

Quantum Computing: Some Percepts and Realms of Applications

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ABSTRACT

A quantum computer is akin to a classical computer in multiple ways. Analogous to a conventional computer, the information could be stored in some physical system. One needs to invoke the system, perform some sort of operations possibly by means of running a program, and extract the information. Nevertheless, simply told, quantum computing differs from classical computing in two key succinct elements. Firstly, quantum computers can acquire a well defined quantum state, but subjected to random behavior this is the idea of superposition. Secondly, the random behavior goes in a correlated manner – this is the idea of entanglement. Of course, these ideas are the hall mark of quantum computing counterintuitive though. At a very intricate level, conventional computers are mired in digital logical circuits dealing with long strings of 0's and 1's. While quantum computing runs on quantum bits aptly called QBITS. Qbits need not have to be binary during computations; they can actually exist in well defined combinations of 0s and 1s. This review paper has intuitive intents that are more than one; to provide an exposition of the topic to an interested novice, to explore possible applications of quantum computing, to delineate the prospective stake holders once quantum computing heralds new vistas, to throw the light on this topic in terms of possible disruptions that may happen in foreseeable future, and to emphasize the impacts of quantum computing.

General Terms

Quantum Computers, QBITS, Applications.

Keywords

Quantum computing, digital logical circuits, classical computing, quantum processor, quantum bit, AI

1. INTRODUCTION

Quantum computing in recent years is drawing quite a big attraction and attention from various quarters. To name a few, the industry, and from academia. Broad spectrum interest corporate houses like Google, Microsoft, IBM, Intel and Lockheed Martin are also in this bandwagon. It is worth a little elaboration here. Google AI Quantum is advancing quantum computing by developing quantum processors and novel quantum algorithms to help researchers and developers solve near-term problems both theoretical and practical[1]. Microsoft has a dedicated blog site where a sizable number of articles, blogs and technical notes about quantum computing is heralded day –in–day–out[2]. IBM-Q network is a site which is committed to accelerating and scaling quantum computing and mooring partnerships with Industries for fostering the ecosystem of quantum computing [3]. Intel labs have gone one step ahead that it is producing quantum processors, and doing a system level engineering that said to have targets of producing quantum level computing within ten

years [4]. Lockheed Martin is another giant which has oriented towards quantum computing, quite recently, it has stated that it is possible to spot check millions of line of code to locate glitches in an instant with a quantum computer powered by physics [5].

. On a look back to history, it was Richard Feynman who noted intrinsic parallelism inherent in quantum systems and to advocated to exploit this to application of quantum computers for simulating quantum physics in general and quantum mechanics in particular[6]. Continuing this inkling on quantum computing, universal quantum computer was proposed by David Deutsch in 1985[7]. His proposition also came out in his seminal paper. The parading of quantum computing started slowly rolling and started showing significant discoveries like factoring algorithm by Peter Shor and search algorithm by Lov Grover. Trends continued, and the quantum computing in information security, optimization, and machine learning [8-11]. All these efforts culminated in building the world's first quantum computer in 1999. This computer is said to have built on superconductors by a Canadian company named D-Wave Systems [12]. After a yawning gap of almost 8 years, qubit quantum computer was demonstrated in 2007, which was followed by 128 qubits, 512 qubits and 2000 qubits during 2010, 2013 and 2018 respectively[13-14].

The fundamental principles of quantum computing stem from the theory of quantum mechanics. The clear differences between explanations provided by conventional, or classical, physics are highlighted by several unique quantum principles. Chief among these founding principles are the concepts of superposition and entanglement as well as the intrinsic randomness that appears in quantum mechanical measurements, i.e., the uncertainty principle. It is the application of these ideas to the theory of information that led to the development of quantum information theory, in which quantum computing originates alongside quantum communication and quantum sensing among many others.

There have been several proposals on physical realization of quantum bits (qubits) and the investigations are being carried out at small research laboratories. Nevertheless, solid state qubits are finding predominant applications in Industrial scenario [15,16]. However, industrial applications of quantum computing are beyond the scope of this paper. The rest of the paper is articulated as follows, section II elaborates on qubits, section III makes a detailed foray into quantum logic gates, section IV explores some of the current applications of quantum computing, section V showcases the flipside and brownie side of quantum computing, and the paper is also concluded there.

2. THE QUBIT

The classical computers manipulate individual bits, 0 and 1, to store information as binary data, whereas quantum computers use the probability of an object's state before it is measured. Therefore, it gives them the potential to process exponentially more data compared to classical computers. Unlike classical computers that use the binary bit, quantum computers use qubits that are produced by the quantum state of the object to perform operations. Since these qubits are quantum in nature, they follow phenomena like superposition and entanglement. Superposition is the ability of a quantum system to be in multiple states at the same time. Entanglement is the strong correlation between quantum particles. These phenomena help the quantum computer work with 0, 1, and superposition of 0 and 1, giving them the advantage in doing complex calculations that modern classical systems cannot do or would take a significant amount of time to get the desired result.

Thus quantum computer is impregnated with qubit replacing the conventional bits (0 and 1). A qubit is a smallest element for storing and processing information in a quantum computer. It can be implemented using different physical systems .The qubit can attain two important states, namely, the ground state and the excited state at the same instance of time. Quantum bits (qubits) based on individual trapped atomic ions are a promising technology for building a quantum computer¹. The elementary operations necessary to do so have been achieved with the required precision for some error-correction schemes. However, the essential two-qubit logic gate that is used to generate quantum entanglement has hitherto always been performed in an adiabatic regime (in which the gate is slow compared with the characteristic motional frequencies of the ions in the trap, resulting in logic speeds of the order of 10 kilohertz. There have been numerous proposals of methods for performing gates faster than this natural 'speed limit' of the trap. Here we implement one such method¹¹, which uses amplitude-shaped laser pulses to drive the motion of the ions along trajectories designed so that the gate operation is insensitive to the optical phase of the pulses. This enables fast (megahertz-rate) quantum logic that is robust to fluctuations in the optical phase, which would otherwise be an important source of experimental error. We demonstrate entanglement generation for gate times as short as 480 nanoseconds—less than a single oscillation period of an ion in the trap and eight orders of magnitude shorter than the memory coherence time measured in similar calcium-43 hyperfine qubits. The power of the method is most evident at intermediate timescales, at which it yields a gate error more than ten times lower than can be attained using conventional techniques; for example, we achieve a 1.6-microsecond-duration gate with a fidelity of 99.8 per cent. Faster and higher-fidelity gates are possible at the cost of greater laser intensity. The method requires only a single amplitude-shaped pulse and one pair of beams derived from a continuous-wave laser. It offers the prospect of combining the unrivalled coherence properties, operation fidelities and optical connectivity of trapped-ion qubits with the sub microsecond logic speeds that are usually associated with solid-state devices. A qubit is capable of representing a 0 and 1 at the same instance of time, and this happens under the ambit of a quantum phenomenon known superposition. Simultaneous donning of two values by the qubit lets it to perform huge amounts of computations at once, added to this resulting in massive increase of computational capacity and speed^[17]. A qubit is a programmable silicon quantum chip in which the state to be either 1 or 0 depends on the spinning or rotation

direction of the electron. Qubits are vulnerable for breakage and they require 20 millikelvins of temperature for their sustainability and stability. Qubits are implemented using a two-state quantum mechanical system , these states exit together. This concept is illustrated in figure 1.

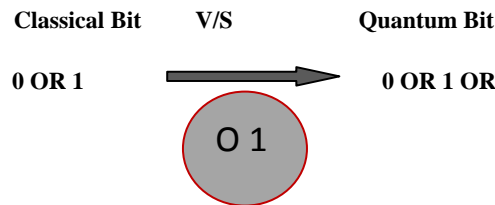


Figure 1. Logical value representation

Another big difference is that while a classical register capable of holding three bits can store one and only one number among eight numbers while a quantum bit can store all 2³ i.e eight number that are generated by permuting the three bits as shown in figure 2. This capability of the quantum register of handling multiple numbers at a time, it is possible to perform operations on all of them, as demonstrated in figure 3. Sufficient enough to say that, quantum computers can perform multitudes of different computations in parallel. Theoretically, it can be said that, a system with N qubits can perform 2^N calculations at once. This has an immediate impact on memory requirement, execution time and efficacy of the algorithm dealing with such a computation. Also, it is imperative, that a computation involving N bits must be in 2^N possible states, with 2^N entries [18]. This scenario provides an impetus for formalism on quantum logic gates [19].

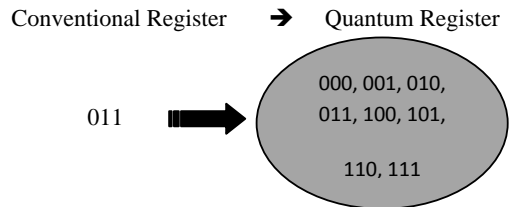


Figure 2. Conventional and quantum registers

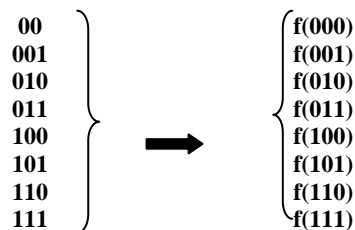


Figure 3: Quantum processor

The multitudes of operations in quantum computing are made possible by allowing the qubits to spin in the ambit of superposition in multiple directions, and also by allowing expansion of Quantum Operations. It is important to note that this systemic process was also made possible by a network of Quantum Logic Gates. There are seven different types of qubits and only four of them are found to be augmentable in quantum computing. These qubits are amenable for

manipulation, they can communicate each other, and the matter is only two qubits would suffice to communicate in order to perform large entangled computations. Entanglement of qubits builds a correlation among them. If one qubit in one state, and the other in some other state, it is the spin directions that are correlated. It so happens that if one electron has spin-up then the other will have spin down and vice versa. Therefore, the manipulation of entangled states plays pivotal role in data processing [20]. The qubits that are augmented in a quantum computer will have to satisfy the criterions like, being scalable, capability to initialize the states, long coherence time, being adaptable to set of quantum gates and specific measurement capability [21].

2. QUANTUM LOGIC GATES AND QUANTUM COMPUTER

In the digital design, any computation is considered to be equivalent to the action of a circuit built out of a handful of different types of Boolean logic gates acting on some binary (i.e., bit string) input. Each logic gate transforms its input bits into one or more output bits in some deterministic fashion according to the definition of the gate. By composing the gates in a graph such that the outputs from earlier gates feed into the inputs of later gates, computer scientists can prove that any feasible computation can be performed.

It goes without saying that, the making of a quantum computer would imperatively involve the quantum logic gates similar to their counterparts in conventional computers. Here in this case a ‘gate’ is an operator that acts on a small number of qubits to produce some logical output [22]. Analogous to AND, OR and NOT gates in a conventional computer, we find NOT gate, controlled-NOT gate and Hadamard gate. Quantum logical gates are represented by unitary matrix. The number of qubits in the input and output of the gate must be equal. A gate which acts on qubits is represented by a $2n \times 2n$ matrix. The gates unlike conventional ones, act upon the quantum states that are represented as vectors. Quantum states are represented by kets. The exploration of logical gates in a deeper perspective is not in the ambit of this paper. However, for the sake of clarity and completeness the general systemic layered architecture of quantum computer is presented in figure 4. It is important to note that the hardware configuration or implementation of a quantum computer needs the backing of conventional computer particularly to monitor and maintain the field [23]. Therefore some researchers in this area prefer to call quantum computers as quantum accelerators.

1	Q Algorithms
2	Programming Paradigms and languages
3	Q Arithmetic run time compiler
4	Q Instruction set Architecture
5	Micro architecture
6	Quantum to classical
7	Quantum chip

Figure 4. Quantum Computer Architecture

The layers and their brief description are presented in Table 1. The quantum chip is made using materials that possess strong electronic correlations and some type of electronic order such as superconducting, and magnetic order. This special kind of chip provides the environment where qubits are defined and thrive.

Table 1: The layers of quantum computer architecture and their description

Layer 1	Mathematical implementation of algorithms for various applications is built with quantum properties.
Layer 2	This layer provides standard quantum language and operators. Its syntax resembles the syntax of the C programming language and its classical data types are similar to primitive data types in C
Layer 3	Facilitates the intermediate representation for quantum instructions. Eg: QASM- Quantum Assembly Language
Layer 4	Provides a shared classical / quantum memory models
Layer 5	Defines the arrangement of Processor, local register alignment and memory.
Layer 6	This enables the reading state of qbit.
Layer 7	Provides the interconnection of qbits.

Two additional functional criteria are necessary for a quantum computer with geometrical constraints on the layout of the quantum register. In particular, layout constraints may impose restrictions on which register elements can be addressed by multi-qubit gates, e.g., nearest neighbors within a two-dimensional rectangular lattice design. Physical layout restrictions may be overcome by moving stored quantum states between register elements. This is accomplished using the SWAP gate, a unitary operation that exchanges the quantum state between two register elements. In addition, a MOVE operation can support long distance transport of a stored value, in which the register element itself is displaced. The latter proves useful for distributed quantum registers that may require interconnects, aka communication buses, to SWAP register values. The necessity of these functions depends on the purpose of the quantum computer and especially the limitations of the technology. Presently, all technologies for quantum computing face some constraints on register layout

4. APPLICATIONS OF QUANTUM COMPUTING

Notwithstanding the scientific and engineering challenges facing the development of quantum computers, considerable progress is being made toward applying the technology to commercial applications. Some of the applications are in combinatorics problems, cyber security, materials and pharmaceuticals, banking and finance, and advanced manufacturing. While quantum computers are not yet available at the scale needed to solve all of these combinatorics problems, we identify three types of near-term opportunities resulting from advances in quantum computing: quantum-safe encryption, material and drug discovery, and quantum-inspired algorithms. Sometime in the next 10 years, quantum computing is expected to experience widespread commercial adoption. Early adopters are already exploring opportunities to leverage this emerging technology to provide disruptive computing solutions. While not ready for widespread commercial adoption, quantum computing is ready for organizations to explore and prepare for possible use cases and applications so they can enjoy the “quantum advantage” as the technology is rolled out for commercial use.

In a nutshell, it can be said that classical computers beat about the bush say when trying to design drugs, while running AI or machine learning algorithms and while solving complicated

mathematical equations. Quantum computers present themselves with a different architecture [24] that is built on laws of nature and therefore capable of hard problems with astounding speeds. Some of the prospective areas of applications where quantum computers are envisaged to find pride of place are explained in the following paragraphs.

4.1 Health Care

Current generation computers are limited in simulating the size and complexity of molecules that are essential elements of drug development. As an example if the number of atoms that are to be dealt in a drug development exercise is N , then the interactions that are to be carried out among these atoms is of exponential complexity. It is experimented and found that the quantum computers will pave the way for much large sized molecules for simulation thus facilitating interactions between drugs and huge number proteins (of the order $20K+$) to be encoded in human genome. This has shown highly ambitious advancements in pharmacology.

4.2 Diagnostics and Treatment

Most faster and accurate diagnostics is possible with quantum technologies. AI and Machine learning amalgamated with quantum computations can really boost pattern recognition in MRI driven medical images. In the same token, the radio therapy treatments which depend on the ability to rapidly model and simulate complex scenarios can be dealt with ease with quantum computing directed towards delivering optimal treatments. This is because the therapists can run innumerable simulations with in no time thus minimizing the possible radiation damages to healthy tissues.

A quantum computer can allow looking into every known type of molecule at unprecedented speeds, test drug compositions on any cell known to humans — and all in the shortest time imaginable. Quantum computing will be another tool that can be used to find answers to such diseases as Parkinson's, cancer and other ailments that take away so many lives every day.

While testing on living organisms and cells is one way to advance achievements in the pharma and healthcare space, quantum computing can also enable a new type of experimentation and testing that is not feasible today due to the limitations of the current technology. Known as in silico clinical trials, these experiments are conducted in a completely simulated environment. According to the Medical Futurist, what quantum computing can do is fuel the creation of virtual environments where professionals will be able to analyze variables like body fluids, circulation, electrolytes, hormones, metabolism and skin temperature on digital replicas of humans. And then there is the intricate world of genetics and genomics that has made full strides in the past few decades. What started as a quest to decode the human DNA has now turned into a rich space of exploration, where people have the ability to identify their health risks and even trace their ancestry back to their origins. Quantum computing will no doubt further this leap and allow for infinitely faster analysis and accurate predictions of potential genetic illnesses, making it possible to take preventative action ahead of time and gain a deeper understanding of genetic composition in as little time as possible.

In totality, the processing power that quantum computing promises opens the door to the goal that the healthcare and pharmacy industries have long sought out. That goal is to be

predictive and preventative, rather than reactive and delayed. While today, most sophisticated technologies allow to cure a large variety of conditions, it is hoped for quantum computing and its incredible power to foresee and effectively uproot such conditions ahead of time. The amount of data generated day-to-day and the amount of specific patient data already available will create a fertile ground for the quantum machines to do their work and produce valuable and in-depth analysis that will not only help contribute to curing but aid in preventing certain diseases.

4.3 Finance and Marketing

With quantum computers in place, automated high frequency trading will be a passé. Quantum computers can run complex algorithms that can invoke trading automatically and effectively manage share dealings considering all possible market variables. With quantum computing the high-volume trading can be too fast.

As far as marketing is concerned, the aggregation and analysis of huge volumes of consumer data could be done with in no time. Added to this, big data analytics will provide e-commerce and government agencies to target consumers, voters with communications cut short to their preferences. Ultimately, quantum computers will help financial services to:

- Increase investment gains
- Reduce capital requirements
- Improve the identification and management of risk and compliance
- Open new investment opportunities.

4.4 Detection of Fraud

It is well known that the major part of fraud identification lies with pattern recognition. Quantum computing is proved to facilitate machine learning at a faster rate i.e., reducing the training time drastically thus reducing the time required for detection.

The technologies and methods used for fraud prevention, control and management are an example of continuous applied innovation. In any financial entity, systems and procedures are able to stop near 100% of all fraud attempts. Nevertheless, these impressive results leave little room for complacency. Fraudsters are continually developing new schemes and scaling the volume of their attacks. We need new technologies, methods and processes to recognize patterns in data which are indicative of fraudulent activity. Quantum computers use concepts and phenomena at the core of quantum mechanics to compute under a fundamentally different approach. Most notably, the exploitation of superposition allows quantum computers to encode 2^n values, being n the number of qubits. This, along with entanglement, makes possible to evaluate simultaneously numerous possible solutions. This parallelization increases the efficiency of the computation.

4.5 Logistics

Improved data analysis and modeling will enable a wide range of industries to optimize workflows associated with transport, logistics and supply-chain management. The calculation and recalculation of optimal routes could impact on applications as diverse as traffic management, fleet operations, air traffic control, freight and distribution.

In other aspects of the supply chain, quantum computing has also been identified as a key technology. Operational processes can be expedited by relying on the technology's speed and accuracy, which will maximize the simultaneous packing capacity of parcels for freight transport worldwide. Quantum computers will also help build a more resilient supply chain, as it supports adaptive re-planning and reallocation of assets in the event of unexpected shutdowns, late shipments or order cancellations.

Despite the potential of the technology, widespread usage is still years away, as questions remain over the highly touted capabilities of quantum computers. While its properties are suited for creating unshakable communication within the supply chain, another quantum computer user with malicious intent could still overcome it. After all, traditional encryption codes that take a supercomputer years to crack, now only require a matter of minutes with a quantum computer.

4.6 Meteorology

Accurate weather forecasts are pretty difficult as it involves huge number of parameters that are uncertain. Machine learning using quantum computers will result in improved pattern recognition, making it easier to predict extreme weather events and potentially saving thousands of lives year. Climatologists will also be able to generate and analyze more detailed climate models; proving greater insight into climate change and how we can mitigate its negative impact.

Weather forecasting requires analysis of vast data, including various dynamic factors such as air temperature, pressure and density, all of which interact in complex ways. However, using conventional computers, or even supercomputers, to produce numerical weather and climate prediction models has limits. Furthermore, typical computers may not be quick enough to keep up with rapidly changing weather conditions while processing meteorological data. Here the quantum computing comes into play. Quantum computing will enhance weather forecasting on both a local and a larger scale, allowing for more advanced and precise warnings of extreme weather occurrences, perhaps saving lives and minimizing property damage on an annual basis. A quantum computer capable of improving traditional mathematical methods for tracking and forecasting weather by handling large volumes of data more efficiently and quickly, harnessing the computing power of qubits, and employing quantum-inspired algorithms. Quantum machine learning can also improve pattern identification, which is critical for interpreting the weather.

4.7 AI Applications

The last few years have seen revolution and investment explosion in both quantum computing and artificial intelligence. For many years, the AI research groups have explored several allied areas, including spatial and temporal reasoning, constraint solving, and uncertainty in AI. The aim of our current and future research in QSI is to discover the deep interaction between quantum computing and artificial intelligence. Besides the above classical topics, the AI group is interested in developing novel and efficient methods for learning quantum states or measurements for small-mid size quantum devices, in designing algorithms and measurements that can efficiently handle big quantum data, and in developing and applying quantum algorithms to solve hard constraint satisfaction and optimization problems.

The latest incarnation of machine learning, deep learning, is pushing the limits of what traditional computers can handle. Large transformer models, such as OpenAI's GPT-3, which has 175 billion parameters, take months to train on classical computers. As future models grow into the trillions of parameters, they will take even longer to train. That is one reason why users are adopting novel microprocessor architectures that deliver better performance than what traditional CPUs and even GPUs can deliver.

The complexity and size of our data sets are growing faster than our computing resources and therefore place considerable strain on our computing fabric. While today's computers struggle or are unable to solve some problems, these same problems are expected to be solved in seconds through the power of quantum computing. It's predicted that artificial intelligence, and in particular machine learning, can benefit from advances in quantum computing technology, and will continue to do so, even before a full quantum computing solution is available. Quantum computing algorithms allow us to enhance what's already possible with machine learning.

Additionally, big breakthroughs are expected when quantum computers are available due to the integration of very different data sets. Although this may be difficult without human intervention at first, the human involvement will help the computers learn how to integrate the data in the future. So, if there are different raw data sources with unique schema attached to them (terminology and column headers) and a research team wants to compare them, a computer would have to understand the relationship between the schemas before the data could be compared. In order to accomplish this, breakthroughs in the analysis of the semantics of natural language need to happen, one of the biggest challenges in artificial intelligence. However, humans can give input which then trains the system for the future. The promise is that quantum computers will allow for quick analysis and integration of our enormous data sets which will improve and transform our machine learning and artificial intelligence capabilities.

5. CONCLUSIONS

This paper presented a detailed review of quantum computing and its application areas. Quantum computing allows us to solve some problems much faster than existing classical algorithms. Yet, the quantum computer has been believed to be no more powerful than the most general computing model—the Turing machine. Quantum computing offers new capabilities across many different sectors including logistics, finance, health services, and entertainment. Capabilities for genuinely private computation and record storage, truly random number generation, and smarter artificial intelligence are sure to enable far more innovative applications than those described here. The outstanding demand for these services warrants consideration of the value that quantum computing brings to consumer applications. In the near term, cloud-based access to quantum-enabled data centers and servers is the most likely means by which any application will interact with a quantum computer, and few consumers will have or need direct access to QPUs. However, a new cadre of quantum device engineers and application developers will be necessary to support this novel hardware and software.

Publicly available quantum computing has been on the horizon for decades, yet there's still no reliable forecast for when products capable of widespread adoption will get released, exactly what form the systems will take or how

broad and deep quantum computing impact will be. There are many technical challenges when it comes to getting a broadly applicable quantum computer to be useful at scale. And quantum computers are racing against classical computers, which have also been improving very rapidly in power, versatility and ease-of-use. The bottleneck for quantum computers is that correctly reading the results of a quantum calculation is prone to a very high error rate and the delicate superposition state can deteriorate before the correct result is presented as an output.

In a nutshell, quantum computing is poised at a deeply fascinating point of inflection. A sizeable survey of literature is anything to go by, the achievement of long term practicality. Will require more and more innovative ideas.

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