aerospace Center through startups and the Australian-German Quantum Brilliance company (HPCWIRE, 2022), which will be mentioned later in this text.

The race to build quantum computers has been contested in recent years, and these machines will soon deliver significant advances for humanity. However, today's

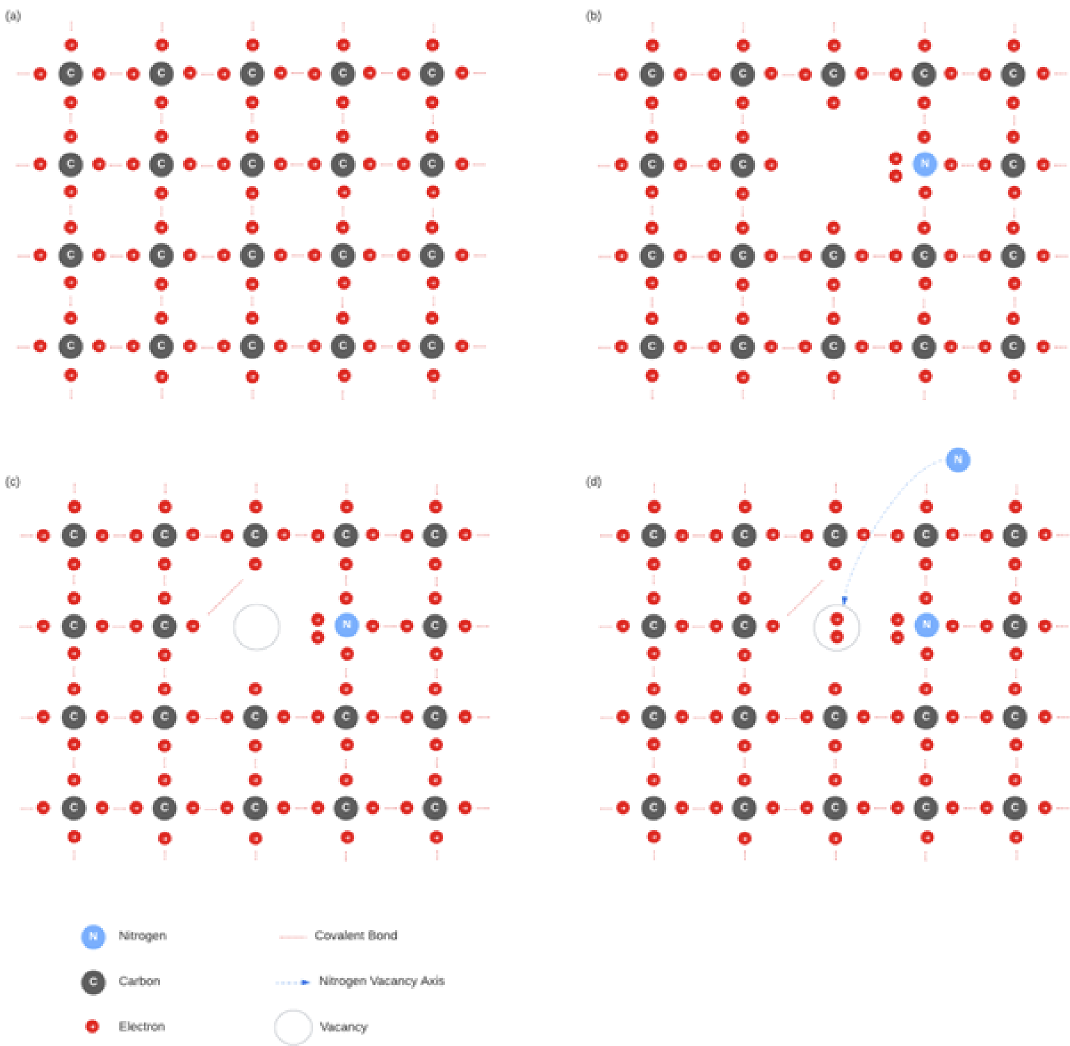


Figure 13: NV (Nitrogen Vacancy) Diamond Structure

quantum computers are large closed cabinets occupying significant amounts of space. Given this current architecture model based on silicon and superconductor materials, there are clear difficulties in miniaturizing these devices soon. This is because, in addition to computers, the cooling systems are also very large due to the requirement of temperatures near absolute zero. However, a new type of architecture has been gaining strength in recent years: diamond-based quantum computers with nitrogen vacancy. One of the processes used for construction is based on the epitaxial growth process, where carbon atoms are deposited within the diamond structure. These diamonds are usually purer than those found in nature. However, like in nature, the process is not perfect, and there are flaws within the carbon network structure. Alongside the Nitrogen Vacancy Diamond manufacturing process, nitrogen is included in the structure. Diamonds with nitrogen, both natural and synthetic, have a yellowish color if they have nitrogen within their crystalline structure.(PEZZAGNA, 2021)

Nitrogen atoms replace carbon atoms in the structure. When these atoms are inserted adjacent to the carbon structure, nitrogen vacancy centers are created. The challenge in this process is to create several adjacent nitrogen vacancy centers, allowing quantum entanglement. These centers can then be used as qubits for quantum computing at ambient temperatures, significantly reducing the quantum computer's size, as there is no need for the entire cooling apparatus to maintain the entanglement state. The Australian-German Quantum Brilliance company, in partnership with the University of Stuttgart and the Fraunhofer IAF institute, has 2U servers with 5 qubits that do not require cooling. These servers are called quantum accelerators, similar to a graphics card that accelerates image processing and calculations. The company believes that in the coming years, they will be able to develop new machines with up to 50 qubits and has already been working toward that goal (HPCWIRE, 2022). The architecture of Quantum Brilliance products is based on NV (Nitrogen Vacancy) diamonds, and the company aims to provide quantum computers in the future that could even match cars and health electronic devices, using quantum processing to accelerate calculations that would depend on supercomputers in a portable and affordable way. The technology based on nitrogen vacancy diamond processors may make quantum computing accessible at home and on the go in the near future!

Quantum Brilliance has also developed a new precise technique for NV diamond construction with a bottom-up manufacturing process in carbon layers using a lithography technique. In addition to this manufacturing process, the integrated quantum chip miniaturizes magnetic, optical, and electrical systems, techniques that the company plans to use for the construction of future 50-qubit quantum computers mentioned earlier (HPCWIRE, 2022). The company intends to launch these computers in 2025. The German Aerospace Center recently invested 57 million euros in the development of nitrogen vacancy-based processors through startups SaxonQ and XeedQ (QCI, 2023). The XQ1, presented by the startup XeedQ, was the world's first mobile multi-qubit quantum processor operating at room temperature. The race for the development of portable quantum computers is on, and it is being dominated by NV diamond-based architectures. The company aims to reach 50 qubits by 2026. Although the XQ1 is the size of a small refrigerator, efforts are being made to miniaturize these devices. The current accelerators from Quantum Brilliance occupy 19 inches, and the future accelerators will be the size of gaming video cards (QUANTUM, 2023). In theory, quantum computers with 300 bits could perform more calculations than the total number of atoms in the universe. Another important advantage of NV diamond-based quantum computers is that the carbon layers within the diamond's crystalline structure prevent external interference. This allows for fewer errors generated by qubit decoherence. With fewer interferences and larger amounts of nested nitrogen vacancies through the process developed by Quantum Brilliance, there are fewer errors, allowing quantum computers to extend their processing time and volume of data to be calculated.

The University of Hong Kong, through engineers and physicists, has been developing a new technique for NV diamond construction using a precision nanometer-scale printing process. This technology will allow the creation of noise-free quantum memories and processors. (HKU, 2023)

5 The Challenges of the Future

It would be very interesting for universities in Ireland to join forces with the government for the development of these machines and simultaneously include quantum computing disciplines for their students. The time window to embrace these initiatives may be very small, and mastering these quantum computing technologies can be crucial for the future scientific and technological development of Ireland.

We will address some issues in this work. One of them is quantum photosynthesis, a problem debated by the scientific and biological communities for many years, as the efficiency index of plant photosynthesis processes reaches values close to 97%. Many physicists believe that this efficiency can only be achieved through a quantum process where photons propagate in wave form within the chloroplast. Recently, a group of researchers identified a Bose-Einstein process within photosynthesis, a state-of-matter behavior where atomic particles have no movement and can only be achieved at temperatures near absolute zero (LERNER, 2023). This work will present an application based on quantum computing using the QisKit language based on Python. This application will be tested on various quantum computers and service providers to analyze efficiency, costs, compatibility, and the performance of the computers offered.

The second test will be based on the use of Bitcoin mining algorithms. The goal is to analyze the cost of running this algorithm using classical computers and quantum computers, examining the performance and the cost involved in this processing. Currently, bitcoin mining machines consume significant amounts of electrical energy, potentially making the adoption of this monetary model economically unviable due to energy consumption.(CHO, 2021)

Finally, a brief essay will be presented for the development of a quantum computer project. The goal is to create a foundation for a future project that culminates in the first open-source quantum computer so that universities and students can access this technology, and it can be replicated simply, practically, and affordably by universities and entities navigating this ocean of great opportunities.

6 Conclusion

The Large Hadron Collider (LHC) is the largest machine ever built by humanity. The LHC has rewarded particle science with the discovery of the Higgs boson. However, the LHC is not just a machine; it depends on other machines and thousands of scientists involved locally and around the planet (DITTMAIER, 2013). Intensive computing use is deeply necessary for these discoveries to be made. Advanced research in big science depends on clusters of supercomputers running 24x7, incurring exorbitant costs in machine acquisition and maintenance (SHIERS, 2007). There are applications that take up to 2 years to run on these supercomputer clusters, entering long queues for their turn to run, according to Brazilian astrophysicist Roberta Duarte (ROBERTA, 2021) and an error in a program leads to long delays and immense financial costs. This kind of science is far from less-developed and undeveloped countries, making big science a distant dream for these nations.

It is important to note that India's moon landing has boosted its self image (ABRAHAM, 2023), However, little is said that, thanks to aerospace technology, India has improved its agricultural productivity, ensuring food security for millions of Indians (CASSIDY, 2021). Advanced science and cutting-edge technology impact the quality of life in countries where these disciplines occur. Quantum computing opens an opportunity that can deepen the improvement of science and technology in countries that need to provide better living conditions and economic development for their people. Quantum computing based on NV (Nitrogen Vacancy) Diamonds may in the future miniaturize and reduce the size of quantum computers, enabling the construction of quantum computer clusters (LERNER, 2023). It becomes essential to invest in this type of technology to give students access to this new technology that will open new doors for human development. Ireland needs to embrace this cause and invest time and resources in the pursuit of the development and improvement of this type of technology as well as its use.

During the tests, some relevant aspects that may be considered important for future users of quantum computing applications include the unavailability of services on Amazon Web Services and other similar service providers such as IBM, Microsoft Azure, and Google Cloud Platform. Many quantum computers take hours or even days to be made available to run applications. Although batch processing is possible, it makes debugging the code impractical. While Qiskit, a Python-based language, can be used to run on various environments due to its compatibility announced by providers, the machines are technologically incompatible for certain types of quantum gates and composite gates. The differences force the developer to spend valuable time changing the code structure by decomposing the gates to a lower level to ensure their code runs. The problem of changes due to architectural incompatibility along with the unavailability of machines delays the entire project. Debugging becomes an insane task because errors will only be visible hours or even days later, making error correction inefficient.

Quantum computers have been a promise of significant progress, as noted by the writer and scientist Michio Kaku (KAKU, 2023) in his latest book on Quantum Supremacy. Richard Feynman (FEYNMAN, 1986) was one of the early advocates for the construction of a quantum computer to simulate quantum physical effects impossible to simulate on classical computers. The goal of this work was to validate Richard Feynman's dream, and today, quantum computers are a reality. However, developing applications for them is complex, as quantum computers rely on classical computers for input, data preparation, and data output.

Both quantum and classical computers associated with them were analyzed, revealing that it requires a lot of patience to build, debug, and run applications. Availability was also assessed, and it is quite disappointing; most machines from various providers are unavailable most of the time. Development interfaces, such as Jupyter, run in containers with limited memory, competing for processing time with queues of potential users. The demand is highly suppressed, IDEs are limited, and only about 1 out of 10 attempts run efficiently. Quiskit is a development language compatible with all providers, enabling applications to run on different types of quantum computers, but not all share the same quantum gates. Finding the right libraries for compatible running demands time, patience, and considerable effort, but it is possible to build an application that can run on all of them.

Despite the encountered difficulties, there is still enthusiasm for quantum machines and applications. Within them lie relevant aspects for the future of humanity. The truth is that we need more quantum computers at this moment, and although there are limitations, many things can be accomplished in both scientific and commercial areas.

An important point in Bitcoin application testing was the number of interactions of the Grove algorithm. Increasing interactions simultaneously creates sequences of replicas of the initial circuit, introducing greater complexity. Results were more complex when analyzed based on the number of interactions. Initial Bitcoin tests used 11 bits, corresponding to the number of qubits available on IonQ. Models with 23 bits, such as the IonQ Aria, faced challenges, often reaching the container's memory limit, leading to application cancellation. Tests were then limited to 11 bits for all quantum computers and providers. Similar issues occurred on AWS, hindering test progress in that environment. Microsoft's Quantum Azure environment seemed reliable, while challenges in finding concise and comprehensive documentation for GCP's quantum server environment prevented adaptation due to application errors and library incompatibility, despite Qiskit being a common language.

The IBM Experience Lab is an intriguing environment, with some difficulties due to memory usage limits. However, IBM's environment has the highest availability of quantum computers for use, featuring a user interface for both the quantum computers' dashboard and general usage. Using IBM Quantum Experience is recommended, and although there are minor differences in calling quantum computers for processing, the Bitcoin program, when correctly defined, can be compatible with other computers offered by Azure Quantum.

The Rigetti environment required some changes that, although small, demanded a significant amount of time to adapt the application for it to run. Even after these efforts, only the simulated environment offered some success in execution, albeit limited in the number of interactions that increase the circuit's complexity. The same increase in interactions ran successfully in IBM and IonQ environments, highlighting the low maturity level of the Rigetti environment integrated with the Microsoft Azure platform. Another crucial aspect is the low availability of machines for usage. The combination of these issues creates little incentive for the practical application of quantum computing in a mature commercial environment, potentially causing strategic differences in businesses. The difficulties may discourage future developers on this platform, reducing the market's prospects for having a considerable number of competent professionals capable of making quantum computing a significant differentiator in the progress of humanity in the near future.

A lot has been said, and the promise is significant for quantum computing, but the lack of available development environments and hardware severely compromises the future of quantum computing. The difficulties and the absence of environments synchronized with up-to-date code packages, coupled with high demand and low supply, create an unpleasant situation for developers and investors looking at these machines and designing a future strategy for their businesses based on this promising technology. It is essential for providers to have a greater commitment to this future, lacking more strategic vision and investments so that this new technology can take off and progress.

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