Quantum Computing Overview and Noisy Intermediate-Scale Quantum (NISQ) Technology

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1. Abstract

Quantum computing has become much more than a buzzword term in recent years. While many properties and concepts of quantum mechanics have been understood for decades, being able to read, write, and manipulate quantum information is a relatively recent technological advancement that is still in its infancy. The field of quantum computing is interesting in part due to its largely unexplored nature, but also for some of the advantages over classical computing it offers. It is important to note quantum computing is not a "silver bullet" to many problems, and being mindful that valid business cases for supporting research into the field must be presented to maintain credibility.

Understanding the basics behind quantum mechanics is essential to understanding how it is able to be used for computations. While having a quantum physics background is not necessarily a prerequisite to understanding and implementing quantum algorithms and software, it certainly helps keep things in perspective as to the feasibility of certain problems and solutions. Due to the complex and expensive nature of the hardware required to build controllable quantum systems there are many current challenges and opportunities for improvement. Different paths and options have arisen in an attempt to combat these limitations, such as Noisy Intermediate-Scale Quantum (NISQ) computing, simulations of quantum systems on classical computers, and cloud-based services with time sharing options.

2. Quantum Mechanics Context

There are many aspects to quantum mechanics that could be considered irrelevant to computing. For computing professionals interested in the software, algorithms, and potential output of quantum systems it may be justifiable to limit the understanding strictly to the basic principles of quantum mechanics [1]. Specifically, exactly how quantum computations compare to classical computations is of particular interest to this field of study. A core concept to understand is how quantum bits (qubits) compare to classical bits, and how entanglement, superposition, and gate operations can influence the state of an n-qubit system.

Part of what makes the absence of in-depth knowledge of quantum mechanics viable as far as computing is concerned is the vagueness in requirements with which quantum computers are implemented. In general, a qubit may be implemented by any subatomic particle that has some variable measurable property such as electron spin, photon polarization, or superconductor charge [1, 2]. These values can either be at an extreme maximum, an extreme minimum, or somewhere in between. Compared to a classical bit with only a 1 or 0 available as possible values, a qubit can have a type of "gradient" in its value usually denoted by complex numbers or by a wave function Ψ [3].

A common illustration of this concept is to use what is known as a Bloch sphere to show how a qubit can store its information [3]. A Bloch sphere is a three-dimensional sphere with a radius of 1 that has its "top" and "bottom" poles assigned vector values of $|0\rangle$ and $|1\rangle$ respectively [3]. This way in writing these vector values with the vertical bar and arrow is known as Dirac ket notation (or simply Dirac notation) [3]. A qubit's value can be represented by its "spin" which when mapped onto such a sphere can be denoted by using only two values, written as latitude (θ) and longitude (ϕ) [3].

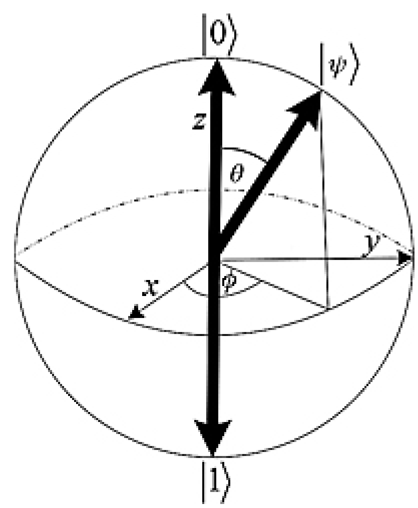

Figure 1. Bloch sphere. [3]

There is much more physics and mathematics behind these concepts, but this high-level understanding is sufficient for now. By imagining the vector $|\Psi\rangle$ inside the Bloch sphere one can begin to see how a qubit's value can be seen as some combination of 0 and 1 by looking at its angles in relation to the poles. It might be interesting to attempt to implement a simulation of Bloch spheres and associated values using quaternions. This is one way to visualize the fundamental building block of a qubit, and how its quantum information is "stored."

While the Bloch sphere illustration above shows a constant vector "value" of $|\Psi\rangle$, it is extremely interesting in that this is really a value of this qubit at a specific point in time. It turns out that when dealing with quantum mechanics and extremely small sub-atomic particles a microscopic object can "hazily" be in more than one state at any given instant [3]. This is what is known as "superposition" and is the last cornerstone of basic quantum mechanics discussed here before diving deeper [3]. In the example above, the "spin" of the qubit in some sense has multiple different angles θ and ϕ simultaneously [3]. This is the context in which the now famous thought experiment Schrödinger's cat is derived. The idea is a cat inside a sealed box is considered both alive and dead at the same time (superposition) until one looks into the box and the quantum superposition ends and the state "resolves" to either the dead or alive value.

3. Diving Deeper – Entanglement and Quantum Gates

Every time one "looks inside the box," hereafter referred to as "measuring" the quantum state, the superposition collapses to the true or false (1 or 0) values that computing professionals need to solve the provided problems [3]. To observe or measure the quantum state produces disturbances in the system itself causing this collapse, and forces a different way of thinking of how to execute operations [2]. A quantum computing system provides a challenge in that it requires three main points to be viable [2]:

- One must be able to control the system from outside the system itself
- The system needs to be isolated such that there are no disturbances
- The qubits need to be read out of the system to find a computation result

Reading a qubit, causing a disturbance, and forcing its value to resolve to a 1 or a 0 is considered an operation on the qubit itself and is considered a quantum gate [2, 3]. Recall classical computing gate operations such as AND, NOT, OR, XOR and so on. These are no longer viable ways of applying logic to qubits, since qubits do not fit the traditional molds of classical bits while in their superposition state.

As alluded to in the last bullet above, one qubit is not nearly enough. What happens when adding more qubits into a system? Because we are dealing with subatomic particles, it is unsurprising that qubits may interact with each other. For example, when considering electron spin or superconductor charge, we know from elementary physics that opposite charges attract and like chargers repel. The predictable outcome of qubits interacting with each other is known as entanglement [3]. When dealing with entangled qubits, by measuring some of them, the values of others are automatically known [3].

Purposefully entangling qubits and forcing different "spin" values to produce a desired quantum state of superpositions is considered exercising logic with quantum gates [3 - 6]. Much in the same way classical gates are combined to form classical circuits (i.e. "full adders," etc.), by stitching quantum gates together one is able to form a quantum circuit, which is essentially the implementation of a quantum algorithm [5].

Because one can never be sure of what the actual complex superposition value of the qubit is, the best we are able to do is to "bite the bullet" and measure the qubit, which injects a disturbance into the system and collapses the value to a 1 or 0. Without going too extreme into the linear algebra, one should be aware of the ability to represent a qubit's state not only as a vector, but as a matrix of probabilities that it will collapse into a specific 1 or 0 value [3, 5]. With this assumption, quantum gates can then be described in theory as "unitary matrices" that act on one or more qubit probability matrices [5]. Another interesting research opportunity might be to see how or if these computations can be simulated with GPU shader acceleration. Currently there are usually only one-qubit or two-qubit gates that are "naturally" supported by most quantum computing devices [5]. For clarity's sake the common "CNOT" gate is below.

By transforming the Dirac notation of a qubit's values to a matrix notation we begin to see how some of these linear operations can be performed. A classical bit (what the qubit value ultimately collapses to) can be represented by two 2 by 1 matrices [1]:

$$|0\rangle = \begin{matrix} 0 \\ 1 \end{matrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad |1\rangle = \begin{matrix} 0 \\ 1 \end{matrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Figure 2. 2 by 1 matrices of 0 and 1 states. [1]

By examining the matrix in brackets note how the value 0 is on the bottom of the $|0\rangle$ vector/state and the value of 1 is on the bottom of the $|1\rangle$ vector/state. A way to remember this correlation is to go back to the Bloch sphere illustration, where the value of 1 is on the "bottom" pole, where the bottom pole represents the "on" state. Using this same line of thought one can consider the aforementioned superposition states and the representation of these values using complex numbers. A way to illustrate a qubit is as

$$\begin{matrix} 0 \\ 1 \end{matrix} \begin{bmatrix} c_0 \\ c_1 \end{bmatrix}$$

Figure 3. 2 by 1 matrix of complex numbers. [1]

where c_0 and c_1 are both complex numbers, and $|c_0|^2 + |c_1|^2 = 1$ [1]. This means that c_0^2 and c_1^2 are the probabilities that when measuring the qubit (and causing its superposition collapse) the state will be found as $|0\rangle$ and $|1\rangle$ respectively [1]. With this matrix in mind examine the quantum CNOT gate, which stands for "controlled NOT" or "conditional NOT" [1]. These quantum gates might be described as similar to a classical comparison of an "exclusive not" gate where one "control" qubit is entangled with the "target" qubit [1].

$$CX = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Figure 4. CNOT gate CX and the "controlled" gate CZ.

Note the CNOT's matrix with relation to the identity matrix. Interesting that when multiplied by a 4 by 1 base 2 matrix certain values are flipped or not.

4. Fragile Hardware, Noise, and Error Correction

There is a balance between "interfering" with the system to apply the logic gates, and leaving it well enough alone to not disrupt the fragile quantum state [2]. Having a system isolated enough to produce even a handful of qubits is hard enough, often requiring extreme hardware to enforce near absolute zero temperatures to reduce noise [2, 4]. "Noise" in this context is any external force that influences the quantum state of the qubits attempted to be measured and used for calculations [2]. Because these sub-atomic particles are so microscopic and delicate, any and all changes to electromagnetic fields surrounding them can wildly influence results [2, 3].

Quantum Error Correction (QEC) provides some protection and isolation for the quantum system [2, 4, 5]. QEC "distributes a logical state among many physical qubits via quantum entanglement" [4]. What this means is that current technologies inevitably produce a lot of noise in quantum computations, but there are ways to account for the error at the cost of using many more qubits [2]. Recent shifts in perspective challenge this tradeoff by arguing that because real qubits are so hard to come by, using them for error correction is an improper use of resources and they would be better suited to performing additional computations. This of course comes with the risk of increased noise, but in certain circumstances and problems this may be acceptable [2].

Noisy Intermediate-Scale Quantum computing is the realization of this tradeoff [2]. This technology is available today, and provides scientists with as many as 50 to a "few hundred" qubits to work with [2]. 50 qubits are significant in that with this small number it is already beyond what can be simulated by "brute force using the most powerful existing digital supercomputers" [2]. While these types of quantum computers are not good for solving problems where precise measurements are necessary (i.e. breaking RSA with Shor's Algorithm) they are well suited for solving optimization problems and could be used for AI research, Neural Networks, and more [2]. It may be possible that this technology could also be used for research into finding optimal solutions of where to place mesh network equipment to obtain strong signal strength to as many endpoints as possible.

5. Scalability Challenges and Execution Analogy

The reason why such a small number of qubits can surpass classical computers for certain problems has to do with the entanglement idea mentioned before and the nature in which quantum computations are executed. Up to now the idea of two qubits interacting with each other via entanglement has been discussed. But when more than two qubits are introduced into the system, it is actually an *exponential* increase in the number of combinations of possible superpositions of the entangled qubits, as each qubit can interact with the others [6]. This inevitably leads to less stability the more qubits involved, further complicating the complexity of scaling out physical quantum computers with larger available quantum registers [2].

The final high-level thought to note is how the desired output is actually obtained. Recall that the qubits are manipulated via quantum gates usually in the form of entanglement with other qubits and carefully controlled electromagnetic properties. But the key difference to a classical computer in this regard is that these gates are not executed step by step, but rather these gates are applied to the entire system "as a whole" taking advantage of the properties of superposition allowing the qubit "value" to be more than one thing at a time [6]. John Preskill provides an excellent analogy to this concept in the form of a book. To summarize his thought, he compares reading a book page by page to classical computing [2]. By contrast, if there were such a thing as a "quantum book" reading page by page would be meaningless, as the book's information could only be understood "all at once" due to the nature of the pages being "entangled" with each other [2]. It is this instantaneous nature of computing many different values all at once that is ultimately the core advantage of quantum computing.

6. Closing

While not a perfect solution to all problems, the hope is that systems like NISQ computing will offer an essential stepping stone towards the quantum computing of the future. Enabling this type of research is critical to spurring the advancements needed to the hardware that allows the execution of the software. Minimizing the impact of QEC by either building systems less susceptible to noise, and/or larger systems that allow for more qubits to be used for the correction operations will help in these efforts. Quantum computing researchers today have the opportunity to focus on optimization type problems with NISQ computers to build strengths in the field.

7. Citations

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