Quantization of High-Performance Computing

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***Abstract*—As the present era has moved towards venturing with technology to fulfill its daily requirements of life, the pressure on the technical infrastructure has increased multiple folds. So, the concept of High-Performance Computing has risen to fame. Big tech firms have moved to the use of highly capable computing infrastructure, which are capable of performing calculations much faster than conventional desktops, they are known as supercomputers.**

A supercomputer performs some large, complex calculations by aggregating computing power, which would, in turn, upscale the speed of the computers. But there are some cases where these supercomputers also fall short of capabilities, then there comes into light the Quantum Computing that exploits the concept of Quantum Mechanics, which is quite mystical in itself and defies our intuition, to avail us with the capabilities for performing more complex calculations. It opens us the door for solving problems that are quite impossible to solve using the current processing speeds of our classical computers.

Quantum Computing in the present stage is a matter of academia in its pursuit of development rather than a practical achievement, but these computers once in full fling action will far exceed the potential of our Present-Day classical computers, which are at their peak of proficiency.

Thus, this paper proposes the idea of raising the bar of High-Performance Computing by inducting quantum computers as a potential replacement for Supercomputers of the Future.

***Keywords*— Supercomputer, Quantum Computing, Quantum Mechanics, High-Performance Computers.**

I. INTRODUCTION

Computing has been by our sides for quite a time now, and as we see the timeline of its development, it has evolved to its heights in quite a short while, with engineers, scientists and visionaries helping make computers a prominent part of our daily life. The computers have downsized themselves from as big as rooms to a device which could fit in our palms or in the form of glasses right on our eyes. But these devices are quite helpful to fulfill our daily life needs, from programming to media consumption and entertainment.

But these commodity computers fall short of powers, performance and accuracy for problem-solving on large data sets at very high speed in a limited time frame. As the requirement of resources to solve these problems may not be satisfied by these commodity computers, or maybe the problem would demand some specialized arrangements of hardware and software. Problems such as Analyzing stock trends, Weather Forecasting, Climate research, Environment Modelling, Life Sciences Research, Exploration of natural resources, Cryptanalysis and Simulation, which are more on calculations and short of time [2]. These computing challenges are tackled by incorporating the technology known as High-Performance Computing (HPC).

HPC is the application of supercomputers based on parallel processing and pipelining principle, in which multiple processors and storage units individually known as nodes perform a particular operation in parallel with each other to provide superior computational peak performance. These nodes are fed with small units of large problems, which can then be solved simultaneously. These supercomputers have been here for almost 6 decades now and have also grown massively in performance and are capable of providing a peak performance of about 415.53 petaflops [4]. This kind of extensive performance can be gained by some really excellent Hardware and Software integration, to gain some perspective, a Supercomputer developed in Japan, known as Fugaku, has about 7.6 million CPU cores.

But even after these huge advancements and sophistication in the field of computing, many of the problems still remain unresolved due to their appetite for more power and performance which our present-day supercomputers may not be able to deliver. So, a completely new kind of computing has come to our rescue, known as Quantum computing, and the devices that perform quantum computations are known as quantum computers.

Quantum computers approach solving problems in a fundamentally different way, as they leverage quantum mechanical phenomena to manipulate information entirely differently from what the long-standing Classical computers make use of.

In this paper, I would analyze the present growth and potential of growth in the field of quantum computing, as it would be able to fill the void left out by the present supercomputers in the field of High-Performance Computing. And also, would throw light on how computing is achieved by leveraging the magnificence of quantum mechanics.

II. LITERATURE SURVEY

a) Quantum Computing: Progress and Prospects by Emily Grumbling and Mark Horowitz -

The book explains the entire quantum computing environment without losing sight on the computing arena and not deviating much into the spooky science of quantum mechanics. It meticulously retraces the milestones of quantum computing environment of creation and control of quantum bits of information while simultaneously emphasizing advancements in the software side.

b) The Engineering Challenges in Quantum Computing by C. G. Almudever, L. Lao, X. Fu, N. Khammassi, I. Ashraf, D. Iorga, S. Varsamopoulos, C. Eichler, A. Wallraff, L. Geck, A. Kruth, J. Knoch, H. Bluhm, K Bertels -

The Paper examines the technical requirements for gaining computing capabilities by utilizing quantum mechanics, since mapping physics of atomic and subatomic levels to real-world computing systems may be a difficulty in and of itself. It focuses on the electrical, communication, fabrication, and networking components of constructing a functional quantum computer.

c) A Heterogeneous Quantum Computer Architecture by X. Fu, L. Riesebos, L. Lao, C.G. Almudever, F. Sebastiano, R. Versluis, E. Charbon, K. Bertels –

The paper reminisces on the prevalent reality that a quantum computer is functionally dependent on a conventional computer. Because quantum computing chips analogue in nature thus the analogue signal needs to be converted to digital signal and vice-versa, implying that a classical computer needs to be roped in all the time to access a quantum computer.

III. BACKGROUND

In this section, we will review the capabilities of the computers proficient in providing high-performance computing to tackle most of our present-day problems, but not all. So, I propose Quantum Computing as the potential replacement of these Supercomputers to gain access to more power to solve problems that demand more power and performance.

HPC in present times is gained by a category of robust computing machines based on Classical computing. They are sophisticated in design and highly capable of providing us with the required results, and they are called Supercomputers [2].

Supercomputers are the class of exceedingly proficient machines that are large in design, as they are the jacked-up version of commodity computers and possess the computing power of a large number of conventional machines. They are specifically designed to solve complex scientific and industry challenges that are deemed too complicated for personal computers and workstations to handle. Such applications cover a broad spectrum of intensive computing tasks, including meteorological prediction, climate research, oil and gas exploration, simulation, optimization, cryptography, machine learning, artificial intelligence, materials science and many more [2][3].

Modern supercomputers use the so-called parallel computing, in which tasks are broken down into smaller, independent and usually similar parts, which can be executed by multiple processors while exchanging data through shared memory, and the results are integrated as part of an overall algorithm after completion. On the hardware front, these computers are composed of many computing nodes, which are connected through a high-speed network. Each computing node has one or more multi-core/multithreaded processors, memory modules, network adapters and storage drives. Just to gain perspective, the supercomputer developed by IBM in collaboration with Nvidia named 'Summit' has about 36,000 onboard processors with a peak speed of 148.8 petaflops and can so perform 200 quadrillion calculations per second, the task it could compete in 1 hour would take about 30 years for a desktop computer [3].

Even after this sophistication of supercomputers and development within-side the area of HPC, there are gaps that still cannot be filled by these present-day supercomputers, because some special applications require even greater capabilities of calculation and the ability to solve problems even faster. So, to fill the vacuum with power and performance, I would suggest exploring the immense potential of quantum computing.

Quantum computing is a field of computing, dedicated to the development of computing technology by harnessing the unique principles of quantum mechanics or quantum physics, which explains the behaviour of energy and materials at the atomic and subatomic level. Quantum mechanics itself is very mysterious and strange because it bypasses all the rules and regulations that the real world follows, i.e., all the rules laid down by conventional physics are not followed in the quantum world.

Quantum Mechanics describes the behaviour of atoms and fundamental particles, like electrons and photons, and the Quantum Computer works by controlling the behaviour of these particles. But there remains quite a contingency in drawing a relationship between a concept dealing with atoms and something as different as computing [1][5].

Before attempting to establish relationships, we need to understand some of the central concepts of quantum theory. I would state and simplify the Fundamentals of Quantum Mechanics:

- Superposition: It is the fundamental principle of quantum mechanics, it states that like musical waves in classical physics are a combination of different frequencies added together to form a single wave, so in the same way, the quantum states (a state of a quantized system) can be added together, i.e., superposed to yield a new quantum state, and on the contrary, each quantum state can be regarded as a linear combination of other different quantum states. Simplistically, it states that quantum particles can exist in two different states at the same time [1][7].

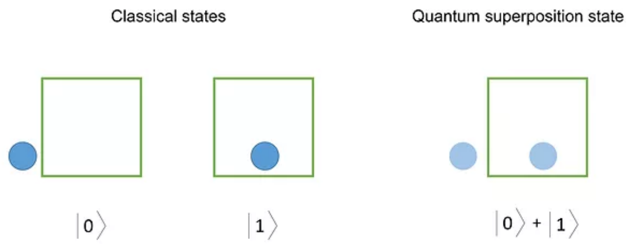

Fig.1: Comparison between Classical and Quantum Superposition State

- Entanglement: It can be explained as an extremely strong correlation that exists between two or more quantum particles irrespective of the distance between them. That is, since the particles interact due to the relationship between them, the quantum state of each particle cannot be described independently, they become a bound system, and measuring one will affect the state of another. This property will be retained even though they are separated by a great distance. Entanglement is said to surround us and penetrate us and bind the galaxies together. One of the most renowned physicists and the greatest minds of all time, Albert Einstein, dubbed this relation between particles at a distance as “spooky action at a distance” [1][11].

Fig.2: Entanglement between two particles

- Quantum interference: Electrons can be in multiple places at the same time or in multiple states at the same time, it is called Superposition. Quantum interference is the inherent behaviour of a qubit, due to superposition, to influence the likelihood of its collapse in one way or another [1]. Quantum computers are designed and built to reduce interference as much as possible and ensure the most accurate results. But, if we try to measure the state, then something strange does happen, the electron stops being in superposition & superposition collapses, and the electron acquires either of the states with the equal probability being in any of the states randomly, which in turn would be a classical thing. It is necessary to deal with this inference to attain quantum computing [5][10].

Now, after knowing these fundamentals of quantum mechanics, we could now understand how they can help us to gain computing capabilities.

As we all know, to perform calculations on a computer, you only need to manipulate the binary numbers 0 and 1, this technique remains intact even in quantum computing, but the difference is classical computing uses the unit of bits which holds the value 0 or 1 at a point of time, but whereas in quantum computing we make use of the unit known as qubit which has a fluid non-binary identity, it can exist in superposition or combination of values $|0\rangle$ and $|1\rangle$ with equal probability of being $|0\rangle$ and $|1\rangle$, in other words, its identity is on a spectrum. Because of this coherent superposition of both states simultaneously, a quantum computer consisting of n qubits can exist in a superposition of 2^n states [6][9].

Fig.3: Comparison between Bit and Qubit states

For instance, with two bits in a classical computer, each bit can store 0 or 1, so together you can store four possible values 11, 01, 10, and 00 – but only one of those at a time. With two qubits in superposition, however, each qubit can be 0 or 1 or both states, so you can represent the same four values simultaneously. With three qubits, you can represent eight values, with four qubits, you can represent sixteen values, etc. So, 300 qubits are equal to more classical bits than atoms in the known universe. A 300-qubit quantum computer can have more computing power than all supercomputers on the planet combined [11].

III. IMPLEMENTATION

When it comes to the implementation of this theoretical computing into real-world capabilities, things continue to be flummoxing due to its sheer scale and complexity.

Challenges for Quantum Computing:

a) Quantum Decoherence:

Entangled qubits do not sustain their entangled state, known as coherence, for a long time. As their quantum states are extremely fragile, it makes using them quite tricky. Before being measured in a quantum computer, a qubit must retain coherence, and loss of coherence is referred to as decoherence [6].

Decoherence occurs in the process of quantum computing when something outside the computer performs an unidentified measurement on a qubit, usually due to a change in temperature, vibrations, cosmic rays, unwanted magnetic and electrical signals or any slightest interference, also called ‘noise', will destroy their two-state superposition. Certain sources of noise are inherent to existing material platforms. This adds an unwelcome element of uncertainty or randomness to quantum computation. Basically, there is no way to predict the outcome of another measurement [8].

Engineers not only have to build the computer itself, but also the ultra-protected environment in which they operate. To eliminate vibrations and other external influences on synchronized qubits, complete isolation is required. The quantum computer's information would be lost if the qubits became decoherent.

Quantum chips must function at extremely low temperatures in order to keep their quantum information intact and avoid decoherence. Temperatures as low as -273.333 °C (-0.18 Kelvin) are required, lower than the outer space, which has temperatures of about −270.45 °C (2.7 Kelvins) [1]. So, to maintain this kind of low temperatures, dilution refrigerators, which are multi-stage coolers based on pumping of cryogenic liquids, are used. At freezing temperatures, atoms and molecules simply move around less. The lower the temperature, the more stable a molecule becomes, resulting in a stable operations of quantum computers [1].

No existing hardware platform can maintain uniformity and deliver the robust error correction necessary for large-scale computing. There's a long wait before that hardware problem gets solved.

b) Quantum Error Correction:

As due to the noise, there are extreme chances of occurrence of decoherence, which would, in turn, affect the quantum states. As Qubits do not have self-course correction so the errors need to be handled explicitly [3].

In a classical computing environment, error correction employs redundancy, i.e., to store the information multiple times, if noise then flips a copy, the machine can find the error by making parity measurements by comparing pairs of bits to see whether they're the same or different. But copying quantum information is not possible due to the no-cloning theorem, which states that there is no way to make an identical copy of an arbitrary quantum state. Another challenge that faces quantum error correction is the problem of wave function collapse, i.e., Measurement of the qubits as part of the error correction procedure should be carried out carefully in order not to cause the wavefunction to collapse and erase the encoded information, and also the errors are continuous [1].

We need to implement error correction algorithms that verify and fix random Qubit errors as they occur. These are complex instruction sets that use numerous physical qubits to effectively prolong the life of information in the system.

So, when a quantum chip is of a particular qubit capacity, we won't be able to use it in its full capacity for calculations, instead some qubits are pre-reserved for error correction.

c) Software Development Challenges:

Software for use in the present time are programs that are developed for computers based on classical computing. As quantum computers are fundamentally different types of computing in emergence, so the software development paradigm must be redesigned, which is quite challenging in itself, as it requires the programmers to completely rethink the operational structure of the computers [1].

A Quantum Computer will require extensive software to function. To support quantum operations, many software tools are required, such as programming languages, to allow programmers to develop quantum computer algorithms, compilers that run them and map them onto quantum hardware, and additional support to analyze, optimize, debug, and test programs for execution on real quantum hardware.

So, for software developers, it becomes imperative to understand some amounts of Quantum Mechanics to look for solutions that can be applied in quantum computing.

d) Massive Size:

The quantum chips use quantum-mechanical phenomena for computation, which deals with fundamental particles at the atomic and subatomic levels, so the size of the quantum chip can be as small as the size of a classical computing chip, but for the quantum chip to act as a machine, it must be coupled with a number of sophisticated devices or equipment like wires, lasers and the cryogenic coolant system known as Cryostat, which is very huge in itself. So, the increase in the qubit size would trigger dimensional changes in the system.

Hardware Structure of a Quantum Computer:

As Quantum computers does not extensively employ the semiconductor industry for its hardware needs, so a new hardware infrastructure needs to be designed to get going with the computations on a Quantum Computing Platform.

Fig.4 below denotes the abstraction of the quantum computing device and describes the hardware infrastructure conceptually.

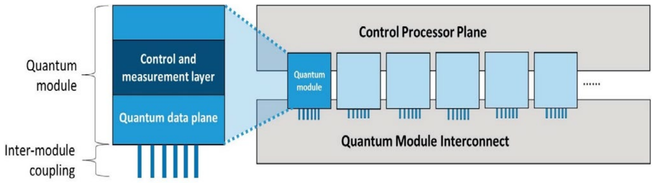

Fig.4: Abstract Structure of a Quantum Computer

➢ Quantum Module-

Quantum Module holds the Qubit, which is the core for the Quantum Computer, and also the Control Unit for handling the operations. It consists of-

- Quantum Data Plane:

The most crucial part of a quantum computer is the quantum data plane. It houses both the physical qubits and the structures that hold them in place. It must also include some support circuitry needed for measuring qubit state and performing gate operations on physical qubits. The data plane must have a programmable "wiring" network that allows two or more qubits interact, so there might be more than one qubit. Since high qubit fidelity necessitates strong isolation from the surroundings, which may limit communication, the computation must be mapped to the layer's particular architectural constraints. Control information is transmitted electrically via wires in some systems, making these wires part of the quantum data plane; in others, it is transmitted through optical or microwave radiation. Transmission must be enforced with a high level of accuracy, affecting only the desired qubits and causing no disruption to the rest of the system's qubits [1][4].

- Control and Measurement Plane:

The control and measurement plane transforms the digital signals produced by the control processor, which indicate the quantum operations to be performed, to the analog control signals used to execute the operations on the qubits in the quantum data plane. It also converts the analog output of the qubit's measurements in the data plan into classical binary data that the controller processor can handle. Since quantum gates are analog in nature, generating and transmitting control signals is difficult. The effects of operations can be influenced by minor errors in control signals or inconsistencies in the physical configuration of the qubit. When the system operates, the errors associated with each gate operation add up. Any flaw in the isolation of these signals can result in small control signals appearing for qubits that should not be appearing, resulting in small errors in their qubit state, assuming there is a method to quantify these errors and software to modify the control signals to drive these errors to zero. Since control signals can communicate with every other control signal, the number of measurements and computations needed to accomplish this calibration more than doubles as the system's qubit count doubles. Unlike classical gates, which are noise-free and have negligible error rates, quantum operations are dependent on the accuracy with which control signals are transmitted and have non-negligible error rates. To achieve this level of precision, advanced generators built with conventional technologies are required. And if the quantum device, in theory, requires an ultrafast operation, no quantum gate can be faster than the control pulse that executes it. The Qubit technologies used to decide the nature of a Quantum Computer's control signals. The gate speed is limited by the quantum data plane, and not the control and measurement plane as our present-day Silicon Technology could support operations that are quite fast enough [1].

➢ Quantum Module Interconnect-

Quantum Module interconnect is used to house multiple quantum modules in it, which would help to create a quantum computer with a higher qubit capacity. It needs to be managed precisely to avoid any type of inference between the multiple modules.

➢ Control Processor Plane-

The control processor plane identifies and initiates the correct sequence of quantum gate operations and measurements. These sequences run the host processor's program for implementing a quantum algorithm. The software tool stack must customize programs for the specific capabilities of the quantum layer. The quantum error correction algorithm will be one of the most important and difficult tasks of the control processor plane. To compute the quantum operations required to correct errors, significant classical information processing is required. Building a control processor plane for big quantum machines is difficult. One method divides the plane into two parts [4].

The first component is essentially a traditional processor that "runs" the quantum software. The second component is a scalable custom hardware block that directly interacts with the control and measurement planes. The difficulty is in developing modular custom hardware that is quick enough and can scale with machine size, as well as in developing the appropriate high-level instruction abstraction.

➢ Host Processor-

This host processor runs a conventional system, which facilitates user interactions, and has a high-speed connection to the control processor. It will run the software development tools used to build programs for use on the control processor, which will be different from those used to control today's classical computers, as well as provide storage and networking facilities that a quantum program may need when running [1][6].

Types of Qubit Designs-

❖ Superconducting Qubits

Superconducting qubits are by far the most common and advanced form of a qubit. They are essentially tiny currents on a chip. The two states of the qubit can be physically realized by either the charge distribution or the current flux. The main benefit of superconducting qubits is that they can be manufactured using the same method that the electronics industry has been using for the past five decades. These qubits are essentially microchips, except that they must be cooled to extremely low temperatures, about 10-20 millikelvin. These low temperatures are needed to make the circuits superconducting; otherwise, they cannot be held in qubit states. Despite the low temperatures, quantum effects in superconducting qubits vanish in an instant. The absence of quantum effects is calculated in the "decoherence time," which is currently in the tens of microseconds for superconducting qubits. Cooling is the most difficult issue for superconducting qubits. Beyond a few thousand qubits, it will become difficult to fit all qubits into a single cooling system [1]. Superconducting qubits are the technology that is used by Google, D-wave, IBM and also several smaller companies. In 2019, Google was the first to demonstrate its "quantum supremacy," which means it carried out a task that a conventional computer would not have been able to complete in a reasonable amount of time. The processor they ran on was 53 qubits. IBM quantum computers also rely on superconducting qubits. The largest is currently 65 qubits and they recently released a roadmap that projects 1,000 qubits by 2023. BM Provides users a platform to experience their quantum computer through their 'IBM Quantum Experience' platform.

❖ Trapped Ion Qubit

Qubits in ion traps are atoms that are lacking any electrons and therefore have a net negative charge. These ions can then be trapped in electromagnetic fields and moved around and entangled using lasers [4]. The scale of such ion traps is comparable to that of Qubit chips. They are also required to be cooled but to temperatures of just a few Kelvins not as low as Superconducting Qubits. Trapped ion computing has the benefit of having longer coherence periods than superconducting qubits i.e., up until a few minutes. Another benefit of trapped ions is that they can interact with more neighbors than superconducting qubits. However, ion traps have several drawbacks. Notably, they are slower to respond than superconducting qubits, and putting multiple Trapped Ions on a single chip is more difficult. But they held up well with the superconducting qubits. Honeywell is the prominent company to make use of Trapped ion qubit and also Honeywell claims to have the best quantum computer in the world by quantum volume, but the startup IonQ uses the same approach.

❖ Photonics

The traditional approach to photonic quantum computing is focused on qubits that are each based on a single photon. Photons are manipulated by mirrors, beam splitters and phase shifters in this technique. The results of these instrumentation are then read using single-photon detectors. The most significant benefit when using photons is that they can be worked at room temperature, and the quantum effects last much longer than in superconducting qubits, usually milliseconds, but up to hours in ideal cases. This minimizes the cost and complexity of photonic quantum computing. The major downside is that due to laser guides and optical components, the devices become very large very quickly [4]. Quantum supremacy was also demonstrated using Photonics chips by Chinese researchers.

❖ Topological qubits

The topological quantum computer is a theoretic quantum computer. Information in topological quantum computers will be stored in the preserved properties of quasi-particles (a physical term which treats elementary excitations in solids, such as spin waves, as particles. Since particles contain no matter, they are known as quasi-particles). Topological qubits are stabilized by changing their structure and enclosing them with chemical compounds that protect them from external interference. The best thing about it is that it will be highly resistant to decoherence [1]. Microsoft is the tech giant that is betting heavily on Topological Qubit based chip for its future Quantum Computer [7].

There are many more approaches underway, but the demonstrations have to be done to gain notice.

IV. Conclusion

Quantum Computing is a challenge of a whole new level, as it is fundamentally different from what we are used to. There is a steady growth in the field of quantum computing, but the growth can be compared to that of computing in the '80s or the Internet in the '90s.

If engineers can figure out the way to be maintained, good coherence time and error correction techniques, quantum computers could one day solve problems that are beyond the reach of classical computers. Quantum computers could be capable of deciphering codes that were believed to be unbreakable. And they could help discover new drugs, improve machine learning systems, solve diabolically complex logistical issues, etc..

But there is one thing we need to know about Quantum computing that it cannot be used for all applications, as the classical computers could handle them, the quantum computers capabilities need to be exploited when the classical computers fall short of capabilities for an application, and also using quantum computers for personal use or non-commercial purpose is still a far thought thing. If we try to make use of a quantum chip to solve a small problem compared to what it is capable of, then it would be like using a hammer where just a scalpel is needed.

Expectations are high, and tech firms and governments are betting billions of dollars on quantum computers. But it's always a gamble because the same quantum-mechanical effects that promise so much power also make these machines very sensitive and hard to control.

Quantum is the language of nature, and quantum computing, which itself exploits quantum physics, will enable us to run precise simulations of the natural world, unlocking answers that would otherwise be unanswered. Currently, quantum mechanics can't fully describe how a quantum computer works, as still the quantum mechanics itself isn't fully described.

There is still a long wait before the pragmatic use of quantum computers for high-performance computing but once it is possible, it will redefine HPC. I would like to reiterate by saying that it would change the way we compute.

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References

[1] Emily Grumbling and Mark Horowitz, "Quantum Computing: Progress and Prospects" National Academies of Sciences, Engineering, and Medicine,2019

[2] Horst Simon, Jack Dongarra, Horst Simon, Erich Strohmaier," High Performance Computing Today",2009

[3] What is high-performance computing? How it works | Netapp, from https://www.netapp.com/data-storage/high-performance-computing/what-is-hpc/

[4] Linder, C. (2020, June 24). Meet Fugaku, the new fastest computer in the world. Popular Mechanics. https://www.popularmechanics.com/technology/a32947920/japanese-supercomputer-fugaku-fastest-computer/

[5] C. G. Almudever, L. Lao, X. Fu, N. Khammassi, I. Ashraf, D. Iorga, S. Varsamopoulos, C. Eichler, A. Wallraff, L. Geck, A. Kruth, J. Knoch, H. Bluhm, K Bertels, "The Engineering Challenges in Quantum Computing", Design, Automation and Test in Europe, 2017

[6] X.Fu, L. Riesebos, L. Lao, C.G. Almudever, F. Sebastiano, R. Versluis, E. Charbon, K. Bertels, "A Heterogeneous Quantum Computer Architecture" Proceedings of the ACM International Conference on Computing Frontiers,2016

[7] What Is Quantum Computing | https://azure.microsoft.com/en-us/overview/what-is-quantum-computing/., May,2021

[8] Understanding Quantum Computing - Azure Quantum | https://docs.microsoft.com/en-us/azure/quantum/overview-understanding-quantum-computing.

[9] Tom Simonite, "Microsoft's Quantum Mechanics" Massachusetts Institute of Technology Review magazine,2014

[10] Yanofsky, N. S. (2007). An Introduction to Quantum Computing. Quantum Physics, https://arxiv.org/abs/0708.0261

[11] Costianes, P. J. Introduction to Quantum Information/Computing, http://dtic.mil/dtic/tr/fulltext/u2/a436335.pdf.,2005

[12] Brian Greene, "The Fabric of the Cosmos: Space, Time, and the Texture of Reality". Alfred A. Knopf division, Random House, ISBN 0-375-41288-3,2004